Assessment of Impacts of Glen Canyon Dam Operations on Water Quality Resources in Lake Powell and the Colorado River in Grand Canyon

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understanding upstream/ downstream ecosystem interactions in the Grand Canyon and Lake Powell.

This document is dedicated to the memory of Dr. Charles L. Drake, who was one of the leading scientists in early Lake Powell research. He was a man of great enthusiasm and vision and, with his cohorts, began a legacy of holistic science. Dr. Drake died in July 1997.

Abstract

The effects of the construction and operation of Glen Canyon Dam have been studied, documented, and manipulated in the downstream environment in Grand Canyon. Glen Canyon Environmental Studies led 13 years of study that focused on addressing and mitigating the adverse impacts of the Dam on that ecosystem. While data has been collected from Lake Powell throughout its filling history, there has been no concerted effort to evaluate the impacts of dam operations on the physical, biological, and chemical processes of the reservoir and downstream releases. Using data from the 33-year history of water quality monitoring on Lake Powell, primarily from Bureau of Reclamation efforts, we will begin to demonstrate the effect of dam operations and other factors on the water quality and hydrodynamics of Lake Powell. Of special importance are the historical record reflecting the flood years of 1980 to 1986, modified operations of Glen Canyon Dam which began in 1991, the results from the Experimental Beach/Habitat Building Flood of the spring of 1996, and most recently, the high sustained releases starting in February 1997. No special data collection was designed to answer the question, but rather, the stock of existing data was analyzed to provide the answers and to fuel the questions that formed the assessment. The results show that, combined with other influences, dam operations have an undeniable effect upon the stratification and mixing of the reservoir, and those effects are consequently passed downstream through the dam. Not all aspects of dam operations could be answered or analyzed under the scope of the nine months allowed for the assessment. The experimental flood demonstrated the effects of using alternate structures for the release of water, in this case, the hollow jet tubes that are positioned 100 feet below the penstock withdrawal ports. The historic record of the 1980's indicated that the combination of high and repeated spring floods and high and sustained discharge from penstocks as well as spillways and hollow jet tubes caused substantial mixing of the reservoir. The recent spring's high-sustained

releases that were not initially accompanied by high inflow demonstrate the isolated effects of above average powerplant withdrawal.

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I. Introduction

The Grand Canyon Protection Act of 1992 requires the Secretary of the Interior to evaluate the impacts of Glen Canyon Dam operations on all affected resources. Although the primary evaluation of these impacts are on resources downstream of the dam, concern has existed that certain aspects of dam operations have the potential to affect various resource attributes upstream of Glen Canyon Dam.

In January 1997, the Grand Canyon Monitoring and Research Center (GCMRC) presented to its Planning and Transition Work Groups, a prospectus for assessing the effects of Glen Canyon Dam's operation on water quality resources in Lake Powell and Glen Canyon Dam releases (Appendix A). This document will serve to define the scope and objectives of this study, and will form the basis for review of the assessment process and results.

Three experienced reservoir limnologists from outside the federal government not currently connected with GCMRC have provided critical review. Three federal limnologists provided additional review from the Bureau of Reclamation and the U.S. Geological Survey. Final results of the assessment will be reviewed by a Science Advisory Group and presented to the Adaptive Management and Technical Work Groups.

A. Scope and Objectives of Assessment

This assessment is an effort to integrate existing data from current and past monitoring programs on Lake Powell in order to evaluate the effects of various aspects of Glen Canyon Dam operations, from 1965 to 1997, on reservoir and release water quality. Primary consideration will be made to peaking power generation, operation of non-power release structures, and potential selective withdrawal. An attempt will be made to identify other factors affecting Lake Powell such as the existence and structure of Glen Canyon Dam, climatological factors, and internal hydrodynamic processes, so that these impacts are not inappropriately associated with dam operations. The assessment will rely mainly on data from the Bureau of Reclamation's long-term limnological monitoring program on Lake Powell, the current monitoring program, implemented in 1990 and currently maintained by GCMRC, and information from other agencies and institutions.

Several factors combine to limit the scope of this assessment. A relatively short time frame was specified for completion of this study. Budgetary constraints limit the amount of financial and human resources dedicated to this process. The quality and completeness of data from past monitoring efforts may be insufficient for certain evaluations and may not have focused on important affected resources. Some information has not yet been organized into a form that facilitates analysis and some samples await analysis. Therefore, the scope of this study will be limited to the analysis of those data which have been 1) consistently collected over a long period of time; 2) are readily available for computer analysis; and 3) will most likely show the effects of dam operations on the chemical and physical limnology of the reservoir.

In this context, the term *water quality* is used to include the various physical, chemical, and biological attributes that characterize a body of water in terms of its hydrodynamic properties, chemical composition, and the organisms that live in it. Its use is not intended to connote any value judgments based on suitability for a given use.

B. Purpose of Assessment

The closure of Glen Canyon Dam in 1963 caused major changes to the physical, chemical and biological characteristics of the Colorado River in Grand Canyon. These changes are well documented and include the removal of sediment and the moderation of temperature, salinity and other chemical extremes. Operation of the dam for peaking power generation resulted in the removal of seasonal discharge variability and its replacement with daily discharge fluctuations

(Gloss *et al.* 1981, Ward and Stanford 1983, Stanford and Ward 1986, 1991, Angradi *et al.* 1992, Stevens *et al.* 1997).

Concurrently, changes were also made to the Colorado River as it began to form Lake Powell upstream of Glen Canyon Dam. The river was slowed and began depositing sediment in the reservoir basin. Vertical temperature and chemical gradients appeared in the reservoir body due to seasonal density variations of the inflows, climatic factors, and the mid-depth location of the powerplant penstocks. Certain aspects of dam operations over the past 33 years are hypothesized to have impacts to many of the reservoir's resources, especially water quality. Comprehensive scientific assessments have not been conducted to determine the extent of these impacts.

Current and past monitoring programs on Lake Powell have been designed with fairly broad perspectives in order to understand more about processes that affect various resource areas of concern. Understanding and monitoring salinity trends and patterns in the Colorado River and its reservoirs has long been important to maintaining adequate quality for downstream uses under future water development conditions and has been a primary focus of Reclamation's long-term monitoring program. Chemical changes occurring in a filling reservoir have implications to maintaining fisheries and supplying nutrients to downstream environments. More recently it has become important to understand the processes in Lake Powell that determine the physical, chemical, and biological characteristics of downstream releases to the Grand Canyon ecosystem. This was a primary objective for the revision of the Reclamation 's Lake Powell monitoring by the Glen Canyon Environmental Studies office in 1990. Evaluation of a potential selective withdrawal structure on Glen Canyon Dam will require an understanding of hydrodynamics, warming processes, thermal budgets, and biological effects upstream and downstream of Glen Canyon Dam. The effects of planned or unforeseen operational changes at Glen Canyon Dam may have far reaching effects on varied physical, biological, and cultural resources in the Grand Canyon and on Lake Powell.

The challenge of any long-term monitoring program is to collect data focused on addressing issues of current concern while being broad based and of sufficient quality to answer questions which may arise in the future while maintaining a reasonable expenditure of resources. It is our belief that data from past and existing monitoring programs on Lake Powell can be evaluated to identify effects of various aspects of operation of Glen Canyon Dam and, at the same time, provide valuable information to scientists and managers from a broad variety of resource areas. By balancing information needs, resource expenditures, and monitoring program objectives, a valuable evaluation tool for future adaptive management may be maintained.

C. *Affected Resources*

Many processes in Lake Powell are influenced by factors not directly related to dam operations such as inflow hydrodynamics, climatological conditions, and the existence and structure of Glen Canyon Dam. However, some water quality attributes of Lake Powell and downstream releases may be affected by certain aspects of the operation of Glen Canyon Dam. These effects can be evaluated from data developed in existing monitoring programs.

Three main interlinked resource categories may be affected by the operation of Glen Canyon Dam and other factors. Physical and chemical conditions in Lake Powell address evaporative water loss, temperature regime and heat budget, salinity levels, hydrodynamics and mixing patterns, nutrient and trace element concentrations, and sediment deposition. These characteristics, in turn, influence the biological resources of Lake Powell and the Colorado River below the dam. Affected biological components may include primary productivity, algal and zooplankton abundance and composition, and the dynamics of fish populations, waterfowl, and higher species. The third affected resource category involves social and economic components such as power production, water delivery, cultural and historic resources, recreation and public health.

While direct linkages exist among these resource categories, identification and evaluation of effects to all these resource categories is impossible within the current time constraints, budget setting, and data limitations. The scope of this assessment will therefore mainly focus on the various physical and chemical water quality attributes associated with Glen Canyon Dam operations for which information has been or is currently being gathered.

II. Background Information

Concurrent with historical changes in dam operations and reservoir conditions, Reclamation has maintained a water quality monitoring program on Lake Powell since 1965. By associating the monitoring effort with historical dam operations, increased understanding can be gained of effects of dam operations on reservoir resources.

A. Brief History of Lake Powell and Glen Canyon Dam Operations

Lake Powell has had a relatively short existence as an operating reservoir. Its history can be described in terms of three major periods in Glen Canyon Dam operations.

1963-1980. The seventeen-year period from 1963 to 1980 resulted in the eventual filling of Lake Powell to its normal pool elevation of 3700 ft. With minor exceptions, this period was characterized by constantly increasing reservoir elevations, increasing depth of the penstock withdrawal zone, and continual inundation of new areas of the reservoir basin. Stable stratification patterns in temperature and salinity developed from the constant withdrawal at the penstock level.

1980-1990. Relatively full reservoir levels characterize the period from 1980 to 1990. A succession of high runoff years in the early and mid 1980's brought the reservoir 8 feet above its normal pool level in July of 1983. Because of the need for increased releases from Glen Canyon Dam, the spillway structures and hollow jet bypass tubes were operated on several occasions. This allowed significant amounts of water to be released from levels above and below the penstock zone. These factors combined to cause nearly complete mixing of the reservoir in 1985, due to the high volume of reservoir throughput and the operation of the alternative release structures. In the late 1980's, drought conditions returned to the upper basin and resulted in decreasing reservoir levels and the return of strong chemical stratification below the penstock level.

1990-1997 The period from 1990 to 1997 was marked by a series of manipulations to the operation of Glen Canyon Dam for scientific and environmental purposes. Before this time, the dam was operated primarily for peaking power generation and water delivery to the Lower Basin States. In 1990, Phase II of the Glen Canyon Environmental Studies and the development of the Glen Canyon Dam EIS began. As part of the GCES Phase II Integrated Research Plan (USBR 1990), a series of research flows was initiated from June 1990 to August 1991. These flows ranged widely in daily fluctuations and ramping rates, interspersed with periods of steady flow. In November 1991, following the research flow period, the Secretary of the Interior implemented the Interim Operation Criteria, which set limits on minimum and maximum discharge, daily range of discharge, and hourly ramping rates. These criteria remained in place until October 1996, when the Secretary signed the Record of Decision for the preferred alternative of the Glen Canyon DAM EIS (U.S. Bureau of Reclamation 1995 and 1996).

Of significance during this latter period was the experimental beach/habitat building flow in March and April 1996. This 7-day discharge of 45,000 cfs included a release of 15,000 cfs from the river outlet works of Glen Canyon Dam. The operation of this structure released water from

100 feet below the penstock withdrawal zone and weakened the strong chemical stratification that had previously built up below that level.

In February 1997, increases in Upper Colorado River Basin runoff forecasts prompted an increase in Glen Canyon Dam releases that were sustained at levels above 20,000 cfs for the remainder of the summer months. This represented a different operational pattern to handle the forecasted runoff than in 1983, which experienced similar hydrologic conditions.

B. Reclamation Monitoring Program

Table 1. Major Features of Monitoring Program Phases

	Phase 1 1965-1971	Phase 2 1972-1981	Phase 3 1982-1990	Phase 4 1990-Present
Frequency: forebay reservoir	monthly quarterly	monthly monthly	quarterly to yearly	monthly quarterly
number of stations	8	8	8-10	15-20
Parameters	Temp. DO (Winkler)	Temp. DO (Meter)	Multiprobe profiling (T, SC, DO, pH, ORP)	Multiprobe profiling with datalogger
chemistry	Major Ions	Major Ions	Major Ions (Shipboard processing)	Major Ions Nutrients
sampling interval	50 ft	50 ft	50 ft	Variable
biological sampling	none	none	qualitative plankton	chlorophyll phytoplankton zooplankton
inflow monitoring	none	none	selected sites	selected sites
tailwater monitoring	none	none	below dam T, SC	below dam Lees Ferry T, SC, DO

The Bureau of Reclamation initiated a water quality monitoring program on Lake Powell in 1964 to gather information on initial water quality conditions and to observe changes as the reservoir filled and matured. This program has continued to the present. Based on sampling frequency, spatial resolution of measurements, and changes in instrumentation, four distinct phases of monitoring activity can be identified (Table II-1).

From 1965 to 1971, monthly sampling of the Glen Canyon Dam forebay and quarterly surveys of the entire reservoir for temperature and salinity characterized monitoring activity. Measurements and samples were collected at 50-foot depth intervals at seven locations on the reservoir.

From 1972 to 1981, the frequency of lake-wide surveys was increased to a monthly basis.

From 1982 to 1990, sampling activity steadily declined to single lake-wide surveys in 1988 and 1989. Despite the decline in sampling frequency, advances in instrumentation allowed the collection of higher quality data at finer depth resolution. Continuous monitoring of temperature and salinity of the tailwater was initiated during this period.

In 1990, concurrent with the implementation of GCES Phase II studies, Reclamation's Lake Powell monitoring program was restructured. Monitoring frequency was returned to a level of monthly forebay surveys and quarterly lake-wide surveys. During the Phase II Research Flow period from 1990 to 1991, the monthly forebay surveys were conducted by the US Geological Survey (Hart and Sherman, 1995)). This restructuring resulted in a redistribution of resources to allow the collection of data at a finer spatial resolution while reducing the number of samples collected for chemical analysis. Sampling for nutrient chemistry and biological conditions was also initiated. The objective of this phase of monitoring activity was to establish a program of basic data collection that would balance cost with the ability to track changes in reservoir and release water quality and evaluate the effects of Glen Canyon Dam operation on these resources

Various agencies and institutions during Lake Powell's history have conducted other work. Studies have been conducted by educational consortiums and federal and state agencies on subjects that include sedimentation, circulation patterns, trace element chemistry, remote sensing, and public health issues (Potter and Drake, 1989).

C. Details of Current Monitoring Program

The current monitoring program was initiated in 1990 in response to the need to understand how physical and chemical processes in Lake Powell and the operation of Glen Canyon Dam influence the quality of water released to Colorado River in Grand Canyon. Based on limited personnel and financial resources, efforts were made to incorporate existing technology to improve the overall quality and resolution of measurements taken, eliminate unnecessary activities, and automate routine data collection tasks. This program balances a broad based, high quality, data collection program with limited resources.

1. Quarterly Lake Wide Sampling

Based on characteristic seasonal patterns and conditions, lake-wide sampling is conducted on Lake Powell on a quarterly basis. Efforts are made to describe the physical and chemical conditions of the major strata of the reservoir in the main Colorado River channel and the major tributary arms of the San Juan and Escalante Rivers.

Sampling takes place over a week-long period and consists of measurements and chemical samples collected at 20-25 established stations along the main channel and major tributary arms. After initial surface observations are made, a profile of the physical parameters of temperature, specific conductance, dissolved oxygen, pH, redox potential, and turbidity throughout the water column is collected. This provides details of the density stratification patterns separating the significant layers of the reservoir, location of inflow currents, dissolved oxygen patterns and overall chemical conditions in the reservoir. Results are recorded on portable data logging equipment for immediate viewing in the field and automated transfer to data management systems.

Based on the stratification patterns seen from the physical profile, depths for discrete chemical sampling are determined, with the objective of characterizing the major ion and nutrient content of the significant layers of the reservoir. Sample processing is performed on shipboard for later analysis at a remote laboratory. Alkalinity titrations of these samples are also performed on shipboard.

Biological sampling consists of chlorophyll sampling of surface samples, collection of discrete samples for phytoplankton and vertical tows for zooplankton.

2. Monthly Forebay Sampling

Monitoring of the forebay of Lake Powell is performed monthly at the long-term Wahweap station. This site has been sampled monitored throughout Lake Powell's history and is located in the main channel at the confluence with Wahweap Bay, 2.4 channel kilometers upstream of Glen Canyon Dam. Chemical and biological sampling similar to that for major stations on quarterly surveys is also performed.

3. Tailwater Monitoring

Continuous water quality data collection is maintained at three locations in the Glen Canyon Dam tailwater. The first and most long-term running station is a perforated pipe below the river outlet works (a.k.a., hollow jet valves), immediately downstream of the Glen Canyon Dam powerplant on the left wall. This site has been in operation since August 1980 measuring temperature and specific conductance at intervals of two hours or less. Dissolved oxygen monitoring was initiated November 1990; pH measurements were started July 1995.

A second station is near the USGS Lees Ferry stream gage (09380000), in operation since October 1991, recording temperature, specific conductance, and dissolved oxygen. pH measurements were added August 1996.

III. Assessment Process and Data Analysis

A. Data sources

The assessment process consisted of integrating water quality data from various monitoring phases to describe historical and seasonal patterns and trends in the water quality of the main-channel reservoir body and the Glen Canyon Dam forebay, identify seasonal and long term variability, and describe unusual conditions associated with reservoir operations or other factors. Water quality data is present in the form of surface observations from a site visit, profiles of physical parameters through the water column, and the results of laboratory analyses of chemical samples. Hydrologic data was acquired to build a database of historical inflows, reservoir contents and surface elevation, Glen Canyon Dam powerplant releases, and non-power releases from alternate outlets on Glen Canyon Dam to associate water quality changes with hydrologic or operation patterns of the dam.

1. Lake Powell

a. Physical Profiles

A large part of the assessment analysis is based on the evaluation of the profiles of physical parameters collected on lake-wide surveys at each established station and monthly at the Wahweap forebay station. These profiles provide fine detail of changes through the water column. The increase to the number of main channel stations and the monthly frequency of forebay sampling provides adequate longitudinal and temporal resolution, respectively, for the purpose of describing vertical density gradients, longitudinal reservoir gradients, and the seasonal and temporal variation seen in these patterns.

Temperature patterns lend information to warming processes, thermal content of the reservoir, and density characteristics. Consistent temperature has been regularly collected through the reservoir since monitoring began in 1964

Specific conductance is an indicator of a solution's ability to conduct electricity, a function of the amount of total dissolved substances (TDS) in solution. It is much more readily determined in the field than a laboratory analysis for TDS and is therefore used as an indirect measure of salinity. As such, specific conductance measurements give an indication of the chemical makeup of a parcel of water and can be used to identify its origin and density characteristics. Field measurements of specific conductance were not taken during most of the 1970's. Where absent, they were replaced with lab-measured values.

Dissolved oxygen measurements can give an indication of biological and physical processes at work in the reservoir, the amount of organic material carried by a water parcel, and its degree of atmospheric exposure. Oxygen is produced as a byproduct of photosynthetic activity and is consumed by respiratory and decomposition processes. High oxygen concentrations are therefore seen near the surface in the early summer when photosynthetic activities are high. Oxygen concentrations may be depressed at density gradient boundaries or in the deeper portions of the reservoir due to buildup, at these locations, of autochthonous or allochthonous organic material subject to bacterial decomposition.

b. Chemical Samples

The collection and analysis of chemical samples is valuable for determining the chemical composition of the major ionic constituents that comprise the dissolved substances in a body of water. This information may be used to determine a fingerprint of the water to identify its source, the degree of saturation of a particular mineral, or suitability for a given use, such as irrigation.

Chemical analysis is frequently the only way to determine the quantity of certain substances in solution, such as nutrient compounds.

c. Biological Samples

Biological monitoring in Lake Powell was initiated in 1990 to attempt to establish a link between chemical and physical characteristics and higher trophic levels. The analysis of these samples has not been fully completed. Furthermore, most biological activity in Lake Powell that would be identified by the analysis of zooplankton and phytoplankton samples takes place near the surface and is probably less effected by normal dam operations than other chemical and physical indicators. Therefore, although these samples may prove valuable in identifying water quality effects and trophic linkages, their analysis has not been incorporated into this assessment.

2. Glen Canyon Dam Releases

a. Hydrologic Data

Data to quantify the amount of water discharged from Glen Canyon Dam comes from two main sources. The most immediate source is powerplant releases from Glen Canyon Dam. These data are the result of powerplant hydropower generation, integrated on an hourly period, and converted to discharge in cubic feet per second (cfs) depending on generator rating curves and powerplant head. These data form the basis for meeting the operational constraints set by the Glen Canyon Dam EIS and Record of Decision. Data exist from 1965 to the present and separate powerplant release from those of alternate spillway and river outlet works structures (U. S. Bureau of Reclamation, 1921-1997).

The other source of hydrologic data is the U.S. Geological Survey (USGS) stream gage, Colorado River at Lees Ferry, AZ (09380000). Discharge data is obtained every half hour from satellite telemetered stream gage measurements applied to a discharge rating curve. These unit value data begin in January 1985 and continue through the present. Daily values exist for the Lees

Ferry gage from October 1921 and are used to represent pre-dam conditions in the Colorado River (U.S. Geological Survey, 1985-1996)

b. Time Series of Physical Parameters

The varying quality of Glen Canyon Dam releases were studied using data from two sources. The USGS has maintained water quality monitoring for salinity and specific conductance at the Colorado River at Lees Ferry gage (09380000) since 1944. These data exist in USGS daily values tables. Prior to 1977 single daily measurements for specific conductance were made (daily values statistic code 00011). Since that time, specific conductance has been measured at specific intervals with automated mini-monitor instrumentation; mean daily values are calculated from these data (daily values statistic code (00003).

Reclamation began its water quality monitoring of the Glen Canyon Dam tailwater as part of Phase I of the Glen Canyon Environmental Studies program in August 1988. This program was begun with measurements of temperature and specific conductance at bi-hourly intervals. As instrumentation improved, measurement of dissolved oxygen was added in June 1991; pH measurements began in July 1995. Monitoring at Lees Ferry was initiated in October 1991. This monitoring has been conducted with various versions of the Hydrolab™ Corporation's Datasonde and Recorder submersible multi-parameter data logging instrumentation (Hydrolab, 1994). These monitors are serviced on a monthly basis. The Grand Canyon Monitoring and Research Center (GCMRC) currently maintains this program.

c. Chemical Analysis

The Colorado River at Lees Ferry gage (09380000) gage is maintained as part of the USGS National Stream-Quality Accounting Network. Analysis of a broad range of water quality parameters and contaminants is conducted on samples collected on a bimonthly basis.

As part of the monthly servicing of the tailwater instrumentation maintained by GCMRC, samples are collected and analyzed for major ionic constituents and nutrient concentration and analyzed according to standardized procedures (APHA, 1992). Biological samples similar to those collected at reservoir stations are also collected.

B. Data management

Prior to the mid-1980s all data was stored as hard copy records in binders. Over time, more data can be generated and stored electronically, but a large quantity of historical data has remained in hard copy form. During the past seven years, efforts have been made to enter these data into electronic formats to facilitate data management and analysis. Recently a large project involving entry of the past 34 years of chemical analyses was completed.

A relational database was designed and implemented in the mid-1980s to store and manage data from physical profiles and laboratory analyses. This database has under gone several changes and refinements. Currently available data is now served from an Ingres database management system. Data is transported from this system to SAS© software (SAS© Institute Inc., 1996) for statistical analysis, summarization, and graphical representation. Work is currently in progress to move this database to the Grand Canyon Monitoring and Research Center's Information Technology program under the Oracle database management system.

C. Data Analysis

Three-dimensional analysis for depicting longitudinal changes through the reservoir and temporal changes in the forebay was done with Surfer© and Grapher© software (Golden Software, 1996 and 1994), which performs interpolation, gridding, and contouring of three dimension data. With this software, images may be generated which depict changes in temperature, for example, on a two-dimensional framework of depth through the water column and distance from the dam, giving, in effect, a cross-sectional view of water quality conditions throughout the reservoir body.

This is also used to display changes in a given parameter with depth at the forebay station over a sequence of time. These three-dimensional analyses form the primary basis for describing water quality patterns in the reservoir.

IV. Results

A. Lake Powell

1. Introduction to Limnology

Interpreting the trends and history of Lake Powell's requires the grasp of some basic limnological principles as well as some specifics peculiar to Lake Powell (Wetzel 1975, Cole 1994). There are a few components that drive the seasonal and yearly patterns of the lake; resulting in fairly predictable horizontal and longitudinal stratification (Figs. 1,2a, 2b, 3a and 3b; Merritt and Johnson 1979, Gloss *et al.* 1980, Edinger *et al.* 1984, Stanford and Ward 1986, Potter and Drake, 1989, Thorton *et al.* 1990).

It is important to first become familiar with the most common and pertinent limnological terminology, then to build an understanding of the basic processes that drives the conditions found in the reservoir. Only then can valid conclusions be drawn that differentiate inflow processes from discharge dynamics.

a. Stratification:

1) Vertical Stratification

Lakes exhibit vertical stratification based on density gradients. (Fig. 1)

Epilimnion: The surface layer of the lake characterized by the least dense water resulting from warmer temperatures and lower conductance. It is the most biologically active portion of the lake due to light availability and higher oxygen concentrations.

Metalimnion: A boundary or steep gradient between the epilimnion and the hypolimnion.

Hypolimnion: The dense, cold, saline water at the bottom of the lake. It is fairly stable and resistant to mixing. It is dark and has low oxygen levels; consequently bacteria tend to be the dominant life form.

Thermocline: A thermal boundary or gradient between water masses of different temperature.

Chemocline: A chemical boundary or gradient between water masses of different salinity.

Meromictic: A condition of persistent high salinity in the hypolimnion that resists mixing because of a strong chemocline.

Hypoxia: Low levels of oxygen associated with bacteriological respiration and chemical reduction.

Anoxia: The absence of measurable oxygen in a water body.

2) Horizontal Stratification

Horizontal or longitudinal stratification gradients are generally a reflection of the distance from the riverine inflow.

Riverine conditions dominant in the reach where the river is still flowing within a channel even though it may be just below the lake level. This condition consistently exists within the Cataract Canyon reach.

A Transition zone occurs as the river conditions merge with the typical deep lake conditions.

Lacustrine conditions are characterized by pronounced vertical stratification as described above.

b. Hydrodynamic processes

Hydrodynamic processes are those that drive the stratification and mixing of the lake and include:

Density: The property of denser masses to sink is key to lake dynamics. Temperature and dissolved chemicals are the fundamental components that determine density differences. Warmer water is less dense than cold water (down to 4°C), and pure or "fresh" water is less dense than water with many dissolved chemicals (reflected by measurements of electrical conductivity or salinity--terms used here interchangeably).

Advective Flow: A lateral or pushing current, typically horizontal, driven by the momentum of an inflowing current.

Convective circulation: As stratified water cools in the fall, the surface becomes denser than the underlying layers, eventually displacing it as the warmer water rises. This vertical density driven mixing is enhanced by wind action. The depth of convective mixing is dependent on the volume of the spring flood, as well as on the coldness of the winter. Sufficiently deep or aggressive mixing may penetrate metalimnion.

Density currents: A water mass that seeks its own level based on differences in density from adjoining water masses. Its movement also involves an advective component from river inflow. This includes the bottom hugging winter flows in Lake Powell.

Withdrawal currents: The current patterns established in a lake due to the operations of withdrawal ports in a dam. In general, increases in discharge result in a 3rd power increase in kinetic energy available for mixing, as $KE \propto Q^3$ (Thorton *et al.* 1990); this extends the vertical draw of the outlets. Hence, the increase from a discharge of 5000 cfs to 30,000 cfs increases mixing and destratification by 216-fold, while total discharge only increased by 6-fold.

Wind Mixing: The vertical mixing of surface layers of a lake due to wind shear. Its effect is deepest when combined with convective mixing on a homogeneous mass than on a strongly stratified water body.

Diffusion, Dispersion and Entrainment: Diffusion is the passive mixing of water across a concentration gradient. Dispersion is the active mixing of water across a concentration gradient involving advective movement. Entrainment also involves advective movement that incorporates water from adjoining masses of water.

2. Seasonal Patterns seen at Lake Powell

All the above properties come to bear on the mixing and stratification of Lake Powell's waters. Traditional categories of epilimnion, metalimnion and hypolimnion tend to oversimplify the stratification of Lake Powell, which can have up to 4 or 5 chemoclines and several thermoclines separating various flows. Differences in stratification occur in a temporal dimension as well as vertical and longitudinal. The following describes the dominant seasonal inflows and circulation cells of Lake Powell (bottom panel, Fig 1). Timing of these events can typically vary a month or more in either direction. Isopleths for temperature, conductivity and dissolved oxygen for 1975 and 1976 (Figs. 2a and 2b) show a sequence of generally typical snapshots of water quality, as do the isopleths of the longitudinal profiles (Figs. 4-10).

a. Surface Processes:

Spring Flood: This is the yearly dominating lake event, dictated by the magnitude and timing of the spring headwater snow-melt coming down Cataract Canyon and the San Juan River and into Lake Powell from May to July. These waters are typically fresh (lower conductance/ salinity) and initiate the warming processes in the lake since the rivers are the first to warm. The spring freshet may begin injecting at the surface, but the bulk of the flood drops 10 to 20 meters below the surface of the lake as spring progresses and the lake surface warming exceeds river temperatures. Though not as warm as the lake's surface, the volume of relatively warm flood water will dictate the thickness of the epilimnion.

The fresh waters of the typical spring flood reach the dam by July as the last of the snow-melt enters the reservoir. A small flood moves toward the dam more slowly than a large flood and its signature may not be seen at the dam before it is dissipated by convective mixing in the fall.

Although riverine waters are well oxygenated, the organic and chemical nutrients within the flood waters place a high oxygen demand that results in a precipitous drop in oxygen levels beginning in July and continuing through fall. The trace of this dissolved oxygen sag, superimposed and just below the flood plume, denotes the settling of detritus that fuels the hypoxic (or low oxygen concentration) cycle.

Convectively Mixed Epilimnion: Autumn surface cooling and convective mixing begins lake-wide in September and reaches it deepest extent around January. The previous spring's flood is mixed with past years' floods and may entrain the top of the hypolimnion; the conductance of the convectively mixed epilimnion is a reflection of these layers. Almost any size flood will significantly freshen this layer, but larger floods produce greater freshening. It is likely each mixing event is entraining floods or the convectively mixed epilimnion from two or more previous years.

Not only does a large flood result in a much fresher convection cell, but, again, it also produces a thicker and warmer body of water. The cooler temperatures and the mixing process result in progressively elevated dissolved oxygen levels in this layer as winter progresses. This results from the higher oxygen-carrying capacity of cold water as well as algal productivity that thrives on the mixed and composted flood waters. As winter progresses into spring, oxygen levels increase, typically exceeding super-saturation from February to May.

b. Bottom Processes:

In the winter, cold temperatures combine with advective currents from the inflows to produce bottom hugging density currents. In Lake Powell these cold bottom plumes repeatedly divide into three distinct masses depending on the time and meteorological conditions under which they form. These bottom plumes are critical to the long term chemical and physical conditions found in the hypolimnion (Edinger *et al.* 1984, Merritt and Johnson 1978, Johnson and Merritt 1979, Gloss *et al.* 1980, Stanford and Ward 1991). One year's events can sometimes be tracked for years if mixing is unable to penetrate the hypolimnion.

Late Summer/ Fall SWARM (Saline WARM water): In late summer /early fall the river inflow has become very warm and saline due to the reduced hydrograph, irrigation return flows and greater solubility of salts in the geologic stratum of the watershed. Initially this flow intrudes into the spring flood below the lake's surface, but as fall progresses, this mass becomes colder and eventually sinks. The late summer salinity plume is convectively mixed with the colder bottom hugging flow; which we have dubbed the fall SWARM bottom flow because of it's high Salinity and relative WARMth (compared to other bottom layers). Oxygen levels are typically low due to high oxygen demand from the inflow. This cell of water is the greatest contributor of salinity to the hypolimnion on an annual basis. As the SWARM plug flows downlake, it incorporates-- through diffusion, dispersion and entrainment --the previous winter's underflows that have remained relatively stagnant since the spring flood first appeared. When this saline mass of water reaches the dam (between February and March), it contributes to the state of meromixis if of sufficient salinity to resist subsequent mixing.

Deep Winter FRESCO: During the deepest cold of winter, convective mixing is most extensive. In the inflow area, the winter river inflow is at its coldest, most oxygen saturated, and saline. This cold saline winter inflow is mixed (convective mixing and entrainment) with the last of the spring flood near the inflow. A relatively FRESh plug of the lake's COldest most oxygenated water results. The FRESCO bottom flow follows the SWARM plug down the bottom of the lake, typically set in motion in January and February.

The FRESCO's downlake momentum will eventually reach the SWARM which has made contact with the dam. The momentum of the FRESCO rocks the hypolimnion like a lever, moving the uplake chemocline downward as the chemocline at the dam moves upward. It is at this time that the highest conductivity, lowest temperature and lowest dissolved oxygen levels are discharged from the penstocks, as seen in Lees Ferry water quality (Figs. 12-15). At this point uplake, the fresh cold bottom plug typically has three options. 1) Hypolimnetic Overflow: If the FRESCO flow is not sufficiently cold or the chemical gradient between it and the meromictic salty warm bottom plug is too great, its momentum will carry it over the hypolimnion where it is entrained by the penstock withdrawal plume suction from dam releases pull it up toward the penstocks. The penstocks will continue to draw on this layer (as well as others) until the following winter when the next SWARM reaches the dam. This is the most common scenario, occurring 14 of the past 33 years. 2) Hypolimnetic Underflow: If it is sufficiently cold and dense, the FRESCO will continue downlake on the bottom, displacing the hypolimnion upward toward the penstocks and perhaps not stopping until it reaches the dam if of sufficient magnitude. An underflow that reaches the dam is the most efficient process for removing meromixis and restoring oxygen to the hypolimnion without non-powerplant releases. This is also the least common scenario, occurring only 6 times since Powell's filling (1973, 1983, 1984, etc.). 3) Hypolimnetic interflow: Several factors can contribute to this process. If the advective forces are removed from the bottom currents through diversion to surface flows in the spring, the bottom currents stall and the plumes substantially slow or cease to move toward the dam. The discharge from the dam may continue to pull the FRESCO through the SWARM at a depth that corresponds to the relative density and momentum of the respective flows. Furthermore, if the chemical or thermal gradients are insubstantial, the FRESCO and SWARM plugs may mix through diffusion and dispersion. This interflow is more common-occurring approximately 12 of the past 33 years. The amount of meromictic removal is a function of the depth of the interflow.

Late Winter SCOOL: The final of the three bottom hugging winter plumes, the late winter SCOOL plug has higher salinity concentrations than FRESCO but is not as cold. There are less of the previous spring's floodwaters left to convectively mix with the saline but warming riverine water. This Saline and COOL flow forms around March and follows the FRESCO plume down the lake's bottom. Its progress is typically stalled by April or May when warming and the advective flow forces are diverted to the spring flood at the surface. Organic and chemical oxygen demands, low light availability, and prolonged stagnation keep oxygen levels low in this cell. It typically does not move downlake until the following winter when the SWARM's bottom hugging flow will entrain it as its flows to the dam. An animated sequence of the longitudinal salinity profiles for Lake Powell since 1965 can be found at website www.usbr.gov/gces. This demonstrates the inflow and outflow dynamics under various filling, drought and flood cycles.

c. Side Channel influences

While the most of the side channels have not been examined throughout Lake Powell's history, the San Juan and Escalante Rivers have been received some attention, primarily with the instigation of the GCES program. The Escalante River contributes only ~5% of the total inflow to Lake Powell, yet produces a regular and pronounced effect on the main channel salinity and dissolved oxygen levels (Figs. 8-10). Stagnant conditions and very low oxygen levels frequently produce an oxygen sag and a salinity peak in the main channel year round, frequently at penstock levels. The San Juan Arm, on the other hand, has greater discharge rates and does not suffer from the anoxic conditions found in the Escalante arm. Occasionally the San Juan channel produces a bottom flowing FRESCO plume in the winter that reaches the main channel of the lake, creating a rise in oxygen concentrations that does not correspond to cold temperatures arising from the main channel.

3. Historic Patterns seen at Lake Powell

In the following discussion, We found it useful to use a ranking system to compare lake attributes and reactions against such outside factors as total inflow or outflow for the year, coldness of winter, hotness of summer. A table of these rankings is found in the appendix.

a. Filling Period (1963-mid 1970's)

While Lake Powell did not reach full pool until 1980, by 1973 to 1975 it reached a level of normal fluctuations. By the mid-1970's most of the indicator parameters (temperature, conductivity and dissolved oxygen) had stabilized. This early period of filling was characterized by low lake volume and reduced releases, resulting in a higher exchange rate for the water within the lake: between 124% to 380%. This indicates that the entire lake's water quality was more rapidly dictated by inflow water quality than in subsequent periods, and such was the case in the 1960's.

Interpretation of this period is hampered by erratic data collection--there are holes in temperature and dissolved oxygen data at critical junctures, as well as irregularities in the temporal sampling. Some conclusions can still be drawn from this period.

One of the signatures of this filling cycle was an 8th ranked flood (the 8th highest annual inflow in Lake Powell's history) in 1965. This tremendous volume of water appeared at the dam with the lowest conductance values recorded since the lake's filling.This plume of fresh water shows clearly in Fig. 3a and the longitudinal plots of Fig. 4, but doesn't have the diluting effect that one could expect from the mass it represents, for it is flushed from the lake within 2 years. It is apparent is some of it is mixed into the hypolimnion by early 1966, but by 1967, the fall SWARM plug has substantially salinized the lake. In spite of the high volume turnover rates for the 1960's, this extremely salty hypolimnion (values up to 1300 μS/cm) developed with only one season's inflow, but required 5 ½years to dilute to previous levels. One reason is the nature of the

SWARM flow to quickly dominate the hypolimnion if it is of sufficient salinity, while the diluting processes of the hypolimnetic overflow or underflow is less efficient. Winter inflow salinity values today range from 800 to 1200 μS/cm. This cycle of events is a product of the low level of the lake, and the placement of the penstocks and river outlet works, which were both functioning in this period.

In addition, the left river diversion tunnel, at the bottom of the dam, had not yet been sealed, and was used for discharges when the lake level had not yet reached the jet tubes or penstocks or when higher discharge could not be achieved through the penstocks and jet tubes alone (U.S. Bureau of Reclamation, 1970, Martin 1989). At these low lake levels, both upper release ports drew from the epilimnion, stripping out the spring floodwaters before they were integrated into the lake's depths, while the diversion tunnel drew off the deepest hypolimnetic waters. The result was rapid turn-over of the lake's volume in 1965 with pronounced refreshment of the hypolimnion. The diversion tunnel was permanently sealed in September 1965. The bi-level epilimnetic withdrawals that followed in 1966 and strong SWARM currents that followed in the late 1960's resulted in an exceptionally persistent and very saline hypolimnion-meromixis-- that dominated the lake through 1971.

Oxygen levels for this period remained fairly high. Although the early dissolved oxygen data was sometimes noisy, the pattern of winter oxygenation predictable under the circumstances. Although quite saline, the winter bottom flows were cold and well oxygenated. Furthermore, these flows were entering a smaller lake and the cold, oxygenated FRESCO plume had less distance to travel to the dam than in later years when the lake was deeper and longer.

b. Drought Cycles

For the purposes of this assessment, basin-wide drought is measured by the total inflow to the lake and not local weather patterns. At least 5 major drought cycles can be observed in the long term forebay plots in Fig. 3a, denoted by a low inflow (as well as outflow) hydrograph, decreasing or low lake levels, and generally increasing salinity levels. Some of the droughts may have consisted of only one or two year, such as 1964, 1972, 1976 to 1977 and 1981, yet it can be seen they had an immediate and persistent effect upon the hypolimnion. Other droughts continued for years, such as the 3 sub-normal years from 1966 through 1968, and the most recent drought from 1988 to 1992. These longer droughts produced greater meromixis in the hypolimnion, as well as substantially higher levels in the epilimnion.

As happened in 1966, the effects of a strongly saline SWARM bottom current, such as typically follows a dry year, has an immediate and strong influence on hypolimnetic conductance. Decreasing lake volumes characteristic of drought cycles exacerbated the concentration of salts in the lake. Dissolved oxygen levels, on the other hand, could be elevated during drought if lake levels dropped sufficiently to allow the winter oxygen plume a shorter approach to the dam.

Rapid releases that are not accompanied by matching inflow volume will result in a drop in lake elevation. At this time, water stored in the more eutrophic side bays enter the mainstem (Thorton *et al.* 1990). This process will contribute to meromixis during drought periods.

While the data during the 80's flood was compromised, the temporal resolution dwindled to 1 or 2 trips per year for 4 years from 1988 to 1991. Inflow volumes indicate these were drought years, but little information can be garnered from this period except a 5 year trend. While trends manifested in the forebay data could be compared to similar periods to suggest the processes behind the long and short term trends, there remain questions for this period. The monthly lake-wide trips from 1971 to 1982 proved invaluable in discerning the patterns to the processes. This period of decreasing resolution identifies the value of the quarterly lake wide sampling for determining lake-wide processes that are manifested in the forebay data.

c. Flooding Cycles

While the salinization of the lake from a drought cycle can be manifested abruptly within the hypolimnion, the freshening qualities of a flood may take several years to mix throughout the lake (Fig. 3a). This relates to the density and mixing properties of the SWARM flows versus the FRESCO flows. One sinks easily to the hypolimnion and mixes with previous cells and evades the penstocks, the other tends to slide over the first and is evacuated at the penstocks. When a very fresh flood follows a drought, the steeper salinity gradient poses a greater challenge to the mixing and sinking forces.

The flood years of the 1980's were a dramatic example of the wettest series of years since 1921. The vast volume of fresh, oxygenated water, combined with the operation of the spillways and river outlet works brought the lake to as complete a mixing as it has approached in its history. It was with one of the worst cases of bad timing that the Bureau of Reclamation decided to scale back sampling of Lake Powell at this time. This was a great loss from the perspective of understanding limnological processes.

B. Glen Canyon Dam Releases

Since the filling of Glen Canyon Dam, water quality conditions in the Glen Canyon Dam tailwater have changed substantially. Before Glen Canyon Dam the river was characterized by wide fluctuations in discharge, sediment load, temperature and salinity content. Due to the presence of the dam and the location of the penstock structures for powerplant releases there has been a marked reduction in the variance of all these parameters. Discharge is now a function of predetermined annual release volumes, monthly scheduled releases, and daily fluctuations in response to power demands and operational constraints (Fig 11). Temperatures have been greatly reduced and fluctuations now range between 7 and 12 °C, reduced from a pre-dam range of 0 to nearly 30 °C (Fig. 12). Fluctuations in salinity have been similarly reduced (Fig. 13).

1. Historical trends

a. Temperature

Fluctuation in temperature patterns became reduced to their current levels by about 1973, at which point the reservoir had filled sufficiently to isolate the penstock from the seasonally warming surface waters (Fig. 12). Since that time, annual mean temperatures have been fairly stable between 8 and 10 °C. Increases in instantaneous and mean temperatures were seen in 1978 when the reservoir was drawn down due to drought conditions and in the mid 80's and a result of the operation of the spillway release structures. Since the implementation of interim flows at Glen Canyon Dam annual mean temperatures and variation appear to have been reduced because of constrained release patterns.

b. Salinity

Salinity patterns in the Colorado River have been representative of hydrological and climatic conditions throughout the Colorado River basin. Although much moderated from pre-dam patterns some cyclic patterns appear to be present in the relatively short existence of Glen Canyon Dam. Annual salinity variations, like temperature, were brought to stable levels in 1973 after the reservoir had reached a surface elevation above 3600 ft. Some notable variations occur (Fig 14). After initial filling of the reservoir to the penstock level in 1965, the river outlet works and bypass tunnels were operated, releasing a large volume of water to keep the reservoir at the penstock level. This routed the early summer runoff quickly through the reservoir and replaced the existing, more saline water near the dam with much more dilute water. This is shown by a marked decrease in salinity levels of the Glen Canyon Dam releases in 1965. Peaks in salinity occurred later in the late 1960's and again in 1980 following drought years with associated reservoir drawdown and corresponding higher salinity levels in the reservoir. Salinity was markedly reduced with the high water years of the mid-80's at which time dilute water replaced most of the reservoir's contents.

After the low water years from 1989-1993 the reservoir was again drawn down, resulting in a peak in the overall salinity trend. Since that time salinity levels have gradually declined and reached a level of nearly 400 mg/L TDS in early 1997, the lowest level since 1984. If above average runoff and reservoir releases continue, this level should decline further.

2. Seasonal Patterns

Seasonal patterns in the Glen Canyon Dam releases are a function of meteorological conditions, internal reservoir mixing processes, inflow hydrology and the operation of the dam.

a. Temperature

An asymmetric annual temperature pattern appears in Glen Canyon Dam releases, with temperatures gradually warming through the year from a low point of 7 to 8 °C in February or March to a maximum point in December of 10 to 12 °C. This is followed by a sudden drop to its minimum value with a few months (Fig 15). This pattern is most likely due to the gradual penetration of surface warming through the summer. Winter convective mixing in the upper layers of the reservoir then takes place, drawing relatively warmer surface water to levels at or near the penstock. The magnitude of the maximum release temperature appears to be a function of the thickness of the mixed upper layer. This is the result of the volume of low-density inflow from the previous season's runoff, which arrives near the dam and defines initial conditions for the winter convection process, and the severity of the winter cooling and its effect on the convective process. Only in certain years do withdrawals seem to be come from the mixed isothermal epilimnion. The sudden drop in temperature which follows is most likely due to the continuation of the convective process, but is also strongly affected by the upwelling of cold saline water from the hypolimnion caused by the dense winter underflow currents in the reservoir. The period of sudden drop also corresponds with high powerplant releases in the month of January that may augment the amount of hypolimnetic water discharged while this upwelling occurs.

b. Salinity

Specific conductance cycles follow an opposite pattern compared to temperature (Fig 15). As early summer inflows have more influence on the downstream reservoir, water at the penstock level becomes progressively more dilute. Minimum salinity levels are reached concurrently with maximum temperature patterns; maximum salinity occurs with minimum temperatures.

V. Discussion

A. *Value of Existing and Past Monitoring Programs*

The primary focus of this assessment is to identify the effects of Glen Canyon Dam's operation on the water quality of Lake Powell and the Colorado River below Glen Canyon Dam. This assessment was based on data from several sources and includes inflow hydrology, Glen Canyon Dam release hydrology, measurements of physical water quality parameters from within Lake Powell and dam releases, and the results of chemical analyses of water samples collected from the reservoir and its releases. These data were evaluated in the context of the history of Lake Powell with its initial filling and fluctuating reservoir levels, changing climatic patterns, and changing operations criteria. Attention was given to seasonal patterns, operation of non-power release structures, and other significant events such as special releases.

Much more data exists than what was readily available for analysis with the short time frame of this assessment. Some data, such as dissolved oxygen and pH do not exist with sufficient long-term quality to evaluate over the complete history of Lake Powell, but are valuable for shorter-term analysis. Other data have only recently been collected and do not lend themselves to historic comparison. Several aspects of the assessment were frustrated by the lack of consistent data collection at a regular time interval. Resultant data gaps during significant parts of Lake Powell's history have subjected some conclusions to inference and speculation.

Several aspects of the historical data set proved very valuable to the assessment. Monthly lake-wide reservoir surveys from 1971 to 1982 gave valuable information about the fate of advective density currents through the reservoir. Consistent tailwater monitoring provided information about variation in Glen Canyon Dam releases between monthly measurements. The current monitoring program in the reservoir is characterized by quarterly lake-wide surveys and monthly forebay surveys and includes measurements with higher resolution through the water column and along the length of the reservoir. These data have given much information to inflow hydrodynamics, the effects of Glen Canyon Dam release patterns, and seasonal dissolved oxygen dynamics mediated by biological and hydrological processes.

When past monitoring programs have focused on specific aspects of Lake Powell water quality, the resultant database is less amenable to analysis of long-term trends or patterns. The challenge of designing any long-term monitoring program is to consistently collect those data that will be valuable to long-term and short-term analysis, at a level of detail sufficient to accurately identify trends and patterns, while maintaining a reasonable expenditure of resources to allow for the continuation of data collection. The direction of a program such as this must be flexible to accommodate changes in political and financial climate and respond to new information needs as more knowledge is gained. It is felt that the current monitoring program on Lake Powell provides consistent data collection with a sufficiently broad-based scope while keeping expenditures at a reasonable level. Within this context, the program can be modified to meet changing information needs and objectives.

B. Assessment of Factors Affecting Water Quality Conditions

The assessment process showed that the water quality in Lake Powell is affected by a variety of factors, none of which can be truly separated from the others except, perhaps, by artificial scenarios presented to a numerical hydrodynamic model of Lake Powell. Model development for

Lake Powell is not yet at a point where this type of modeling is possible. This section will describe some of the important factors affecting reservoir and release water quality, primarily focusing on the operation of Glen Canyon Dam.

1. Meteorological Conditions

Weather patterns play a significant role in determining inflow density, reservoir warming and stratification, convective mixing processes, and variation in release quality, both on a daily and seasonal basis. Warming or cooling of reservoir inflows from localized or seasonal meteorological conditions can affect the density of these currents, the depth at which these currents enter the reservoir, and the amount of diffusive mixing that occurs between the inflow and the receiving reservoir water. The surface temperature of the reservoir is affected by these conditions and results in setting up stratification during spring warming or breaking down this stratification through convective mixing with the onset of colder winter conditions. The amount of cloud cover over the reservoir affects how much radiant energy the reservoir receives to raise its heat content or stimulate photosynthetic processes. Wind patterns from storm events can impede the onset of stratification or accelerate convective mixing. Of significance to downstream releases, wind events can cause internal seiches, or oscillations of stratification boundaries in the reservoir that can cause temporary fluctuations in temperature or salinity levels in the tailwater (Fig 16).

2. Inflow Hydrology

One of the most important factors driving short-term and long-term processes in the reservoir is the inflow hydrology, characterized by the volume and quality of inflows to Lake Powell and their seasonal variation. Approximately 57% of the inflow volume occurs from April to June due to snow-melt runoff (Gloss et al. 1981). This runoff is characterized very low salinity snow-melt that has warmed on its course through the canyon lands. This combination results in a large volume of low-density water that overrides the surface of the reservoir and extends downstream, reaching the vicinity of the dam later in the year. The volume and duration of the runoff appears to dictate the downstream extent and the thickness of this layer of water.

This provides the initial conditions for convective mixing later in the winter. Convective mixing involves cooling the surface of the reservoir, which increases its density. This water sinks and mixes with deeper water of equal density with the assistance of wind action. The more winter cooling the deeper the level of mixing. If the previous spring's runoff does not have enough volume to reach the downstream portion of the reservoir, convection is mainly a result of the cooling process. However, if a heavy spring runoff results in a large volume of snow-melt water near the reservoir, this thick layer is already relatively homogenous. Winter cooling can then mix a large portion of the epilimnion to depths at or below the level of penstock withdrawal. This results in direct withdrawal of epilimnetic water and has been seen during winter months following high runoff from the previous spring. Examples of this occurred in early 1996 and 1997.

Reservoir inflows during the winter months are characterized by cold water of higher salinity compared to those of other times of the year. These conditions result in inflows with the highest densities of the year entering the reservoir. Therefore, this water plunges when it meets the reservoir and flows along the bottom of the reservoir. Its ultimate fate depends on preexisting conditions in the hypolimnion. If water in the deepest portion of the reservoir is of greater density than the winter inflow, the inflow will override the hypolimnion and eventually be discharged through the penstock outlet. This appears to happen after a saline hypolimnion has been established, usually following years of low runoff. If, on the other hand, the inflowing water is of greater density than the hypolimnion, it will displace the deeper body of water and route it through the release structures.

Regardless of whether the inflow density current overrides or displaces the hypolimnion, there is a consistent annual pattern of apparent upwelling of the more saline hypolimnion each winter into the penstock withdrawal zone. This usually occurs shortly after the first of the year and may be the result of the momentum of the winter inflow density current temporarily displacing the horizontal upper boundary of the hypolimnion. This causes, in effect, an internal oscillation or seiche of this boundary. The effect downstream is that during this period of hypolimnetic upwelling, dam releases suddenly become colder and more saline. This usually coincides with high winter releases from Glen Canyon Dam.

3. Glen Canyon Dam Operations

a. Presence and Structure of Glen Canyon Dam

Glen Canyon Dam has three structures from which water can be released (Fig 17). The majority of Glen Canyon Dam releases are through eight penstock intakes which route water to the powerplant turbines with a combined capacity of 940 cms (33,200 cfs). The penstocks withdraw water from an elevation of 1058 m (3470 ft) above mean sea level, or a depth of 70 m (230 ft) when the reservoir is at full pool with a surface elevation of 1128m (3700 ft). When release requirements dictate, an additional 425 m^3/s (15,000 cfs) can be discharged through the river outlet works which are situated at an elevation of 1028 m (3374 ft), 30 m below the penstock structures. The third means of withdrawal is from the spillways that have a combined capacity of 5890 m^3/s (208,000 cfs) and withdraw water from elevations above 1122 m (3680 ft). Releases from the river outlet works and the spillways bypass the powerplant and can not be used for hydropower generation. In 1965, high releases were routed through two bypass tunnels used during the construction of the dam. The upper portions of these tunnels were subsequently plugged; the lower portions became the lower spillway tunnels.

The location of the penstock intakes primarily defines the quality of Glen Canyon Dam releases. Variation in temperature, salinity, and other water quality characteristics are greatly reduced from pre-dam conditions (Figs. 11 and 13). The penstock withdrawal zone is deep enough that it is isolated from the wide seasonal fluctuations of the epilimnion, except at times of epilimnetic withdrawal as described in the previous section. Suspended sediment has essentially been removed due to settling in upstream portions of the reservoir. The structure of Glen Canyon Dam also creates 6.12 maf (7.55 km^3) of inactive and dead storage in Lake Powell below the penstock elevation, unavailable for hydropower generation. Cold saline water of high density can build up in this area and remain relatively isolated from other mixing processes in the reservoir. Organic material entering the hypolimnion will accumulate and decompose, gradually lowering dissolved oxygen levels. This water will remain relatively stagnant until it is displaced by inflows of higher density or flushed by high reservoir throughput. The process of intrusion of saline water into the hypolimnion, followed by decreasing oxygen levels until the hypolimnetic water is replaced appears during three periods in Lake Powell's history, from 1967 to 1973, from 1978 to 1982, and from 1991 to 1997.

b. Annual Release Volumes

Annual release volumes from Glen Canyon Dam are dictated by the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs (PL 90-537) and the development of an annual plan of operation based on streamflow histories, water supply probabilities, anticipated depletions, and other legal and institutional requirements. Glen Canyon Dam is legally required to release a minimum of 10.2 km^3 (8.23 maf) of water per year for downstream compact and treaty requirements. Since construction of the dam, this amount has been exceeded during five separate periods. In 1965, releases were increased following 2 years of low releases during the initial filling stages of Glen Canyon Dam. In the spring of 1973 a court order directed the drawdown of

Lake Powell to the 1094 m (3,590 ft) elevation to avoid impinging on Rainbow Bridge National Monument. During this period there was maximal powerplant production at Glen Canyon Dam. For a third time, after initial filling of Lake Powell was achieved in 1980, releases again exceeded 10.2 km^3 (8.23 maf). For the period of 1983 to 1987 annual releases were well above this level corresponding with wet conditions in the Upper Colorado River Basin. From 1995 to 1997, annual releases again exceeded the minimum requirements. Each of these periods was followed by a reduction in the salinity of the hypolimnion.

c. Monthly Release Volumes

Monthly release volumes are determined as part of the development of the Annual Operating Plan and are based on anticipated power demands, forecasted inflows, and other factors such as storage equalization between Lake Powell and Lake Mead. Typically, high releases occur in the month of January and again in August, in response to increased power demands during these months. Of significance is that high release volumes do not always concur with peaks in reservoir inflow. An important effect of this timing is that high releases in January occur during the upwelling of saline hypolimnetic water normally seen shortly after the first of the year. This upwelling and its subsidence appear to be a function of the winter density currents impinging on this body of water. The significance of the high January release volume is that more saline water is removed from the reservoir during this upwelling than if releases were lower. Therefore, the timing of these high releases facilitates the replacement of the hypolimnion near the dam.

d. Daily Release Volumes

Under existing operating criteria dictated by the recent Glen Canyon Dam EIS and Record of Decision releases cannot exceed 25,000 cfs except under emergency conditions or when required for flood control. Furthermore, during high release months, daily fluctuations cannot exceed 8000 cfs per day. Prior to June 1990, Glen Canyon Dam releases fluctuated widely, averaging between 13,000 and 16,000 cfs per day.

Water quality monitoring at an adequate time interval was not in place directly below the dam until after August 1988. Therefore, evaluation of water quality changes due to daily fluctuations is not possible for this period. However, the research flow period of June 1990 to August 1991 contained several flow scenarios representative of past operations in which wide fluctuations occurred. During this time, measurements of temperature and specific conductance were being taken at intervals of 2 hours or less. A common occurrence was a distinct fluctuation in daily temperature and specific conductance as shown for Research Flow "E" during late September 1990 (Fig 19).

e. Use of alternate release structures

Besides the penstocks, Glen Canyon Dam is equipped to release up to 256,000 cfs. The 8 penstocks account for a capacity of 33,200 cfs, discharging at 1057.66 meters (3470 feet) amsl or 70.1 meters below full pool. The four hollow jet tubes or river outlet works are rated to release 15,000 cfs at a depth of 99.4 meters below full pool or 1028.4 meters amsl (3374 feet). The spillways can each release 104,000 cfs, provided the lake can adequately submerge the outlet ports at an elevation of 1111.9 meters (3648 feet) or 15.86 meters below full pool. With concerns of possible spillway damage, safety and power revenue losses, the alternate release ports have been used sparingly.

1) 1965-1966 releases for filling Lake Mead.

The early filling stages of Lake Powell came at the expense of Lake Mead's pool level. When the operation of Mead's penstocks was in jeopardy, Glen Canyon Dam was forced to substantially increase downstream discharges starting in February of 1965. The river outlet works and diversion tunnels were operated in conjunction with the penstocks to discharge up to 58,000 cfs;

40% of the year's discharge came from the river outlet works and left diversion tunnel between February and August (Fig. 11), and for 3 months the bypass releases exceeded the penstocks. The effects of this discharge can be seen in the isopleths (Fig. 4). Much of the spring flood was withdrawn by the high penstock and river outlet works releases drawing horizontally across the lake, while the diversion tunnel directly released the most extreme hypolimnetic waters. By October of 1965, the spring flood had been drawn downstream from the Bullfrog station, 170 kilometers above the dam. It was unusual that such a large spring flood (9th highest of 33 inflows to Lake Powell) was no longer present as far uplake as the inflow in fall. In this instance, the operation of these outlets emulated the spillways by drawing from the fresh flood waters of the epilimnion, while the hypolimnion was evacuated from the lake's bottom. Dissolved oxygen appears to be elevated as a result of the high throughput and a hypolimnetic underflow.

2) 1980's flood years

The 1980s included one of the most distinct flooding periods in the southwest since detailed records began in the early 1920's. From 1979 to 1988, the Colorado River basin received 6 of the 10 greatest flood events in Lake Powell's history (Table 2). The flooding of the mid-eighties is attributed to the weather phenomenon of El Niño, a pattern that is currently building in the Pacific Ocean and which may compete with that of 1983. The results to Lake Powell were 5 years of back to back above average flooding. Unfortunately this unusual period was accompanied by decreasing sampling; from 5 lake-wide trips in 1983, to 4 in 1984, 3 in 1985 and 1986, 2 in 1987 and 1989, and 1 each in 1988, 1990 and 1991. With less than 4 trips per year, the inferences become uncertain.

The period preceding the flood years included a strong drought in 1977 that produced a strong chemocline below the penstocks, followed by 8th and 12th ranked high floods in 1979 and 1980 that significantly refreshed the hypolimnion. In 1981 a fairly strong drought introduced another saline SWARM cell to the hypolimnion that set the stage for the series of floods. Lake levels were already high preceding the 1983 flood, about 5 meters short of full pool.

In 1983, the lake reached full pool by June 8th, but it was nearly a month before the inflows peaked on July 1st. The spillways were opened on June 2nd to be followed by the river outlet works on June 7th. Cavitation and erosion within the spillway tunnels lead to their shutdown on August 1st, and it was August 11th before the jet tubes were shut down. The reservoir appeared to be poised for a deeply centered hypolimnetic overflow (or interflow) previous to the flood. Through the course of the withdrawals from all 3 depths, a pattern of *equi-potential flow*-through overrides the interflow pattern. We use the term *equi-potential flow-through* to describe the conditions that accompany high discharges through multiple outlets. The resulting horizontal stratification pattern is characterized by weak vertical thermal and chemical gradients that are relatively uniform from the inflow to the dam. It is assumed velocities across the reservoir are relatively homogeneous as they approach the dam. Hence, the SWARM cell of the hypolimnion is almost entirely eliminated by the end of summer, leaving a small isolated cell of the cold FRESCO cell in front of the dam.

Table 2: Lake Powell inflow, outflow, spillway and jet tube operations, and lake elevations for selected years.

Water Year	Inflow-MAF	Rank of Flood (out of 33 yrs)	Dam Releases MAF	Spillways: MAF, % Total	Jet Tubes: MAF,% of Total	Max Lake Elev-ft
1965	14.30	9	10.82	0%	4.2 MAF, 40%	3533.9
1973	15.64	5	10.11	0%	0%	3646.2
1979	14.64	8	8.30	0%	0%	3684.8
1980	13.22	12	10.91	0%	0%	3700.6
1983	20.83	2	17.49	1.9 MAF, 11%	1.8 MAF, 11%	3708.3
1984	21.68	1	20.50	0.1 MAF, 1%	2.6 MAF, 12%	3702.5

1985	18.21	4	19.09	0%	1 MAF, 5%	3700.1
1986	18.40	3	16.85	0%	0.9 MAF, 6%	3700.0
1987	14.23	10	13.43	0%	0%	3698.5
1996	11.28	19	11.47	0%	0.2 MAF, 2%	3688.3
1997	14.62+	~6	12.10+	0%	0%	3695.1

Dissolved oxygen values become very unstable at this time due to faulty and erratic instrument readings. Some of the more reasonable values and patterns suggest a high degree of oxygenation of the hypolimnion accompanied by modest metalimnetic dissolved oxygen sags following the spring flood. Under more typical release patterns we would expect a major flood event that follows drought conditions to introduce a large quantity of organic carbon creating that would create a high biological oxygen demand (BOD). While there are repeated episodes of metalimnetic hypoxia throughout the 1980's, they are not severe, nor do they translate to subsequent hypoxia in the hypolimnion. Spillway withdrawals have intercepted part of the spring flood along with the high organic concentrations it entails. This effect could be real or it could be an artifact of poor data quality and low temporal resolution, but epilimnetic releases in the 1960's produced similar patterns. Dissolved oxygen values present more questions than they answer, which may be addressed if the current scenario of continued high anticipated flows is manifested.

The reservoir conditions preceding the 1984 flood are significantly fresher than the previous year. A very cold winter and low chemical gradient created a good opportunity for a thorough underflow winter current. This process may have been initially augmented by high river outlet withdrawals (running above recommended capacity for 2½ months) and eventually discharges out-competed the underflow currents, entraining much of the convectively mixed epilimnion. Although monitoring resolution was inadequate to capture the exact process of flow, another *equi-potential flow-through* appears to have eliminated any significant trace of a hypolimnion.

The spillways were not operated until August to test repairs, again at an opportune time to draw off high BOD from the spring flood.

Temporal data resolution is problematic beyond 1985. There was no winter sampling and it can only be inferred that a hypolimnetic underflow occurred. It is in early summer of 1985 that the Lake Powell reached its most isotonic state, with conductivity varying only 76 μS/cm from top to bottom at the dam (contrasting with 635 μS/cm in 1965 or 285 μS/cm at this writing). There were no spillway releases in 1985, but the river outlets discharged at capacity (15,000 cfs) for over a month in May and June. The reservoir experiences equi-potential flow-through once again.

A repeat of 1985 conditions was approximated in 1986. The hollow jet tubes were operated above capacity for a month in May and June. A hypolimnetic underflow is indicated by temperature and dissolved oxygen trends, with a less pronounced *equi-potential flow-through.* Slightly high salinity values began setting up in the hypolimnion.

Throughout this period that utilized the alternate releases / non power structures, surface warming did not appear to be significantly affected by spillway releases. This can be attributed to a number of items. As mentioned earlier, epilimnetic thickness and heat content appears to be controlled by volume of inflow more than any other factor. Furthermore, the intensity of warming at the surface of the lake is more dependent on small scale warming trends. In the face of these first two factors, spillway discharges during flooding events did not appear to have an appreciable effect on heat content of the lake or maximal heating of the surface. Caution must be applied due to poor temporal data resolution.

3) The Spike Flow, 1996

In spring of 1996, the first habitat/ beach building experimental flood was applied to demonstrate the use of controlled dam releases to enhance habitat in the Grand Canyon. The experimental floods were originally intended for use in low flow years so that subsequent high flows would not degrade any benefits derived from the high flows, such as newly formed beaches and backwaters. The conflict between pure scientific experimentation and concerns of water managers situated the first experimental flood between several high inflow years. This has brought a different perspective to the results of the spike flood as well as depriving lake researchers from a more ideal hydrodynamics experiment.

Table 3. Spike discharges in acre-feet and percentage of total spike discharge compared to the volume of the lake below those levels.

Dam Outlet	*Acre-Feet of Spike Discharge*	*% of Spike discharge*	*% of volume turnover below port depth*
Penstocks	506,072	4.41%	16.48%
Jet tubes	216,742	1.89%	102.24%
Total for Spike	722,814	6.30%	23.54%

The years preceding the spike flood included 2 high floods (1993 ranked 12th, 1995 ranked 6th) that were beginning to break down a resistant chemocline that developed in the drought years of 1988 to 1992. The winter of '95-'96 was fairly mild and the winter FRESCO plume of cold fresher oxygenated water was well established in a hypolimnetic overflow pattern by early March. The SWARM plume was relatively fresh due to a dilute fall inflow. It had hit the dam and was being levered up by the force of the FRESCO cell when the hollow jet tubes were opened on March 26th. Seven continuous days with the jet tubes and penstocks at capacity (45,000 cfs) produced a marked and immediate evacuation of the hypolimnion at those levels, as evidenced in Figs. 3b, 8-10. The discharge from the jet tubes was equivalent to the volume in the lake below the jet tubes, while the volume discharged from the penstocks was approximately 16.5% of the hypolimnion below the depth of the penstocks (see table II). The spike flood enhanced and reinforced the flow patterns already in action, seen in the cropping of the overflow in the longitudinal plots (Figs. 8-10) and the accelerated conclusion of the hypolimnetic upwelling seen in the forebay plot in figures 3a and 3b. Complete analysis of the spike flood results are reported in Hueftle *et al.* (1998, in review).

f. Unique use of the penstocks

1) 1973 Rainbow bridge drawdown

In March of 1973 a high snowpack presaged a substantial rise in lake elevation. Concerns over the reservoir impinging on Rainbow Bridge National mounted. As a result, 41 days of steady penstock withdrawals averaging 28,300 cfs (23% of the year's discharge) brought the lake level to 1094 m (3590 feet). A stay on a court order allowed the reservoir to continue filling by May 1. Reservoir conditions before the release included a very cold hypolimnetic underflow and a relatively high winter inflow volume, resulting in high oxygen and low salinity winter underflows. This cold flow wedged the salty SWARM cell to the level of the penstocks where it was released downstream (figure 5). This episode demonstrates the effectiveness of hypolimnetic underflow as a refreshing agent when combined with well-timed dam discharges. The freshening effect of this combination persisted in the hypolimnion for several years.

2) 1997 High Steady Flows

The winter of 1996-1997 resulted in another year of above average snowpack on a watershed that had received 4 years of heavy precipitation in the last 5 years. With lake levels still high from the preceding year, dam releases were raised to an average of 27,000 cfs by February 18th with the intention of avoiding power plant bypasses. For the next 5 months (and counting) releases were maintained at levels between 21,000 cfs and 27,000 cfs, providing a strong, steady pull on the reservoir at penstock levels.

A lake-wide sampling trip within a week of the elevated releases revealed a relatively cold oxygenated FRESCO plume poised for a possible hypolimnetic underflow or a deep interflow.

Three months later the upper portion of the hypolimnion had been almost entirely stripped out. The resulting hypolimnion had the lowest conductivity and the highest oxygen levels that the forebay had experienced since the 1987. The June 1997 isopleths (figures 3b, 8-10) demonstrate a deep hypolimnetic flow that was drawn up vertically 60 meters toward the penstocks.

The effects of these strong sustained releases were enhanced by the conditions created by the spike flood releases the previous spring. The chemocline had been weakened by the refreshment of the meromixis that resulted from the jet tubes releases in 1996. In addition, the SWARM formed in the fall of 1996 appears to be relatively low in salinity because of a low salinity inflow and the dominance of a fresh convectively mixed epilimnion, further weakening the chemocline. Thus the deep winter interflow and high sustained releases were optimally positioned to draw off the remaining meromixis at greater depths. If projections of a strong El Niño weather pattern occur in 1998, it can be expected that even deeper mixing and oxygenation could occur next year, possibly emulating conditions of the mid 1980's.

VI. Conclusions

A. Influence of dam operations on lake water quality

As discussed in the preceding section, many factors are significant to determining the water quality of Lake Powell and Glen Canyon Dam releases. Data for this evaluation is based on a 33-year data set from a broadly focussed long-term monitoring program conducted by the Bureau of Reclamation, Glen Canyon Environmental Studies, and the Grand Canyon Monitoring and Research Center. There exists a complicated linkage between climatic and meteorological factors, Colorado River basin hydrology, physical hydrodynamic processes, the presence and structure of Glen Canyon Dam, and the operation of the Dam itself.

It is impossible to discern the extent and degree that each of these factors has on determining reservoir and release water quality because seldom, if ever, do these factors operate independently of one another. Glen Canyon Dam has changed the overall quality of the Colorado River in Grand Canyon, the dam operates to supply required amounts of water to the Lower Basin States and generate hydropower with current constraints, and global-scale climatic patterns determine decadal-scale patterns in water availability.

The focus of this assessment is to identify the effects of the operation of Glen Canyon Dam on reservoir and release water quality. Within the scope of evaluating readily available data within a short time frame, several factors that affect patterns and changes in the physical and chemical characteristics of water in Lake Powell and Glen Canyon Dam releases were identified that can be attributed to the operation of Glen Canyon Dam. These factors range from those determined mainly by the Long-Range Operating Criteria to those affecting day-to-day operations under the current constraints of the Glen Canyon Dam EIS and Record of Decision. Other effects may be ascertained as other sources of data are developed, additional analyses are performed, and the ability to model operating scenarios and environmental factors is enhanced.

1. Release volumes

Glen Canyon Dam must operate in response to hydrologic conditions in the Colorado River basin and downstream water delivery requirements. At the same, dam safety considerations must be met, hydropower generation must be maintained, and recent operating criteria must be followed. Reservoir releases must respond to these outside factors and will follow overall patterns in Colorado River Basin hydrology. The existence of Lake Powell and the amount of water passing through the system moderate the salinity levels in Lake Powell and water released from Glen Canyon Dam. High sustained releases as seen in 1973 and 1997 act to increase mixing of the reservoir beyond that caused by other processes.

The effects of reservoir drawdowns can be seen in the buildup of a saline body of water in the deepest portions of the reservoir, which shows progressive loss of dissolved oxygen until its eventual replacement during wet hydrologic cycles.

2. Timing of Reservoir Releases

Differential monthly volumes released from Glen Canyon Dam can have a significant effect on salinity on dam releases and the amount of salinity stored in Lake Powell. While the dam is not operated for this purpose, high releases in January draw larger volumes of saline water from the reservoir during a period of hypolimnetic upwelling into the zone of penstock withdrawal.

3. Operation of non-power release structures

a. River Outlet Works

One of most striking effects of Glen Canyon Dam operations is the use of alternate release structures to route releases exceeding power plant capacity for flood control, storage equalization, surplus deliveries, or experimental ecosystem enhancements. River outlet works structures were operated in 1965, during the mid-1980's, and again in the spring of 1996, as part of the Experimental Beach/Habitat Building Flow. The operation of these structures released water from deeper levels in the reservoir, enhancing advective flow at these levels, and promoting the mixing of the reservoir and reduction of the meromictic hypolimnion and hypoxia.

b. Spillways

The spillway structures were operated during 1983 and 1984 and showed enhanced routing of warm, epilimnetic water from snow-melt runoff through the reservoir. They also result in the release of warm dilute water downstream that may be of very different quality than that normally discharged from the dam. By routing the dilute snow-melt downstream before subsequent mixing to the lower depths of the lake, spillway releases could increase the reservoir salinity budget. In the same manner, the dissolved oxygen sag that normally accompanies the riverine snow-melt could be routed out of the reservoir.

Operation of the spillways can also be viewed as a simulation of operation of potential selective withdrawal structures due to their location in the warm water near the surface of the reservoir.

4. Changes in Variability of Downstream Releases

Since the implementation of the Interim Operations Criteria in November 1990 and the subsequent EIS Record of Decision, daily fluctuations and the rate of change of these fluctuations have been significantly reduced. Compared to previous conditions, it is apparent that mean annual temperature and the annual variability of temperature in Glen Canyon Dam releases have been reduced.

Evidence of daily fluctuations in temperature and specific conductance of dam releases in response to high fluctuating flows is less apparent under the current operating criteria that under historical operation scenarios.

These changes have significance to the future potential of the study of seasonally adjusted steady flows as stated in the US Fish and Wildlife Service's Reasonable and Prudent Alternative to the Glen Canyon Dam EIS. These flows could be expected to exhibit less variation in release water quality than currently exists.

B. Integration with Downstream Systems

1. Grand Canyon Aquatic Ecosystem

Chemistry data for nutrient concentrations collected in Lake Powell and in downstream releases have only been collected since 1992. In addition to the lack of historical data to make comparisons, levels of phosphorous compounds are often below standard detection levels. Therefore, a complete analysis of chemistry data from Lake Powell was beyond the scope of this assessment. However, it has been noted that nutrient concentrations in the deeper portions of Lake Powell can be three to four times higher than those in the epilimnion. This could have significance for the aquatic ecosystem downstream of Glen Canyon Dam. Recent studies have noted a shift in the community structure of primary productivity below Glen Canyon Dam which has been concurrent with a gradual reduction in salinity levels as well as shifts in dam operations (Benenati, P.L *et al.* in press). An unknown portion of the dissolved mineral load on Glen Canyon Dam releases is comprised of nutrient compounds and the observed salinity reductions may indicate reduced nutrient delivery to the aquatic ecosystem. Changes in dam release timing and magnitude impact community structure and biomass of primary producers such as *Cladophora glomerata.* The community has shifted to other algal forms since the high sustained releases of 1995, many of which are a poorer substrate for the aquatic food base which supports the fishery.

Other authors have reported alterations of downstream aquatic ecology in conjunction with dam operations, including Ward and Stanford (1983), Angradi *et al.* (1992), Ayers and McKinney (1996), Stevens *et al.* (1997).

2. Lake Mead

Releases from Glen Canyon Dam have relatively stable physical characteristics, within the observed range of fluctuation, compared to pre-dam releases. As such, the water entering Lake Mead has more uniform density characteristics. The patterns of seasonal overflow and underflow seen in Lake Powell inflows are not present in Lake Mead, which has affected the behavior of this large body of water since the presence of Glen Canyon Dam (Evans and Paulson 1983). It is possible, under future hydrologic conditions, operational scenarios, or the use of a selective withdrawal structure that this pattern could be modified to produce occasional periods of inflows routing through the upper layers of Lake Mead, which could have an enhanced effect on the biology of the reservoir.

Literature Cited

Angradi, T.R., R. W. Clarkson, D. A. Kinsolving, D. M. Kubly, and S. A. Morgenson. 1992. Glen Canyon Dam and the Colorado River; responses of the aquatic biota to dam operations. Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, AZ. Cooperative Agreement No. 9-FC-40-07940. Arizona Game and Fish Department, Phoenix, AZ.

APHA, 1992. Standard methods for the examination of water and wastewater. 18th edition. APHA, Washington, D.C.

Ayers, A. D. and T. McKinney. 1996. Water chemistry and zooplankton in the Lake Powell forebay, Glen Canyon Dam discharge and tailwater. Prepared for the Bureau of Reclamation, Upper Colorado Region, Glen Canyon Environmental Studies, Flagstaff, AZ. Cooperative Agreement No. 9-FC-40-07940. Arizona Game and Fish Department, Phoenix, AZ.

Benenati, P.L, D. Blinn, J.P. Shannon. 1998, Response of primary productivity flow regimes and water quality changes in the Colorado River, Lees Ferry, AZ. (In press)Cole, G. A. 1994. Textbook of Limnology. Waveland Press. Prospect Heights, Illinois.

Edinger, J. E., E. M. Buchak, D. H. Merritt. 1984. Longitudinal-Vertical Hydrodynamics and transport with chemical equilibria for Lake Powell and Lake Mead. Pages 213-222, *in* R. H. French (ed): Salinity in watercourses and reservoirs. Salt Lake City, Utah: Butterworth, Boston.

Evans, T.TD., and L.J. Paulson. 1983. The influence of Lake Powell on the suspended sediment-phosphorus dynamics of the Colorado River inflow to Lake Mead. *In* V. D Adams and V. A Lamarra (eds): Aquatic Resources Management of the Colorado River.

Gloss, S. P. L. M. Mayer, and D. E. Kidd. 1980. Advective control of nutrient dynamics in the epilimnion of a large reservoir. Limnology and Oceanography 25: 219-228.

Gloss, S. P., R. C. Reynolds Jr., L. M. Mayer, and D. E. Kidd. 1981. Reservoir influences of salinity and nutrient fluxes in the arid Colorado River Basin. Pages 1618-1629 *in* H. G. Stephan (ed.), Proceedings of the Symposium of Surface Water Impoundments. American Society of Civil Engineers, New York.

Golden Software, Inc. 1994. Grapher, version 1.24.

Golden Software, Inc. 1996. Surfer, version 6.04.

Hart, R.J., and K.M. Sherman, 1996. Physical and Chemical Characteristics of Lake Powell at the Forebay and Outflows of Glen Canyon Dam, Northeastern Arizona, 1990-91. U.S. Geological Survey Water-Resources Investigations Report 96-4016.

Hydrolab Corportation. 1994. Hydrolab Surveyor 3 Multiparameter Water Quality Monitoring Instruments, Operating Manual. Austin, TX, U.S.A.

Hueftle, S.J., and L. E. Stevens. 1998. Experimental flood effects on the limnology of Lake Powell reservoir, southwestern USA. Ecological Applications. (In review).

Johnson, N. M. and D. H. Merritt, 1979. Convective and advective circulation of Lake Powell, Utah-Arizona, during 1972-1975. Water Resources Research. 15(4):873-884.

Martin, R. 1989. A story that stands like a dam, Glen Canyon and the struggle for the soul of the west. Henry Holt and Company, New York, New York.

Merritt, D. H. and N. M. Johnson. 1978. Advective Circulation in Lake Powell, Utah-Arizona. Lake Powell Research Project Bulletin # 61. Institute of Geophysics and Planetary Physics, University of California, Los Angeles,CA.

Potter, L. D. and C. L. Drake, 1989. Lake Powell: Virgin Flow To Dynamo. University of New Mexico Press. Albuquerque, New Mexico. 328 p.

SAS Institute Inc. 1996. Version 6.12. SAS Institute, Inc., Cary, NC, 27513.

Stanford, J. A. and J. V. Ward. 1986. Reservoirs of the Colorado River system. Pages 375-383 *in*: The Ecology of River Systems, ed. B. R. Davies and K. F. Walker.

Stanford, J. A. and J. V. Ward. 1991. Limnology of Lake Powell and the Chemistry of the Colorado River. Pages 75-101 *in* Colorado River Ecology and Dam Management.

Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich and C. C. Coutant. 1996. A General Protocol for restoration of regulated rivers. Regulated Rivers: Research and Management, 12:391-413.

Stevens, L. E., J. P. Shannon and D.W. Blinn. 1997. Colorado River Benthic Ecology in Grand Canyon, Arizona, USA: Dam, Tributary and Geomorphological Influences. Regulated Rivers: Research and Management, 13:129-149.

Thornton, K.W., B. L. Kimmel, F. E. Payne, ed. 1990. Reservoir Limnology: Ecological Perspectives. John Wiley and Sons, Inc. New York, NY.246 pp.

U. S. Bureau or Reclamation. 1921-1997. Hydromet database. Online data retrieval. Upper Colorado Region, Salt Lake City, UT.

U. S. Bureau or Reclamation. 1970. Glen Canyon Dam and Powerplant, Technical Record of Design and Construction. A Water Resources Technical Publication. United States Bureau of Reclamation. Washington, D.C.

--. 1990. Glen Canyon Environmental Studies Phase II draft integrated research plan. Bureau of Reclamation, Salt Lake City, UT.

--. 1995. Operation of Glen Canyon Dam. Final environmental impact statement. Bureau of Reclamation, Salt Lake City, UT.

--. 1996. Record of Decision for Operation of Glen Canyon Dam Final Environmental Impact Statement. Department of Interior. Department of Interior. Washington, D.C.

U.S. Geological Survey, 1985-96. Water Resource Data for Arizona, Water Year 1985-1996. Water Data Report. AZ-85-1 to 96-1. U.S. Geological Survey, Department of Interior. Washington, D.C.

Ward, J. V. and J. A. Stanford. 1983. The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. Pages 347-356, *in* T. D. Fontaine & S. M. Bartell (eds), Dynamics of Lotic Ecosystems. Ann Arbor Science, Ann Arbor.

Wetzel, R. G. 1975. Limnology. W. B. Saunders Co., Philadelphia, PA. 767 pp.

Appendices

A. Assessment Prospectus

A. Table A-1

Ranking of Inflow and outflow hydrographs, seasonal temperatures, and ratings of winter underflow currents.

Year	Outflow Rank	Inflow Rank	Winter Coldness	Summer Hotness	Summer Hotness Surf H_2O temp	Winter Underflow
1963	35	33				
1964	34	30	14			
1965	9	9	24	28		u
1966	32	22	18	17		p
1967	33	26	5	24	15	p
1968	19	20	1	30	17	p
1969	14	15	11	10	9	p
1970	15	14	12	22	4	o
1971	16	16	6	1	21	o
1972	11	23	10	14	2	o
1973	10	5	7	18	12	u+

1974	24	19	17	13	7	o
1975	12	13	13	20	8	p
1976	17	24	20	2	13	o
1977	25	34	19	15	6	pu
1978	18	21	30	3	5	p
1979	21	8	4	8	19	o+
1980	8	11	26	6	11	o
1981	22	31	31	16	14	o
1982	20	17	21	19	18	p
1983	3	2	23	26	20	po
1984	1	1			16	eqp
1985	2	4		9	25	eqp
1986	4	3	29	23	24	eqp
1987	5	10	16	29		u?
1988	26	25	15	12		---pu?
1989	31	32	3	4		---(o?)
1990	27	35	27	11		---(o?)
1991	28	29	2	27	23	---(o?)
1992	30	28	9	21	22	pu
1993	29	12	8	25	10	pu
1994	23	27	22	5	1	o+
1995	13	6	25	7	3	o
1996	7	18	28			o
1997 (to 8/20/97)	6	7	(moderate to cool)			p
Total:	35	35	32	30	25	33

u=Hypolimnetic underflow (Occurred 3 times in 33 years, 9.1%)

p= Hypolimnetic partial under- or overflow (interflow) (Occurred 12 times in 33 years, 36.4%)

o=Hypolimnetic overflow (Occurred 14 times in 33 years, 42.4%)

eqp = Equi-potential flow-through (Occurred 3 times in 33 years, 9.1%)

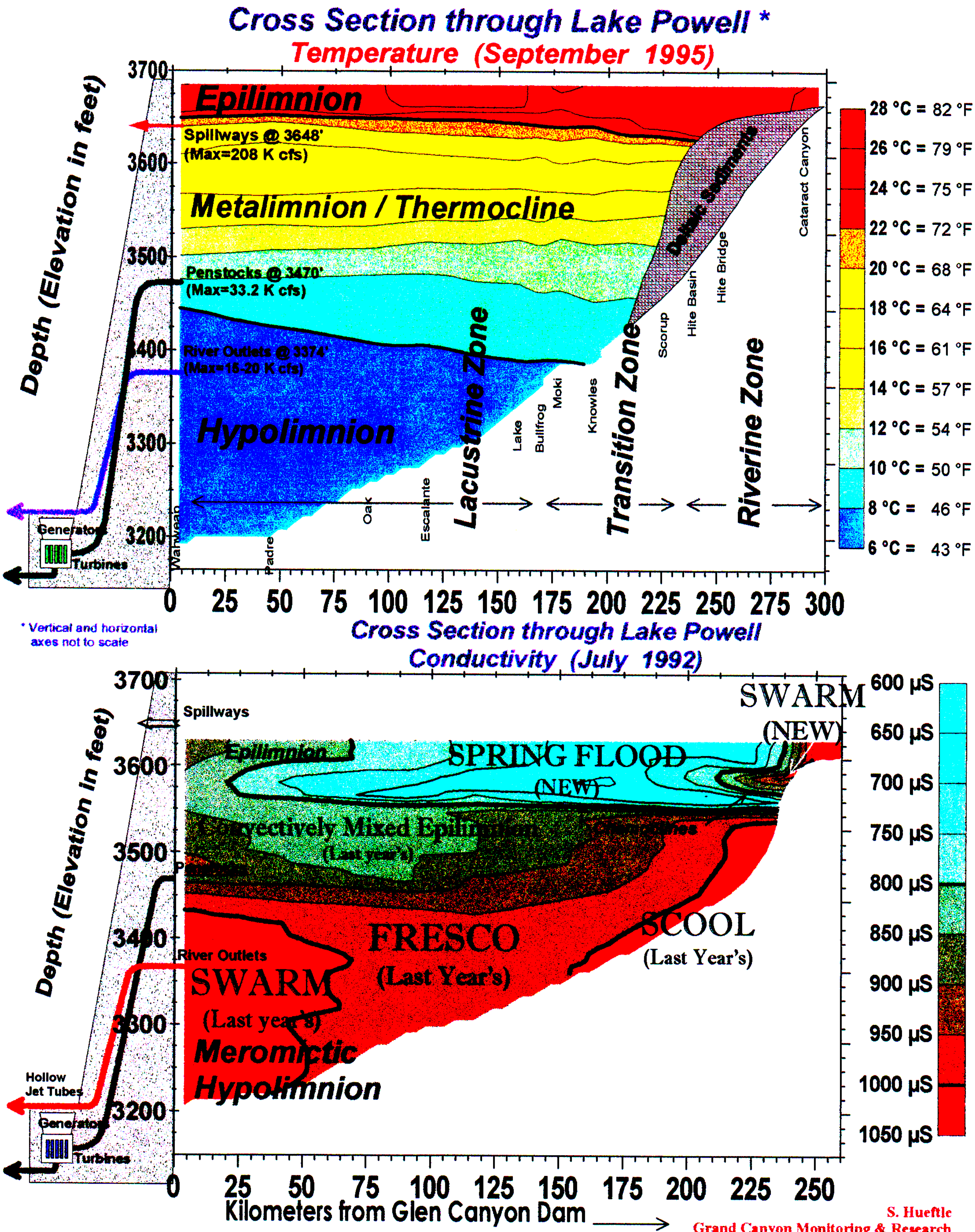

Figure 1: [Top] Thermal Stratification and longitudinal zones of Lake Powell with structural attributes of Glen Canyon Dam. [Bottom] Conductivity isopleth with Lake Powell's circulation cells present for past and present seasons.

Temperature (°C), Conductivity (µS/cm), and Dissolved Oxygen (mg/L) in Lake Powell; September 1974 to August 1975

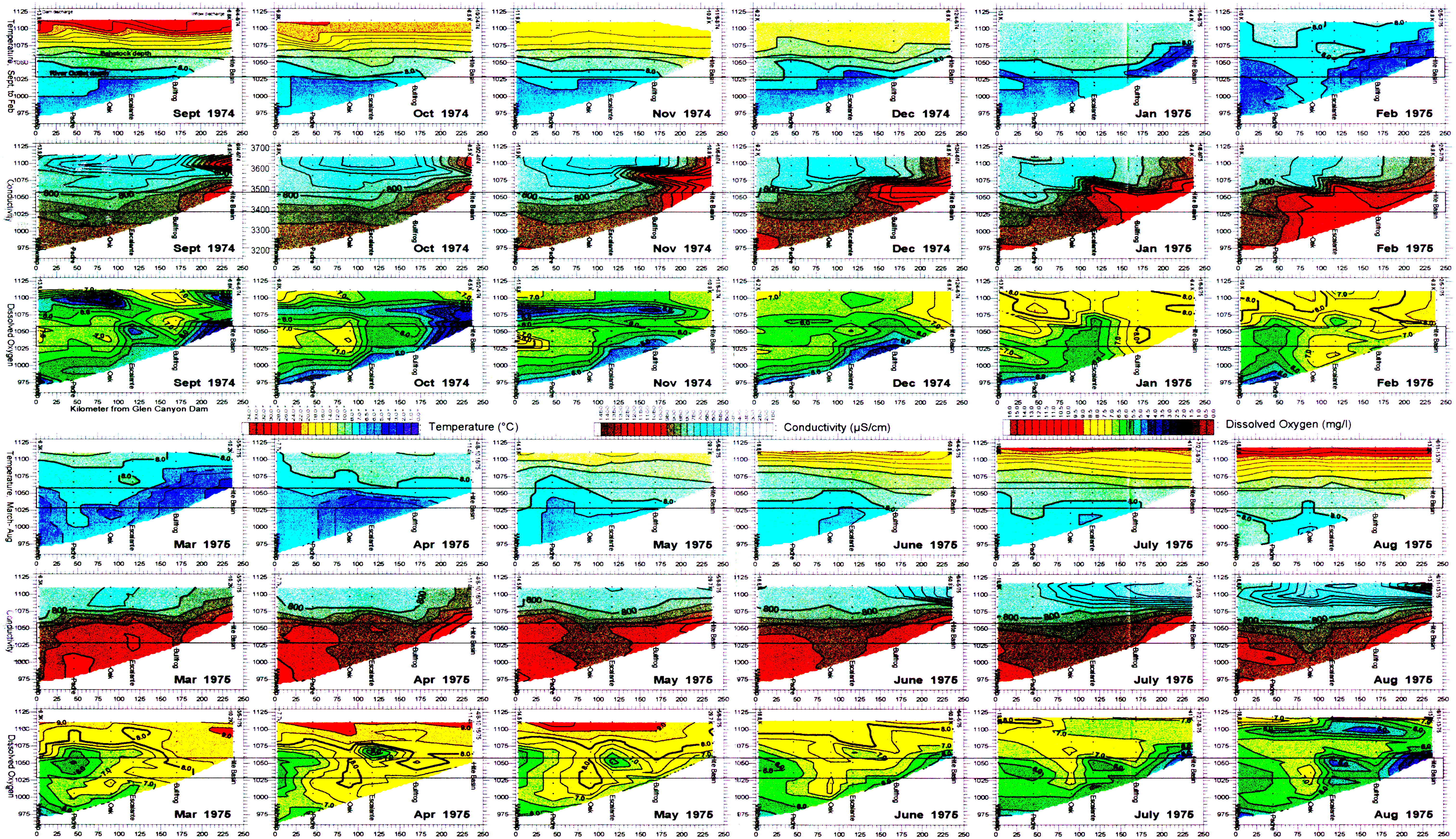

Figure 2a: One typical year's progression from stratification of summer through seasonal changes back to summer. Some irregularities may exist in the data, particularly in the dissolved oxygen. Penstock and river outlet levels indicated at 1057.7 and 1028.4 m, respectively. Exact sample date, monthly inflow and outflow indicated on plot's top.

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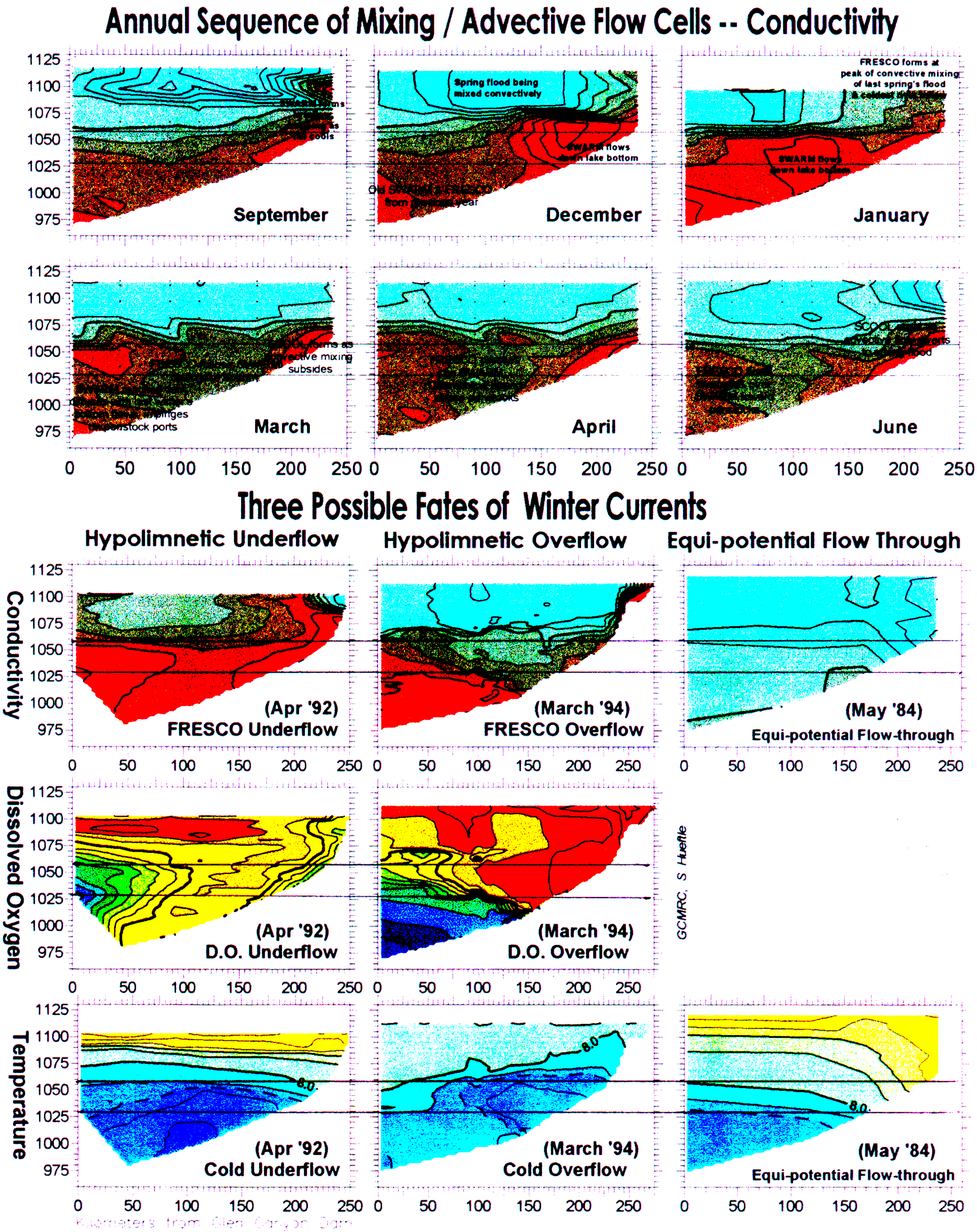

Figure 2b: [Top] Sequence of 6 conductivity isopleths demonstrate the most common annual scenario of winter interflow/overflow. [Bottom]: Example of 3 possible winter underflow currents: Underflow, Overflow & Equi-potential Flow-Through for conductivity, dissolved oxygen, and temperature.

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HISTORICAL TRENDS IN TEMPERATURE, CONDUCTIVITY, AND DISSOLVED OXYGEN, FOREBAY OF LAKE POWELL, 1964 TO 1997

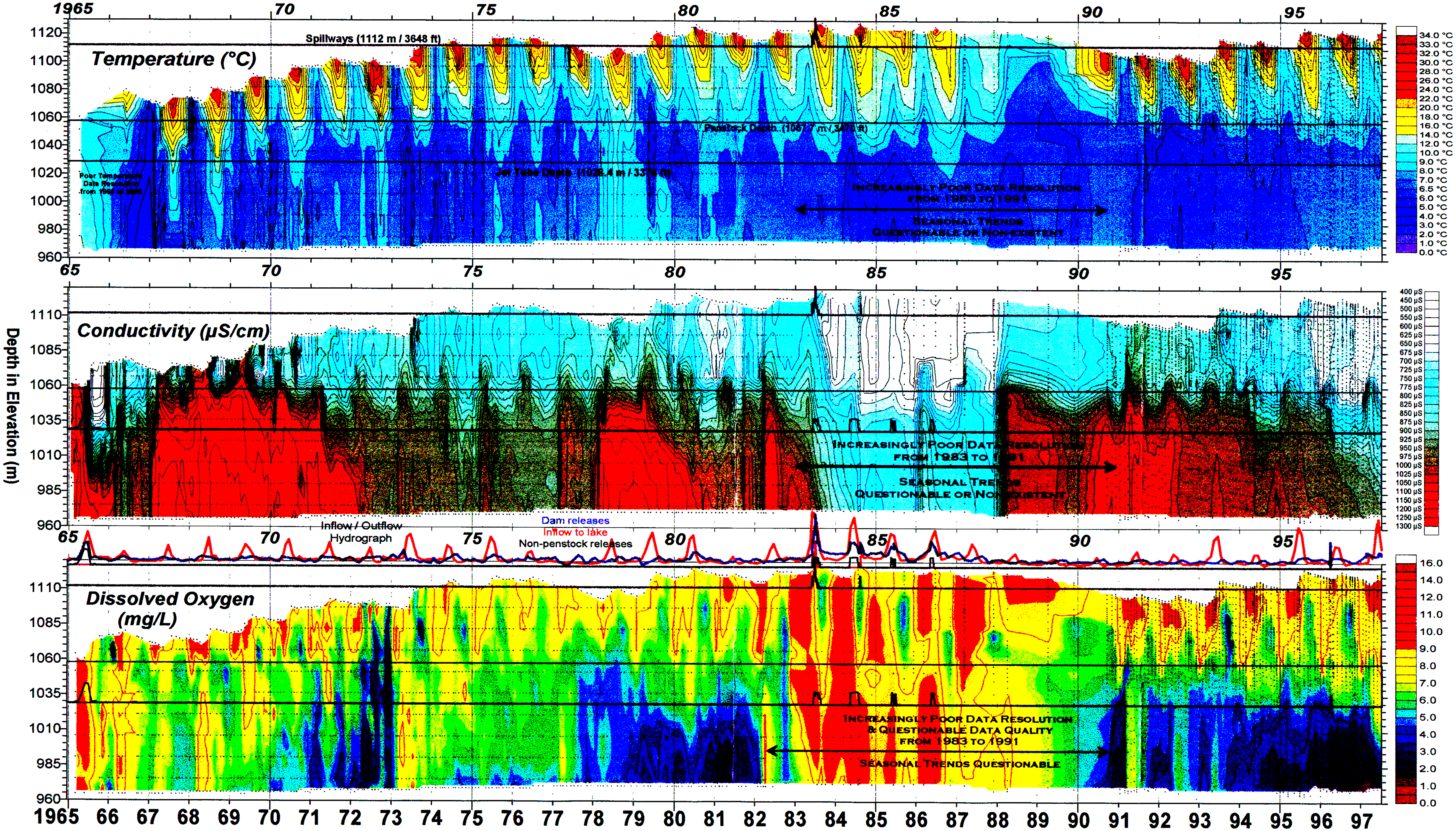

Figure 3a: Temperature, conductivity, and dissolved oxygen at the forebay of Lake Powell from December 1964 to July 1997. Spillways, penstocks, and river outlet works indicated at 1058, 1028 and 1112 meters depth. Samples annotated with dots. Qualitative hydrograph for outflow (blue line), inflow (red line), spillway and jet tube releases between conductivity and dissolved oxygen plots. PROVISIONAL DATA

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Lake Powell near the Forebay, February 1992 to August 13, 1997

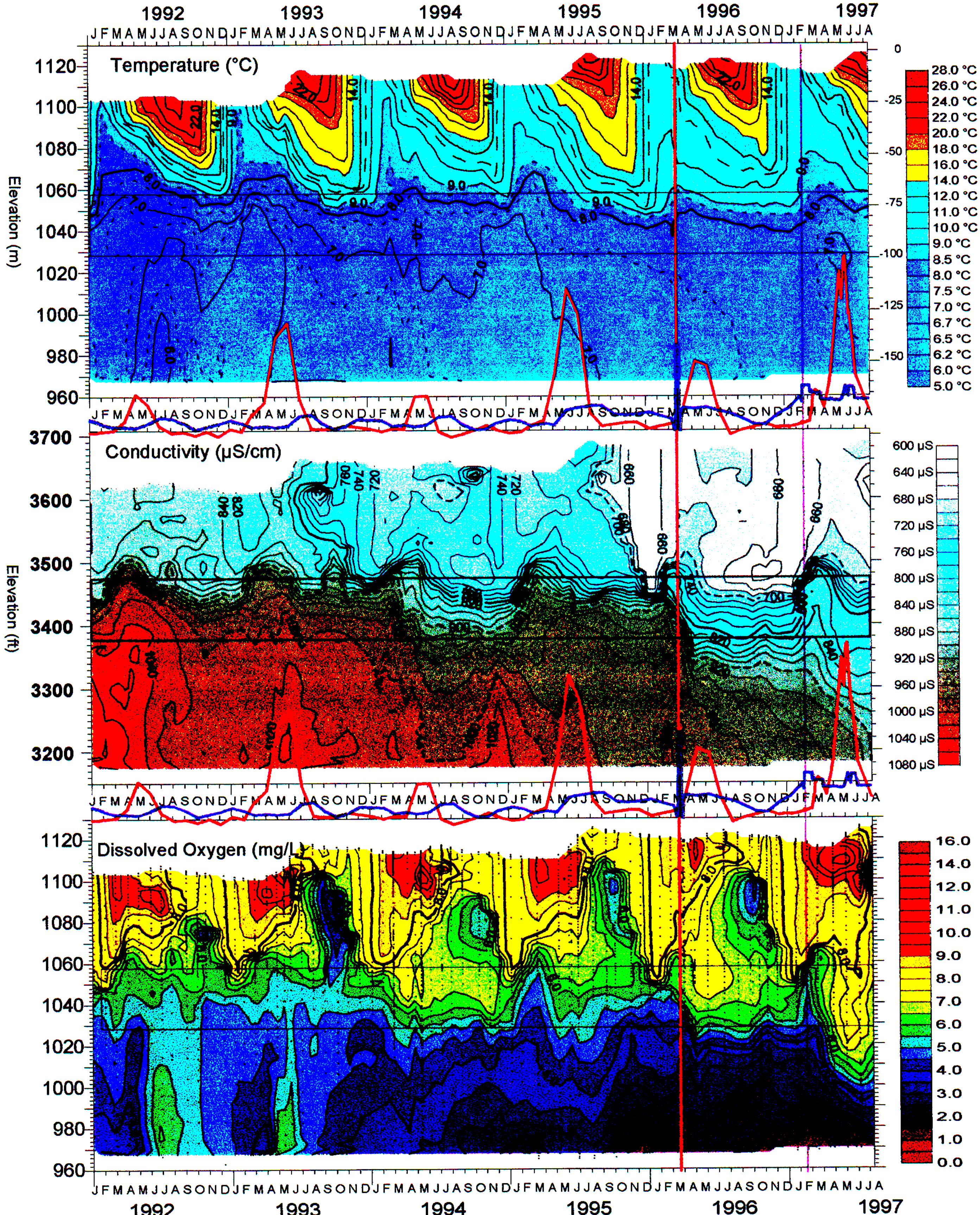

Figure 3b: Temperature (°C), conductivity (µS/cm), dissolved oxygen (mg/L) at Wahweap station in Lake Powell from February 1992 to August 13, 1997, including results from experimental flood (red line). Penstocks indicated at 1057.7 m & jet tubes at 1028.4 m. Hydrograph of inflow is indicated by red line & outflow in blue.

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Lake Powell Drawdown for Mead, 1965 and 1966

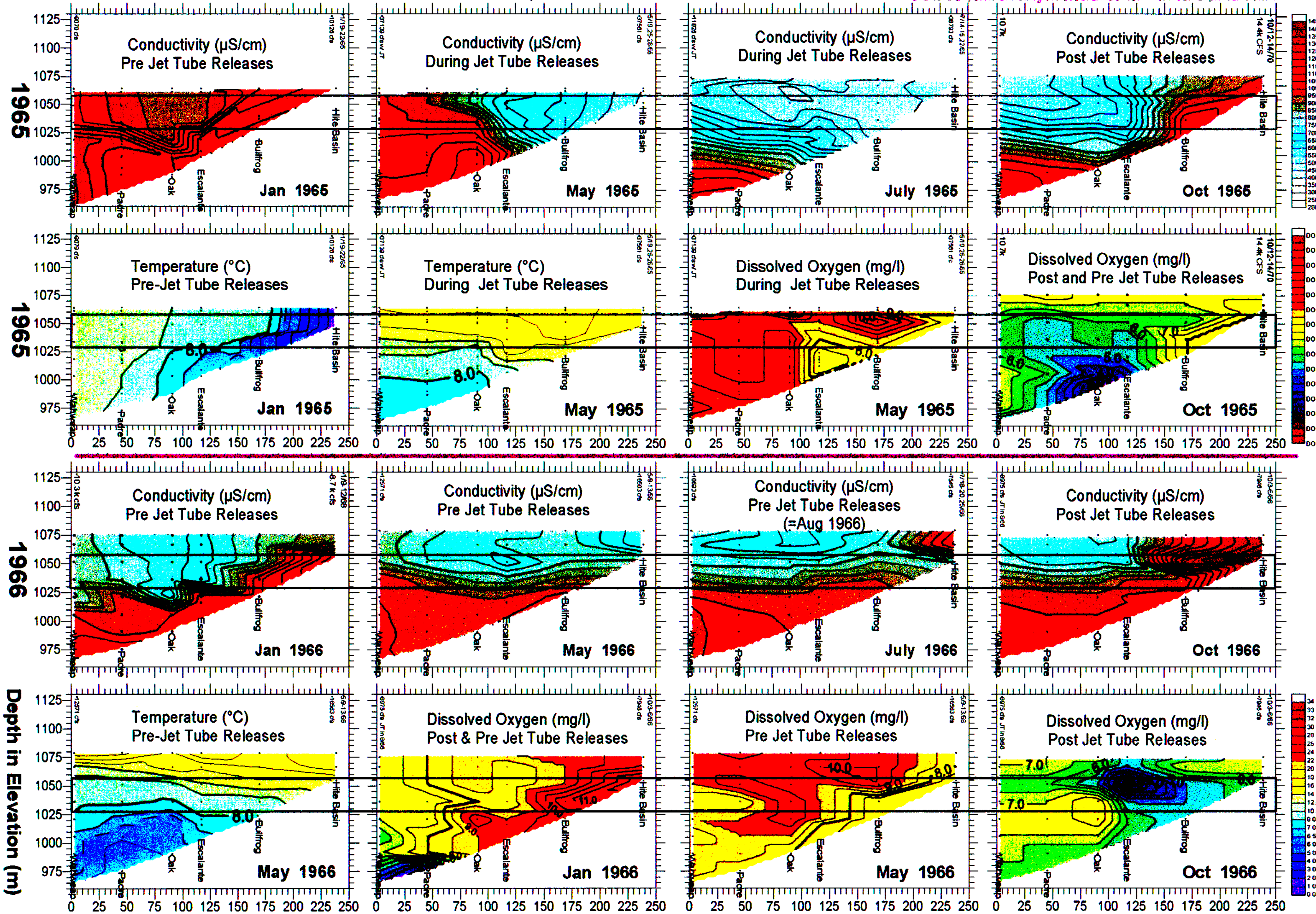

Figure 4: Conductivity, temperature and dissolved oxygen for 1965 and 1966. Before, during and after Lake Powell jet tube releases of 2/65 to 8/65 and 8/66 for elevating Lake Mead. Depth of penstocks (1057.7 m) and jet tubes (1028.4 m) indicated by black lines.

1973 Rainbow Bridge Drawdown, Penstocks Only

Conductivity (μS/cm), Temperature (°C), Dissolved Oxygen (mg/L) in Lake Powell

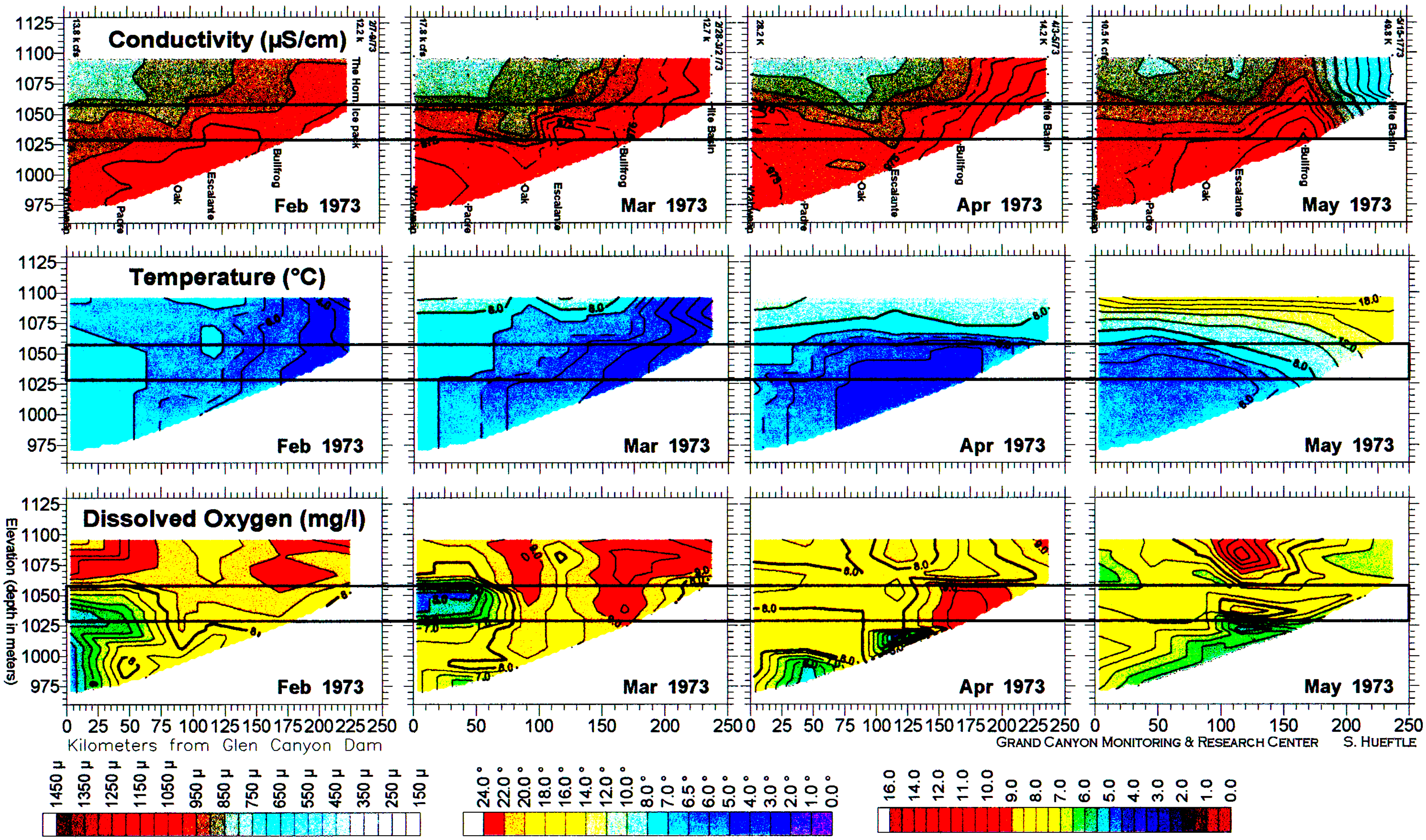

Figure 5: Longitudinal profiles of Lake Powell for February, March, April and May, 1973. Drawdown of Lake Powell in anticipation of large spring flood and concerns for inundation of Rainbow Bridge. Penstock discharges were elevated from March 22, 1973 to May 1, 1973. Discharges during elevated releases averaged 27 K cfs, accounting for 2.29 MAF (million acre-feet) or 22.6% of water year 1973's total discharge. Penstocks and river outlet structures (not used) are indicated 1057.7 m and 1028.4 m, respectively. Average monthly discharge and exact sample date are indicated at top of conductivity plots.

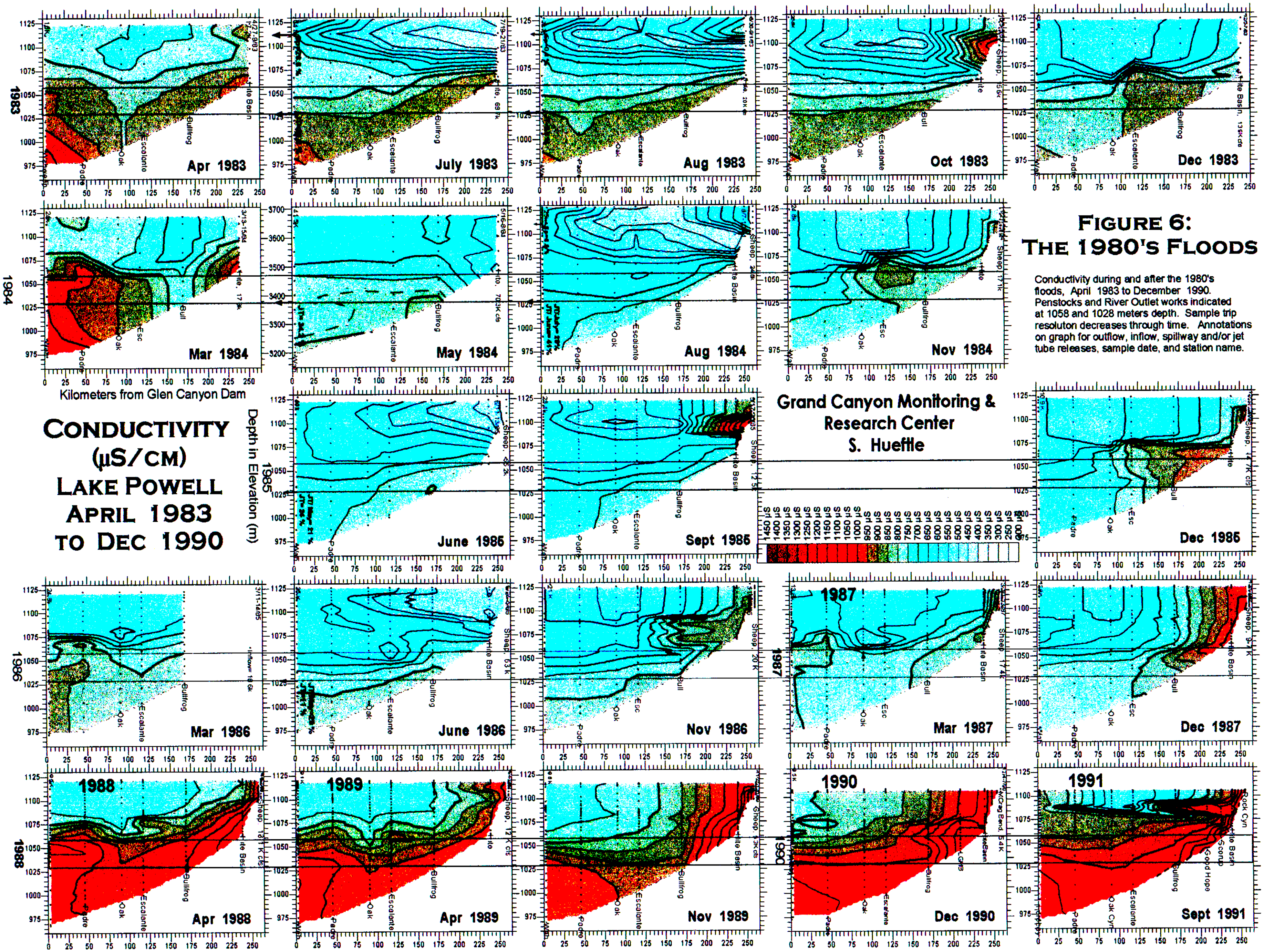

Figure 6: The 1980's Floods

Conductivity during and after the 1980's floods, April 1983 to December 1990. Penstocks and River Outlet works indicated at 1058 and 1028 meters depth. Sample trip resoluton decreases through time. Annotations on graph for outflow, inflow, spillway and/or jet tube releases, sample date, and station name.

Conductivity (µS/cm) Lake Powell April 1983 to Dec 1990

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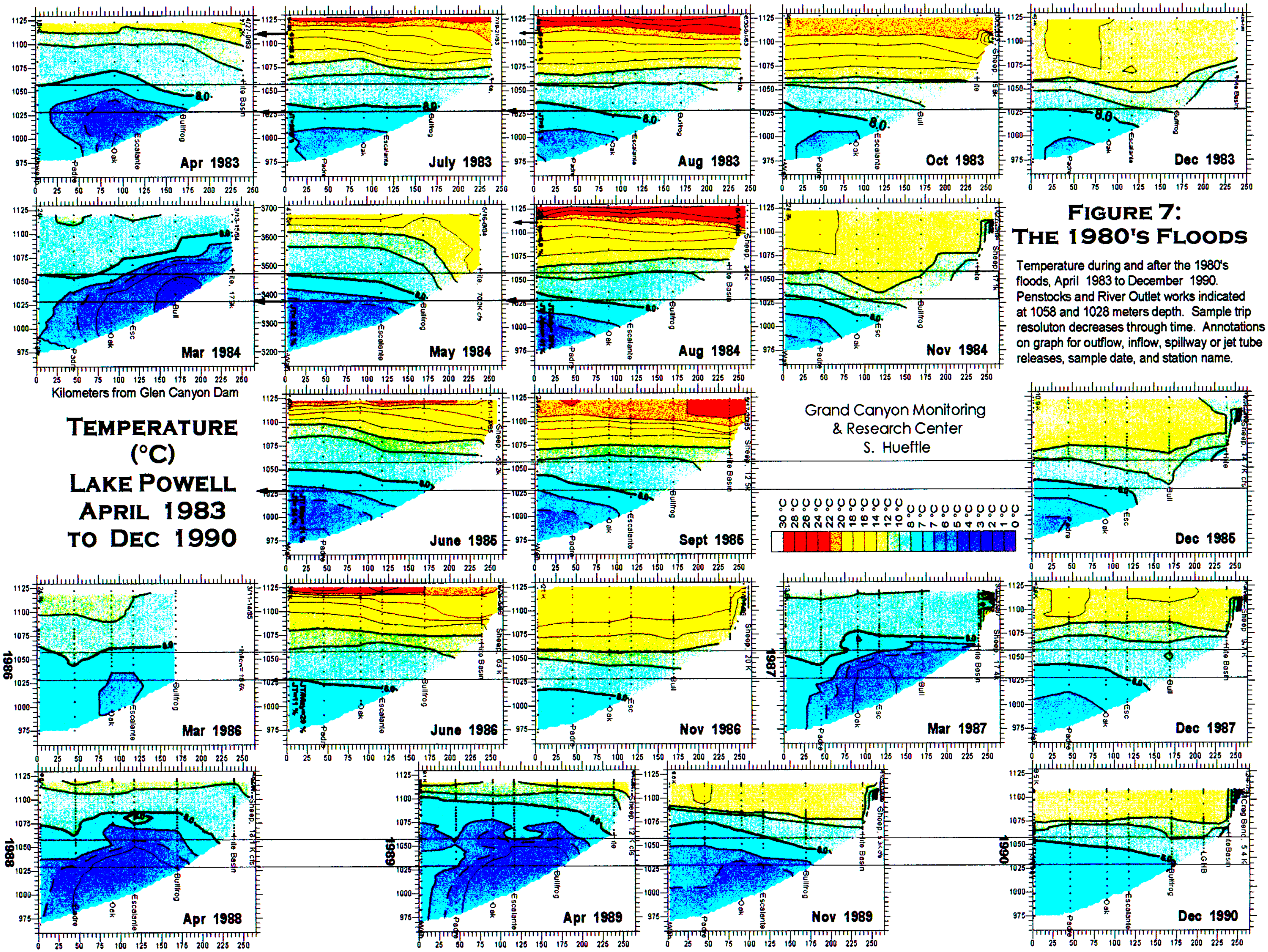


Figure 7: The 1980's Floods

Temperature during and after the 1980's floods, April 1983 to December 1990. Penstocks and River Outlet works indicated at 1058 and 1028 meters depth. Sample trip resoluton decreases through time. Annotations on graph for outflow, inflow, spillway or jet tube releases, sample date, and station name.

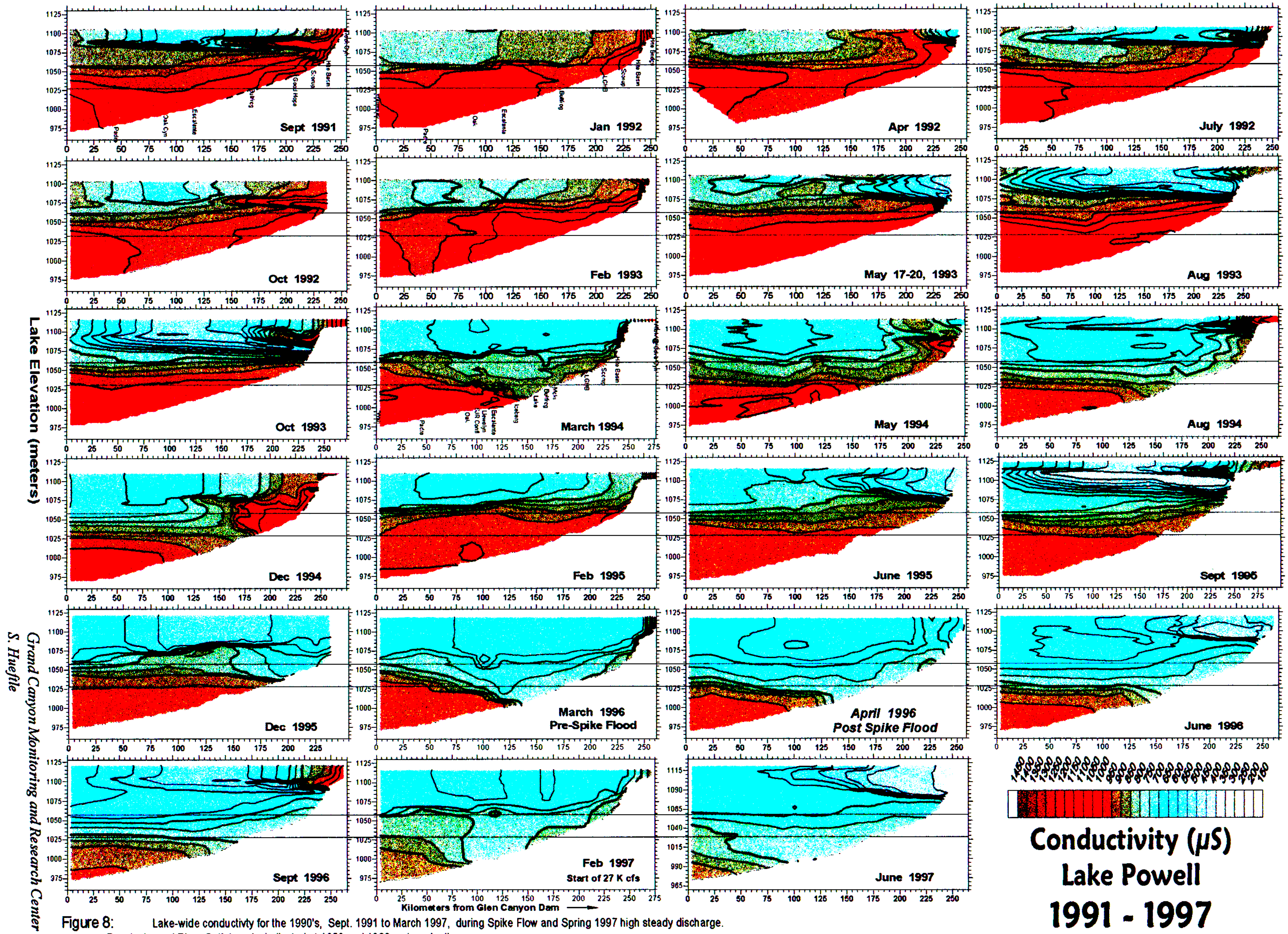


Figure 8: Lake-wide conductivty for the 1990's, Sept. 1991 to March 1997, during Spike Flow and Spring 1997 high steady discharge. Penstocks and River Outlet works indicated at 1058 and 1028 meters depth. (08/25/97)

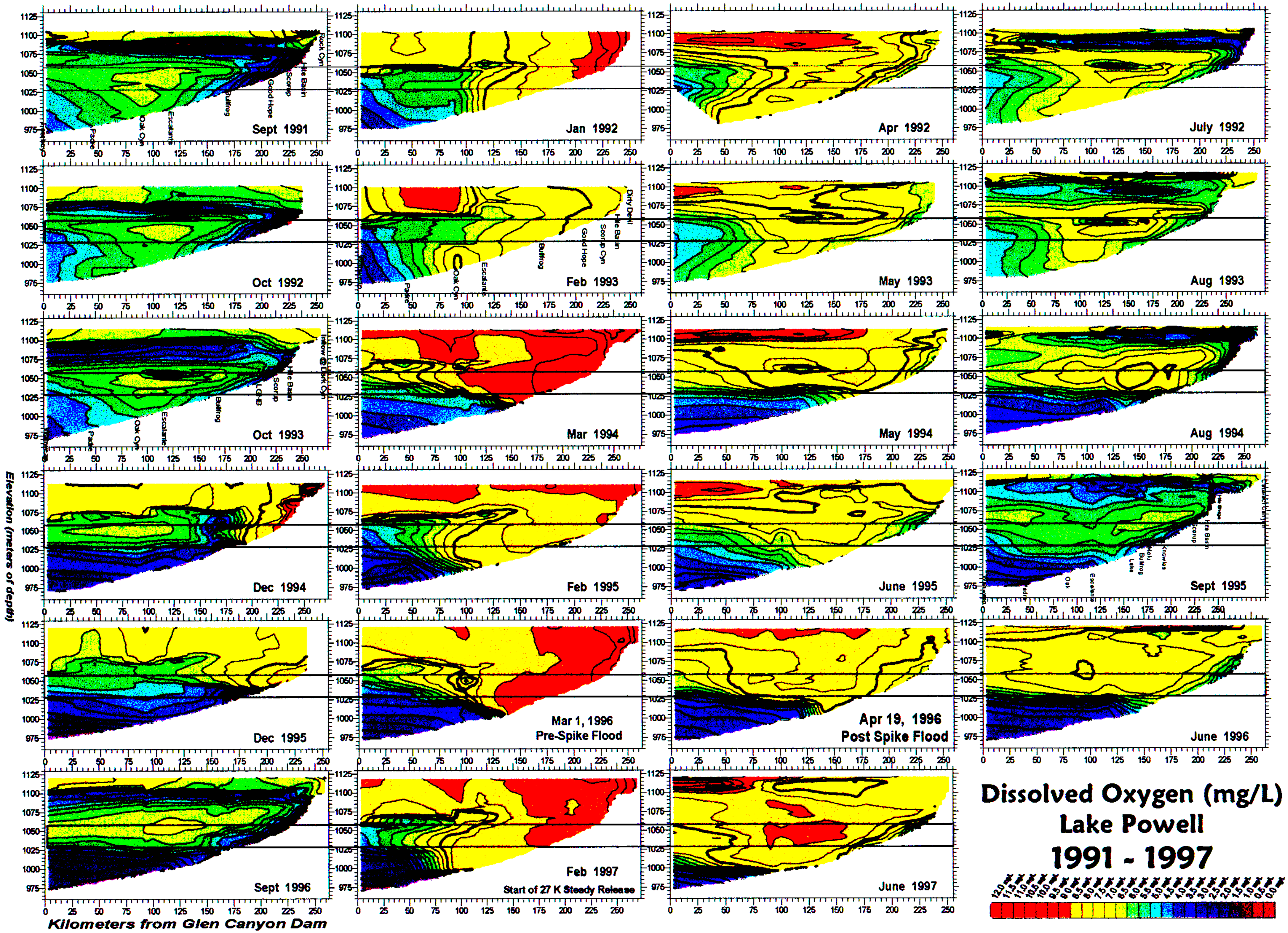


Figure 9: Lake-wide dissolved oxygen for the 1990's, Sept. 1991 to March 1997, during Spike Flow and Spring 1997 high steady discharge. Penstocks and River Outlet works indicated at 1058 and 1028 meters depth.

Grand Canyon Monitoring and Research Center
S. Hueftle

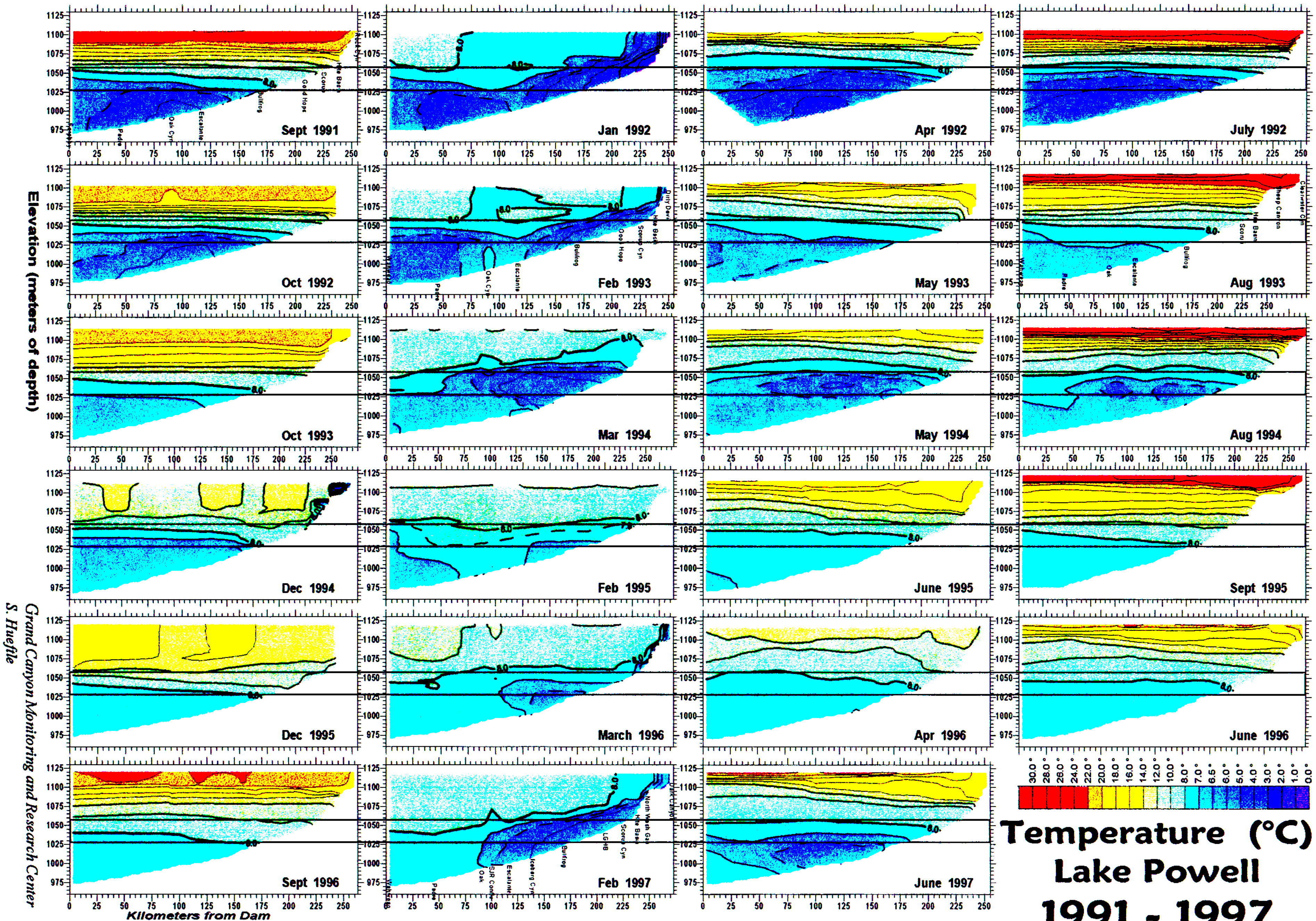


Figure 10: Lake-wide Temperature for the 1990's, Sept. 1991 to March 1997, during Spike Flow and Spring 1997 high steady discharge. Penstocks and River Outlet works indicated at 1058 and 1028 meters depth.

(09/15/97)

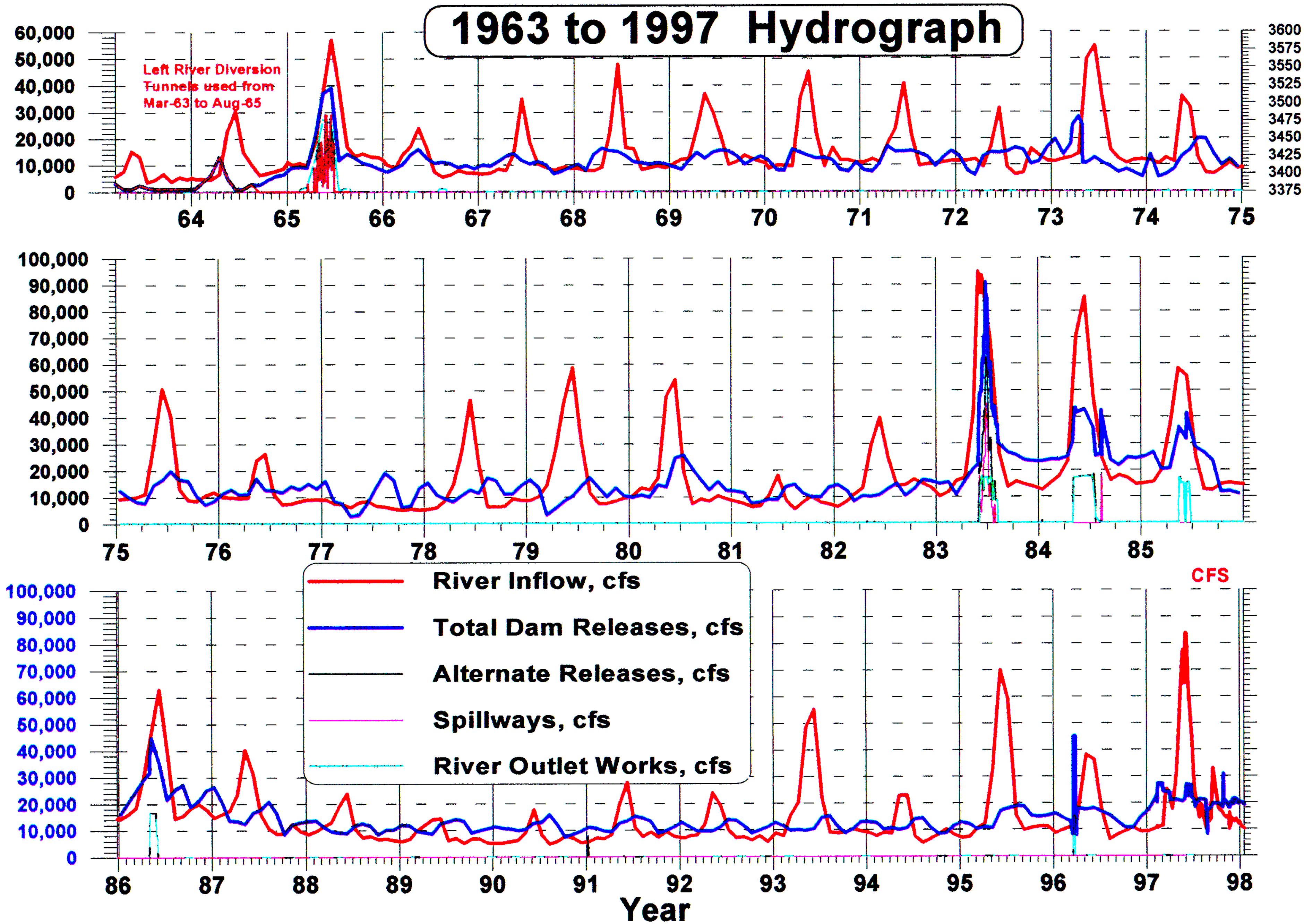


Figure 11a: Hydrograph of Lake Powell inflows and outflows from 1963 to 8/1997. Dam releases are subdivided into spillway releases (elevation 1111.9 m/ 3648'), and river outlet works or hollow jet tubes (elev. 1028.4 m/3374').

Grand Canyon Monitoring & Research Center, S. Hueftle

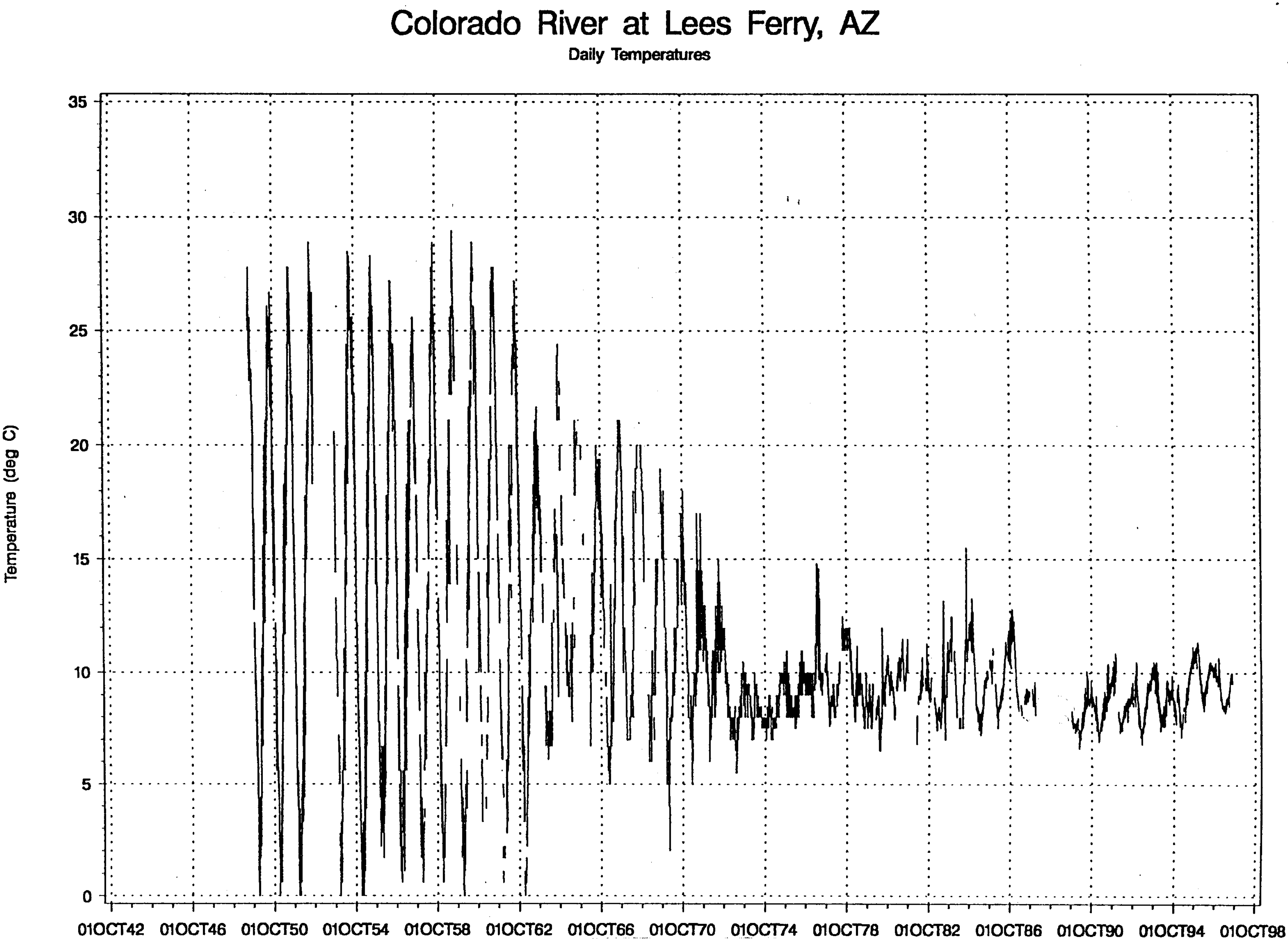


Figure 12: Historical daily temperature values at Lees Ferry,

Colorado River at Lees Ferry, AZ

T.D.S. – QW Data

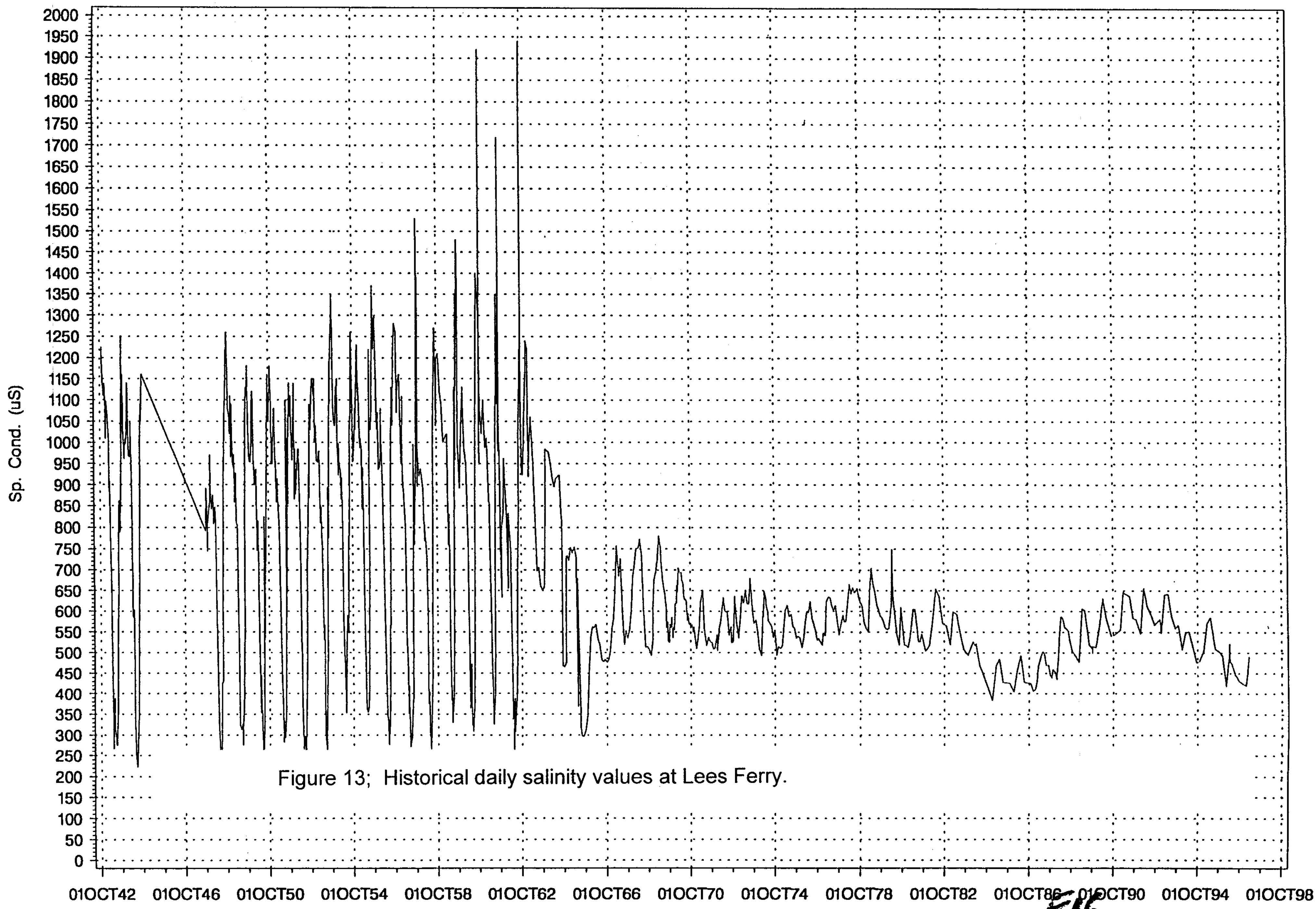


Figure 13; Historical daily salinity values at Lees Ferry.

F16

Colorado River at Lees Ferry, AZ

T.D.S. – QW Data

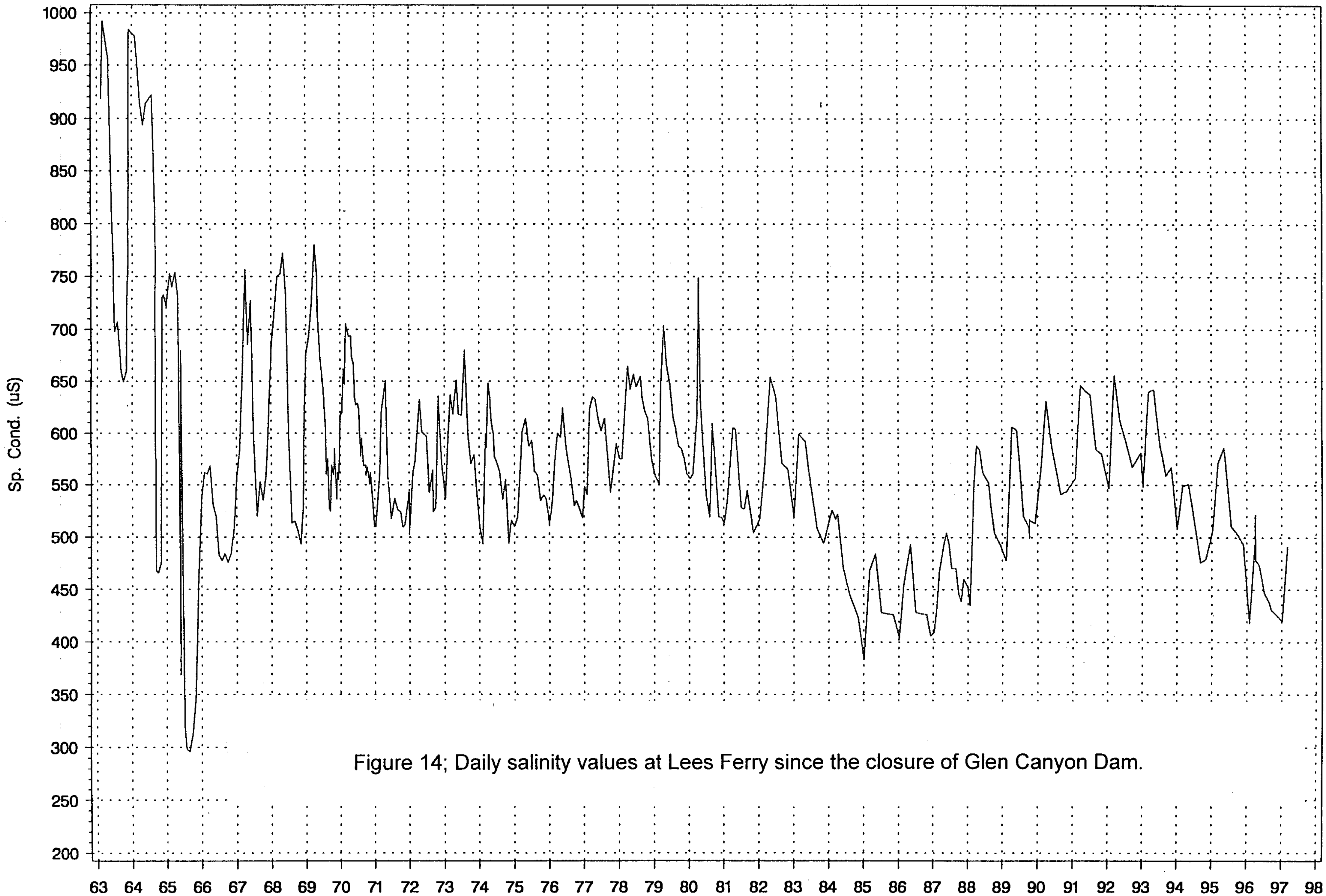


Figure 14; Daily salinity values at Lees Ferry since the closure of Glen Canyon Dam.

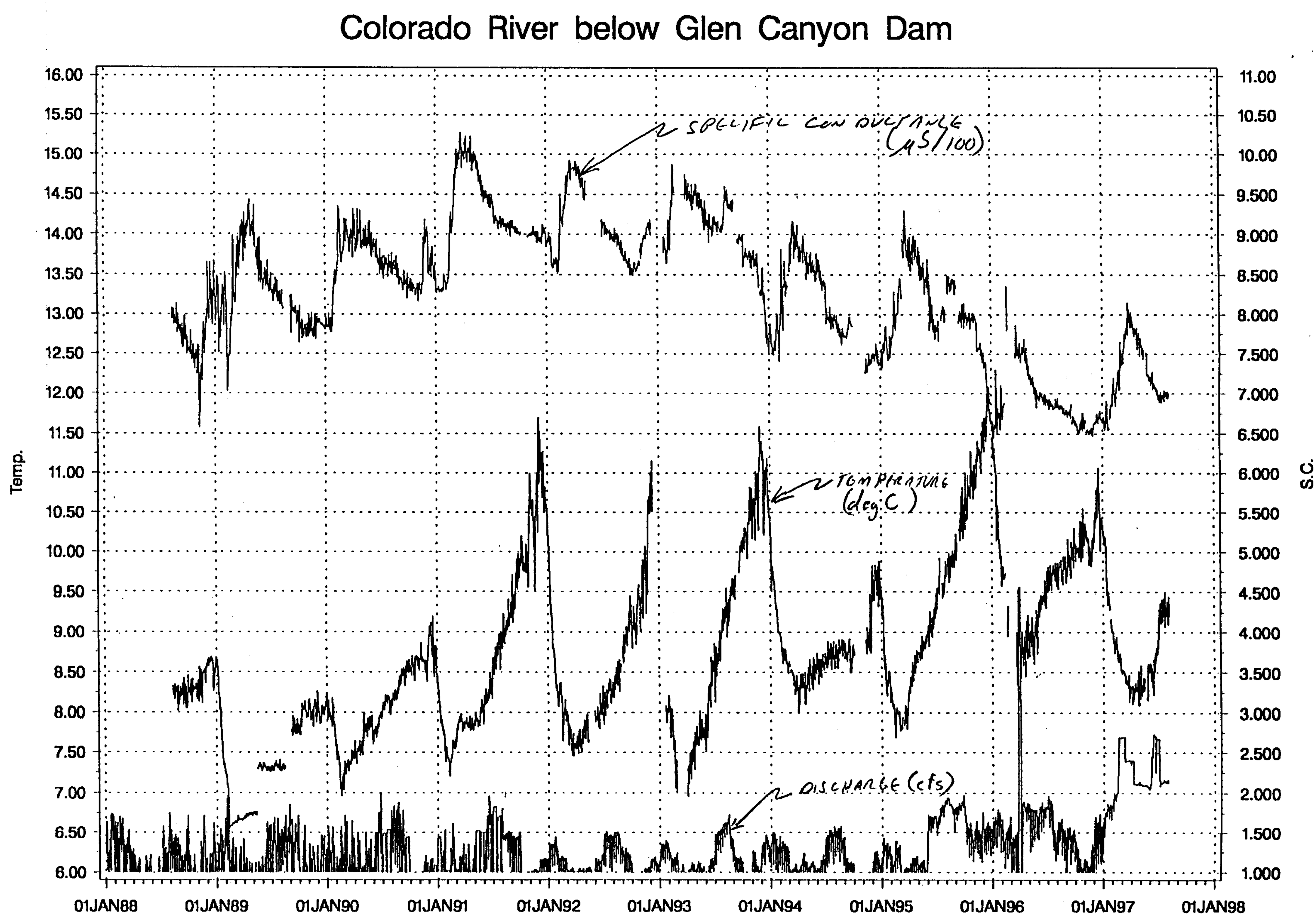


Figure 15; Instantaneous specific conductance, temperature, and discharge below Glen Canyon Dam.

NOTE: Specific Conductance (green) in mS * 10; Discharge (blue) in cfs/10,0000

Fil. BV 05

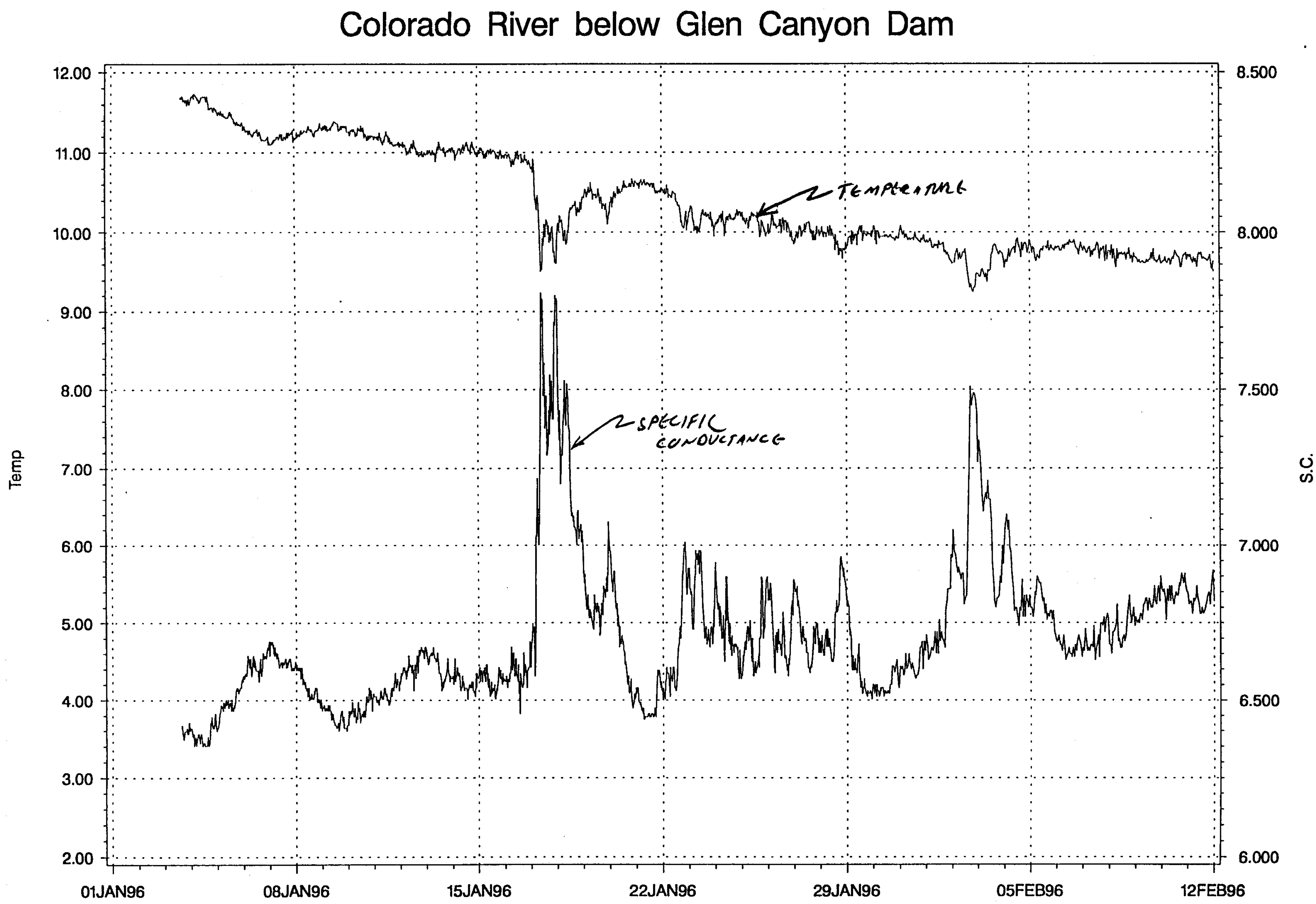
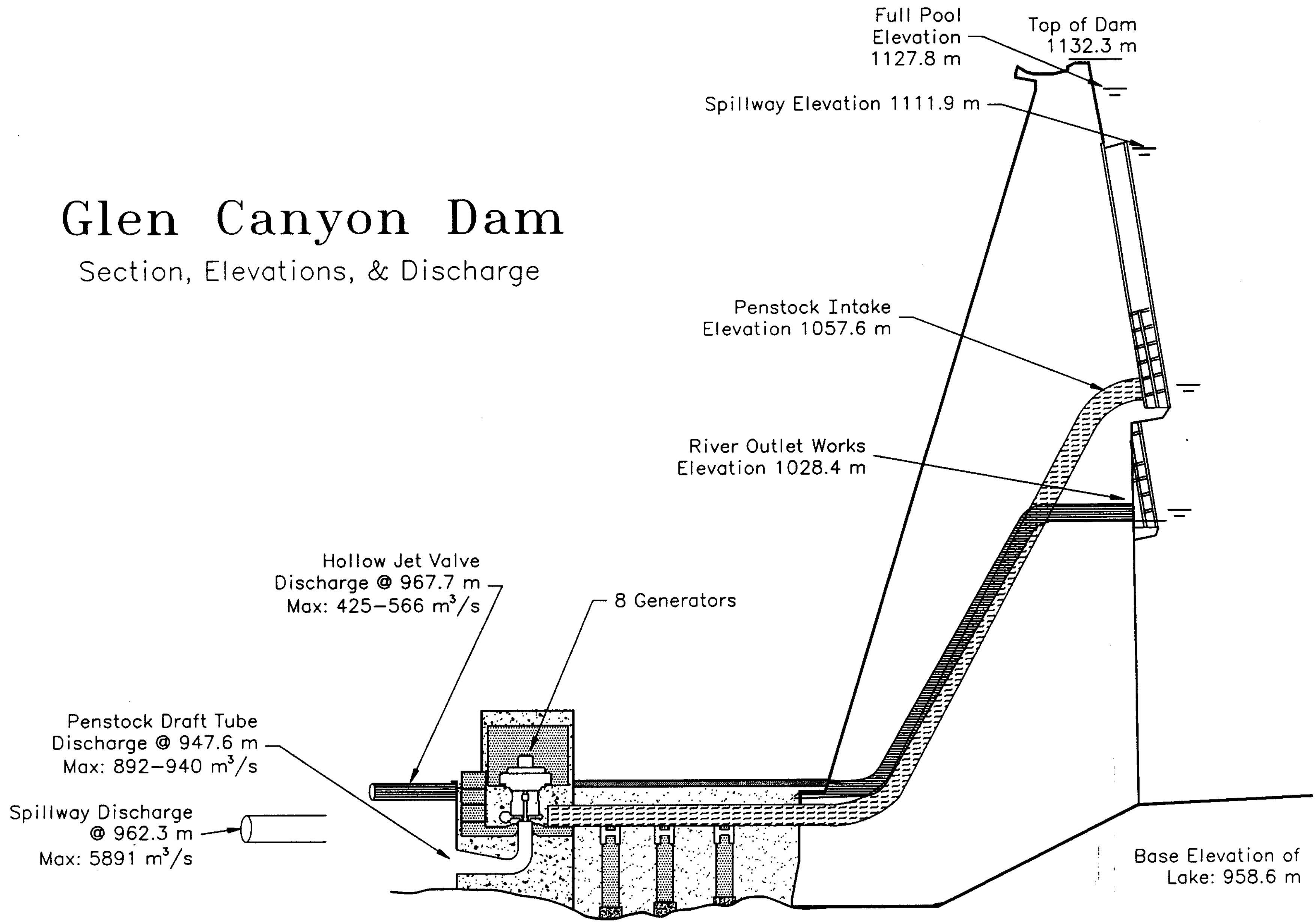


Figure 16; Instantaneous specific conductance, temperature below Glen Canyon Dam showing effects of internal oscillations in Lake Powell during winter months.

Glen Canyon Dam

Section, Elevations, & Discharge



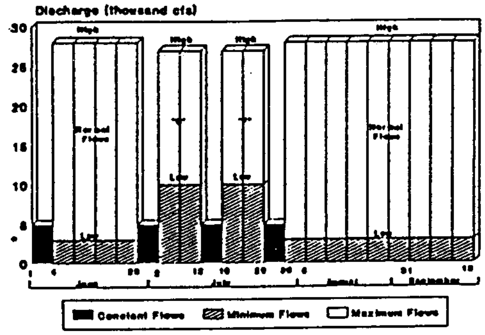
*Recommended discharge followed by maximum possibe discharge.

GLEN CANYON ENVIRONMENTAL STUDIES

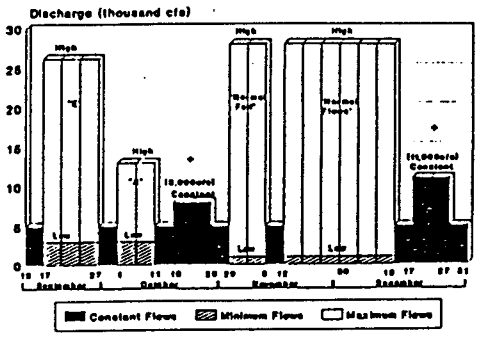
RESEARCH FLOW SCHEDULE

Calendar Year 1990

June - September, 1990



September - December, 1990



- The 3-day 5,000 cfs constant flows are scheduled to begin at 12:01 a.m. on Friday and conclude at 12:01 a.m. on Monday

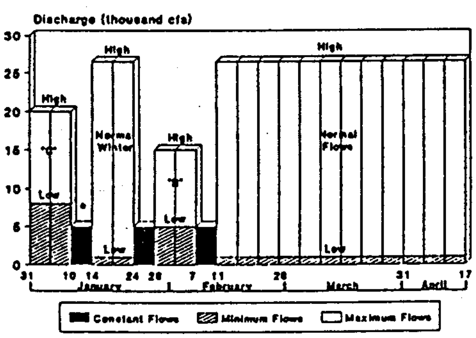
+ The 8,000 cfs and 11,000 cfs constant flows will last 11 days each

GLEN CANYON ENVIRONMENTAL STUDIES

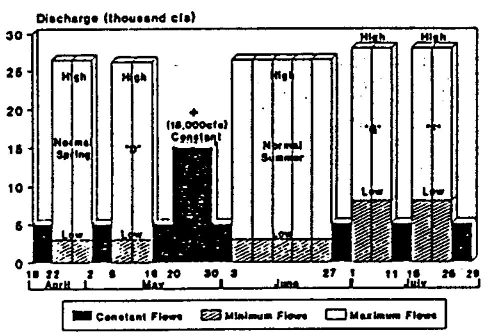
Research Flow Schedule

Calendar Year 1991

January - April, 1991



April - July, 1991



- The 3-day 5,000 cfs constant flows are scheduled to begin at 12:01 a.m. on Friday and conclude at 12:01 a.m. on Monday

+ The 15,000 cfs constant flows will last 11 days

Figure 18; Research flow schedule during GCES Phase II studies.

Reseach Flow "E"

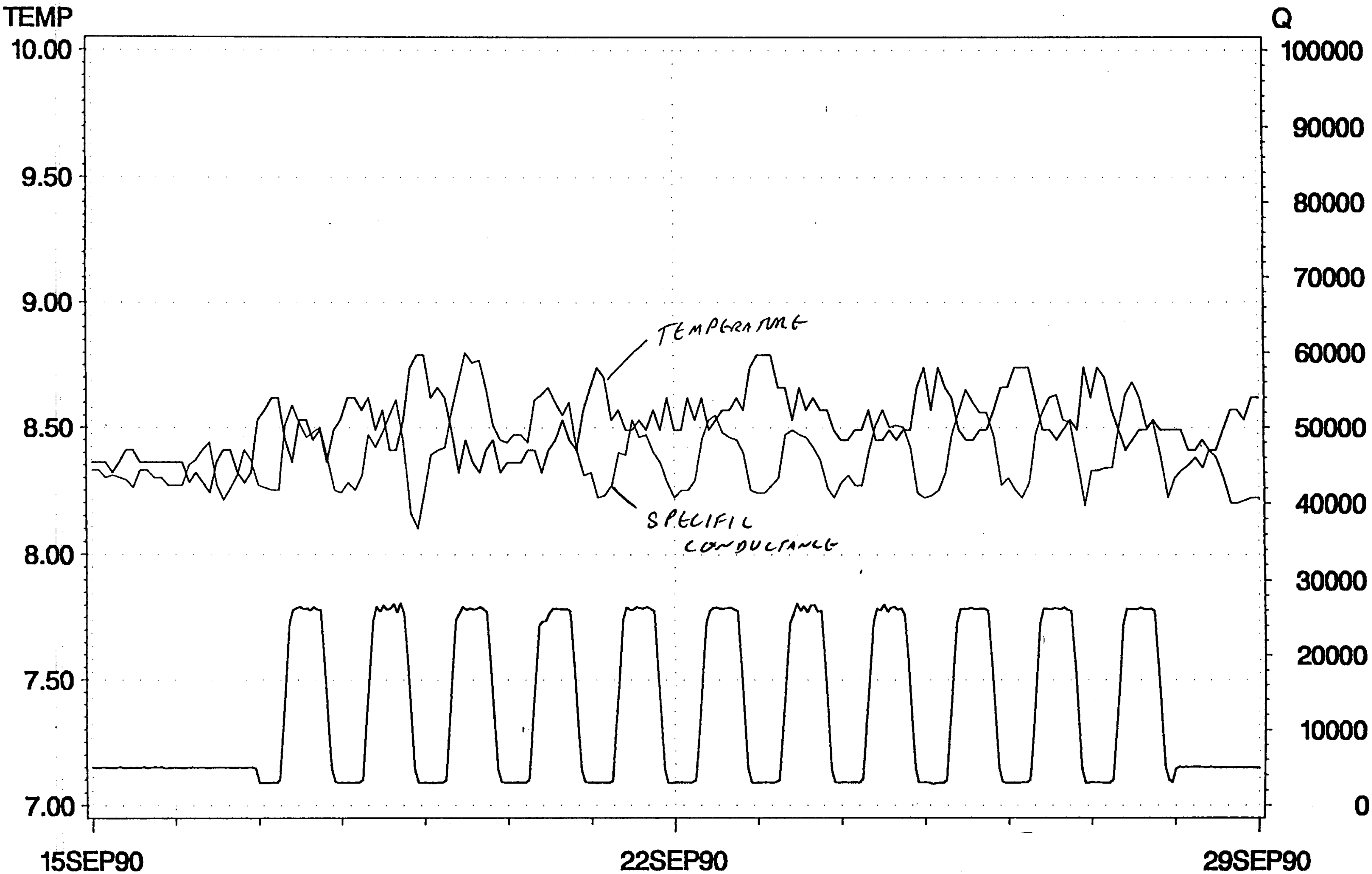
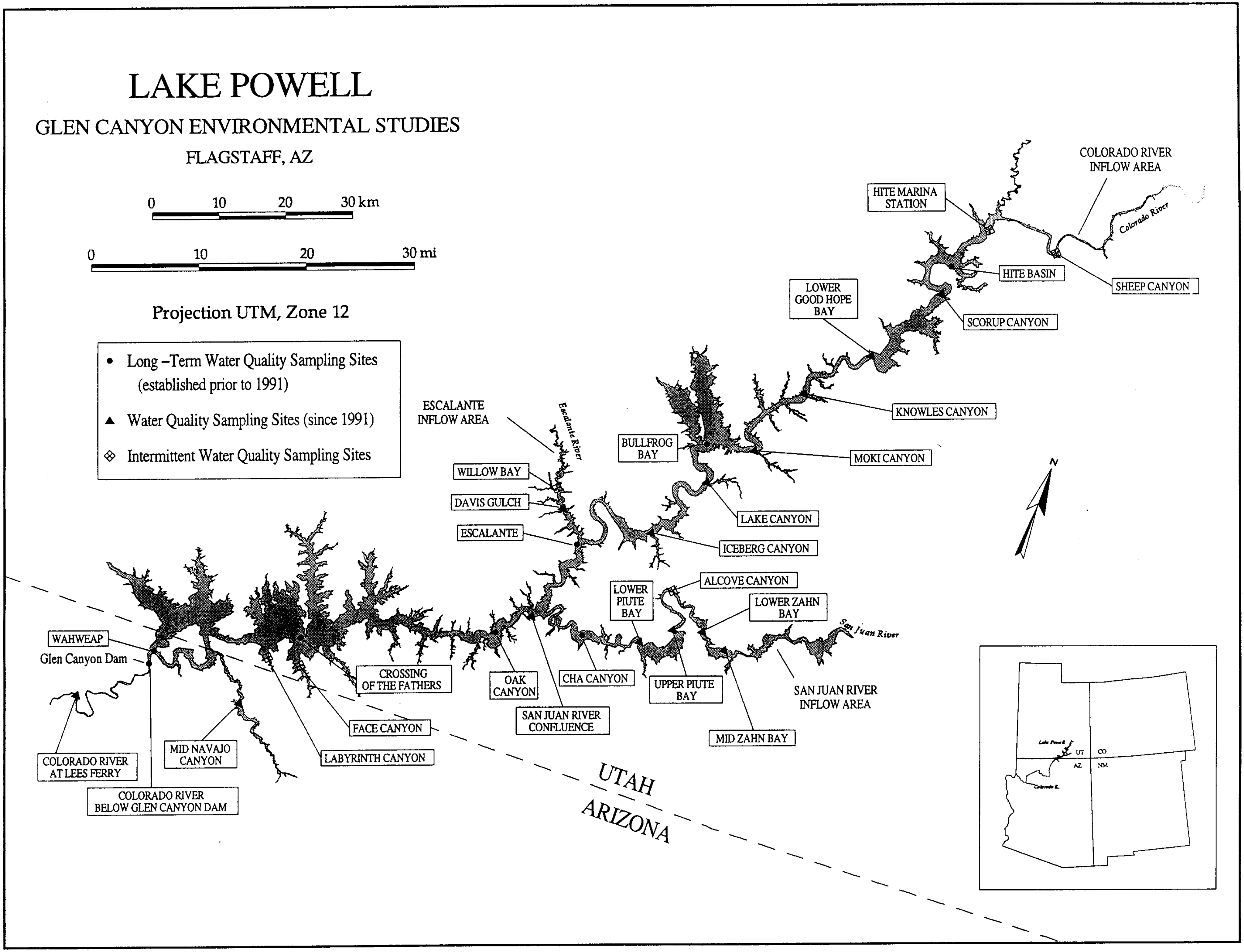


Figure 19: Effects of fluctuating releases on discharge water quality below Glen Canyon Dam during Research Flow "E".


LAKE POWELL
GLEN CANYON ENVIRONMENTAL STUDIES
FLAGSTAFF, AZ
0 10 20 30 km
0 10 20 30 mi
Projection UTM, Zone 12
Long –Term Water Quality Sampling Sites (established prior to 1991)
Water Quality Sampling Sites (since 1991)
Intermittent Water Quality Sampling Sites
COLORADO RIVER INFLOW AREA
Colorado River
HITE MARINA STATION
HITE BASIN
SHEEP CANYON
LOWER GOOD HOPE BAY
SCORUP CANYON
KNOWLES CANYON
MOKI CANYON
BULLFROG BAY
LAKE CANYON
ICEBERG CANYON
ESCALANTE INFLOW AREA
Escalante River
WILLOW BAY
DAVIS GULCH
ESCALANTE
ALCOVE CANYON
LOWER PIUTE BAY
LOWER ZAHN BAY
San Juan River
UPPER PIUTE BAY
CHA CANYON
SAN JUAN RIVER INFLOW AREA
MID ZAHN BAY
SAN JUAN RIVER CONFLUENCE
OAK CANYON
CROSSING OF THE FATHERS
FACE CANYON
LABYRINTH CANYON
WAHWEAP
Glen Canyon Dam
MID NAVAJO CANYON
COLORADO RIVER AT LEES FERRY
COLORADO RIVER BELOW GLEN CANYON DAM
UTAH
ARIZONA
N
UT
CO
AZ
NM

Prospectus for an Assessment of Impacts of Glen Canyon Dam Operations on Water Quality Resources in Lake Powell and the Colorado River in Grand Canyon

W.S. Vernieu, S. Hueftle, D. Garrett
January 21, 1997

The Grand Canyon Protection Act of 1992 requires the Secretary of the Interior to evaluate the impacts of Glen Canyon Dam operations on all affected resources. Although the primary evaluation of these impacts are on resources downstream of the dam, concern has existed that certain aspects of dam operations have the potential to affect various resource attributes upstream of Glen Canyon Dam. These include, but are not limited to, physical, chemical, biological, cultural, social, economic, and public health resource attributes. During fiscal year 1997, the Grand Canyon Monitoring and Research Center will conduct an assessment of the effects of the operation of Glen Canyon Dam on the physical, chemical, and biological water quality resources in Lake Powell and the Colorado River immediately below the dam. This study will rely on data from the Bureau of Reclamation's long-term limnological monitoring program and information from other agencies and institutions. Findings of this assessment will be presented to the Adaptive Management Work Group (AMWG) in the summer of 1997. Based on these findings, the AMWG will recommend future monitoring and research programs for Lake Powell.

Introduction

The closure of Glen Canyon Dam in 1963 caused major changes to the physical, chemical and biological characteristics of the Colorado River in Grand Canyon. These changes are well documented and include the removal of sediment and the moderation of temperature, salinity and other chemical extremes. Operation of the dam for peaking power generation resulted in the removal of seasonal discharge variability and its replacement with daily discharge fluctuations.

Concurrently, changes were also made to the Colorado River as it began to form Lake Powell upstream of Glen Canyon Dam. The river was slowed and began depositing sediment in the reservoir basin. Vertical temperature and chemical gradients appeared in the reservoir body due to seasonal density variations of the inflows, climatic factors, and the mid-depth location of the powerplant penstocks. Certain aspects of dam operations over the past 33 years are hypothesized to have impacts to many of the reservoir's resources, especially water quality. Comprehensive scientific assessments have not been conducted to determine the extent of these impacts.

It is, therefore, the intent of this project to conduct an assessment of changes and/or impacts that occurred to Lake Powell water quality resources from dam operating criteria during the period of Glen Canyon Dam's operation, from 1965 to present. Impacts to other resources noted above are beyond the scope of this project and will not be addressed.

In this context, the term *water quality* is used to include the various physical, chemical, and biological attributes that characterize a body of water in terms of its hydrodynamic properties, chemical composition, and the organisms that live in it. Its use is not intended to connote any value judgements based on suitability for a given use.

Affected Resources

Many processes in Lake Powell are influenced by factors not directly related to dam operations such as inflow hydrodynamics, climatological conditions, and the existence and structure of Glen Canyon Dam. However, some water quality attributes of Lake Powell and downstream releases may be affected by certain aspects of the operation of Glen Canyon Dam. These effects can be evaluated from data developed in existing monitoring programs.

Three main interlinked resource categories may be affected by the operation of Glen Canyon Dam and other factors. **Physical and chemical** conditions in Lake Powell address evaporative water loss, temperature regime and heat budget, salinity levels, hydrodynamics and mixing patterns, nutrient and trace element concentrations, and sediment deposition. These characteristics, in turn, influence the **biological resources** of Lake Powell and the Colorado River below the dam. Affected biological components may include primary productivity, algal and zooplankton abundance and composition, and the dynamics of fish populations, water fowl, and higher species. The third affected resource category involves **social and economic components** such as power production, water delivery, cultural and historic resources, recreation and public health.

While direct linkages exist among these resource categories, identification and evaluation of effects to all these resource categories is impossible in one year under the current budget setting. The scope of this assessment will therefore be limited to the various physical, chemical, and biological water quality attributes associated with Glen Canyon Dam operations for which information has been or is currently being gathered.

Scope and Objectives of Assessment

The Grand Canyon Monitoring and Research Center (GCMRC) will undertake a one year assessment of the effects of Glen Canyon Dam operation, from 1965 to 1996, on the physical, chemical, and biological water quality characteristics of Lake Powell. This assessment will draw mainly from Reclamation's long term water quality monitoring program on Lake Powell but will also be supported by information from other studies and existing literature. It will be conducted by analysts from GCMRC in consultation with three reservoir limnologists currently not connected with the Center. Preliminary findings will be made available in late summer 1997. Final results of the assessment will be reviewed by a Science Advisory Group and presented to the Adaptive Management and Technical Work Groups at the end of fiscal year 1997.

The primary focus of this assessment will be to determine the effects of dam operations, as specified in the Glen Canyon Dam EIS and Record of Decision, on reservoir and release water quality. Primary consideration will be made to peaking power generation, operation of non-power release structures, and potential selective withdrawal. An attempt will be made to identify other factors affecting Lake Powell such as the existence and structure of Glen Canyon Dam, climatological factors, and internal hydrodynamic processes, so that these impacts are not inappropriately associated with dam operations. This assessment will not address direct impacts to fisheries, public health, recreation, or other social and economic resources other than to identify possible linkages between these resources and water quality changes. This limited scope does not assume negligible impact to these resources. Although impacts could be occurring to all these resources, the reduced scope of this assessment relates primarily to the following institutional constraints:

1. A 10-month assessment period
2. A restrictive budget
3. The availability of data for assessments from Reclamation monitoring programs that are limited primarily to physical, chemical, and biological resource attributes.

Background Information

Concurrent with historical changes in dam operations and reservoir conditions, Reclamation has maintained a water quality monitoring program on Lake Powell since 1965. By associating the monitoring effort with historical dam operations, increased understanding can be gained of effects of dam operations on reservoir resources.

<u>Brief History of Lake Powell and Glen Canyon Dam Operations</u>

Lake Powell has had a relatively short existence as an operating reservoir. Its history can be described in terms of three major periods in Glen Canyon Dam operations.

1963-1980. The seventeen-year period from 1963 to 1980 resulted in the eventual filling of Lake Powell to its normal pool elevation of 3700 ft. With minor exceptions, this period was characterized by constantly increasing reservoir elevations, increasing depth of the penstock withdrawal zone, and continual inundation of new areas of the reservoir basin. Stable stratification patterns in temperature and salinity developed from the constant withdrawal at the penstock level.

1980-1990. The period from 1980 to 1990 was characterized by relatively full reservoir levels. A succession of high runoff years in the early and mid 1980's brought the reservoir 8 feet above its normal pool level in July of 1983. Because of the need for increased releases from Glen

Canyon Dam, the spillway structures and hollow jet bypass tubes were operated on several occasions. This allowed significant amounts of water to be released from levels above and below the penstock zone. These factors combined to cause nearly complete mixing of the reservoir in 1985, due to the high volume of reservoir throughput and the operation of the alternative release structures. In the late 1980's, drought conditions returned to the upper basin and resulted in decreasing reservoir levels and the return of strong chemical stratification below the penstock level.

1990-1996. The period from 1990 to 1996 was marked by a series of manipulations to the operation of Glen Canyon Dam for scientific and environmental purposes. Before this time, the dam was operated primarily for peaking power generation and water delivery to the Lower Basin States.

In 1990, Phase II of the Glen Canyon Environmental Studies and the development of the Glen Canyon Dam EIS began. As part of the GCES Phase II Integrated Research Plan, a series of research flows was initiated from June 1990 to August 1991. These flows ranged widely in daily fluctuations and ramping rates, interspersed with periods of steady flow. In November 1991, following the research flow period, the Secretary of the Interior implemented the Interim Operation Criteria, which set limits on minimum and maximum discharge, daily range of discharge, and hourly ramping rates. These criteria remained in place until October 1996, when the Record of Decision for the preferred alternative of the Glen Canyon Dam EIS was signed by the Secretary of the Interior.

Of significance during this latter period was the experimental beach/habitat building flow in March and April 1996. This 7-day discharge of 45,000 cfs included a release of 15,000 cfs from the river outlet works of Glen Canyon Dam. The operation of this structure released water from 100 feet below the penstock withdrawal zone and weakened the strong chemical stratification that had previously built up below that level.

Reclamation Monitoring Program

The Bureau of Reclamation initiated a water quality monitoring program on Lake Powell in 1964 to gather information on initial water quality conditions and to observe changes as the reservoir filled and matured. This program has continued to the present. Based on sampling frequency, spatial resolution of measurements, and changes in instrumentation, four distinct phases of monitoring activity can be identified.

(1) From 1965 to 1971, monitoring activity was characterized by monthly sampling of the Glen Canyon Dam forebay and quarterly surveys of the entire reservoir for temperature and salinity. Measurements and samples were collected at 50-foot depth intervals at seven locations on the reservoir.

(2) From 1972 to 1981, the frequency of lake-wide surveys was increased to a monthly basis.

(3) From 1982 to 1990, sampling activity steadily declined to single lake-wide surveys in 1988 and 1989. Despite the decline in sampling frequency, advances in instrumentation allowed the collection of higher quality data at finer depth resolution. Continuous monitoring of temperature and salinity of the tailwater was initiated during this period.

(4) In 1990, concurrent with the implementation of GCES Phase II studies, Reclamation's Lake Powell monitoring program was restructured. Monitoring frequency was returned to a level of monthly forebay surveys and quarterly lake-wide surveys. Monthly forebay surveys were conducted by the US Geological Survey during the Phase II Research Flow period from 1990 to 1991. Resources were shifted to allow the collection of data at a finer spatial resolution while reducing the number of samples collected for chemical analysis. Sampling for nutrient chemistry and biological conditions was also initiated. The objective of this phase of monitoring activity was to establish a program of basic data collection that would balance cost with the ability to track changes in reservoir and release water quality and evaluate the effects of Glen Canyon Dam operation on these resources.

Other work has been conducted by various agencies and institutions during Lake Powell's history. Studies have been conducted by educational consortiums and federal and state agencies on subjects that include sedimentation, circulation patterns, trace element chemistry, remote sensing, and public health issues. Findings from selected analyses that relate to water quality changes associated with dam operations will be incorporated in this assessment.

Method of Assessment

The various aspects of Lake Powell water quality changes associated with dam operations will be addressed based on the existence of available information. While limited information is available from other sources, most information exists from the Reclamation long-term monitoring program regarding the physical, chemical, and biological aspects of Lake Powell water quality. Evaluation of each of these water quality components will form the basis of the assessment.

The physical aspects of hydrology and dam operations are very well documented and complete. Temperature and major ion chemistry measurements in Lake Powell cover its entire history except for sparse coverage during the 1980's. Dissolved oxygen, pH, and water clarity measurements are incomplete or questionable during certain periods. A regular program of nutrient chemistry sampling and biological measurements was not initiated until 1990, but some synoptic data from the early 1980's exist in this area. While no regular monitoring program for trace element chemistry has existed, some synoptic studies of trace element concentration in water and biota have been conducted. Biological sampling of the reservoir was begun in 1990; analysis is pending for many of these samples. The assessment will be based on the most complete data set possible.

Several tasks are required to complete this assessment. (1) Questions to be answered in the assessment will be developed, in cooperation with three independent reservoir limnologists, to assure appropriate focus to the analysis. (2) A literature review of reservoir water quality effects from dam operations will be conducted. (3) All existing Reclamation data not currently in electronic format will be incorporated into existing databases. (4) Identification, enumeration, and analysis of existing biological samples must be completed. (5) Evaluation of existing quality assurance/quality control data must be made to define levels of precision and accuracy. (6) Other tasks include minor modification of existing database structures and continued development of methods for data analysis. (7) An evaluation will then be made by the analysts and the contract limnologists regarding the effects of dam operations on the physical, chemical, and biological aspects of Lake Powell water quality. The continuation of the existing monitoring program will continue with minor modifications.

The product of this assessment will be an analysis of the effects of dam operations on Lake Powell and Colorado River water quality, an evaluation of the significance of these effects on the various affected resources, and a discussion of possible effects of future proposed structural and operational changes to Glen Canyon Dam. Recommendations for future monitoring and research activity will also be developed.

Assessment Schedule and Budget

The schedule for conducting the assessment is as follows:

- January 31, 1997: Completion of study plan and implementation of study.
- February 15, 1997: Selection of three research limnologists for cooperative question formulation and interpretation of analyses.
- July 1, 1997: Completion of data analysis.
- August 1, 1997: Development of draft interpretation of assessment.
- September 1, 1997: Peer review of analysis.
- November 1997: Adaptive Management Work Group presentation of results of assessment.

Presentation to the Adaptive Management Work Group will be preceded by significant involvement of the GCMRC Planning Group (Technical Work Group) to assure appropriate response to stakeholder information needs.

It is proposed that this assessment be completed within the FY 1997 proposed monitoring budget for Lake Powell of $225,000. To meet this budget constraint, the Lake Powell monitoring program for FY 1997 may be reduced in scope and intensity.

Assessment of Impacts of Glen Canyon Dam Operations on Water Quality Resources in Lake Powell and the Colorado River in Grand Canyon

EXECUTIVE SUMMARY

August 22, 1997

William S. Vernieu
Susan J. Hueftle
L. David Garrett

Grand Canyon Monitoring and Research Center
121 E. Birch Avenue, Suite 307
Flagstaff, AZ 86001-4652

Assessment of Impacts of Glen Canyon Dam Operations
on Water Quality Resources in Lake Powell
and the Colorado River in Grand Canyon

EXECUTIVE SUMMARY
August 22, 1997

Introduction

The Grand Canyon Protection Act of 1992 requires the Secretary of the Interior to evaluate the impacts of Glen Canyon Dam operations on all affected resources. Although the primary evaluation of these impacts is on resources downstream of the dam, concern has existed that aspects of dam operations may affect various resource attributes upstream of Glen Canyon Dam. In January 1997, the Grand Canyon Monitoring and Research Center (GCMRC) presented a prospectus for assessing the effects of Glen Canyon Dam's operation on water quality resources in Lake Powell and Glen Canyon Dam releases to its Planning and Transition Work Groups. This document summarizes the scope and objectives of this study, describes the assessment process, and presents the major conclusions formed from the assessment.

Scope and Objectives

This assessment integrated data from current and past monitoring programs on Lake Powell since 1965 in order to evaluate the effects of various aspects of Glen Canyon Dam operations on reservoir and release water quality. Primary consideration was given to historical aspects of dam operations and those relating to the 1996 Record of Decision on the Operation of Glen Canyon Dam, and includes peaking power generation, timing of seasonal variations in discharge, and operation of non-power release structures. Other factors affecting Lake Powell such as hydrologic effects, climatological factors, internal hydrodynamic processes, and the existence and structure of Glen Canyon Dam were identified so that these impacts were not inappropriately associated with dam operations. The assessment relied mainly on data from the Bureau of Reclamation?s long-term limnological monitoring program on Lake Powell and that currently maintained by GCMRC, and information from other agencies and institutions.

Several factors combined to limit the scope of this assessment. A short time frame of six months was specified for completion of this study. Budgetary constraints limited the amount of financial and human resources dedicated to this process. The quality and completeness of some data from past monitoring efforts was insufficient for certain evaluations. Some information has not yet been organized into a form that facilitates analysis and some samples await analysis. Other useful information has only recently been collected and does not lend itself to historical comparison. Therefore, the scope of this study was limited to the analysis of those data which:

1. have been consistently collected over a long period of time,
2. were readily available for computer analysis, and
3. were most likely to show the effects of dam operations on the chemical and physical limnology of the reservoir.

Historical Conditions and Dam Operations

Glen Canyon Dam has three structures from which water can be released. The majority of Glen Canyon Dam releases are through eight **penstock intakes** which route water to the powerplant turbines with a combined capacity of 33,200 cfs. The penstocks withdraw water from an elevation of 3470 ft above mean sea level and are situated at a depth of 230 ft when the reservoir is its full pool elevation of 3700 ft. When release requirements dictate, an additional 15,000 cfs can be discharged through the **river outlet works**, located at an elevation of 3374 ft, 96 ft below the penstock structures. The third means of withdrawal is from two **spillways** that have a combined capacity of 208,000 cfs and withdraw water from elevations above 3648 ft. Releases from the river outlet works and the spillways bypass the powerplant and can not be used for hydropower generation. Approximately 6.1 million acre feet (maf) of Lake Powell's 26.2 maf capacity exists as inactive storage below the zone of penstock withdrawal to the powerplant.

Several distinct periods of interest during Lake Powell's existence were identified. These included the initial filling period from 1963 to 1980, a period of relatively full reservoir levels from 1980 to 1990 and the past seven years of modified operation of Glen Canyon Dam for scientific and environmental purposes. Within these periods were cycles of varying hydrologic conditions, characterized by changes in salinity and temperature patterns in the reservoir and downstream releases.

Several different aspects of dam operations were identified during these periods. In 1965, high releases from Glen Canyon Dam included the operation of the spillway and river outlet works. High sustained powerplant releases were discharged in 1973 to prevent reservoir levels from entering Rainbow Bridge National Monument. The flood years of the mid-1980's resulted in river outlet works discharge from 1983 to 1986 and operation of the spillways in 1983 and 1985, in addition to high sustained penstock releases. Before 1990, in addition to providing water to meet downstream demands, Glen Canyon Dam was primarily operated for maximizing hydropower revenues. Following a fourteen-month period of research flows and the passage of the Grand Canyon Protection Act in 1992, Glen Canyon Dam was operated in a manner to protect and mitigate adverse impacts to the natural resources in Grand Canyon National Park and Glen Canyon National Recreation Area. This resulted in dam operations constrained within minimum and maximum discharges, daily fluctuations, and hourly rates of change. In 1996, an experimental beach/habitat building flow was conducted, followed by high sustained powerplant releases during most of 1997.

Methods

Information used for the assessment analysis came from several sources. Identification of patterns and historic trends in Lake Powell were primarily derived from measurements of temperature, specific conductance, and dissolved oxygen, collected at specific locations throughout Lake Powell. These data were derived from the currently maintained long-term water quality monitoring program on Lake Powell. Lake-wide profiles exist at intervals ranging from monthly to annually, and are currently collected on a quarterly basis. These data describe seasonal convective mixing processes and the movements of important advective inflow currents through the reservoir. They are represented by three-dimensional colored isopleths that show a given parameter on a vertical cross-section of the reservoir along the main channel of the Colorado River. Profiles of the forebay above Glen Canyon Dam have also been collected at varying intervals and are currently collected on a monthly basis. These data show the entire history of Lake Powell's seasonal variations and decadal-scale hydrologic changes over a broad variety of dam operations. They are represented by three-dimensional isopleths displaying a parameter's concentration with depth through the 33-year history of Lake Powell at the forebay.

The analysis of historical changes in Glen Canyon Dam releases relied on daily temperature and salinity measurements recorded by the US Geological Survey (USGS) at the Lees Ferry gage, approximately 16 miles downstream from Glen Canyon Dam. More recent changes and smaller time-scale processes were evaluated from data supplied by a tailwater monitoring program initiated by the Glen Canyon Environmental Studies program in 1988. The operation of Glen Canyon Dam was analyzed from discharge data from the powerplant and alternate release structures. Inflow data came primarily from USGS gages on the Green, Colorado, and San Juan Rivers upstream of Lake Powell.

Results and Conclusions

Major water quality changes in Lake Powell are strongly influenced by runoff and weather patterns. Lake Powell's history has been characterized by several periods of *meromixis*, the buildup of a saline body of water in the deepest portions of the reservoir, which becomes isolated from other reservoir mixing processes. Meromixis is detrimental to the water quality of Lake Powell because this region of high salinity stagnates and dissolved oxygen levels decrease over time. Eventually meromixis can lead to severe water quality problems which include toxic products of hydrogen sulfide, ammonia, and other nutrients. In addition to its biological toxicity, hydrogen sulfide is highly corrosive and can cause much damage to powerplant turbines and other release structures.

Meromixis is initiated in the fall when saline inflows form density currents that flow along the bottom of the reservoir and accumulate near the dam. This dense saline layer stabilizes and can become isolated from other mixing processes in the reservoir for periods of several years. The meromictic layer can extend upstream beyond Padre Bay, 30 to 40 miles from Glen Canyon Dam. Meromixis ends only after the strong chemical stratification is weakened and cold oxygenated winter inflows of sufficient density displace the meromictic zone.

The operation of the three possible outlets for Lake Powell has had a substantial effect on the water quality of Lake Powell. The most important of these effects is on the reduction in size and intensity of the meromictic layer that builds up below the normal penstock withdrawal zone. Three different operating scenarios have reduced meromixis during Lake Powell's history:

1. high sustained releases from all three outlet structures occurring in June and July 1983,
2. high sustained releases from the river outlet works and penstocks occurring in 1965, from 1984 through 1986, and in 1996, and
3. high sustained releases from the penstocks alone in 1973, during the mid-1980's, and in 1997.

The effects of any one of these operations are amplified if dam operations of the previous year weakened density stratification and weakened meromixis.

It must be noted that the periods of reduced meromixis have coincided with periods of high inflow and reduced salinity to Lake Powell, evidence of the overriding effect of climatic and hydrologic conditions to Lake Powell water quality. Nevertheless, operation of the alternate release structures and high sustained powerplant releases have an unmistakable effect on routing fresh water through the reservoir at deeper levels and significantly enhancing the reduction of meromictic conditions. This effect was most recently seen with the immediate routing of fresh water to the level of the river outlet works from the experimental flood in 1996 and with the gradual breakdown in chemical stratification associated with high sustained powerplant releases in 1997.

Daily fluctuations within historic power plant capacity showed measurable water quality changes in downstream releases during periods when chemical stratification boundaries were near the penstock withdrawal zone. During high releases, the zone of influence of penstock withdrawal is enlarged and can include water from deeper, more saline portions of the reservoir. Timing of high releases from Glen Canyon Dam with seasonal upwelling of the meromictic hypolimnion can enhance the evacuation of this layer and help weaken chemical stratification and further reduce meromictic conditions.

Releases from Glen Canyon Dam through Lake Powell's history have shown trends that are representative of decadal-scale hydrologic conditions in the Upper Colorado River basin. However, these trends also indicate patterns directly influenced by Lake Powell processes and dam operations. Increases in instantaneous and mean annual temperatures at Lees Ferry were seen in 1978 when the reservoir was drawn down due to drought conditions. Temperature increases were also seen coincident with the operation of the spillways in 1983. Salinity peaks at Lees Ferry are associated with periods of reservoir drawdown in 1978 and 1993. Salinity decreases were seen with the operation of the river outlet works in 1965 and during the high water years of the mid-1980's. Salinity levels had dropped in recent years and are expected to continue this decline if above-average runoff and reservoir releases continue.

The challenge of designing any long-term monitoring program is to consistently collect those data that will be valuable to long-term and short-term analysis, at a level of detail sufficient to accurately identify trends and patterns, while maintaining a reasonable expenditure of resources to allow for the continuation of data collection. Past and current monitoring programs have had a broad based focus, providing data on a wide range of physical, chemical, and hydrologic processes in Lake Powell. The most valuable aspects of these programs are seen with data collected at regular intervals with sufficient spatial and temporal resolution. These data have given much information to inflow hydrodynamics, the effects of Glen Canyon Dam release patterns, and seasonal dissolved oxygen dynamics mediated by biological and hydrological processes.

Recommendations

These analyses identify impacts of several scenarios of dam operations of selected resources in Lake Powell. Due to time constraints, a complete analysis could not be conducted. It is possible that additional analysis will provide greater clarification of identified impacts.

The Grand Canyon Monitoring and Research Center feels sufficient scientific evidence exists to warrant continued study of the impacts of dam operation on water quality in Lake Powell and Glen Canyon Dam releases. The Center therefore, requests approval to conduct the following activities in Lake Powell during fiscal year 1998.

1. Continue the current GCMRC monitoring program for the period of October 1997 to October 1998.

2. Conduct additional assessment of existing data relating to Lake Powell and release water quality. This includes analysis of chemical and biological data that were not performed due to time and monetary constraints. A revised assessment will be completed in January 1998.

3. Review with the Technical Work Group, in January 1998, all existing knowledge related to the effects of Glen Canyon Dam operations on the water quality in Lake Powell and downstream releases.

4. Develop, with the Technical Work Group, objectives and information needs for any future Lake Powell water quality monitoring and research programs. This activity would occur in January to March 1998.

5. Develop for Adaptive Management Work Group and Technical Work Group approval, a proposed monitoring and research plan for any specified future Lake Powell water quality monitoring programs. The draft plan would be produced by June 1, 1998.

Monitoring and research activities of the Center beyond October 1, 1998 (fiscal year 1999) would be based on review and approval of a Lake Powell Water Quality Monitoring and Research Plan. The Plan would be submitted to the Adaptive Management Work Group for approval in June 1998.