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Bureau of Reclamation
Lake Powell Water Quality Monitoring Program

William S. Vernieu
Hydrologist

US Bureau of Reclamation
Glen Canyon Environmental Studies
PO Box 22459
Flagstaff, AZ 86002-2459

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Chapter 1

INTRODUCTION AND BACKGROUND

Glen Canyon Dam was completed in 1963 and represents the primary regulatory feature of the Colorado River Storage Project. Glen Canyon Dam, constructed and operated by the Bureau of Reclamation, impounds the Colorado River to form Lake Powell, a 26 million-acre foot reservoir with a surface area of 65,069 ha (160,784 ac) extending 290 km (180 miles) up the Colorado River at its full pool elevation of 1128 m (3700 ft) above mean sea level. Shoreline length has been estimated at 3,057 km (1900 mi). The drainage area above Lake Powell is 279,000 km^2 (108,000 mi^2) (Stanford and Ward, 1990). Lake Powell is located on the border of Utah and Arizona (Figure 1). Lake Powell began filling in 1963 and reached a full pool elevation for the first time in June of 1980.

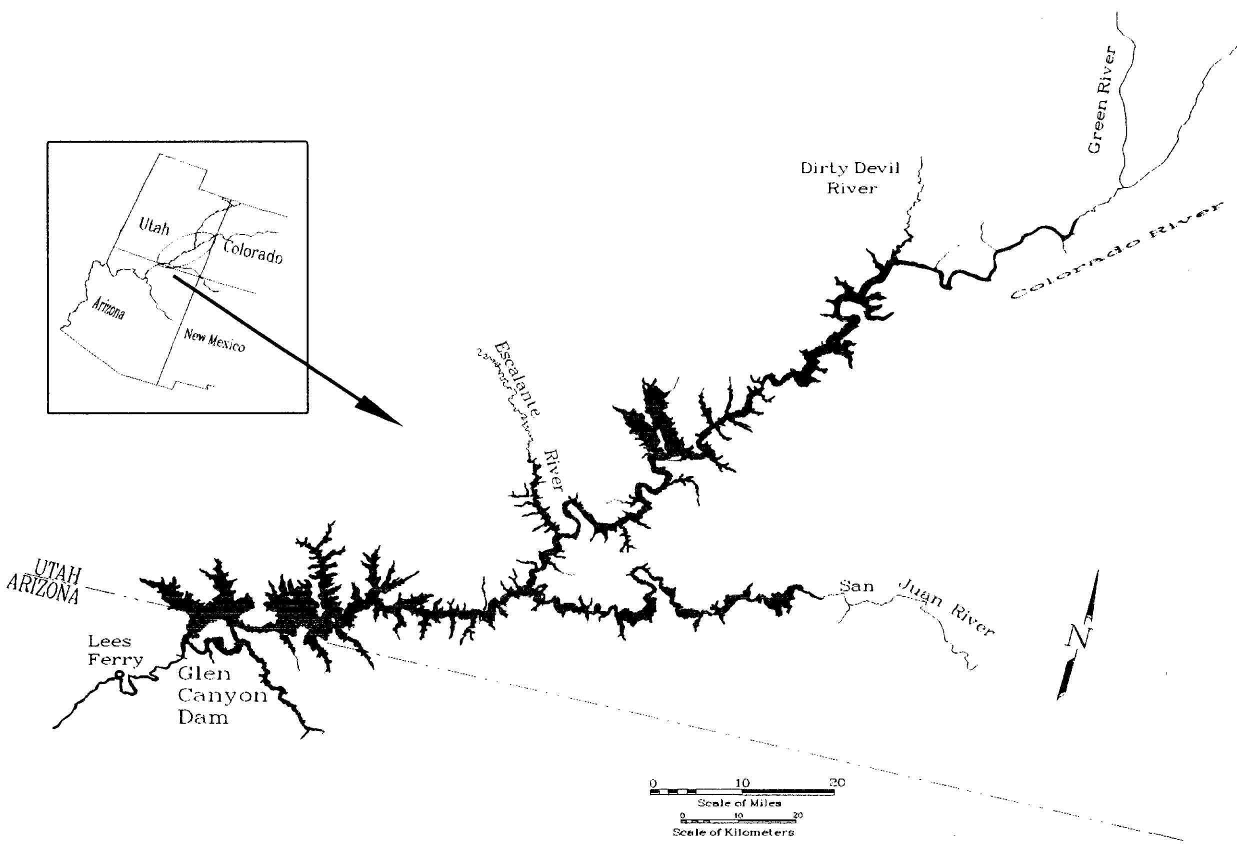

Figure 1. Lake Powell geographic setting and major tributaries

Purpose and Scope

The purpose of this report is to describe the history and current state of water quality monitoring activities conducted on Lake Powell by the Bureau of Reclamation since 1965. It will discuss the characteristics of the main phases of previous monitoring activity and describe, in detail, the program which is currently in place. Related programs conducted by other agencies or institutions on Lake Powell will be briefly identified.

A separate report presents a summary of the detailed information gathered from this program and provides an analysis of past and current conditions and trends.

Glen Canyon Dam Operation

Glen Canyon Dam was authorized by the Colorado River Storage Project (CRSP) Act of 1956 (Public Law 485, 84th Cong., 70 Stat. 105; 43 United States Code 620). The CRSP directed the Secretary of the Interior to construct, operate, and maintain the dam for specific project purposes. These purposes include the storage of water in the Upper Colorado River Basin for release downstream, consistent with the Colorado River Compact of 1922 and the Upper Colorado River Basin Compact of 1948, and the generation of hydroelectric power, maximizing the amount of power and subsequent revenues generated. The Colorado River Basin Project Act of 1968 (Public Law 90-537) further defined the operating criteria and long term management of Lake Powell and the operation of Glen Canyon Dam. The Grand Canyon Protection Act of 1992 (Public Law 102-575) directs that the dam be operated to protect, mitigate impacts, and improve values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established.

The principal guidelines for operating Glen Canyon Dam on an annual and monthly basis are contained in the Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs (P.L. 90-537) which is formally reviewed by the Secretary of the Interior every five years. This law directs the development of an annual plan of operation based on streamflow histories, water supply probabilities, anticipated depletions, and other legal and institutional requirements.

Prior to 1991, Glen Canyon Dam had been operated for peaking power generation to meet legal mandates. Historically, powerplant releases ranged from a minimum of 28 cms (1,000 cfs) to more than 850 cms (30,000 cfs), approaching maximum powerplant capacity. Daily powerplant releases fluctuated on occasion by more than 566 cms (20,000 cfs). Historic releases from Glen Canyon Dam are shown in Figure 2.

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 three separate periods. 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

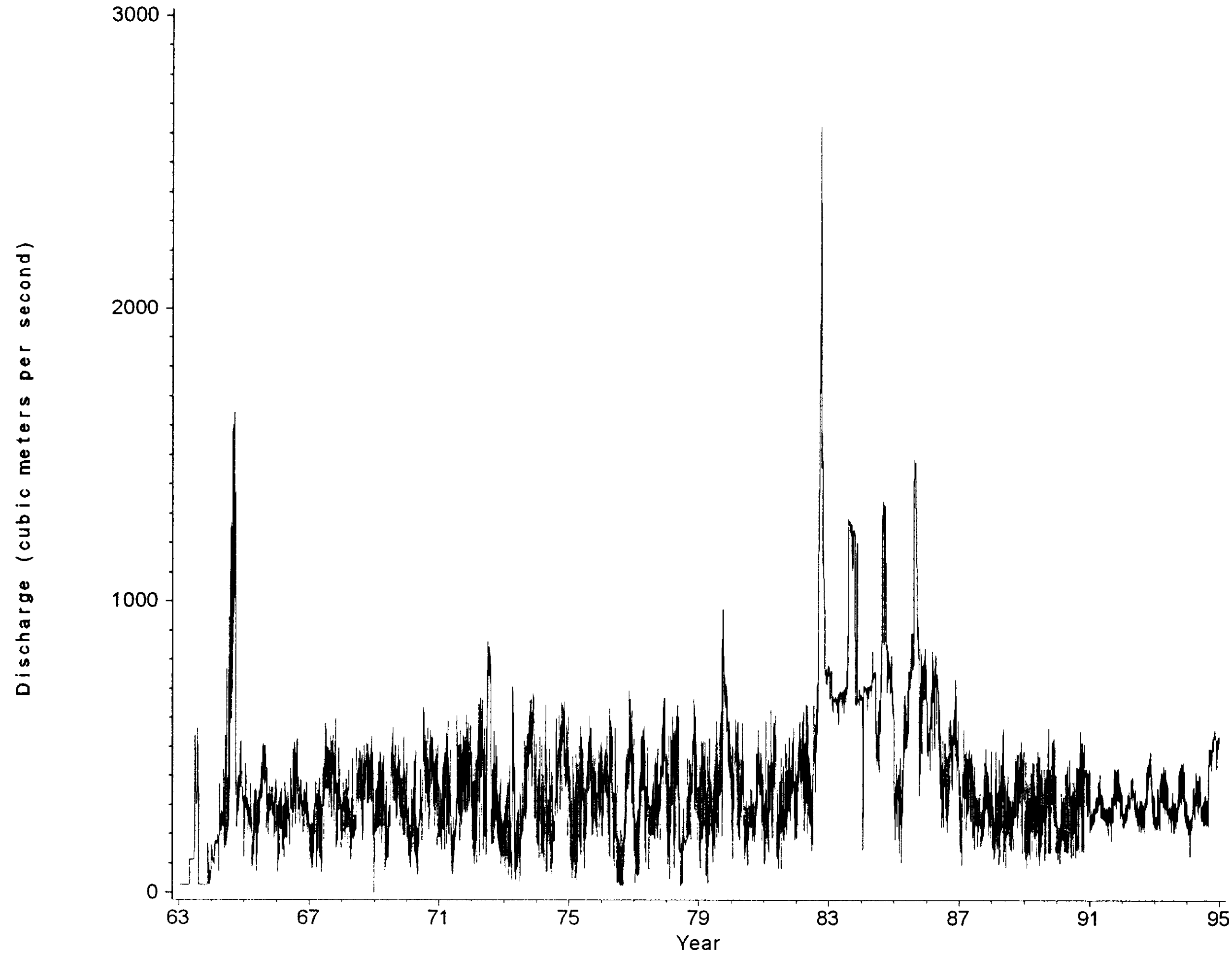

Figure 2. Historic releases from Glen Canyon Dam.

Rainbow Bridge National Monument. During this period there was maximal powerplant production at Glen Canyon Dam. 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.

As part of Phase II of the Glen Canyon Environmental Studies (Bureau of Reclamation, 1990) a series of research flows was conducted from June 1990 through July 1991. These flows consisted of 11 days of fluctuating or steady discharge followed by three days of constant 141 cms (5,000 cfs) discharge.

After an initial evaluation period, interim operating criteria were formally established on November 1, 1991. The purpose of these interim flows is to protect downstream resources until the completion of the Glen Canyon Dam Environmental Impact Statement (GCDEIS) and implementation of the Record of Decision by the Secretary of the Interior. These criteria restrict Glen Canyon Dam discharges between a minimum of 141 cms (5,000 cfs) and a maximum of 566 cms (20,000 cfs) with daily fluctuations not to exceed 227 cms (8,000 cfs) in high release months. It further restricts the rate of change in discharge, or ramp rate, to 42.5 cms (1,500 cfs) per hour for decreasing flows (down-ramp) and 70.8 cms (2,500 cfs) per hour for increasing flows (up-ramp). The GCDEIS preferred alternative (Bureau of Reclamation, 1995), which awaits the Secretary of Interior's Record of Decision, maintains these criteria with the exception of increasing the maximum discharge to 708 cms (25,000 cfs) and increasing the up-ramp rate to 113 cms (4,000 cfs) per hour.

Water can be released from Glen Canyon Dam by three methods (Figure 3). The preferred method of discharge is through the powerplant turbines which can release a maximum of 940 cms (33,200 cfs) . Water is supplied to the turbines from the penstocks which withdraw water from Lake Powell at an elevation of 1058 m (3470 ft). Additional releases from Glen Canyon Dam can come from the river outlet works with a capacity of 425 cms (15,000 cfs) which withdraw water from an elevation of 1028 m (3374 ft), or from the two spillways on either side of the dam which have a combined capacity of 5890 cms (208,000 cfs) and withdraw water from elevations above 1122 m (3680 ft).

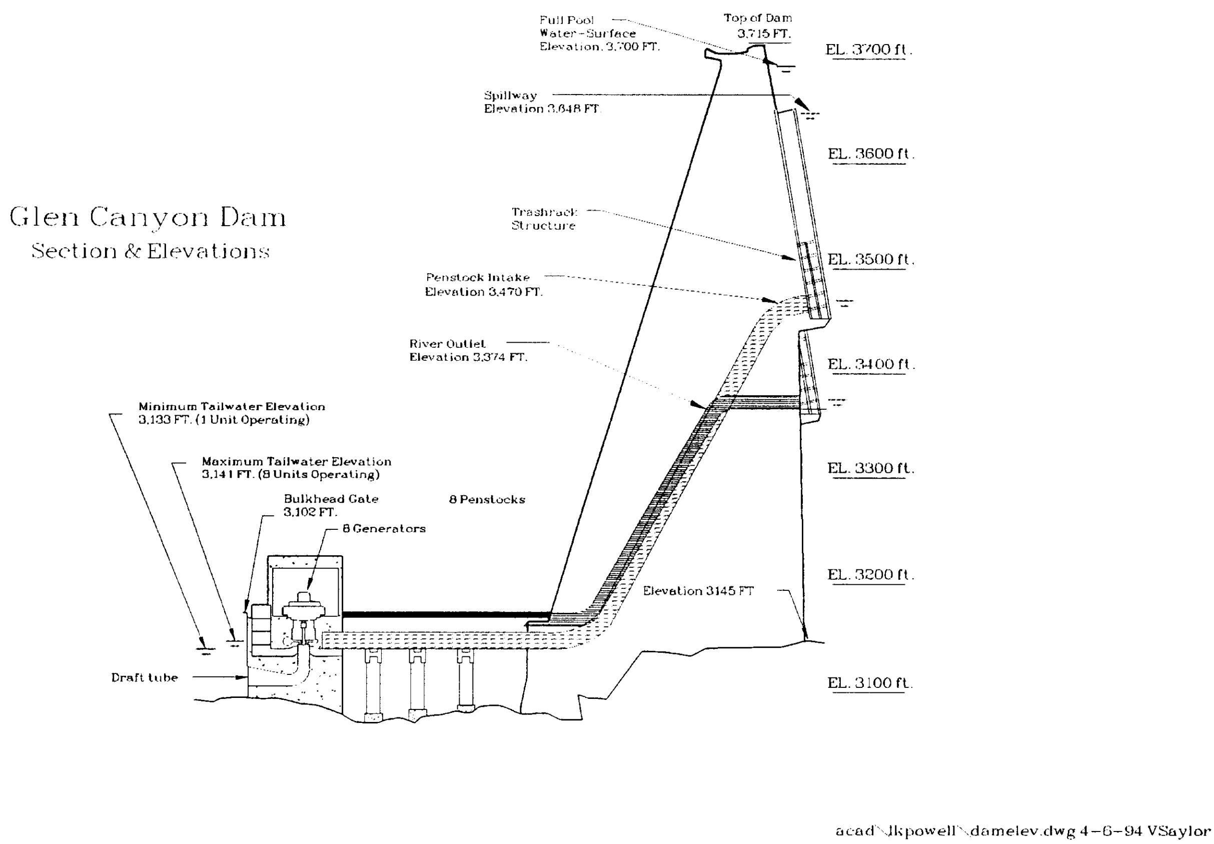

Figure 3. Glen Canyon Dam cross section and location of release structures.

Filling History

Glen Canyon Dam began storing water in Lake Powell when the diversion tunnels of the dam were closed on March 13, 1963. Lake Powell's filling period continued until June 22, 1980, when its surface elevation reached its full pool level of 1128 m (3700 ft), following a prolonged drought period from 1975 to 1978.

After the initial filling of Lake Powell was accomplished, several years of above average hydrology followed. Lake Powell's surface reached an historically high level of 1130 m (3708 ft) on July 4, 1983 (Potter and Drake, 1989). During the late 1980's another drought period ensued which resulted in decreasing surface levels until 1993, when the lake began a second filling cycle. It was filled to near capacity in July 1995, reaching an elevation of 1126 m (3693 ft) (Figure 4).

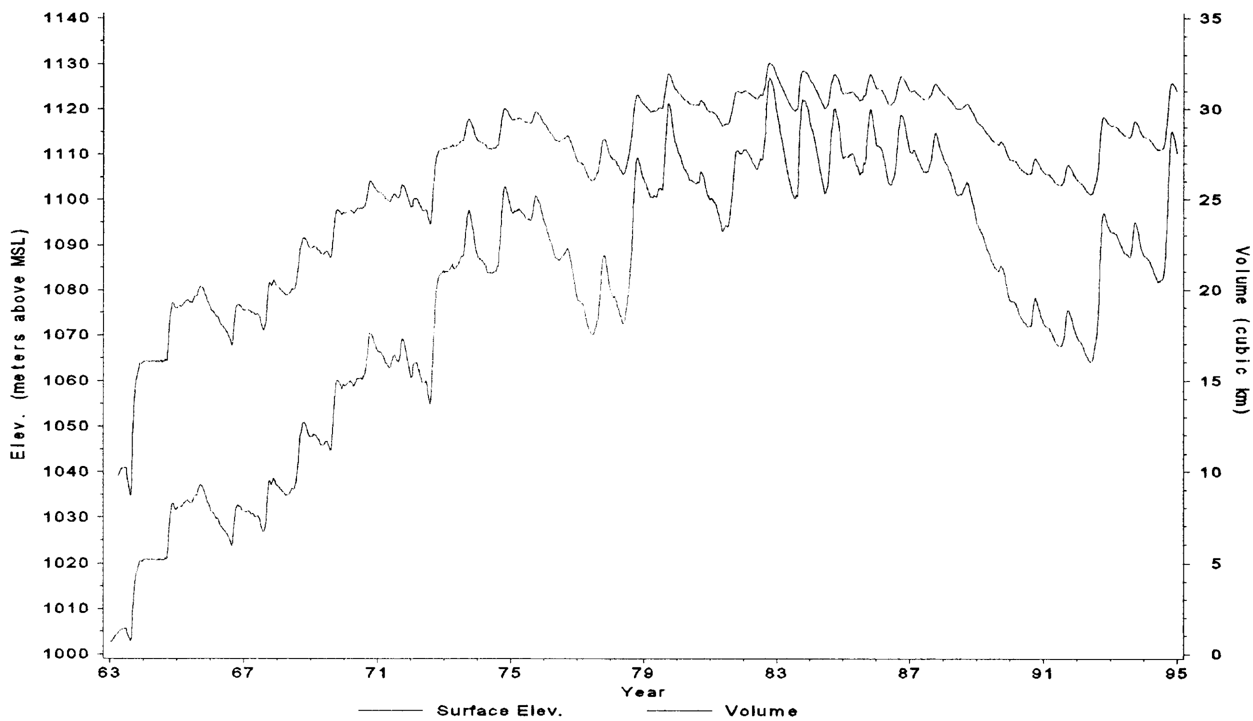

Figure 4. Lake Powell surface elevation.

The fact that Lake Powell has undergone only two complete filling cycles in its 33 years of existence indicates that it is still a very young reservoir. Significant changes in the reservoir's physical and chemical characteristics and aquatic ecology may be expected in future years.

Colorado River Hydrology and Physiographic Setting

The principal inflows to Lake Powell are the Colorado River, Green River, San Juan River, and, to lesser extents, the Escalante and Dirty Devil Rivers. The basin draining into Lake Powell has a

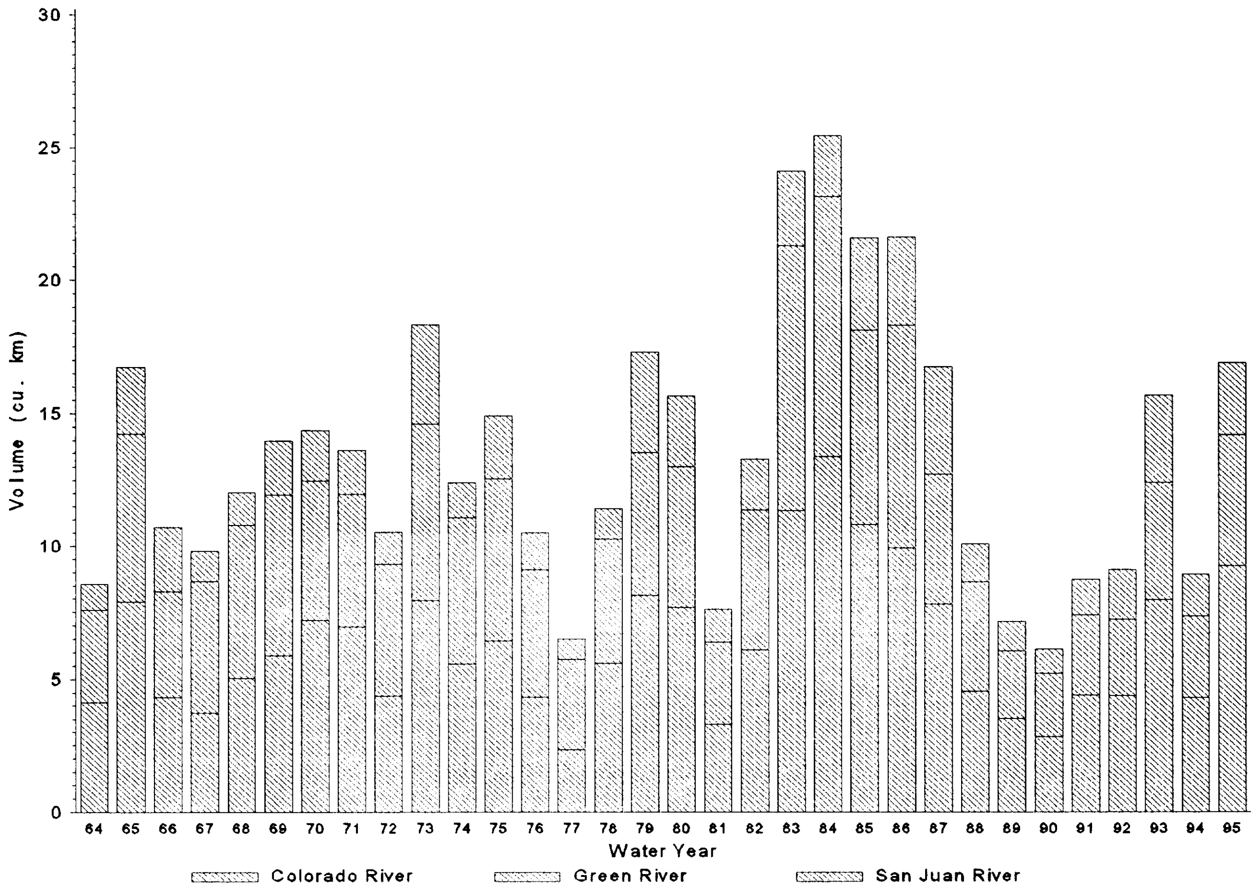

Figure 5. Annual inflow volumes to Lake Powell from major tributary sources.

combined area of 278,900 km^2 (107,700 mi^2). The Colorado River subbasin is essentially unregulated above its confluence with the Green River in Canyonlands National Park and has a drainage area of 97,600 km^2 (37,700 mi^2). The Green River, with a drainage area of 116,800 km^2 (45,100 mi^2) is regulated by Flaming Gorge Dam. The San Juan River has a drainage area of 64,500 km^2 (24,900 mi^2) and is regulated by Navajo Dam.

Based on the results of a recent analysis of water years 1964 through 1995, combined inflows to Lake Powell have averaged 14.2 km^3 (11.5 maf), ranging from a low of 6.46 km^3 (5.24 maf) in 1990 to a high of 26.7 km^3 (21.7 maf) in 1984 (Figure 5).

Maximum inflow peaks have ranged from 396 cms (14,001 cfs) in 1977 to 3,476 cms (122,739 cfs) in 1983. Yearly minimum inflows have ranged from 8.1 cms (2,850 cfs) in 1964 to 302 cms (10,655 cfs) in 1986.

The combined Colorado and Green Rivers represent 80% of the annual inflow; the San Juan River represents 15% of this volume. Approximately 57% of the inflow volume occurs in the spring (April-July) due to snow melt runoff (Figure 6). These figures compare closely with previously conducted analyses (Gloss et al. 1981). .

These tributaries pass through irrigated basins and are subject to a wide variety of municipal, industrial, and agricultural uses in their travel to Lake Powell. There are no major water diversions from Lake Powell; however some transbasin diversions occur in the upper reaches of Lake Powell's tributaries

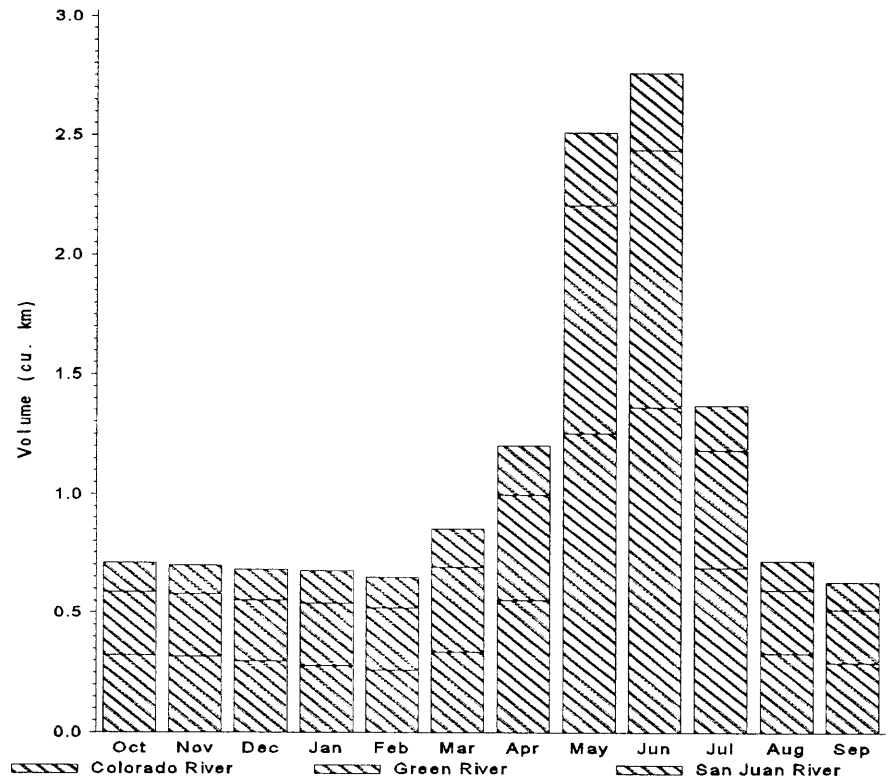

Figure 6. Mean monthly inflows to Lake Powell (water years 1964 -1995).

The waters of the Green, Colorado, and San Juan Rivers travel through a wide variety of geologic strata from their respective headwater sources in the Wind River, Colorado Rockies, and San Juan mountain ranges. Significant mineral loading from natural sources occurs as the rivers flow through sediment formations such as the Mancos Shale, which have been deposited in marine environments. Salinity increases also occur as the rivers flow through the Paradox Basin, extending roughly from the upper portion of Lake Powell easterly to the Utah-Colorado state line. This region is characterized by thick salt deposits which are exposed to the surface in a variety of valleys formed by collapsed salt domes.

The geologic features of the area surrounding Lake Powell consist mostly of the upper sedimentary formations of the Colorado Plateau. These features range through Cretaceous formations (Straight Cliffs sandstone, Tropic and Mancos shales, and Dakota sandstone), the Jurassic San Rafael Group (Bluff sandstone, Summerville formation, Entrada sandstone and

Carmel formation), the Jurassic-Triassic Glen Canyon group (Navajo sandstone, Kayenta formation and Windgate sandstone), the Triassic Chinle and Moenkopi formations, the Permian Cutler and Rico formations, to the Pennsylvanian Hermosa formation and the gypsiferous Paradox formation (Potter and Patterson, 1976). Structural features including monoclines, domal uplifts, and faults characterize portions of Lake Powell and the Upper Colorado River basin, in general.

Lake Powell and most of the Glen Canyon National Recreation Area are within the Upper Sonoran climatic zone at elevations of 1067-1524 m (3500-5000 ft). Average annual precipitation is about 15 cm (6 in). The high average monthly temperature, occurring in July, is about 36°C (97°F); the minimum average monthly temperature is -4°C (24°F) and occurs in January (Potter and Drake, 1989).

Chapter 2

Reclamation Water Quality Monitoring Program

Background

Reclamation initiated a limnological water quality monitoring program on Lake Powell in 1965. The objectives of this program were to gather information on initial water quality conditions in Lake Powell and to track these conditions as the reservoir filled and matured. Later objectives included monitoring the reservoir to determine its effect on salinity levels in down stream releases. Field data collection activities were accomplished by personnel at Glen Canyon Dam (CRSP Power Operations Office) under the direction of Upper Colorado Regional Office in Salt Lake City, Utah. This monitoring program has undergone several significant changes but has remained in effect through the present.

The current phase of the program has been in place since 1990 and is coordinated and directed through the Glen Canyon Environmental Studies Office in Flagstaff, Arizona. Additional objectives include studying physical, chemical, and biological processes in the reservoir and how these processes affect the quality of releases to the downstream ecosystem. The current program includes quarterly limnological surveys of physical, chemical, and biological conditions at multiple stations throughout Lake Powell. Monthly profiles of common water quality parameters are collected in the forebay, immediately above Glen Canyon Dam. In addition to lake-based sampling, temperature, specific conductance, and dissolved oxygen are continuously monitored in the tailwater below the dam and at Lees Ferry by remote instrumentation.

Objectives

Specific objectives of the different phases have varied during the program's history, with the general goal of the program to determine how limnological processes in Lake Powell affect physical, chemical, and biological conditions in the reservoir and in the Colorado River releases from Glen Canyon Dam. The evaluation of these processes and conditions provides information necessary to understand salinity levels in the Colorado River, support of native and non-native fisheries in Lake Powell and the Colorado River below the dam, and effects of release water quality on the ecosystem in Grand Canyon below Glen Canyon Dam.

The objective of the existing Bureau of Reclamation Lake Powell limnological monitoring program is to monitor and evaluate the short-term and long-term processes affecting the physical, chemical, and biological aspects of reservoir and dam release water quality. The program is conducted at a level which allows significant changes to be observed and evaluated on time scales ranging from monthly and seasonally to the entire history of the reservoir's existence. These observations have led to the development of research questions which focus on specific management concerns and enhancements of the monitoring program.

Data gathered from the program are managed and analyzed so that information collected over various time scales may be compared, integrated with related data from other sources, and properly stored and archived. Analytical tools have been developed and maintained to enhance the retrieval, visualization and interpretation of the data. The information is made available to resource managers, scientists, and other interested parties through the development of periodic reports, journal publications, and presentations at scientific meetings and other forums. Presentations of work related to Lake Powell have been made in forums such as the American Society of Limnology and Oceanography, the North American Lake Management Society, the Arizona Hydrological Society, and National Park Service Symposia. Regular reports of quarterly field activities are regularly disseminated to interested parties and an annual summary is presented to an interagency group of parties involved in Lake Powell monitoring.

Historical Monitoring Program

Specific details are not available from the early phases of the Reclamation monitoring program regarding objectives, crew members, equipment, and field methodologies used in sampling activities. Information from this period is recorded on field sheets, boat pilot logs, and records of chemical analysis. Since 1982, more detailed records of the limnological monitoring program have been kept and reside within the Glen Canyon Environmental Studies Office in Flagstaff, AZ.

Four distinct phases can be identified from reviewing the history of the monitoring program (Figure 5). These phases are characterized by varying objectives and program goals, level of sampling density and frequency, and on available instrumentation technology (Table 1). Table 2 lists the stations which are part of the current monitoring program and identifies those associated with the historical long term program. The following section describes each phase of the monitoring program and its characteristics.

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

	Phase 1 1965-1971	Phase 2 1972-1981	Phase 3 1982-1990	Phase 4 1990-Present
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

Table 2. Lake Powell Water Quality Monitoring Stations (LT- long term stations since 1965 designated in **bold**, INF - inflow, OCC - occasional, PRO - profiles only, no chemistry).

Station Code	**Previous Code**	**RCD (km)**	**Station Name**	**Type**
Colorado River Main Channel (river channel distance from Glen Canyon Dam)				
	SCGC0000		Colorado River at Lees Ferry	
	SCUCLP11		**Colorado River below Glen Canyon Dam**	LT
LPCR0024	SCUCLP12	2.4	**Wahweap**	LT
LPCR0453	SCUCLP13	45.3	**Crossing of the Fathers**	LT
LPCR0905	SCUCLP14	90.5	**Oak Canyon**	LT
LPCR1169	SCUCLP16	116.9	**Escalante**	LT
LPCR1400		140.0	Iceberg Canyon	PRO
LPCR1589		158.9	Lake Canyon	PRO
LPCR1692	SCUCLP17	169.2	**Bullfrog**	LT
LPCR1772		177.2	Moki Canyon	PRO

Station Code	Previous Code	RCD (km)	Station Name	Type
Colorado River Main Channel (river channel distance from Glen Canyon Dam)				
LPCR1932		193.2	Knowles Canyon	PRO
LPCR2085		208.5	Lower Good Hope Bay	
LPCR2255		225.5	Scorup Canyon	
LPCR2387	SCUCLP18	238.7	**Hite Basin**	LT
LPCR2478		247.8	Colorado River at Hite Marina	
LPCR2510	SCCR1420	251.0	Colorado River at Hite Bridge	INF
LPCR2618	SCCR1480	261.8	Colorado River below Sheep Canyon	INF
Escalante Main Channel (river channel distance from confluence)				
LPESC119	SCESC055	11.9	Escalante at Davis Gulch	
LPESC200	SCESC095	20.0	Escalante at Willow Creek	PRO
LPESC276	SCESC122	27.6	Escalante above Garces Island	PRO
LPESC312	SCESC130	31.2	Escalante Inflow	INF
San Juan River (river channel distance from confluence)				
LPSJR193	SCUCLP15	19.3	**Cha Canyon (SJR)**	LT
LPSJR329	SCSJR180	32.9	Lower Piute Bay (SJR)	
LPSJR431	SCSJR250	43.1	Upper Piute Bay (SJR)	
LPSJR625	SCSJR350	62.5	Lower Zahn Bay (SJR)	
LPSJR686	SCSJR400	68.6	Mid Zahn Bay (SJR)	
LPSJR834	SCSJR440	83.4	San Juan River below Copper Canyon	INF
Other Tributary Stations				
LPNVC124	SCNVC055	12.4	Mid Navajo Canyon	
LPFAC001	SCFAC015	3.9	Face Canyon	OCC
LPWST001	SCWST025	4.1	West Canyon	OCC
LPLAB001	SCLAB001		Labyrinth Canyon	OCC

Phase 1 1965-1971

The first phase of the Reclamation's Lake Powell monitoring program was initiated through a directive from the Upper Colorado Regional Director, dated January 7, 1965. In this memo, the initial locations of sampling stations were specified, along with the sampling activities to be performed at each station.

Methods and Equipment

The frequency of sampling during Phase 1 was similar to that which is currently in place. Sampling was performed in the forebay of the reservoir at a main-channel location at the mouth of Wahweap Creek, generally on a monthly basis. Lake-wide sampling of eight stations was conducted on a quarterly basis (Table 2). These eight stations included six locations on the mainstem Colorado River arm, one location on the San Juan River arm and the Glen Canyon Dam tailwater (Figure 6).

Water column profiles consisted of shipboard measurements of temperature and dissolved oxygen by modified Winkler titration (USGS, 1960). These measurements were performed on discrete samples collected with a Van Dorn style sampler at the surface, bottom, and at 50 foot elevation increments throughout the water column. One sample was collected at each of these 50 foot depths for determination of major ionic constituents. Analysis was performed by the Upper Colorado Regional Soil and Water Laboratory in Salt Lake City.

From 1965 through 1968, sampling was accomplished with the use of a 21 foot runabout boat. In 1969, Reclamation acquired a 31 foot Uniflite cabin cruiser for extended trips on Lake Powell. This boat was operated and maintained by Glen Canyon Dam powerplant personnel. A portable motorized winch was designed and fabricated by powerplant personnel which housed a 1/8" stainless steel cable for deploying and retrieving water samplers.

Discussion

The information gathered during this phase of the monitoring program is valuable because it represents years in which Lake Powell was starting to fill. From this data, coarse patterns of temperature and salinity makeup can be observed through the reservoir. The detail of these initial observations on Lake Powell are limited due to three factors. The first factor is that all measurements were performed on shipboard from samples collected at depth and brought to the surface. Temperature was recorded to the nearest whole degree and oxygen values may have varied from their *in situ* levels. A second factor is that samples were spaced at a 50 foot interval at the seven stations throughout the lake. Because of this, the vertical and longitudinal detail of changes with depth in the water column and through the length of the reservoir are rather coarse.

Phase 2 1972-1982

Phase 2 of the monitoring program began in 1972. This period represents the most intense sampling frequency of the monitoring program. In addition to the continuing interest in identifying changes occurring in Lake Powell as part of its filling process, several other factors contributed to this increased effort. During this period Reclamation was completing most of its major water development projects in the Upper Colorado River basin and funding levels were high. The Colorado River Basin Salinity Control Act of 1974 (Public Law 93-320) was implemented, authorizing several Upper Basin salinity control projects. Interest in Colorado River salinity levels and the reservoir processes affecting these levels was high. A specific area of scientific interest was determining how Lake Powell behaved as a buffer to salinity levels in the Colorado River and if carbonate precipitation was a significant salinity reduction mechanism.

Additional interest during this time was given to refining reservoir mass balance models and determining rates of evaporation and bank storage water loss in Lake Powell. To address this issue, Reclamation instituted a program of meteorological sampling at several locations on the reservoir. The data from this program are currently stored at Glen Canyon Dam.

During the period from 1971 to 1978, an interdisciplinary group of scientists developed the Lake Powell Research Project, funded by the RANN program (Research Applied to National Needs) of the National Science Foundation. This program of applied research represented a wide range of studies on the Lake Powell region ranging from the physical sciences of limnology, geochemistry, and biology to the sociological sciences of archeology and economics. Under the auspices of the RANN program several limnological studies on Lake Powell were conducted. The University of New Mexico and Dartmouth College were involved in various types of limnological research of Lake Powell (Potter and Kidd, 1973; Reynolds and Johnson, 1974; Potter and Pattison, 1976; Bussey et al., 1976; Mayer, 1977; Merritt and Johnson, 1977; Kidd and Potter, 1978; and Condit et al., 1978). The Lake Mead Limnological Research Center at the University of Nevada/Las Vegas conducted several studies on limnology, nutrient loading and eutrophication in Colorado River reservoirs (Paulsen and Baker, 1983). A portion of Reclamation's limnology program supported this work for data collection and logistical support. Data from these programs currently reside with the individual investigators and in published reports.

Methods and Equipment

During this period, the level of sampling was expanded to provide an increased frequency of lake-wide surveys of the eight stations designated in Phase 1 (Table 2). Sampling was performed on a monthly basis initially, and later reduced to a frequency of 8-11 trips per year.

As in Phase 1, samples were collected at 50 foot intervals for major ion analysis. Analysis was performed by the Upper Colorado Regional Soil and Water Laboratory in Salt Lake City. Shipboard measurements of temperature and dissolved oxygen were performed for each sample, utilizing a portable meter instead of Winkler titration for dissolved oxygen levels. Sampling activities for the reservoir surveys employed the 31 foot Uniflite vessel with a crew from the Glen Canyon Dam powerplant.

Multiprobe profiling equipment was implemented at this time using a Hydrolab Series 8000, capable of measuring temperature, specific conductance, dissolved oxygen, pH, and oxidation-reduction potential. A motorized AC powered reel to house the communication cable for this instrument was custom designed and constructed at Glen Canyon Dam. This reel is operated in two positions; a horizontal position when conducting profiles which allow display equipment to rest on top, and a vertical position for motorized retrieval.

Discussion

A considerable amount of information is available from Phases 1 and 2 on temperature, dissolved oxygen, and major ion chemistry at the seven regularly sampled lake stations. The utility of this information is limited by the resolution of hand held temperature measurements, the relatively small number of lakewide stations and the 50 foot sampling interval. These factors combine to reduce the resolution of vertical and longitudinal detail of water quality parameters in the reservoir. The 50 foot interval of sampling depths was utilized in the design of a computerized model to calculate salinity and heat budgets for Lake Powell (Keller, 1982). This information serves to describe the synoptic conditions at a given location in the reservoir but limits the accurate identification of longitudinal and vertical gradients and comparison of these features through time.

Despite the limited vertical and longitudinal resolution of the information collected in Phase 2, temporal resolution of the data was greatly improved. The entire reservoir was sampled on roughly a monthly basis, equal to that of the forebay station. This frequency of sampling allowed changes over a smaller time scale to be seen in the mid and upper portions of the reservoir.

Phase 3 1983-1990

In 1983, at the beginning of Phase 3, Lake Powell had completed its initial filling. The reservoir reached full pool for the first time in June 1980 and experienced its highest level of 1130 m (3708 ft) in July 1983. The monitoring program subsequently was focussed on evaluating Lake Powell as an operational reservoir, having completed its initial filling.

Several other factors combined to shift the focus of Reclamation's monitoring efforts on Lake Powell. The Lake Powell Research Project funded by the RANN foundation was brought to a close. Secondly, the Colorado River Water Quality Improvement Program for salinity control of the Colorado River was reduced as several salinity control projects had been implemented and others withdrawn because of feasibility concerns. A portion of the funding for Lake Powell monitoring was supplied by this program; its reduction resulted in a downsizing of the monitoring program.

The focus of study efforts to understand processes which affect salinity levels in the Colorado River shifted to more of a monitoring objective. By 1987, it was determined that yearly monitoring of Lake Powell salinity levels was sufficient to fulfill Reclamation's requirements of biennial reporting of Colorado River Water Quality conditions. The monitoring information provides input to the Colorado River Salinity Simulation (CRSS) model (USBR, 1985), which in turn generates information for the biennial Quality of Water report (USBR, 1995).

During this period, attention in limnological monitoring efforts was shifted to other Reclamation reservoirs including Flaming Gorge and Ridgway Reservoir, to address heavy metals loading and eutrophication issues.

Methods and Equipment

Sampling frequency on Lake Powell declined from a quarterly basis in 1983 to an annual or biannual basis in the latter part of Phase 3. During this period, however, technological advancements in water quality instrumentation design and a desire for more cost effective techniques resulted in several improvements to the methodology used for lake monitoring activities.

During Phase 3, a Hydrolab Model 8000 multiprobe instrument was used to conduct water quality profiling at each station. This was later replaced with a Hydrolab Surveyor II system. These instruments allowed for *in situ* measurement of temperature, dissolved oxygen, specific conductance, pH and oxidation-reduction potential at various depths at each station. Because conditions can vary rapidly with depth in the reservoir, field protocols were changed to increase the vertical resolution of information collected in the profile. Data began to be collected at smaller intervals to show significant details of stratification in the water column at each station. This allowed for the exact thickness of each stratum of differing water quality to be measured and phenomena such as inflow plumes and dissolved oxygen anomalies to be defined.

To bring the Reclamation water sample collection methods into conformance with accepted EPA, USGS, and other protocols, the processing of samples in the field immediately after collection was begun. This included filtration of water samples through a .45 μm membrane filter and preservation by acidification and/or chilling. Water samples were collected for major ion concentrations only. As in Phases 1 and 2, chemical analysis was performed by the Upper Colorado Regional Soil and Water Laboratory in Salt Lake City until the closure of that lab in 1987. Subsequently, all chemical analysis was performed by Reclamation's Chemistry Laboratory in Denver, CO. On an intermittent basis, samples were collected for nutrient analysis, chlorophyll concentration, and plankton determinations. Measurements of secchi transparency and the observation general weather conditions were added to the data collection program during this period.

Water quality monitoring of the Glen Canyon Dam tailwater was initiated in 1985 in order to continuously track temperature and salinity levels below the dam. A deployment tube was installed below the river outlet works of the dam to house a submersible data logger which continuously records data a specified time intervals. From 1985 to 1990, temperature and specific conductance were measured at hourly intervals with this instrumentation.

The hydrodynamics of Lake Powell are directly affected by the quality and magnitude of inflows from the major tributaries to the reservoir. The nearest continuous water quality monitoring sites for Lake Powell inflows are the US Geological Survey gages on the Colorado River near Cisco, the Green River near Green River, and the San Juan River near Bluff. Because of the distance of these gages to Lake Powell and the diverse geology which these streams flow through before they reach Lake Powell, attempts were made to monitor the inflow water quality in the upper reaches on Lake Powell on the Colorado River arm from 1985 to 1990. Instruments at two locations collected continuous temperature and specific conductance measurements. A station was established in the upper reach of the reservoir below Sheep Canyon which consisted of three continuously recording monitors deployed at different depths. An additional station upstream at Clearwater Canyon was established to more accurately measure the quality of the flowing inflow. These stations were discontinued in 1990 due to falling lake levels and problems encountered with buoy moorings. Inflow monitoring was also conducted near the confluence of the Green and Colorado Rivers from 1989 to 1990 in support of endangered fish studies coordinated through the regional office in Salt Lake City. Data from this program reside in the Glen Canyon Environmental Studies Office in Flagstaff, AZ..

Efforts were initiated during Phase 3 to design, develop, and implement a relational database management system for Lake Powell and other reservoirs in the Upper Colorado basin. This program is discussed in detail in Chapter 5 of this report.

Phase 4 1991-Present

Phase 4 of Reclamation's Lake Powell monitoring program began as part of Phase II of the Glen Canyon Environmental Studies (GCES) in 1991. The conditions which exist today in Grand Canyon below Glen Canyon Dam are influenced by changes in the quality of water released from Glen Canyon Dam. Physical, chemical, and biological processes within Lake Powell define the quality of water released from Glen Canyon Dam and directly affect downstream natural resources.

These factors and the technical needs of the Glen Canyon Dam Environmental Impact Statement led to an expanded Lake Powell monitoring program incorporating several refinements and enhancements. The focus of the monitoring program shifted to an ecosystem perspective to identify and understand the range of processes occurring within Lake Powell and to evaluate how these processes affect conditions observed in the reservoir and in the Colorado River below Glen Canyon Dam. Phase 4 of the monitoring program is designed to integrate with the various studies and monitoring programs conducted on Lake Powell, the Colorado River in Grand Canyon, and on Lake Mead.

The details of the current Lake Powell water quality monitoring program are described fully in Chapters 3 and 4.

Methods and Equipment

The frequency of monitoring has been increased to a level similar to the period from 1965 to 1971, Phase 1. Water quality profiles are conducted at the Wahweap forebay station on a monthly basis, with lake-wide sampling conducted on a quarterly basis. To obtain samples representative of the major strata which comprise the water column, the number of water samples collected for chemical analysis at each station has decreased from previous sampling which was conducted at 50 foot intervals. To better identify longitudinal variation in the reservoir, the number of stations sampled during the course of a quarterly survey has increased to approximately 20. At some of the additional stations, no chemical sampling is performed and profiling is the only activity conducted. With this approach, a balance is made between the need for increased resolution of certain measurements and the reduction of activities for parameters which do not require their previous level of resolution.

To understand the biological component of the Lake Powell/Grand Canyon ecosystem, changes were made to the chemical sample collection program. Samples for the determination of nutrient compounds of phosphorus and nitrogen are collected at all locations where major ion samples are taken. This has required enhancement of field processing and preservation methods and the implementation of a quality assurance program to evaluate the precision and accuracy of the data collected from these samples. Analysis of major ion and nutrient samples has been performed by the Reclamation Chemistry Laboratory in Denver, CO.

A biological sampling program was initiated to evaluate changes and trends in productivity and lower trophic levels in Lake Powell and to evaluate the export of biota in the Glen Canyon Dam releases. The program now includes measurement of chlorophyll concentration and the collection of phytoplankton and zooplankton samples at specific sites throughout the reservoir and in the Glen Canyon Dam tailwater.

Recent developments to the program have included the addition of alkalinity measurements to describe mineral solubility conditions as they relate to carbonate precipitation dynamics. The use of a subsurface viewing scope to improve the consistency of secchi transparency measurements has been incorporated into the sampling effort. The water quality monitoring program of the Glen Canyon Dam tailwater was enhanced in 1991 with the addition of dissolved oxygen measurements below Glen Canyon and the establishment of a second station at Lees Ferry. Measurements of pH were added in 1995 at both stations.

Further enhancements in instrumentation design and computer capability have allowed the ability to collect increased amounts of data in the field, automate the data transfer to the data management system and develop the enhanced tools and protocols to analyze the data. During Phase 4, the relational database management system for Lake Powell water quality was converted and moved to a UNIX computing platform. Changes were made to the system used for analysis and reporting of data in an effort to create a more powerful and flexible system for integration, summarization, and visualization of the monitoring information.

Chapter 3

CURRENT LAKE POWELL MONITORING PROGRAM

History, Objectives and Rationale

The present phase of the Lake Powell monitoring program, initiated in 1991, was implemented as part of the Glen Canyon Environmental Studies Phase II program. The specific objective of the existing Bureau of Reclamation Lake Powell limnological monitoring program is to observe and understand processes affecting the physical, chemical, and biological aspects of reservoir and discharge water quality and evaluate these changes over time. The program is conducted at a level which allows significant changes to be observed and evaluated on time scales ranging from monthly and seasonally to the entire history of the reservoir's existence.

With the initiation of the GCES Phase II studies, it was determined that improvements in the Lake Powell monitoring program were necessary to better describe the hydrodynamic, chemical, and biological behavior of the reservoir and to determine how these factors affect the quality of Glen Canyon Dam releases to the downstream Colorado River ecosystem.

Prior to 1991, monitoring of Lake Powell was focussed primarily on monitoring changes in the filling reservoir and examining salinity levels as part of Reclamation's Colorado River Water Quality Improvement Program (CRWQIP). Initiated in 1965, the monitoring program can be described by four distinct phases, varying in sampling frequency, number of stations, methodology, and objectives. These phases are summarized in Figure 5 and Table 1 and are described in Chapter 2.

Enhancements of Current Program

The collection of water quality profiles from the forebay of the reservoir on a monthly basis was initiated in 1991 to more effectively correlate changes in the reservoir with conditions observed in the water quality. The frequency of lake wide sampling was increased to a quarterly basis to allow the gathering of information about significant reservoir processes that occur on a seasonal basis. The number of stations was increased to provide greater detail in the transition zones of the reservoir, in significant tributary arms and other areas of special interest. The collection scheme of water samples was revised to sample water representative of major strata in the water column, rather than at 50 foot elevation increments. This allowed more stations to be sampled with fewer samples per station. Sampling for nutrient concentration was initiated at all stations where major ion samples were collected. A chemical quality assurance program was initiated to determine variability of analytical results and verify the accuracy and precision of filed collection techniques. A biological sampling program was initiated which included the collection of surface chlorophyll, phytoplankton, and zooplankton samples at all major stations.

Automation of profiling techniques and data transfer methods was initiated. These methods allow 1) profiles to be viewed in the field immediately to aid in selection of sampling depths, 2) the rapid collection of profiles at secondary locations to improve spatial resolution, and 3) improved processing of the data for integration into the Lake Powell database and subsequent analysis and reporting.

Shipboard alkalinity measurements were initiated, concurrent with all collected water samples. This provides the ability to obtain mineral saturation indices to evaluate carbonate precipitation dynamics which may affect salinity levels in the lake. Recent technological advancements have allowed the measurement of turbidity to be included with basic profiles. A viewing scope is now being used to standardize measurements of secchi transparency in the field.

Frequency and Timing of Sampling

Currently, lake wide surveys are conducted on a quarterly basis to correspond to significant seasonal processes occurring in the reservoir. These surveys are timed to coincide roughly with those processes, rather than based on strict calendar intervals.

Late Winter. Late winter sampling is conducted within the period from late January to early March. The objective of sampling during this period is to describe conditions when maximal winter mixing of the reservoir surface has occurred, inflows are low and of high density, and biological processes are at a minimum. The epilimnion of the reservoir has received the maximum amount of mixing from convective processes cooling the lake's surface, depending of the severity of the previous winter months. In the deep areas in the lower to midlake regions of the reservoir, mixing has occurred to its greatest depth, but temperature and chemical stratification persists, with the underlying *hypolimnion,* or bottom layer of the reservoir, containing colder and more saline water. In the upstream areas of the reservoir, where depths are less than the maximum depth of winter mixing, turnover, or complete mixing occurs. Inflows to the reservoir are cold and saline, resulting in densities greater than that of the reservoir. A plunging current flows along the bottom of the lake until it dissipates and mixes with water of equal density. Due to cold conditions, short days, and low angle of sunlight, biological processes are at a minimum and water clarity is at a maximum during this time. Minimal surficial warming of the lake may occur from warm weather during the late winter or early spring but the depth of stratification is retained from the winter's convective mixing process.

Early Summer. Late spring to early summer sampling, in the months of May and June, is performed to describe conditions which have developed during the spring months. By this time, the lake has begun to experience significant thermal stratification, biological processes have increased and the inflows to the reservoir have increased.

These inflows are the result of snowmelt runoff from the high mountains in the upper portions of the basin which have flowed through the warmer lower elevation agricultural areas and canyon lands. These inflows tend to be warm and dilute, resulting in waters of lower density than the reservoir and a current which overflows the surface of the reservoir. This overflow current has extended downstream into the upper portions of the reservoir while the remainder of the reservoir remains relatively unaffected.

As sunlight angle, day length, and ambient temperature increases in the spring, the surface of the lake begins to warm. In areas unaffected by the inflow current, this initiates a thermal density difference with the underlying colder water and a barrier to mixing develops at the *thermocline*, or depth of maximum temperature change. As the surface waters continue to warm, the depth of the thermocline deepens and the thickness of the new *epilimnion*, or surface layer, increases.

Biological processes in these areas of the reservoir increase, resulting from warm conditions, increased sunlight, and higher nutrient levels from winter mixing. The biological processes are limited only by nutrient levels and, in the inflow areas, by available light from the increased turbidity of the runoff inflows. Corresponding to the increased biological productivity, high dissolved oxygen concentrations above the saturation level are usually seen in the epilimnion at this time.

Late Summer. Late summer sampling, performed during the period of early August to late September, represents conditions when the reservoir is at its maximum degree of thermal stratification and surface warming. Biological processes have typically reached their maximum and inflows have tapered off, become denser and have begun migrating to intermediate depths of the reservoir.

The high flows of the spring snowmelt runoff have subsided; the large inflow volume of this water has extended to downstream regions of the reservoir. Inflows have increased in salinity with the return to base flows. Surface temperatures have reached a maximum. These factors combine to increase the volume of the epilimnion and the density gradient between the epilimnion and hypolimnion. The density differences, which define the degree of stratification, and depth of stratification have reached a maximum. Biological processes, which have developed throughout the summer, typically become nutrient limited in the late summer. The resulting biomass from the biological activity, combined with organic matter contained in the runoff volume begins to decompose in the reservoir. This decomposition often results in significant oxygen deficits due to bacterial respiration at the lower boundary of the epilimnion. These metalimnetic oxygen deficits typically reach a maximum during this time.

Early Winter. Early winter sampling is performed within the months of November to December. At this time, the lake has retained its maximum depth of thermal stratification from the summer period and has begun convective winter mixing, resulting in a breakdown of the strong stratification gradient which developed in the summer. Inflow currents are generally low and have cooled considerably, plunging to deeper depths in the reservoir due to their increased density . Biological processes are still active, but on the decline. The metalimnetic dissolved oxygen deficits seen during the late summer may still be present at this time but will begin to disappear as winter mixing processes incorporate the metalimnetic waters into the mixed epilimnion.

Lake Powell Map Development

Using the ARC/INFO geographical information system, a digitized map has been developed from mosaiced Digital Line Graphs (DLG) of USGS 1:100,000 scale maps of the Lake Powell region. The maps include the pre-dam Colorado River channel and those of other major tributaries. Additional information has been manually digitized and added to the maps. Overlays to this map have been developed to include surface hydrology, natural features, roads and other man made features, registered sampling locations, and other pertinent annotations.

Sampling stations on the reservoir have had their geographic coordinates determined using Global Positioning system (GPS) technology. Verbal descriptions and photo documentation for each station have been recorded to aid in relocating a station based on landmarks and other physical features.

Using the GPS coordinates, the sampling stations are incorporated into the digital map as a GIS overlay. Using dynamic segmentation methodology, river channel distances (RCD) to each station, from a fixed reference point, may be determined (Table 2). The base reference point is Glen Canyon Dam for Colorado River main channel stations. For stations on tributary arms, the reference point is the confluence of the tributary with the Colorado River mainchannel.

From this information a revised station coding scheme has been developed which incorporates the general project code, the stream channel of the station and the river channel distance from the given reference point. Historically, stations were numbered sequentially in the order of their establishment. Frequently, there is no information in the station name or code to locate a particular station with reference to another. The new coding scheme allows for the determination of the location of a station within a particular tributary arm from its station code.

The station code for a particular station is an eight character alphanumeric string. The first two letters represent the project; in this case, LP represents the Lake Powell project. The second two to three letters represent the tributary arm; CR represents the Colorado River, SJR the San Juan River, ESC the Escalante, and so on. The remaining characters are integers expressing the number of river channel kilometers in tenths from a given reference point for the tributary arm.

For example, the Cha Canyon station which resides 19.3 river channel kilometers from the pre-dam Colorado River channel on the San Juan River arm of Lake Powell has historically had a station code of SCUCLP15. Under the revised coding scheme, this station has an 8 character identification code of LPSJR193.

This station code uniquely identifies a main channel station. This code, along with other information such a station name, geographical coordinates, state, county, hydrologic basin code forms a record in the WQWM database table STATION which includes all information required by the EPA STORET system to sufficiently identify a sampling location. Each entry to the database for a given sample or measurement will have a station code identifier associated with the data.

Determination of Sample Locations

Initial sampling stations were specified in a directive dated January 7, 1965, initiating the Lake Powell water quality monitoring program. This memo recommended periodic sampling in the months of January, May, July, and October at seven stations and directed samples to be collected at the surface and 50 foot elevation intervals. Measurements for temperature, specific conductance, carbon dioxide, and dissolved oxygen were also specified.

In March 1968, a recommendation was made by the Upper Colorado Regional Engineer to continue the program with quarterly lake surveys collected in July, October, January, and May. Periodic reauthorizations and review of the program occurred in subsequent years.

The original seven stations were equally spaced and determined arbitrarily but have formed the basis for the historical monitoring program. The exact locations of these stations have changed slightly over the years but have generally remained constant within the general area identified.

Since 1991, additional stations have been added to allow for increased spatial resolution of the information collected and to gather information which has not been collected in the past. At each station, a full suite of chemical and biological samples and measurements are collected. As logistical constraints permit, secondary stations have been identified for the purpose of collecting water quality profiles only, without corresponding chemical or biological samples.

When new stations are added, the site is selected based on several considerations. First, is whether the general location will provide the required additional information considering trip logistics and expense of data processing and sample analysis. Secondly, the station is typically located at a narrow point or constriction of the lake surface. This is to avoid anomalies which may be present in open bays due to wind effects or other phenomena which may not be representative of main channel conditions. Furthermore, advective density currents which may be present in upstream reaches can be better defined in a constricted zone rather than thinned and dissipated in an open bay. Lastly, because the station is selected to represent the entire water column of the reservoir, the station is located in the deepest portion of the lake or the original river channel. Other considerations may be incorporated to adjust the sampling location, such as direction of prevailing winds to aid in maintaining position for the duration of sampling and availability of landmarks or other features to aid in repositioning. A repositioning accuracy of 30 m is desired with an acceptable limit of 100 m for Lake Powell.

Several stations have been added in the upstream reaches of the Colorado River arm of the reservoir. This area represents the transition from the shallow riverine conditions dominated by the Colorado River inflow to the deep lacustrine, or lake-like conditions in the downstream portions of the reservoir. In the transition zone, where significant changes can occur in a relatively short distance, there is a need for increased spatial resolution of data to determine the fate of riverine inflows affecting downstream portions of the lake.

Historically, Bullfrog Bay, 169 river kilometers (RK) from Glen Canyon Dam and Hite Basin (RK 239) were the only stations sampled in this transition area (Table 2). Hite Basin usually is well within the transition zone of the reservoir and, at times, influence from the inflowing Colorado River is not well defined. Data from Bullfrog Bay usually has no relation to Hite Basin and has been shown to be at times anomalous, possible because of its location in a large open bay with several tributary inputs and a large amount of human activity. To better define the transition zone, routine stations have been added for the Colorado River inflow, Scorup Canyon (RK 226), Lower Good Hope Bay (RK 208). In addition, secondary stations are profiled as conditions permit at Hite Marina (RK 139), Knowles Canyon (RK 193), Moki Canyon (RK 178) and, in the area between Bullfrog and Escalante, at Lake Canyon (RK 159) and Iceberg Canyon (RK 140).

Stations have also been added on tributary arms which have received limited attention in the past. The San Juan River represents the second largest inflow to the lake and drains a large basin of varying geology and agricultural and industrial uses. The Cha Canyon site ,19.3 RK from the confluence of the San Juan and Colorado Rivers, is the only station that has been sampled historically by Reclamation. Routine stations have been added for the San Juan River inflow, Mid Zahn Bay (RK 62.6), Lower Zahn Bay (RK 62.5), Upper Piute Bay (RK 43.1), and Lower Piute Bay (RK 32.9). Occaisional profiles may be collected at other intermediate locations as conditions dictate.

Due to frequent anomalies seen in the main channel profile at the mouth of Escalante Canyon, a routine station has been added at the mouth of Davis Gulch on the Escalante Arm, 11.9 river kilometers above the Escalante's confluence with the Colorado River main channel. The Escalante River is the third largest tributary to Lake Powell and drains a small basin dominated by agricultural activity. The Escalante River is prone to wide fluctuations in flow from runoff events, delivering spates of water of high oxygen demand to the Escalante arm of the reservoir. Severe oxygen deficits are periodically seen in the hypolimnion at the mouth of Davis Gulch as a result of these inputs. Waters with high oxygen deficits and increased salinity move downstream and are seen at the main channel station at the mouth of the Escalante, but the extent of their influence on advective flow of the main channel dissipates with distance from this station. To further define these patterns, profiles are collected at secondary stations in the Escalante arm at Willow Creek (RK 20.0), Garces Island (RK 27.6), and the Escalante Inflow.

Chapter 4
Field Methodology

Initial Observations

Upon arrival at a sampling location, a general time is recorded, which is used to nominally identify the profile and all samples collected during the site visit. General meteorological observations are also recorded describing cloud cover, wind speed and direction, air temperature, and wave height.

Several secchi depth readings are recorded, both with the unaided eye and with the use of a subsurface viewing scope. The surface elevation of the lake is obtained from daily National Park Service radio reports and the bottom depth is determined using a Lowrance X-16 sonar depth finder.

These readings are descriptive of conditions measured at the surface for a single site visit. They are recorded on the header of the field data sheet and form one observation in the data table SURFACE (Table 3) in the WQWM database. This observation is uniquely identified by the station code and time identified for the site visit which are the key fields of the SURFACE data table. See Chapter 5 for a description of the WQWM database.

Secchi disk transparency is recorded using a standardized 20 cm disc with alternating quadrants of black and white. The secchi disk is attached to a metric surveyors tape or a calibrated line marked in tenths of meters. The disk is lowered over the side of the boat to a depth at which it disappears from view. This observation is made over a sufficient time to allow for variations in surface disturbance and glare. Frequently, several measurements are made by different observers. The secchi depth, observer's initials, and quality of observation conditions are noted on the field data sheet. Beginning in 1994, a subsurface viewscope (Lawrence Enterprises, Aqua Scope II) was employed to eliminate effects of glare or surface disturbances. The viewscope secchi depths are usually greater than those obtained by traditional methods. While they probably represent more accurate estimates of water transparency, they are not comparable to the depths obtained by the traditional methods. Therefore, secchi depths by both methods are recorded for comparison purposes.

Water Quality Profiling

Water quality profiles in Lake Powell are obtained with the use of a Hydrolab H20/Surveyor 3 multi-parameter measurement system. The H20 is a submersible, multi-parameter sonde unit capable of measuring temperature, specific conductance, dissolved oxygen, pH, oxidation-reduction potential, and turbidity. The H20 is connected to the Surveyor 3, a shipboard display and datalogger unit used for calibration of the sonde and for display and logging of the profile readings. These units are connected by a 165 m underwater cable mounted on a AC powered motorized reel. A palmtop computer is connected to the Surveyor 3 and is used to temporarily store readings for immediate display after the profile is completed. This immediate display aids in the selection of sampling depths throughout the water column. Permanent readings are stored in the Surveyor 3 for subsequent downloading and processing.

After the surface observations have been made the water quality profile is conducted. The H20 sonde is lowered to selected depths throughout the water column; readings are stored in the Surveyor 3 datalogger after equilibration at a given depth is achieved and readings have stabilized. The main objective of the profiling effort is to characterize in the major limnological strata which define the water column with sufficient resolution to accurately define boundaries of the strata and other significant phenomena such as inflow density currents and depths at which dissolved oxygen minima or maxima occur.

Initial subsurface readings are taken immediately below the surface and at approximately 0.5 to 1 meter intervals for the first few meters to determine any surface warming phenomena. Below these initial measurements, the "*rule of fives*" is observed to determine intervals between measurements. The "rule of fives" states that if the value of any parameter changes by more than a multiple or fraction of five (ie. 0.5 units for temperature, dissolved oxygen, and ph, or 50 μS for conductance), a smaller depth interval should be chosen, usually with one meter being the minimum interval. If parameters are not changing at this rate, a larger interval (up to 10 meters) is chosen. This allows for sufficient vertical resolution in the profile while allowing for a reasonable time on station to conduct the profile and allowing full equilibration between measurements.

The profile is conducted from the surface to the bottom, with efforts made to come as close to the bottom as possible without disturbing bottom sediments, which can foul sensors and cause ambiguous readings. After the bottom reading is recorded, the datalogging equipment is disconnected, the reel is rotated into its vertical retrieval position and the sonde is retrieved. After retrieval, it is stored in a cylinder filled with lake water between stations.

The readings recorded at each depth are descriptive of the physical conditions at that point in the water column. These readings are additionally recorded on the field data sheet as a backup to the datalogger record. They form one observation in the data table PROFILE (Table 3); each observation is uniquely identified by the station code, time, and depth of the reading.

Chemical Sampling

Water samples for determination of major ion and nutrient concentration are collected at various depths from all regular long term stations on Lake Powell. The main objective of the sampling effort is to characterize chemical conditions at the surface and in each major stratum, or layer of distinct water, through the water column. A secondary purpose is to describe unusual phenomena which occur at specific depths such as a severe metalimnetic oxygen deficit at the thermocline or a narrow inflow plume at the bottom or interflowing into an intermediate layer in the reservoir.

Samples are seldom collected at depths which characterize rapidly changing values of the profile parameters. Since all samples will be correlated with the previously collected profile measurements (temperature, conductance, ph, dissolved oxygen, etc.), the chance of erroneously equating a sample with a profile measurement made at a slightly different depth in that rapidly changing environment becomes significant. If that is the case, the chemical conditions represented by the water sample are not representative of the measurements from the water quality profile. Furthermore, the water present in this transition zone is not representative of any major stratum in the reservoir and reduces the value of a sample collected at this point, except to identify unusual phenomena.

After the profile is conducted, the structure of the profile is determined from readings recorded on the field sheet or from the graphic display of data recorded on the palmtop computer. The objective is to determine depths at which discrete water quality samples are to be taken using the criteria described above.

Sample Collection. Samples are collected using Van Dorn samplers attached to a 160 m stainless steel cable connected to a motorized winch. This task involves two people, one to operate the winch and one to attach and remove the samplers. The cable is marked at one meter intervals for accurate sampling depths. Samplers are lowered in a string to their desired depths and are activated by a weighted messenger which travels down the cable. As one sampler is tripped, it releases a second messenger which, in turn, trips the sampler below. The samplers are retrieved, noted as to which depth they were deployed, and set aside for sample processing.

Sample Processing. For both major ion and nutrient analysis, a total of four subsamples are collected, which include two unfiltered subsamples of 250 ml and two filtered subsamples of 125 ml. The unfiltered major ion subsample is used for the laboratory determination of total suspended solids, pH, specific conductance, and alkalinity. The filtered major ion sample is used for the determination of major dissolved ion concentrations. The unfiltered nutrient sample is used for the laboratory digestion and determination of total phosphorus and total Kjeldahl nitrogen. The filtered nutrient sample is used for the determination of dissolved compounds of phosphorus and nitrogen. Both nutrient subsamples are preserved with sulfuric acid in the amount described below.

Sample Filtration. The Environmental Protection Agency (EPA, 1983) states that samples to be analyzed for the determination of dissolved substances are to be filtered thorough a $0.45\mu m$ membrane filter as soon as possible after collection, preferably in the field. This is performed on shipboard for Lake Powell samples immediately after their collection, usually within 15 minutes. This is accomplished using a peristaltic pump (Geotech Series II) with silicon tubing connected directly to the Van Dorn sampler. A segmented flow of air and sample is used to thoroughly rinse the pump tubing before connecting to the filter apparatus. The filter apparatus is a 47 mm in-line filter holder (Millipore Swinnex 47) housing a 47 mm $0.45\mu m$ polycarbonate membrane filter, low in water extractable compounds (Poretics #1035, lo extractable).

After approximately 50-100 ml pass through the filter apparatus, the filtered subsample is collected into a high density polyethylene bottle which has been pre-cleaned to EPA Contract Laboratory Program (CLP) specifications (I-Chem 300 Series). The pre-cleaned bottles are also used for the collection of unfiltered subsamples.

Preservation. Both types of samples are stored and shipped on ice; the nutrient samples are acidified with 1+9 sulfuric acid (approximately 1.2 N H_2SO_4) in a proportion of 1 ml acid per 250 ml sample. The acid preservation solution is supplied by Reclamation's Denver Laboratory. Fresh acid preservation solutions are used for each reservoir survey.

The purpose of preserving samples collected for later analysis is to 1) retard biological activity, 2) reduce chemical changes occurring between collection and analysis, 3) reduce volatility of constituents, and 4) reduce adsorption affects with the sample container. Although acid preservation is not currently recommended by many other agencies for the determination of soluble reactive phosphate, it has been selected for the Lake Powell program for several reasons.

Recommended methods of preservation include the addition of mercuric chloride ($HgCl_2$) (USGS, 1989), and chilling to 4°C with no preservative and analyzing within 48 hours (EPA, 1983). Neither method is practical for use on Lake Powell. The use of $HgCl_2$ has obvious environmental consequences if spilled and will poison cadmium reduction columns used for nitrate determination. Analysis within 48 hours is not possible due to logistical constraints on shipping samples from remote locations on Lake Powell. The primary reason against using H_2SO_4 is due to possible hydrolysis of polyphosphate compounds which could cause an overestimation of SRP. However, significant concentrations of polyphosphate are typically seen more in sewage effluent discharges and not expected in significant concentrations in Lake Powell. Furthermore, concentrations of SRP are usually well below a detection limit of 5μg/l and any overestimation due to hydrolysis is probably insignificant.

Documentation. The location of all samples collected at a specific station is noted on the field sheet for that station, along with an identifier of the particular Van Dorn sampler that was used, the person collecting the sample, and a sequential field number for each sample. The four bottles comprising the nutrient/major ion subsamples at a given depth are treated as a single sample. Quality control samples collected at a given station are treated and numbered in the same manner as all other samples.

Starting with the first sample of the trip, a sequential field number is assigned to each sample for identification and tracking purposes. This number is recorded on the cap of each bottle as well as on the field sheet and sample labels. Nutrient subsamples are identified by a circled field number on the bottle cap. This allows rapid inventory of the samples before shipment and aids identification in the event of mislabeling.

Each subsample receives a label which identifies the station code and name, sampling time and depth, field number, type of analysis requested, and the presence of any preservative. Label material and marking pens are chosen that are resistant to damage from submersion.

Each sample collected is uniquely identified by the combination of station code, time, and depth of sampling. These fields and other information pertaining to the sample such as laboratory ID numbers for each analysis comprise one observation in the data table LAB_LOG. The LAB_LOG table is used to link sample collection information with the actual analytical results from the laboratory which are contained in the tables, MAJOR_IONS and NUTRIENTS (Table 3).

Transportation and Shipment. After sample processing, samples are stored on ice in coolers for the duration of the reservoir survey. Nutrient samples are stored in a separate cooler from major ion samples. On return from the field, samples are checked to ensure all samples are accounted for and proper documentation has been performed. The coolers are then re-iced and shipped via overnight delivery to Reclamation's water quality laboratory in Denver, CO for analysis.

Trace Element Sampling. Samples for trace element determination are not routinely collected as part of the Lake Powell water quality monitoring program. They have, however been collected on occasion as part of other special studies relating to the reservoir (Miller, personal communications), (Vernieu, 1995, in print). Depending on the objectives of the particular study, special methods are employed when collecting this type of water sample. A non-metallic Kemmerer sampler is used (eg. Wildco #1290), nylon line instead of stainless steel cable is used for deployment of the sampler, plastic gloves are used at all times during the sampling process, reagent grade rinse water is used to clean equipment and ultra pure nitric acid (HNO_3) or other solutions are used to preserve the samples.

Quality Assurance

Quality control procedures are a critical part of the chemical sampling program on Lake Powell. These procedures employed are to 1) verify the lack of contamination of samples from the collection process, 2) establish the variability of sampling methods in the field, and 3) provide an additional means of establishing the precision and accuracy of laboratory analyses over and above the laboratory's internal quality assurance program.

Through the course of a reservoir survey, approximately 10% of the total number of samples collected are quality control samples. Three basic types of quality assurance samples are collected: 1) replicates, 2) blanks, and 3) spikes.

Replicates. Replicate samples are collected to determine the precision of a sampling or analytical technique. Replicates resulting from separate sampling efforts, or **sample replicates**, are used to evaluate the variability or precision of sampling activities. This type of replicate is not routinely collected as part of the monitoring program. It is assumed, for the parameters being analyzed, that the variability of samples collected from a repeated effort at given site is low and previous sampling of this type has shown this to be true.

Replicates resulting from the same sample, or **laboratory replicates** (also called "splits") are used to evaluate the precision of the laboratory analytical process. These samples are collected from a continually mixed sampler and identified as two separate samples.

Blanks. Blank samples are used to determine the presence of, or verify the absence of, any contamination in the sampling or sample processing efforts. A **field blank** is used to evaluate any sources of contamination from any aspect of the sampling or sample processing steps. For this sample, reagent grade water is passed through every step of the sample processing process. The Van Dorn sampler is rinsed three times with reagent grade water, then filled with a sufficient volume to fill all sample bottles. This water is used to rinse the filter apparatus in the same manner that an actual sample in used. It is finally collected into pre-cleaned sample bottles. Field blanks for nutrient analysis are preserved with sulfuric acid; unfiltered blanks are not passed through the filtration apparatus. Any detectable analyte which shows up in these samples is indicative of contamination occurring somewhere in the sampling process.

A **reagent blank** is collected to verify the presence of absence of contamination in the sampling bottles, reagent grade rinse water or acid preservation solution. For this sample, reagent grade water is collected directly into pre-cleaned sample bottles and preserved as appropriate for the analysis. No filtration step is performed, although the bottles for dissolved constituent analysis are still labeled as being filtered. Any detectable analyte which shows up in these samples indicates contamination from sources other than the sampling or filtration apparatus.

Spike samples. Spike samples are collected for two purposes, to evaluate the accuracy of an analytical process and to ascertain the loss of a particular substance from volatilization. For this purpose, a **field spike** is prepared by collecting a known volume of a laboratory replicate of the sample and adding a known volume of a solution of known concentration. This spike solution, prepared at the Denver laboratory, is prepared with known concentrations of the nutrient compounds which are determined in the laboratory analysis. The solution contains concentrations of 10 mg/l SRP (PO_4 as P), 100 mg/l nitrate nitrogen (NO_3 as N), and 10 mg/l ammonia nitrogen (NH_4 as N). Volumes of the spike solution are added to a measured volume of sample such that resulting concentrations are well into the range of detectability and not more than 10 times the concentration of the sample itself. The resulting "spiked" sample is then either transferred directly to sample bottles (for unfiltered subsamples) or passed through the filtration apparatus (for filtered subsamples). When possible, a larger Van Dorn Or other type sampler (Wildco 6.2 l Beta Bottle #1900) is used for this type of sample so that the original sample, the laboratory replicate and the spike my be collected from the same sampler.

Another type of spike sample, a **reagent spike,** is prepared by adding a know amount of spike solution to reagent grade water. The purpose of this type of spike sample is to provide a measurement of analytical accuracy in the absence of any sample matrix effects and to verify the concentration of the spike solution being used.

The purpose of laboratory replicates and field spike samples are primarily to evaluate the performance and quality control of the analytical laboratory. They are intended to be sent to the laboratory as blind samples. An accurate evaluation of these samples requires that the laboratory treat them the same as any other same and not give any preferential treatment to them. To accomplish this, most quality control samples are labeled and identified with station codes, times, and depths in the same manner as other samples. These blind samples are sent to the laboratory for analysis with the actual samples. On field sheets and in the database, these samples are properly identified as quality control samples and are not included in analyses of representative conditions. Exceptions are samples which are included as sample replicates, reagent blanks or reagent spikes; these are identified as such to the laboratory.

Biological Sampling

The goal of the biological sampling program is to provide the linkage between the physical and chemical aspects of Lake Powell water quality and lower trophic levels of the ecosystem. By observing the biological components of the lower trophic levels of the ecosystem, changes occurring in Lake Powell's maturation process may be observed which could have profound effects on the basic evolution of the ecosystem, native and non-native fisheries, recreational uses.

The primary objective of the biological monitoring program is to provide synoptic views of the planktonic community structure associated with each reservoir survey. Detailed observations of short term population dynamics or species level population descriptions are beyond the scope of this objective. The biological monitoring program has been in existence since 1991 with many changes made since its inception. Additional changes are expected as methods and techniques are refined and the results of previous sampling efforts refine its direction.

The biological portion of the Lake Powell monitoring program is comprised of three main components; chlorophyll, zooplankton, and phytoplankton sampling. Field methodology for these components are discussed below.

Chlorophyll. Surface chlorophyll is collected at all routine sample stations. Surface designation refers to discrete samples collected at a depth of 1 meter. The 1 meter depth is defined as representing chlorophyll from phytoplankton suspended in the mixed surface layer of the reservoir. With this definition, sampling anomalies resulting from algae clumped on the surface film are avoided.

It is realized that phytoplankton distributions may not be homogenous throughout the mixed surface layer and may move vertically on a daily basis. It is further assumed that these factors are not significant in light of several factors. Discrete 1 meter sampling depths result in greater consistency, reduced time in the field, increased ease of sampling, and reduction in cost than would a regimen of composite sampling, collecting samples at several depths, or attempting to determine where population concentrations exist in the water column. Previous studies (Korn, Eckhardt, Vernieu 1993) have shown no significant difference in chlorophyll concentrations between discrete samples collected at one meter and composite samples collected between 0 and 5 meters. Variability in the sampling process or chlorophyll analysis and levels of previous analyses are such that any variability in other sampling strategies is assumed to be insignificant. This assumption is consistent within the scope of synoptic monitoring of reservoir conditions. Procedures may be revised with improved analytical methods improve and analysis of results from the current monitoring program.

Chlorophyll is collected in a large Van Dorn water sampler (Wildco #1140 or #1960) from a depth of 1 meter. Alternately, this sample may be collected by pumping with a peristaltic pump from a depth of 1 meter. The sample is filtered through a 47 mm glass fiber filter (Gelman A/E) housed in a 47 mm in-line filter holder (Millipore Swinnex 47) using a peristaltic pump. All sample passed through the filter holder is collected in a large graduated cylinder. The filtered volume is measured to the nearest 10 ml. Because chlorophyll concentrations in Lake Powell are frequently very low, in the range of 0-5 mg/m^3, large volumes of sample are passed through the filter to increase the amount of chlorophyll collected, increasing the resolution of the final analysis.

After the sample and any remaining water in the pump tubing has been passed through the filter, the filter holder is disconnected from the pump tubing and the filter holder is opened under subdued light conditions. The glass fiber filter is then folded in half, with the collected material from the sample on the inside, and blotted to remove excess water from the filter. The filter is then placed into a labeled coin envelope, which will further absorb any excess moisture, and subsequently into a small sealable plastic bag. The sample is then placed into a well insulated cooler containing dry ice and stored for the duration of the reservoir survey. On return from the field, dry ice is replenished and the cooler is shipped overnight, following the shipper's directions for hazardous material, to the Denver Environmental Sciences Section for analysis.

Analysis consists of acetone extraction and spectrometric analysis of the extract. Chlorophyll concentrations are calculated using the tri-chromatic equation (APHA 1002 G., 1985).

Zooplankton.

Determination of Sampling Depths (Hueftle)

Collection of Samples

Zooplankton samples are collected with a Wisconsin style closing net with 80 micron mesh (Wildco #40-A50). This mesh size selects for small plankters such as rotifers and nauplii and provides a more accurate description of the zooplankton community. Samples are collected by means of a vertical tow through the water column, lowering the net vertically to the desired bottom depth and retrieving it at a moderate rate of approximately 0.5 meters per second. This rate is selected to be fast enough to reduce any avoidance reactions of the plankton while not being so fast as to restrict flow through the net mesh.

The zooplankton sample is collected in a removable bucket at the lower end of the net and subsequently washed into a polyethylene sample bottle. The net mesh of the bucket is rinse repeatedly with lake water to wash all organism into the sample an avoid carryover of plankton organisms into the next sample. The sample is preserved with approximately 5 ml of acid Lugol's solution (APHA 1002 B. 1985) and stored at ambient temperature for the remainder of the survey.

All samples are labeled as being zooplankton samples with the station code, time, and depth interval of collection. This information is recorded on the field data sheet and incorporated into a catalog of samples collected throughout the reservoir survey.

Analysis consists of identification to genus level and enumeration of each genus present. Analysis is performed by a contract laboratory according to defined specifications. The actual concentration of plankton in the reservoir is calculated by applying the measured concentration and volume of the plankton sample to the volume of the water column that was sampled with the net by the following formula:

$$C_r = (C_s * V_s) / V_r$$

where

C_r = concentration of plankton in reservoir
C_s = concentration of plankton in sample
V_s = volume of actual plankton sample (cm^3)
V_r = volume of water column sampled in the reservoir (cm^3)
and $V_r = A * L * 100$

$A = (\pi * d^2) / 4$ =area of plankton net opening (cm^2)
$L = D_b - D_t$ = length of water column being sampled (m)

where

d = diameter of plankton net opening =130 mm
D_b = Lower depth of vertical tow
D_t = Upper depth of vertical tow

Phytoplankton. Phytoplankton is much smaller than most forms of the zooplankton and cannot be quantitatively sampled with the use of a net. Therefore, phytoplankton samples are collected as a discrete 1 liter sample which is centrifuged or otherwise concentrated into a much smaller volume for microscopic analysis. Phytoplankton samples are representative of a much smaller volume of water at a discrete depth as opposed to zooplankton samples which are a composite representation of the water column through a specific interval.

Field collection of phytoplankton is usually in conjunction with the collection of a water sample for chemical analysis. Results of the chemical analysis can then be correlated with the results of the phytoplankton analysis. The sample is collected from a well mixed Van Dorn sampler into a 1 liter polyethylene bottle. It is then preserved with approximately 15 ml of acid Lugol's solution and stored at ambient temperature for the remainder of the reservoir survey.

The sample is labeled as a phytoplankton sample with station code, time and discrete depth of sampling. This information is recorded on the field data sheet and incorporated into a catalog of all phytoplankton samples collected during the reservoir survey.

Chapter 5
Data Management and Analysis

History

Before computerized database management systems were used to store and manage data from Lake Powell and other reservoirs, information was stored on field sheets and hard copy reports in the Upper Colorado Regional Office in Salt Lake City. As the amount of information gathered from this program and from other projects increased, the need for a computerized tool for data management and analysis became apparent.

During the 1980's, information from the Lake Powell program was stored in an Rdb database under the VMS operating system residing on a Digital Equipment Corporation (DEC) VAX780 minicomputer in the Upper Colorado Regional Office in Salt Lake City, Utah. Rdb is a relational database management system software product of DEC. Interactive data access was provided by DEC's Datatrieve software. Applications were developed to provide random access to data collected from different stations at different times, tabular reporting and graphical representation of profile information. Concurrent with the development of the Lake Powell data management system were similar databases for other limnological and water quality projects in the Upper Colorado region. As each new database developed, it incorporated new characteristics and enhancements reflective of the specific monitoring program and current state of database management techniques.

As part of this effort, databases were also developed for Flaming Gorge Reservoir, Ridgway Reservoir (Dallas Creek Project), Paradox Valley brine characterization studies, and water quality activities of the Durango Projects Office.

During the development of the Lake Powell Rdb database, a separate data management system for chemical analyses was developed at the Upper Colorado Regional Water Quality Lab. This system allowed for the collection of analytical information from a variety of instruments; the integration of these data into a common system for parameter calculation, quality control analysis, and archiving; and subsequent reporting to Upper Colorado Region offices by means of electronic mail. The system also allowed for the electronic availability of laboratory data for integration with Lake Powell and other databases.

In 1995, the databases for the various Upper Colorado basin projects were consolidated, integrated, and converted to a UNIX-based Ingres database residing on a Data General Avion server in Salt Lake City, Utah (Wheeler, 1995). This new database, developed by GCES and the Upper Colorado Regional IRM staff, was called WQWM, an acronym of its desired function as a tool for Water Quality and Water Management. The database combines information from Lake Powell and the previously separate databases for Flaming Gorge and Ridgway reservoirs . With this design, data from any Reclamation monitoring program can be incorporated into the WQWM database and take advantage of a common set of analytical tools.

While the information collected from the monitoring program is reliably stored, maintained, and readily available electronically in a variety of formats, hard copy records continue to be maintained and reside at the GCES office in Flagstaff, Arizona.

Features

The design structure of the WQWM database allows for the incorporation of similar information from other reservoirs and is flexible to allow for adaptation of other types of data. This database is directly accessible by authorized users from within and outside of Reclamation. Design of the database has used preexisting standards and protocols for station and sample identification, parameter coding and other design considerations from the EPA STORET system whenever possible.

As the database conversion process has taken place, concurrent progress has occurred with the development and refinement of analytical tools to retrieve selected data from the database, perform statistical and other types of numerical analyses, and display these data in tabular and graphical format. Data can also be easily reformatted for subsequent input to other software programs and numerical models. Geographic linkages have been made to the data stored in WQWM for integration with the GCES/GIS long term monitoring database. Under the present system, the INGRES WQWM database functions primarily as a data server, supplying information to client based applications for statistical analysis, reporting, and graphic representation.

Currently, the majority of data analysis is being performed with the use of SAS software (SAS Institute, 1990), which provides comprehensive data management, statistical, and graphical analysis capabilities for data served from the Ingres database. In addition to its analytical capabilities, the SAS system stores and maintains hydrologic, water quality, and climatic databases for the Grand Canyon maintained by the GCES office. Capabilities existing with the SAS system include providing tabular reports, data manipulation, statistical summaries, multi-parameter color graphs of individual profiles, and graphical analysis of time series information (Figure 7).

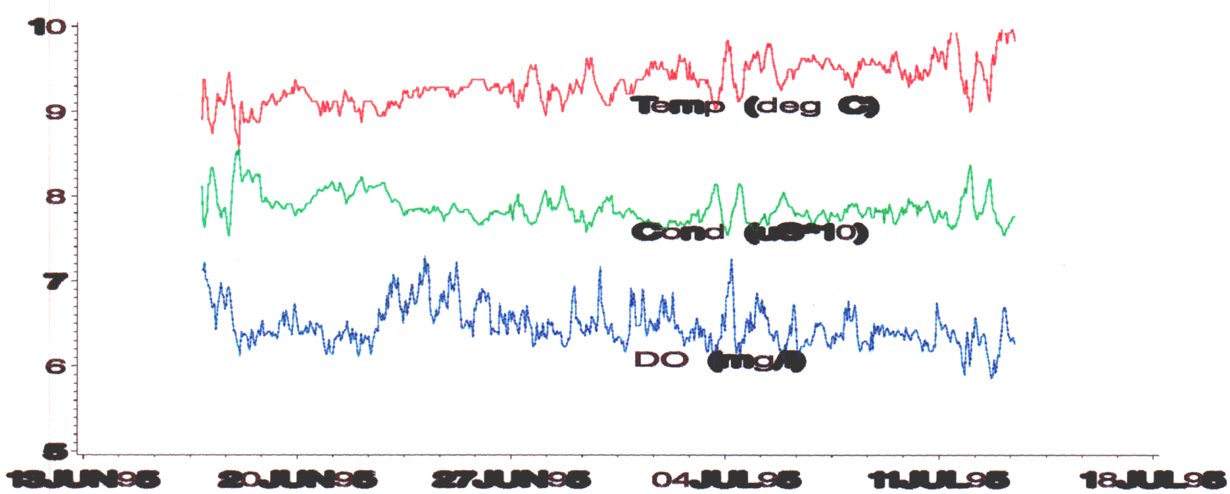

Figure 7. Time series graph of water quality below Glen Canyon Dam.

A three dimensional analysis program called SURFER (Golden Software, Inc.) has recently been implemented to develop isopleths of various parameters of the Lake Powell monitoring program. This provides a valuable tool for depicting information which changes with time at a given station (Figure 8), or which changes longitudinally through the reservoir at a specific time (Figure 9). The isopleths allow increased understanding of advective and convective processes in the reservoir on a spatial and temporal basis. Timing and frequency of sampling efforts and as well as selection of sampling locations are important considerations when using this tool to represent three dimensional data sets.

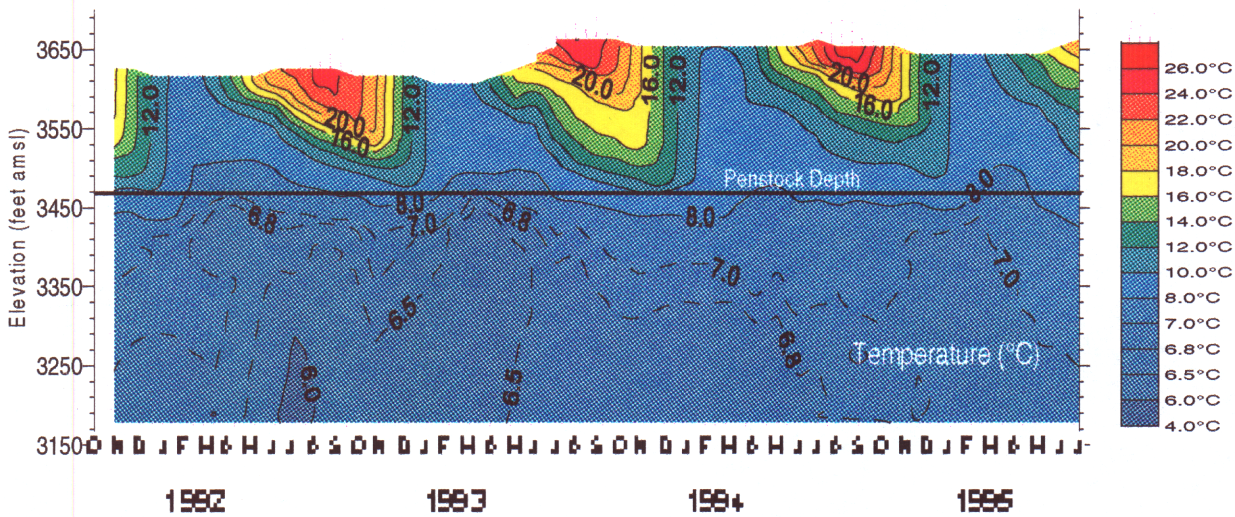

Figure 8. Isopleth of temperature at Wahweap forebay station, 1992-1995.

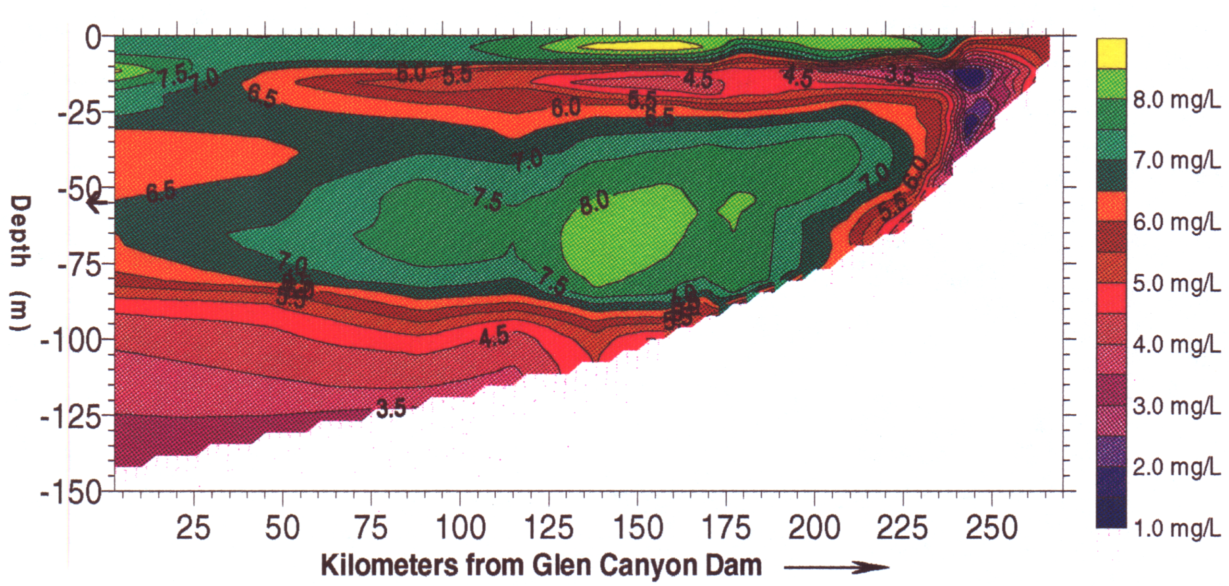

Figure 9. Isopleth of dissolved oxygen levels in Lake Powell, August 1994.

Links are currently being developed using the Microsoft Open Database Connectivity Standard (ODBC) between the SAS system, the Ingres WQWM database, the GCES/GIS geographic information system, and other ODBC compliant applications. The development of this client/server system for information exchange allows the ability to link to different types of data from a variety of distributed databases across different computing platforms.
Recently, a revised station identification scheme has been developed to allow for a standardized system of identifying Reclamation reservoir stations and incorporating this information as spatial data into the GCES/GIS geographical information system. As a result, a digitized map of the reservoir has been developed using GIS. Stations can be located and river channel distances from a given reference point can be determined. A record of visual and verbal documentation, geographical coordinates, and river channel distance is maintained for each main channel station.

Relational Database Concepts

A relational database consists of a one or more of *tables* of information. A table is a collection of information about a particular subject. Tables store information in a two dimensional format, characterized by *records* and *fields*. A record is a collection of fields describing a single entry in the table. Each field contains a specific piece of information describing the data stored in a single record of a table. A record may be referred to as a row, observation, or entry. Afield may be referred to as a column, variable, or data element. Each record in a table contains the same set of fields, and each field contains the same type of information for each record.

In the case of the WQWM database, one table may store data about sampling locations, another table may contain the information obtained from water quality profiles of physical parameters, while another table may contain the results of a particular chemical analysis. In the water quality profile table, each record represents an observation made at a given time, location, and depth, and each field in that record would contain the values of each individual parameter which is measured.

In a relational database, the information in each table is characterized by a field, or combination of fields, called a *key*, which identifies a particular record or group of records. Information from different tables can be cross linked by the key fields to relate different types of information. For example, the table describing sampling locations (STATION) may be linked to the table containing water quality profiles (PROFILE) by the key field STORET_ID (or station code) to relate the station's name and geograpical coordinates with the value of surface temperature on a given date. Similarly, data from a chemical analysis table (NUTRIENTS) may be linked with measurements from the PROFILE table over the key fields STORET_ID, SMPL_DT (sample date), and SMPL_DPTH (sample depth).

Design Considerations

The design of the WQWM database was determined from the consideration of several factors. First and foremost, it should be a repository for all significant information collected by the monitoring program and be easily retrievable for a variety of purposes. It should follow established standards of relational database management principles such as normalization, optimization, and security. It should have a structure compatible with other existing water quality databases such as the EPA STORET system and the USGS WATSTORE system. In some cases, these goals may be conflicting and choices have to be made to achieve an effective compromise. This compromise is usually made in favor of ease of use and data accessibility.

Furthermore, it is not anticipated that the current design and structure of this database will remain static in the future as different types of data are stored and further optimization of the existing design occurs. Therefore, a final goal of the database design is that the data exist in a modular format for ease of portability and the table structure and data definitions remain flexible while ensuring the information's overall integrity.

WQWM Database Structure

The current detailed structure of the Ingres WQWM database is documented in Wheeler, 1995 and contains references to administrative database elements and those of other projects not specifically related to the Lake Powell monitoring program. To simplify this complex structure, only the database design elements which specifically related to the Lake Powell database will be described here.

The tables described in the following section represent the majority of information which has been collected and stored to date. The general function and status of each table is described. The tabular structure of the WQWM database is shown in Figure 10.

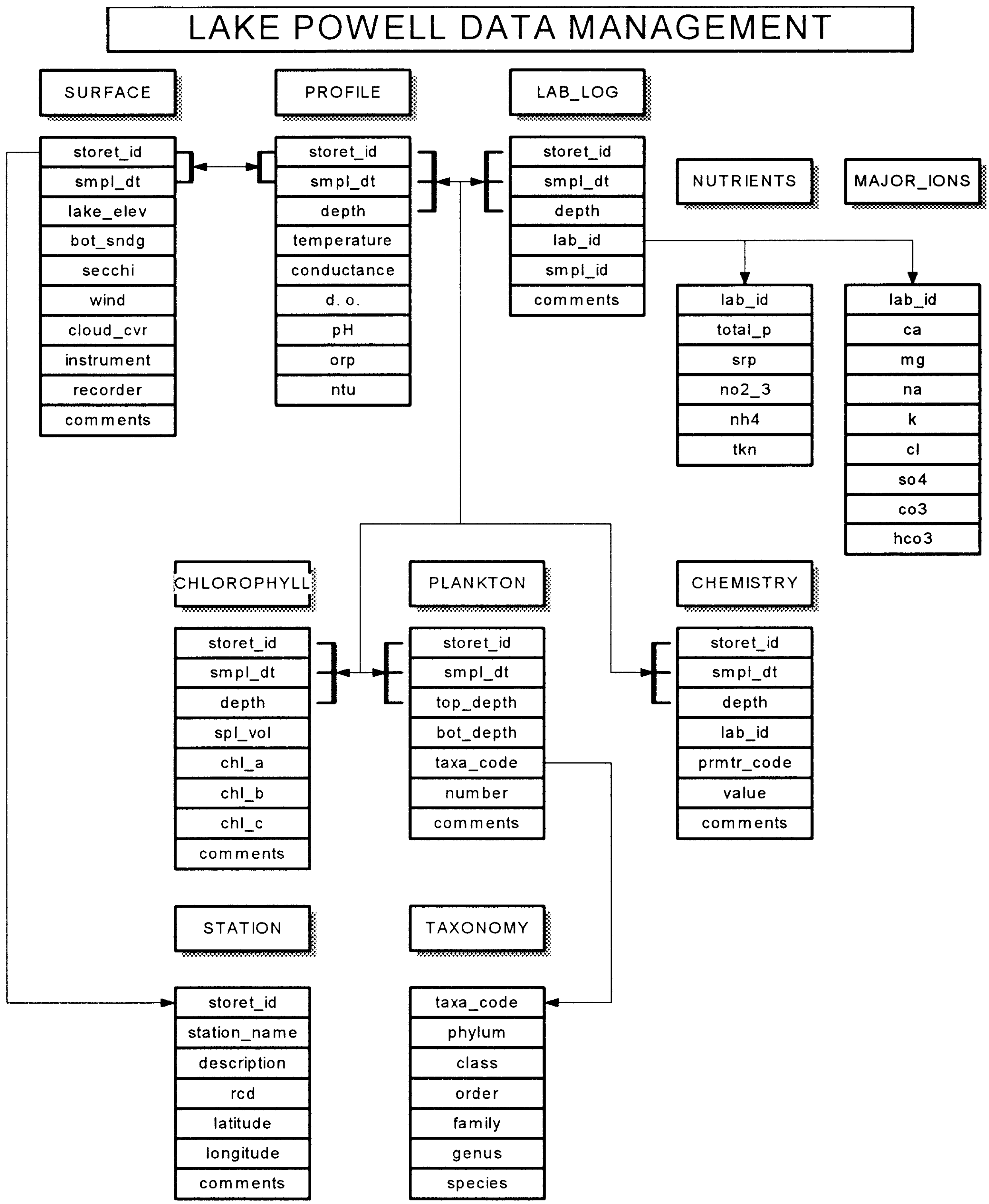

Figure 10. Lake Powell WQWM database structure.

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