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Modeling Dissolved Oxygen in Lake Powell using CE-QUAL-W2

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MODELING DISSOLVED OXYGEN IN LAKE POWELL

USING CE-QUAL-W2

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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ABSTRACT

MODELING DISSOLVED OXYGEN IN LAKE POWELL

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Master of Science

Water quality models in the Colorado River Basin have been developed for the basin, river, and individual reservoirs. They are used to support water quality programs within the basin. The models are periodically reviewed and updated to improve the accuracy of simulations. Improving the usefulness of the Lake Powell model, one of the key reservoirs in the basin, is the subject of this study.

Lake Powell is simulated using a hydrodynamic and water quality model, CE-QUAL-W2. Previously the model has been used at Lake Powell to simulate hydrodynamics, temperature, and total dissolved solids with a reasonable degree of accuracy. An additional parameter, dissolved oxygen, will be added to the simulations and then calibrated with observed data to verify accuracy.

Dissolved oxygen distributions in Lake Powell vary seasonally and change under different hydrologic cycles. They are a function of physical, biological, and chemical processes. Few measurements of these processes in Lake Powell exist. To compensate for the lack of data an empirical method of loading oxygen demand to the model is developed and tested. Observed limnological processes in the reservoir guide the development of the empirical methods. The methods are then tested in 16 year model simulations and compared with dissolved oxygen measurements from the 16 year period. By accurately reproducing the dissolved oxygen distributions the Lake Powell model will have improved accuracy and also broaden its usefulness.

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1 Introduction

The quality of water in the Colorado River Basin is important to millions of municipal, industrial, and agricultural users. Much time, effort, and money has been spent on monitoring, control, and studies of water quality in the basin. Public Law 84-485 Section 15 states:

"The Secretary of the Interior is directed to continue studies and make a report to the Congress and to the States of the Colorado River Basin on the quality of water of the Colorado River," (Department of the Interior, 2005)

The continuation of studies in the Colorado River Basin has included developing water quality models of the entire basin, the Colorado River, and some of its storage reservoirs. The U. S. Bureau of Reclamation (USBR), which operates and maintains several dams along the Colorado River, uses these models to simulate salinity, temperature, and other water quality constituents in the basin and individual reservoirs (Department of the Interior, 2005). The results and information from the models coupled with field data are used to develop monitoring, operation, and management plans as well as guide further research. The subject of this study is the additional development of the Lake Powell water quality reservoir model.

1.1 Lake Powell

Lake Powell was formed with the closure of Glen Canyon Dam in 1963. The reservoir is the second largest artificial lake in the United States and can store up to 27 million acre-feet of water. It extends from Cataract Canyon in southern Utah to behind the dam in northern Arizona (Figure 1-1). The reservoir is long, narrow, and irregular with many side canyons. For more information regarding Lake Powell and Glen Canyon Dam refer to Appendix A.

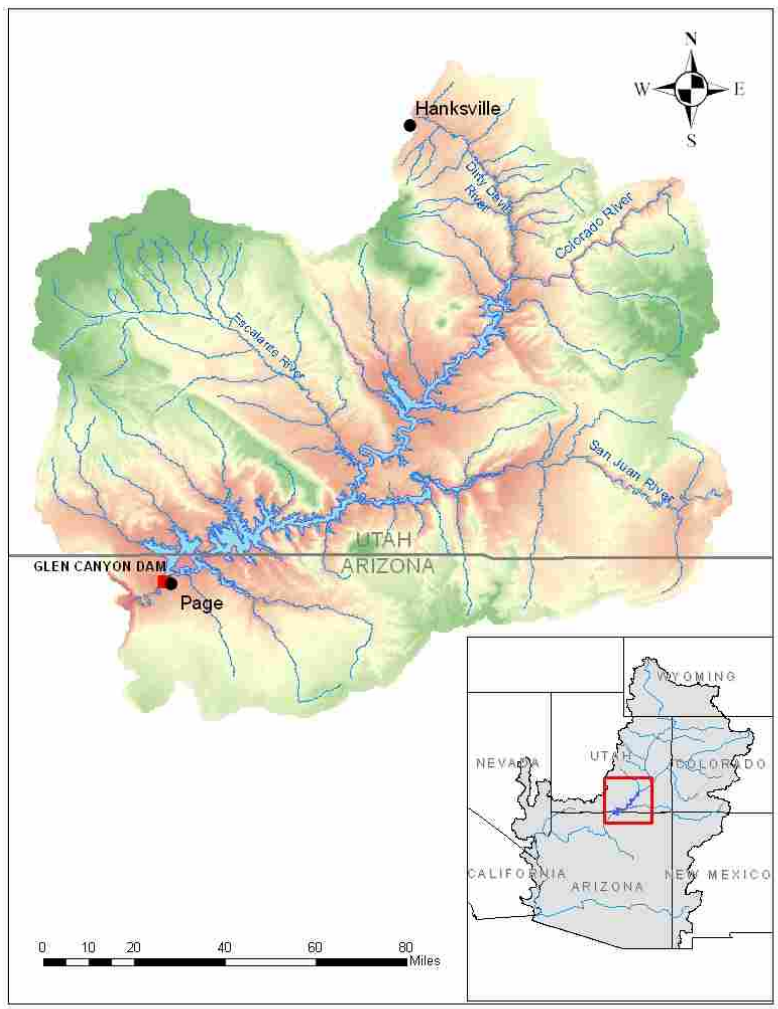

Figure 1-1: Glen Canyon Dam, Arizona and Lake Powell, Arizona-Utah

The construction of Glen Canyon Dam and the creation of Lake Powell significantly altered the flow regime and water quality characteristics of the Colorado River below Glen Canyon and through the Grand Canyon. Historically the river was characterized by muddy, turbid water and extreme seasonal fluctuations in flow and temperature. Now the river is clear and cold with no recognizable seasonal fluctuations in flow. Water quality characteristics in the river below the dam are subject to the discharges and hydrodynamic, chemical, and biologic processes within the reservoir. They have resulted in changes to the aquatic ecosystem downstream of the reservoir (Department of the Interior, 1995). Some effects, such as reduction in seasonal temperature variations, are permanent. Other effects, such as oxygen depleted discharges, occur sporadically. One such event occurred in the fall of 2005. Using the Lake Powell model to understand and simulate these water quality parameters is important for planning and managing both the reservoir and dam.

1.1.1 Lake Powell Model

The Upper Colorado Region of the Bureau of Reclamation has used numerical hydrodynamic and water quality models to simulate circulation, temperature, and total dissolved solids (TDS) in Lake Powell for several years (Miller, 2007). These models have been valuable tools in understanding reservoir processes. They have been used to forecast short-term temperatures and TDS (Department of the Interior, 2005) as well as study the affects of reservoir modifications such as the addition of a temperature control device to the dam (Bureau of Reclamation, 2005) (refer to Appendix B for additional information on the temperature control device). In order to provide decision makers with reliable scenarios for reservoir management and operations, the Lake Powell model is frequently reviewed, modified, and updated to improve accuracy and confidence (Miller, 2007). The following summarizes the history of models applied to Lake Powell and introduces the current model.

1.1.2 Model History

The earliest version of a Lake Powell model was developed by J.E. Edinger & Associates under contract to the Upper and Lower Colorado Regions of the Bureau of Reclamation. The model was developed using LARM, or laterally averaged reservoir model, a longitudinal-vertical time-varying hydrodynamic reservoir model developed by Edinger and Buchak (Edinger and Buchak, 1982). It was used to simulate hydrodynamics, temperature and TDS in Lake Powell for 1973-1974 and 1979-1980.

Another Lake Powell model was developed using the BETTER (Box Exchange Transport Temperature Ecology Reservoir) model developed by Tennessee Valley Authority (TVA, 1990). The Lake Powell BETTER model was built by the Technical Service Center of the Bureau of Reclamation (Bureau of Reclamation, 1999). Hydrodynamics, temperature, TDS, and dissolved oxygen (DO) were simulated for the years 1992-1993.

In 2001 the Upper Colorado Region with J.E. Edinger & Associates converted the Lake Powell BETTER model to CE-QUAL-W2 version 2.0. The model was mostly used to simulate hydrodynamics, temperature, and TDS. Some simulations were done for DO and algae, though these were mostly qualitative. This update also extended the simulation period through 1995. The computational grid used in BETTER was also used for the Lake Powell CE-QUAL-W2 version 2.0 model with some adjustments to match CE-QUAL-W2 file formatting requirements (Miller, 2007).

1.1.3 Current Model

In 2004 a review of the model by the Upper Colorado Region, U. S. Bureau of Reclamation updated the Lake Powell model to CE-QUAL-W2 version 3.2 (Miller, 2007). The period of simulation was increased to 1990-2002 and later updates to the model extended this period through 2005. The model simulates hydrodynamics, temperature, and TDS. The computational grid converted from the BETTER model was replaced by a grid generated from a Digital Elevation Map (DEM) built from topographic maps created by the U. S. Bureau of Reclamation and then digitized by the U.S. National Park Service (Miller, 2007). Increased resolution in the form of additional branches and segments was implemented to better represent the complex geometry of Lake Powell and improve the volume accuracy of the grid. Minor errors and discrepancies found in the previous model during the review were also corrected.

This model of Lake Powell using CE-QUAL-W2 version 3.2, simulating 1990-2005, was used in this study. As the focus of this study is the continued development of the CE-QUAL-W2 Lake Powell model, no other hydrodynamic and water quality model codes were investigated or tested. A new version of CE-QUAL-W2, version 3.5, was released during the development of this study, but the Lake Powell model was not updated to this version because the modifications to the CE-QUAL code were not considered essential to the objectives of this study. A description of the CE-QUAL-W2 model, its development, computational grid, capabilities, limitations, and calibration is included in Chapter 2. Chapter 3 provides a detailed description of the Lake Powell CE-QUAL-W2 model including the grid, assumptions, and calibration results for water balance, temperature, and TDS.

1.1.4 Fall 2005 Oxygen Depletion

The impetus for this study was the previously mentioned discharge of oxygen depleted water. In the summer of 2005 a plume of oxygen depleted water developed in Lake Powell and stretched from the inflow areas to the dam (Figure 1-2). This water was captured in the withdrawal zone of the release intakes (penstocks) and exported through the dam to the river below. DO concentrations in the river dropped below 4.0 mg/L in September 2005 (Figure 1-3). These low levels were of concern to the cold-water fishery below the dam based on requirements of a 1-day mean minimum concentration of 4.0 mg/L, a 7-day mean minimum of 5.0 mg/L, and a 30-day mean of 6.5 mg/L for cold water fish species (U.S. EPA, 1986).

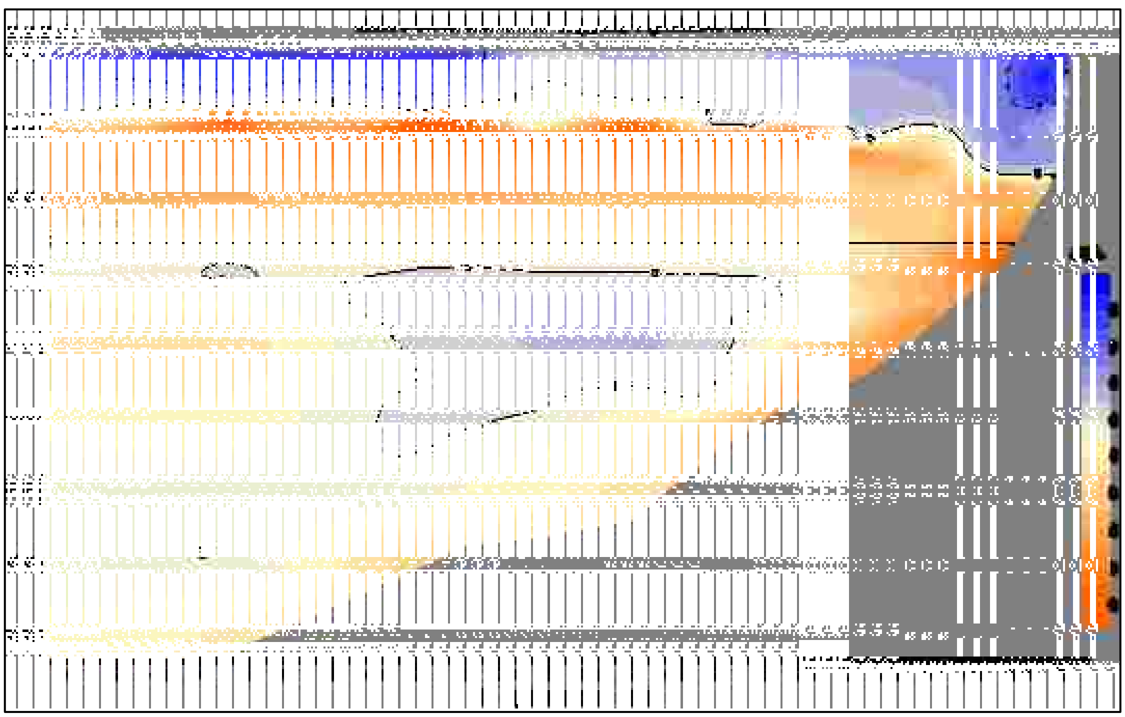

Figure 1-2: Lake Powell, Colorado River channel DO concentrations, September 2005

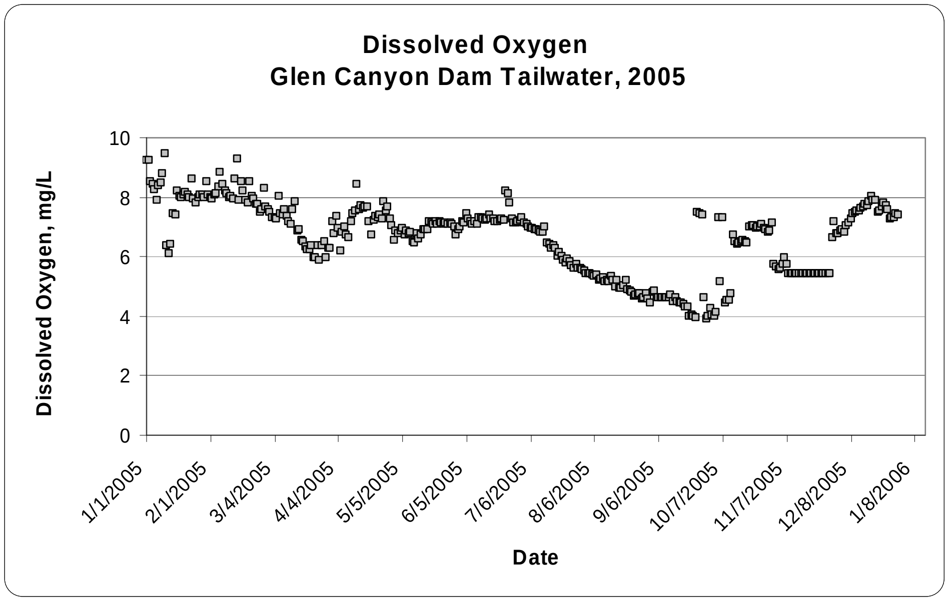

Figure 1-3: Glen Canyon Dam tailwater DO concentrations, 2005

Solutions

Officials from the U. S. Bureau of Reclamation, U. S. Geological Survey (USGS), Arizona Game and Fish Department, and other agencies worked to find a method to increase DO content below the dam (WAPA, 2007). During power generation some aeration occurs as water passes through the turbines. A series of tests were done to determine what operating ranges induced the most aeration. These tests discovered that operating turbines at lower flows and lower generating efficiencies increased aeration most (Bureau of Reclamation, 2007a). As a result more turbines were operated at lower flows to increase DO concentrations. Figure 1-4 shows DO concentrations and flow rates below the dam during the turbine aeration testing. From September 3rd to September 21st releases were highest in the day and lowest at night. The DO concentrations during this peaking pattern were highest at low flows. After September 21st steady releases of about

8000 cfs were made. During this period turbine testing was done as evidenced by large jumps in DO from September 25th to September 28th and October 5th to October 8th. Once aeration from fall turnover had increased DO concentrations in the reservoir above potentially harmful levels power generation returned to normal operations.

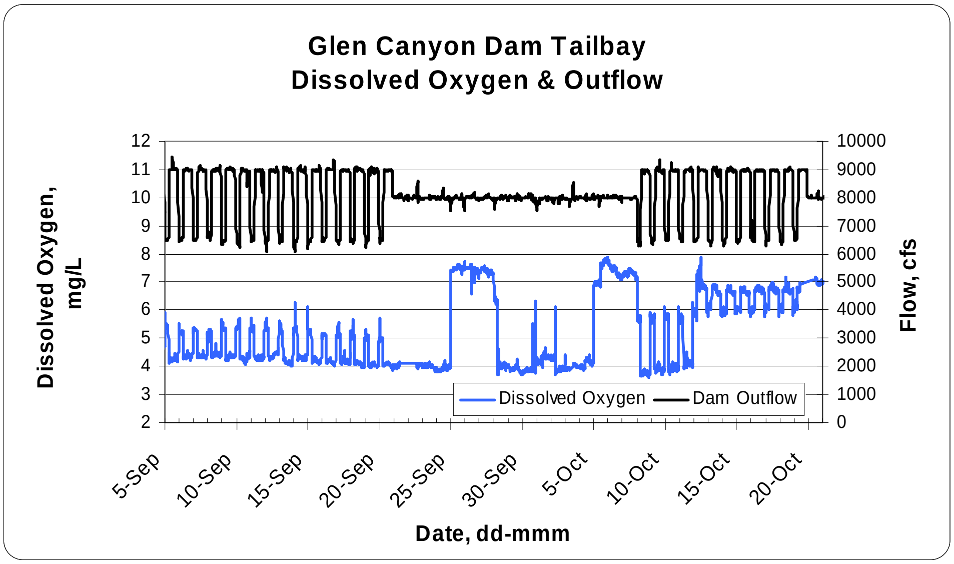

Figure 1-4: DO concentrations and flow rates, turbine aeration testing, September-October, 2005

Impacts

Between Glen Canyon Dam and Lee's Ferry on the Colorado River, a stretch of 16 miles (Figure 1-5), the river is managed as a sport fishery for rainbow trout (U.S. Department of the Interior, 1995). Oxygen poor releases were a concern because aeration in this reach is limited and full saturation does not occur until the river reaches the rapids below this section of river (Vernieu et al., 2005). The low oxygen concentrations had the potential to harm fish and other aquatic organisms. Arizona Game and Fish officials have noted a decline in trout below Glen Canyon Dam since 2000. The decline is believed to be due to several interacting factors to which the low DO in 2005 may have contributed (Persons, 2007).

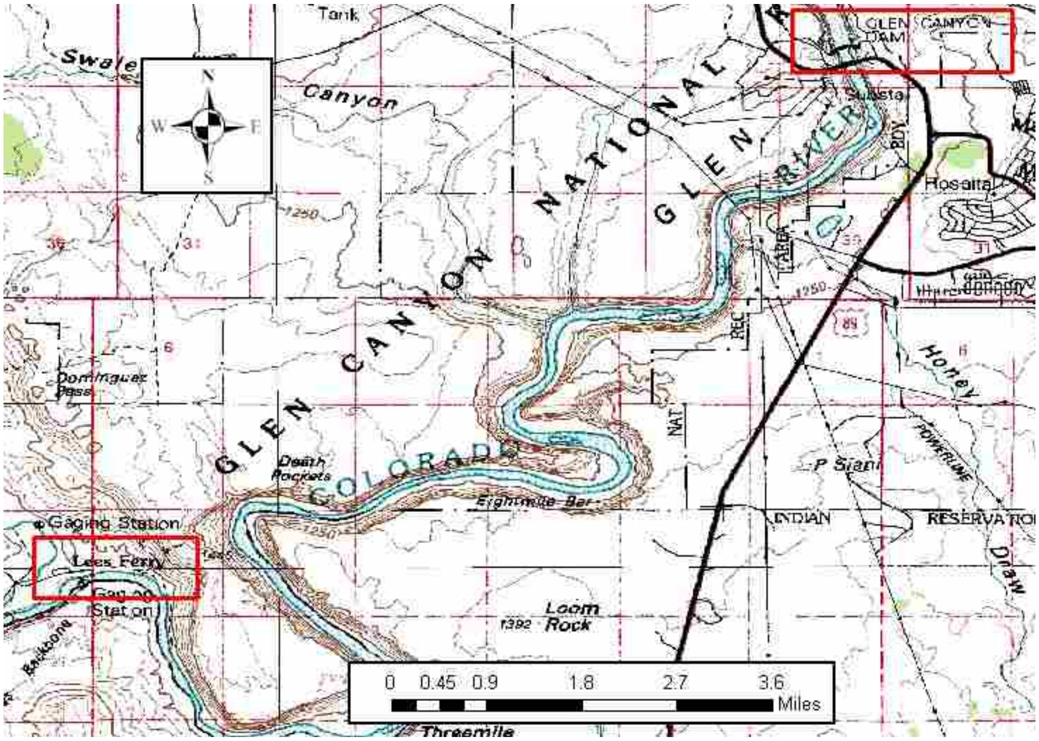

Figure 1-5: Colorado River, Glen Canyon Dam to Lee's Ferry

Operating turbines at lower efficiencies does not optimize power generation and revenues were lost while the turbines were operated at low flows. Lower flows also increase the risk of damaging turbines (U.S. Bureau of Reclamation, 2007a). Considering the impacts to revenue and possible damage to power equipment other solutions may need to be found for increasing oxygen content in releases from the dam.

1.2 Objectives

The low DO content of reservoir releases and the adjustment to dam operations in 2005 led to a need for more information about DO dynamics in Lake Powell. As mentioned previously the Lake Powell model was developed to increase understanding of the reservoir and aid in development of monitoring, research, operational, and management strategies. The goal of this study is to meet the above purposes by expanding the Lake Powell model to simulate DO.

DO has particular importance to both the reservoir and tailwater ecosystems. As stated by Hutchinson "[one] can probably learn more about the nature of a lake from a series of oxygen determinations than from any other kind of chemical data" (Hutchinson, 1957).

Modeling DO also helps improve the reservoir model itself. Besides improving understanding of the system, modeling DO is another method of improving hydrodynamic accuracy of the existing model. According to the CE-QUAL-W2 user's manual "experience has shown that DO and phytoplankton are often much better indicators of proper hydrodynamic calibration than either temperature or salinity" (Cole and Wells, 2003).

DO is a more complex parameter than either temperature or salinity. There are many mechanisms which affect oxygen's solubility, replenishment, and consumption which the model development simulates. These mechanisms must be understood generally and as they relate specifically to Lake Powell. Additional insight gained from a review of literature on DO in similar systems also aids in understanding these mechanisms.

The CE-QUAL-W2 model provides the capability of modeling DO and many of the mechanisms that affect it. Comparing the model parameters with reservoir monitoring data and reservoir studies will help determine which parameters drive the DO dynamics in Lake Powell. Reservoir monitoring data will also be used for calibration of DO.

The objectives of this study are to:

- Update the Lake Powell model to simulate DO and
- Develop an empirical method for loading oxygen demand in the model using relationships with oxygen depletion indicators

These objectives will be accomplished by:

- Improving model calibration of hydrodynamics, temperature, and TDS;
- Understanding processes within the reservoir that affect DO including hydrology, circulation patterns, limnology, and sediment delta interactions;
- Recognizing indicators of oxygen depletion from in situ observations and hydrologic events; and
- Iteratively simulating oxygen demand loading to reproduce past distributions in the reservoir

This report will discuss the development of the model, the DO dynamics in the reservoir, and the methods used to simulate DO in the model. The report will present results from DO simulations. Conclusions from the modeling will be presented and used to recommend future research and monitoring as they relate to improving model performance and reservoir operations.

1.3 Scope

This study was funded by the Upper Colorado Region of the Bureau of Reclamation which operates and maintains Glen Canyon Dam. The Lake Powell model is part of a quality of water program in the Colorado River Basin and supports the advancement of methods for monitoring water quality in reservoirs within the basin (U.S. Department of the Interior, 2005). It is anticipated that the results of the study will be used in connection with management and operations at Glen Canyon Dam, planning for future research of water quality in Lake Powell, analysis of modifications to the dam such as the proposed temperature control device, and developing models for other systems.

It is important to point out that this study will build upon previous efforts to understand and model water quality in aquatic systems around the world. The conclusions and results of this study are not intended to introduce new standards of water quality modeling or supersede previous methods. At the same time previous methods are not directly applied to this case. As stated in the CE-QUAL-W2 manual "black box application of any model is a recipe for failure" (Cole and Wells, 2003). It is the intent of this study to further expand the Lake Powell water quality model and produce useful results, or provide a building block for obtaining useful results.

2 CE-QUAL-W2 Introduction

"CE-QUAL-W2 is a two dimensional, longitudinal/vertical, hydrodynamic, and water quality model. Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients." (Cole and Wells, 2003) Development and evolution of CE-QUAL-W2 has spanned three decades. The model has been successfully applied to lakes, reservoirs, rivers, and estuaries around the world. A brief introduction to the model's history, capabilities, limitations, inputs, and calibration methods follows.

2.1 CE-QUAL-W2 Evolution

The original CE-QUAL-W2 model, known as LARM (Laterally Averaged Reservoir Model), was developed by Edinger and Buchak (1975) beginning in 1975. This model simulated hydrodynamics, temperature, and conservative water quality parameters such as TDS. Additional development allowed for simulation of multiple branches and estuaries and this model code was known as GLVHT (Generalized Longitudinal-Vertical Hydrodynamics and Transport Model) (Cole and Wells, 2003). Water quality algorithms were later added and the resulting code was known as CE-QUAL-W2 Version 1.0 (Environmental and Hydraulic Laboratories, 1986). Subsequent releases included:

- Version 2.0 (Cole and Buchak, 1995)
- Version 3.1 (Cole and Wells, 2003)
- Version 3.2 (Cole and Wells, 2003)
- Version 3.5 (Cole and Wells, 2006)

Modifications to the model have included improvements to computational efficiency and accuracy, transport and mixing schemes as well as additional water quality algorithms, hydraulic structures, and the ability to connect multiple waterbodies.

2.2 Capabilities & Limitations

The CE-QUAL-W2 model is capable of predicting water surface elevations, velocities, temperatures, and several water quality constituents. Geometrically complex waterbodies are represented by a finite difference computational grid. Multiple inflows and outflows to the waterbody are represented through point/nonpoint sources, branches, precipitation, and other methods. Tools are available for modeling hydraulic structures such as spillways and pipes. Output from the model provides options for detailed and convenient analysis.

The model is limited by several assumptions and approximations used to simulate hydrodynamics, transport, and water quality processes. The model solves for gradients in the longitudinal and vertical directions but it assumes lateral gradients are negligible. Hence, it is most applicable to relatively long, deep reservoirs as this assumption would be inappropriate for waterbodies with significant lateral variations. Turbulence is modeled through eddy coefficients of which the user must decide which scheme is most appropriate for an application. The user’s manual includes some guidance on which schemes are appropriate for different systems and recommends default schemes. An algorithm for vertical momentum is not included and results may be inaccurate in waterbodies with significant vertical acceleration. Water quality constituents represented by the model are complex interactions. The methods used to solve these are simplistic descriptions but have replicated observed processes in various systems with impressive results (Cole and Wells, 2003). Several water quality processes are not simulated including sediment transport and accumulation, toxics, and dynamic sediment oxygen demand (Cole and Wells, 2003).

2.3 Input Data

CE-QUAL-W2 is a data intensive application. The data required for an application include bathymetric data, air temperature, dew point temperature, wind speed, wind direction, cloud cover, solar radiation, inflow and outflow volumes, inflow temperatures, precipitation, evaporation, water quality constituent concentrations, and hydraulic and kinetic parameters. The availability and quality of these data directly affect model accuracy and limit usefulness.

2.4 Computational Grid

The bathymetry file of a CE-QUAL-W2 model is the two-dimensional numeric representation of a waterbody and is also referred to as the computational grid. The two dimensions represented are the segments in the longitudinal dimension and layers in the vertical dimension, or the length and depth of a waterbody. The lateral dimension, or width, is not explicitly represented in the grid but an average width is computed and used to determine volume.

The components of the grid are, from smallest to largest, cells, segments, branches, and waterbodies. Figure 2-1 is a simple representation of a CE-QUAL-W2 grid and highlights a cell, segment, and branch. A cell is a single vertical layer within a single segment. Each cell acts as a completely mixed reactor in each model time step. Segments consist of one or more cells and branches are one or more longitudinal segments as shown in Figure 2-1. A waterbody consists of one or more branches. Tributary branches in a system are represented through additional branches which are linked to the main stem branch at a specific segment. One bathymetry files contains the dimensions from a single waterbody. A CE-QUAL-W2 model can include one or more waterbodies.

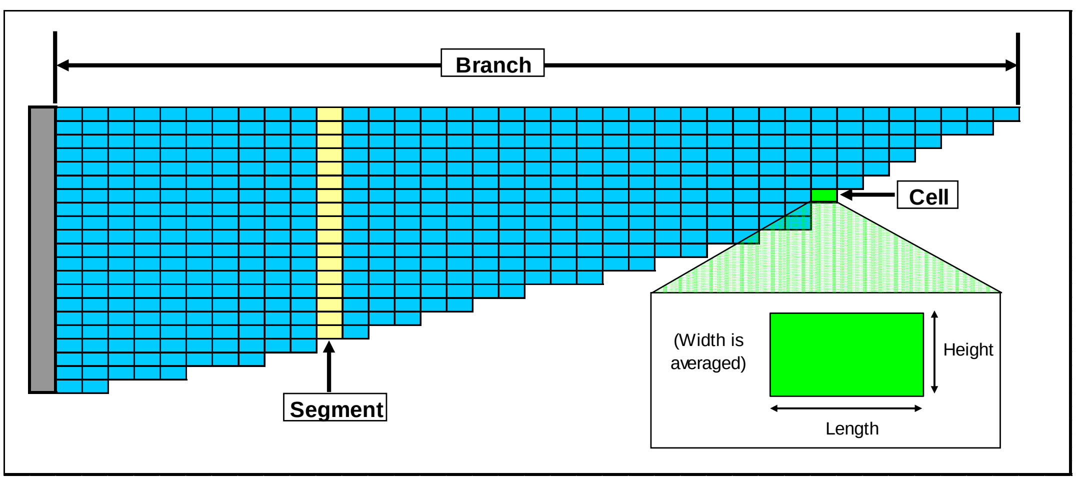

Figure 2-1: Conceptual view of CE-QUAL-W2 grid

The volume of the grid is computed by multiplying a cell's segment length, vertical thickness, and averaged width. The sum of the volume of all cells within the grid is the total storage for the waterbody. The computed grid volume is compared to actual storage-capacity data to verify the model bathymetry accuracy. The assumptions made in developing the initial bathymetry should be reviewed during model calibration to better represent the actual reservoir (Cole and Wells, 2003).

2.5 Calibration

Model calibration involves comparing observed data to modeled, or predicted, results. Calibration is done iteratively until an acceptable fit of the predicted and observed data is achieved. There are no set guidelines for determining what an adequate fit is. The user must decide if and when the model is producing useful results. A typical sequence for model calibration is to begin with the water budget, followed by temperature, and then water quality constituents. Calibration statistics use the absolute mean error (AME) which is computed as follows: (Cole and Wells, 2003)

$$AME = \frac{\sum \left| Prediction - Observed \right|}{number\ of\ observations} \tag{2-1}$$

Other statistics may be used but the AME is preferred because it describes, on average, the difference between predicted and observed values (Cole and Wells, 2003). Hydrodynamic calibration typically goes beyond just calibrating temperature. Other water quality constituents should also be used to verify hydrodynamic calibration. The appropriateness of a constituent for calibration varies between waterbodies. The manual suggests using DO and phytoplankton in addition to temperature and salinity for calibration.

Model calibration also requires testing model performance under different conditions than those used to generate the initial calibration model. This is called verification. In a reservoir application these may include sequences of differing inflow hydrology, reservoir elevations, and release volumes. Confidence in the model improves as different sequences are successfully reproduced. Long-term simulations are good indicators of model calibration quality because they reveal cumulative errors and reduce the influence of the initial conditions. More confidence can be placed in a model if it accurately reproduces observations from the system over a period of several consecutive years with varying hydrodynamics and water quality (Cole and Wells, 2003).

3 Model Description & Development

The Lake Powell model used as the basis for this study simulates hydrodynamics, temperature, and TDS. The simulation period begins January 1, 1990 and extends to December 31, 2005. The following includes a description of the model inputs, computational grid, and assumptions. The calibration section presents the previous temperature and TDS calibration and discusses improvements made during the development of the DO simulation.

3.1 Input Data

Meteorological data for the model are collected at airports in Page, Arizona and Hanksville, Utah. Records are kept by the National Climatic Data Center (NCDC). Both datasets include air and dew point temperature, wind speed, wind direction, and cloud cover observations. The observations at Page are collected at hourly and sub-hourly intervals. Observations at Hanksville are collected during daylight hours. The Hanksville observations are used to fill gaps in the Page meteorological record, except for the cloud cover data. This exception applies to the temperature calibration of the model and is explained in Section 3.4.2.

Inflow records are collected by the USGS and are available for the following tributaries to Lake Powell (Figure 3-1):

- Colorado River near Cisco, Utah, USGS #09180500,
- Green River near Green River, Utah, USGS #09315000,
- San Rafael River near Green River, Utah, USGS #09328500,
- San Juan River near Bluff, Utah, USGS #09379500, and
- Dirty Devil River near Hanksville, Utah, USGS #09333500

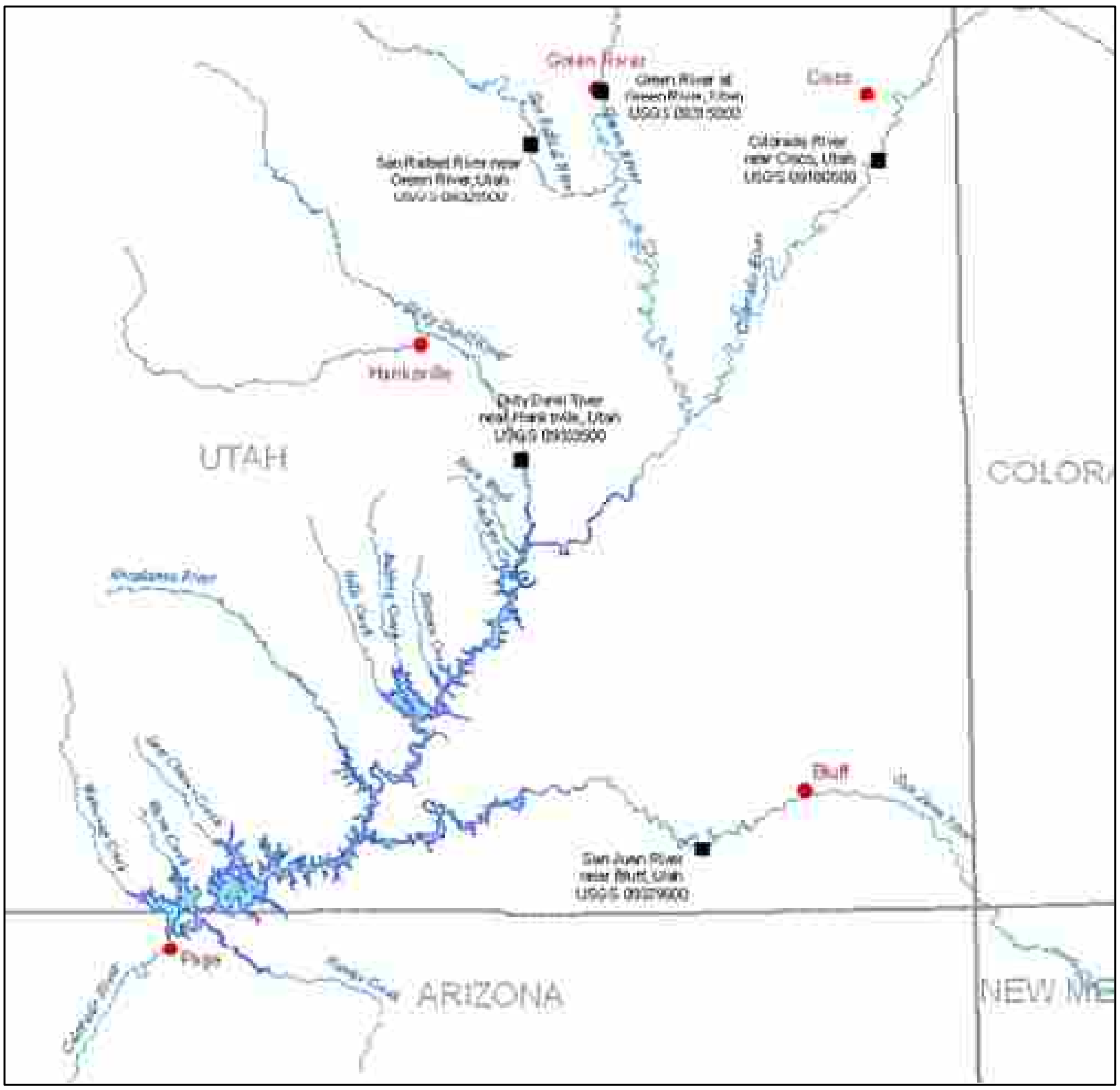

Figure 3-1: Lake Powell tributaries and streamflow gauging stations

Inflow from the Colorado River above its confluence with the Green River, the Green River, and the San Rafael River are summed to form the Colorado River inflow to Lake Powell. Daily mean flow rates are used in the model. For inflows which represent branches or where limited flow records were found, estimates were made. These include: North Wash, Trachyte Creek, Hansen Creek, Bullfrog Creek, Halls Creek, Escalante River, Cha Creek, Rock Creek, Last Chance Creek, Warm Creek, Navajo Creek, and Wahweap Creek (Figure 3-1). All outflow releases are made through Glen Canyon Dam and records are collected by the USBR. Hourly records are used to capture the rapid change in release rates from hydropower generation.

Data for water quality parameters are taken from major tributaries where available. When data are not available, statistical relationships supplement water quality data. Water quality datasets have been collected from the USBR, USGS, and Utah and Arizona State agency records.

3.2 Bathymetry

The bathymetric grid was generated using a DEM and the software, Watershed Modeling System (WMS) (Nelson, 2006). WMS is developed and maintained by the Environmental Management Resource Laboratories (EMRL) as part of the Civil and Environmental Engineering Department at Brigham Young University and in cooperation with the U.S. Army Corps of Engineers. The software has algorithms to divide and subdivide a waterbody into branches, segments, and layers. Using an underlying digital terrain model it can compute the volume of each cell and write the results in a CE-QUAL-W2 bathymetry formatted file.

The Lake Powell CE-QUAL-W2 model bathymetry consists of 9 branches, 90 segments, and 97 layers. Branches have from 3 to 35 segments. Segments range from over 10,000 meters in length to less than 1,000 meters. All layers are 1.75 meters thick. The following channels and/or bays are represented as branches (Figure 3-2):

- Colorado River (Main) channel,
- Bullfrog Bay,
- Escalante River channel,
- San Juan River channel,
- Rock Creek Bay,
- Last Chance Bay,
- Warm Creek Bay,
- Navajo Canyon, and
- Wahweap Bay

Figure 3-3 is a diagram of the Lake Powell model bathymetry with plan, profile, and cross section views of the grid. The profile view is of the Colorado River branch. The color red indicates segments where tributary branches connect. The color green indicates an upstream boundary segment, blue a downstream boundary segment.

The accuracy of bathymetry data was checked using storage-capacity curves. Figure 3-4 is a comparison of the volume computed from the model bathymetry and the Bureau of Reclamation storage capacities. Storage capacity curves show reservoir storage at different reservoir elevations. The comparison of the model volume to the actual storage capacity is made to verify the accuracy of the model grid. The bathymetry generated for the model has a 0.3% error from the 1986 USBR sediment survey storage-capacity curve (Ferrari, 1988).

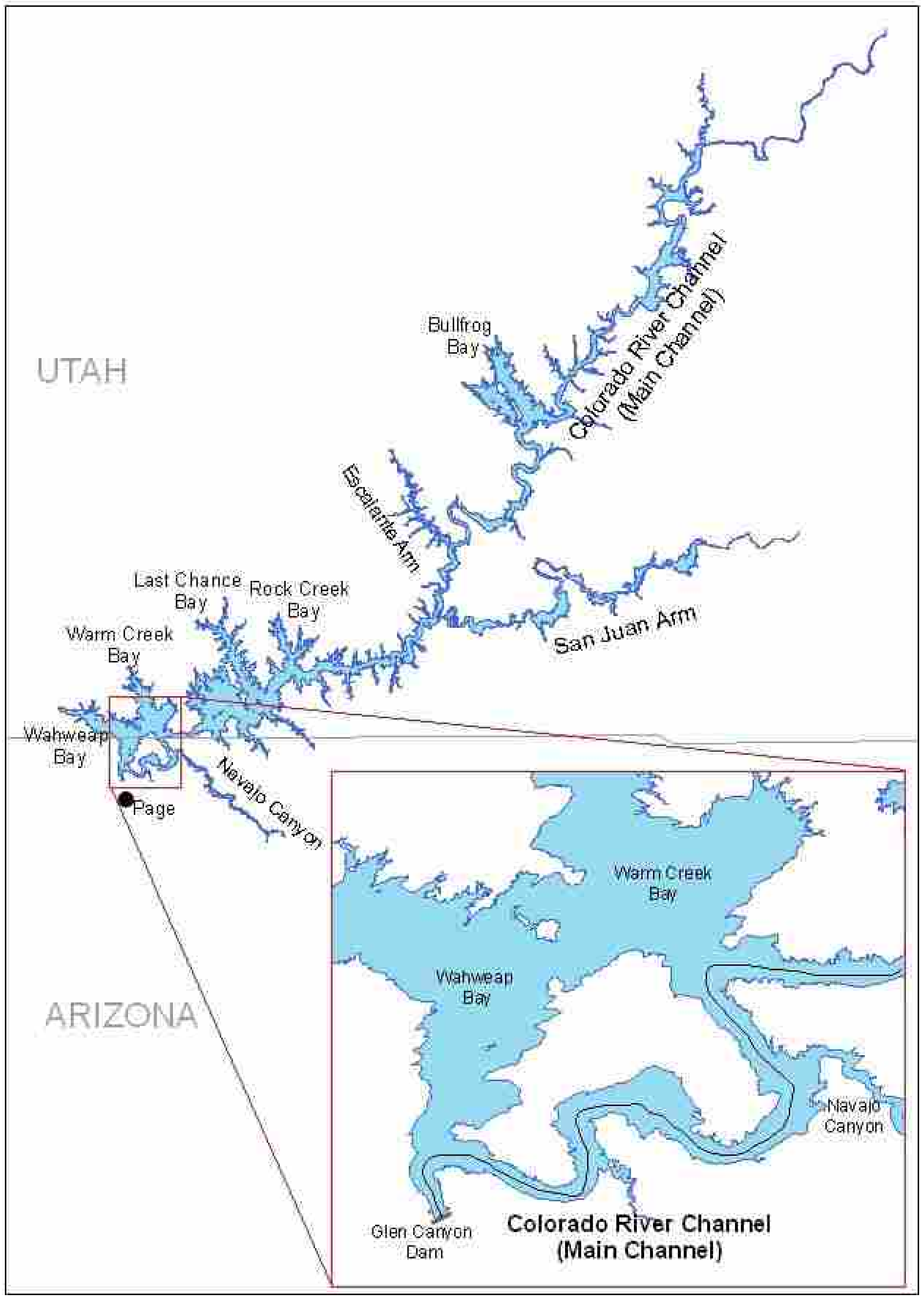

Figure 3-2: Lake Powell map: channels, branches, and bays

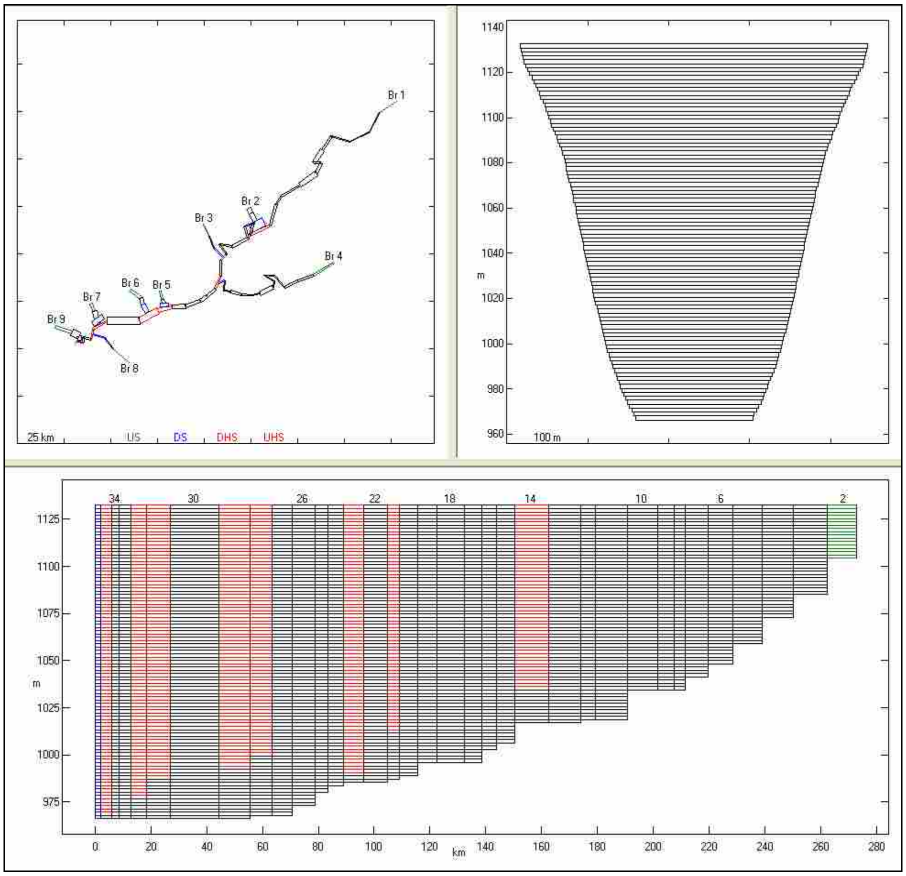

Figure 3-3: Lake Powell CE-QUAL-W2 bathymetry grid

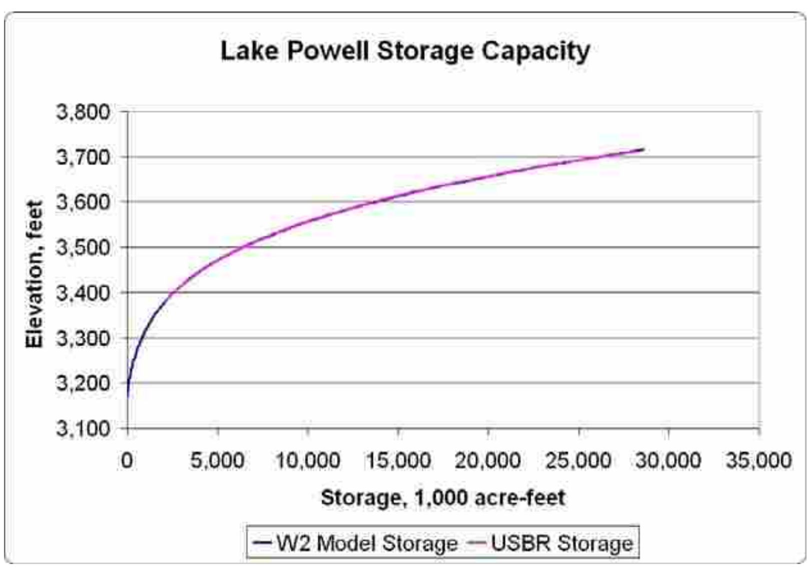

Figure 3-4: Lake Powell model bathymetry and USBR storage-capacity curves

3.3 Assumptions

The input data used in the model are the best available and are assumed to be accurate representations of meteorology, flow, and water quality parameters. Additional assumptions may also affect model accuracy and reliability and are presented below.

Meteorological Variability

Data from the Page, Arizona airport are used to represent meteorological conditions on Lake Powell. Page is located at the southernmost end of the reservoir and while conditions there may not represent conditions over the rest of the lake, especially near the major inflows and the northern end, there are no other weather stations in close proximity to the reservoir with observations as detailed as those at Page. In particular, wind speeds and directions on the plateau where the airport is located may be much different than the wind characteristics inside the narrow, winding canyons. Wind on the water may also vary with the orientation of the canyon and from one location to another.

Typically, model calibration includes adjusting for wind by using the "wind sheltering coefficient", a numerical value typically between 0 and 1 defined for individual segments (Cole and Wells, 2003). Wind speeds values are multiplied by this value to determine an effective wind speed for each model segment. Determining wind sheltering coefficients for Lake Powell was an iterative process and the values used in model simulations for individual segments ranged from 0.35 to 1.0.

Water Balance

The model is calibrated to reproduce water surface elevations observed near the dam. When the reservoir is rapidly rising or dropping the water surface is not level across the length of the reservoir. Only modeled water surface elevations near the dam are compared with recorded elevations, differences at other locations are not considered.

The water budget is not 100% accounted for in the known and estimated inflows and outflows. An additional input referred to as the distributed tributary was created for the model and the flows required to balance the water budget are put in this tributary. These flows may represent precipitation, ungauged tributary flows, bank storage, and other sources or sinks. This mechanism assumes all flow enters the surface cells of the model grid. Large flows from this mechanism may impact water quality so reasonable assumptions are made for assigning water quality constituent concentrations to these flows.

The flows represented in the distributed tributary may not actually enter the reservoir at the water surface. By using this method to balance reservoir elevations, large storm events and bank storage return flows do not enter the reservoir as they actually might, instead the model forces mixing in surface cells. The water quality impacts of these events are not known and are estimated in the water quality constituents assigned to the distributed tributary.

Sediment Transport

Although the suspended solids are part of the model, deposition and scour of sediments are not represented. As sediments settle and are deposited along the reservoir bottom they are lost from the system. In long term observations of Lake Powell this effect is noticeable in the upper reaches of the reservoir as sediment accumulates and raises the bottom elevations of certain locations. This is illustrated by the changing bottom elevation at the Hite Basin monitoring site which is located below the Colorado River inflow area (Figure 3-5).

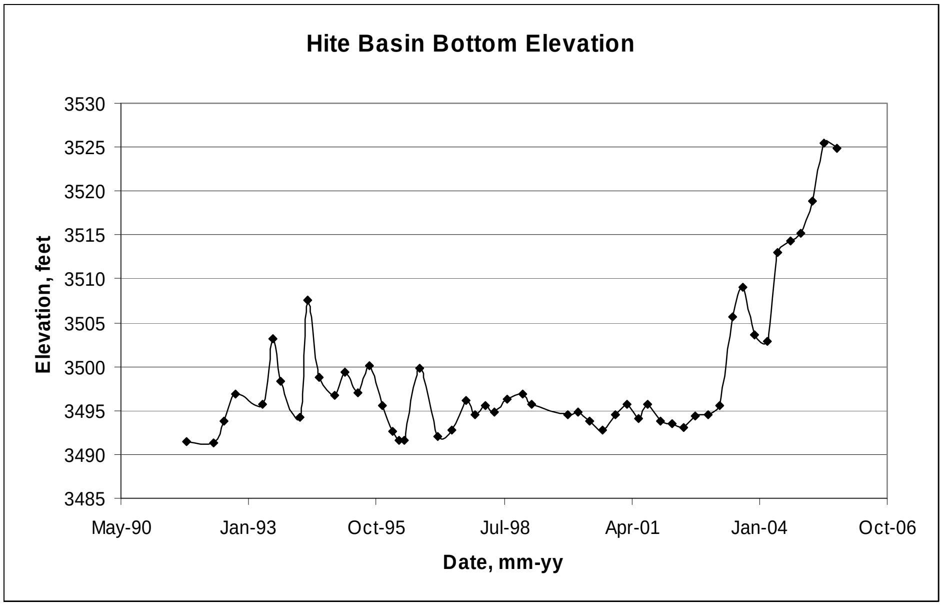

Figure 3-5: Hite Basin monitoring site bottom elevation, 1991-2005

Sediment Delta Interactions

Sediment deltas have accumulated near the mouth of major and minor inflows. As of the 1986 Lake Powell survey the total volume of sediment accumulation was estimated at 868,231 acre-feet, or 3.2% of the total reservoir storage volume below 3700 feet (Ferrari, 1988). Figure 3-6 depicts the original bottom of the Colorado River channel and the average bottom of the reservoir as measured in 1986. Deposition and scour of the deltas resuspends sediment and releases decomposing organic matter (Vernieu et al., 2005). The CE-QUAL-W2 model does not simulate sediment delta scouring, sediment diagenesis of nutrients, or chemical and biological oxygen demand release. Incorporation of these processes is on the edge of modeling and data gathering technology. Because this is likely a significant source of nutrients and oxygen demand to the reservoir the empirical oxygen demand loading, discussed later in this report, attempts to represent the affects of these processes.

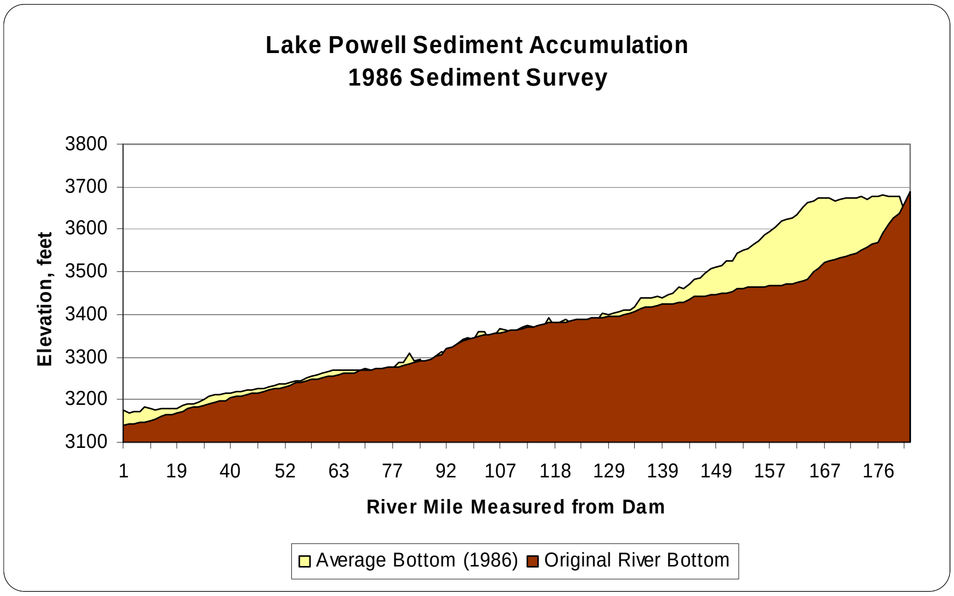

Figure 3-6: Colorado River Channel bottom elevation, original vs. 1986

TDS as a Conservative Parameter

Concentrations of TDS, as represented in the model, are computed by simple mass balance calculations. In reality TDS are not conservative due to mineral precipitation and biological interactions. In Lake Powell precipitation of calcite can potentially reduce TDS concentrations (Reynolds, 1978). The impacts of these interactions are difficult to determine and it is assumed they do not significantly change the TDS concentrations. When this assumption is valid, TDS can be used as a conservative tracer to verify hydrodynamic calibration.

3.4 Calibration

The final step in model development, calibration was done iteratively for water balance, temperature, and TDS. The model was calibrated over the years 1990-2005. Predicted results are compared to observed data from all or part of the period 1990-2005 at 18 locations as well as the tailwater (Figure 3-7). These data are collected as part of a lake-wide monitoring program. Monitoring of reservoir water quality has been conducted since 1964 by the Bureau of Reclamation, Glen Canyon Environmental Studies, the USGS Water Resources Discipline, and the USGS Grand Canyon Monitoring and Research Center (Vernieu et al., 2005). Currently monitoring consists of monthly surveys of the reservoir forebay and quarterly surveys of the entire reservoir.

Within the reservoir calibration statistics are computed for vertical profiles. Calibration statistics for reservoir releases are computed from daily average values of the different parameters and reported in the text. The calibration statistics are presented for the temperature (Section 3.4.2) and TDS (Section 3.4.3)

3.4.1 Water Balance

Calibration of the water balance began with an initial model simulation using all recorded and estimated inflows and outflows for 1990-2005. Daily water surface elevations from the model were then compared to observed water surface elevations. The elevation difference was converted to a volume and the positive or negative volume was added to the model through the distributed tributary. Wind seiching of the reservoir often causes inaccuracy in observed elevations. A ten day moving average of the computed volumes was used to smooth out these inaccuracies. Over the 16 year period the modeled water surface elevations were within 0.10 feet, on average, of the observed elevations (Figure 3-8).

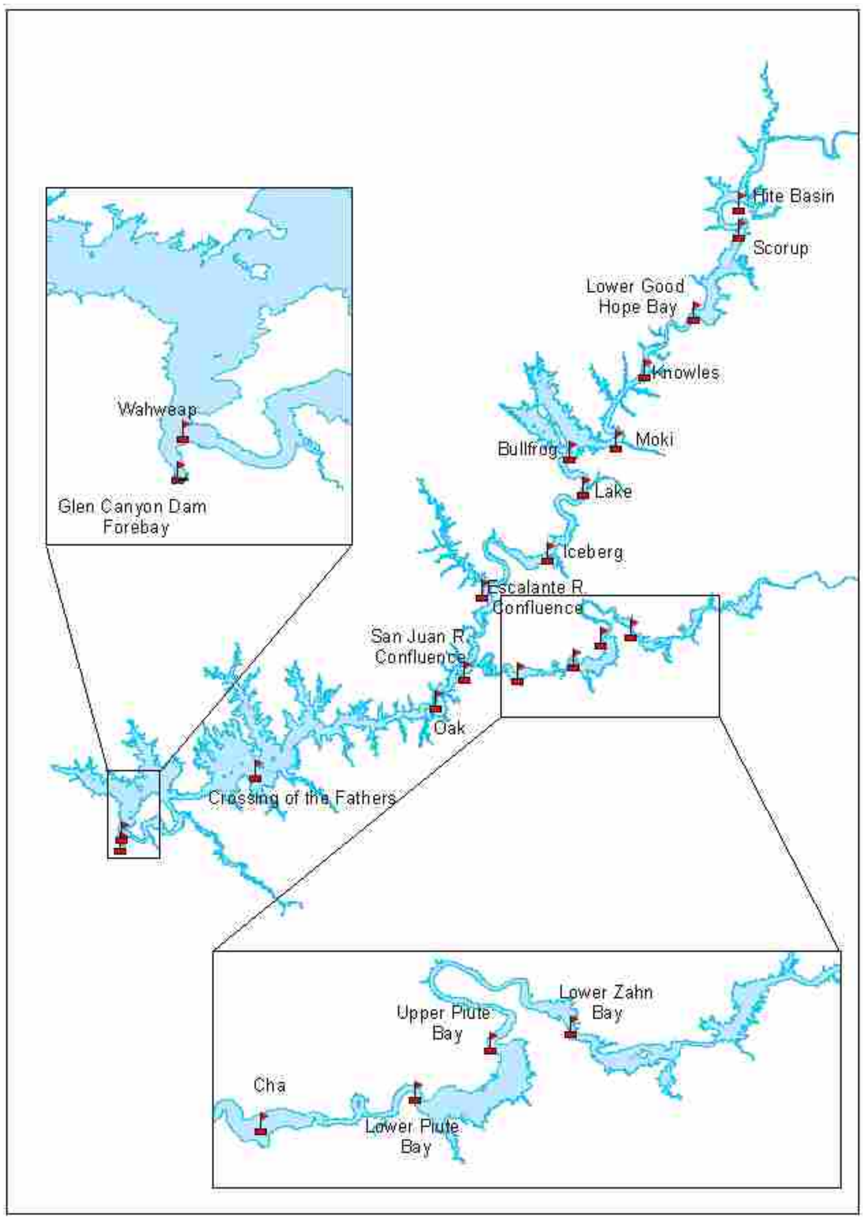

Figure 3-7: Lake Powell water quality monitoring stations

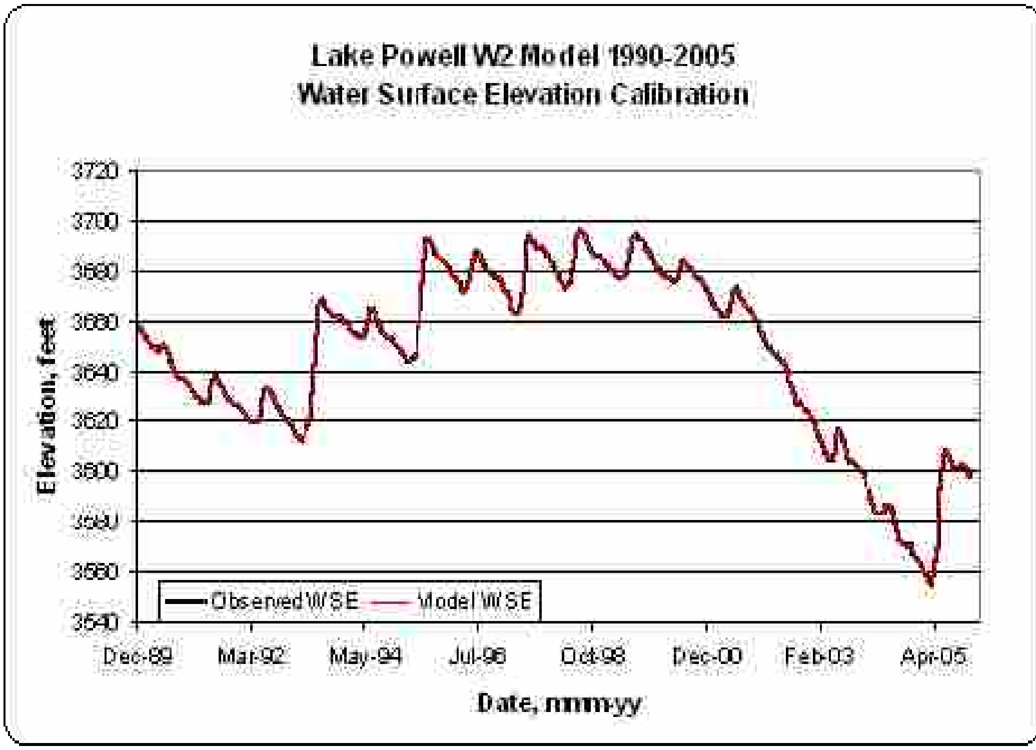

Figure 3-8: Reservoir water surface elevation calibration – observed (black) and modeled (red)

The USBR estimates monthly evaporation volumes from Lake Powell (Dawdy, 1990). Output from the model was compared to these volumes on an annual basis. An explanation of why monthly volumes were not compared is discussed in the temperature calibration (Section 3.4.2). The model was not specifically calibrated to these annual evaporation volume estimates; rather they were used to verify the model's estimates of evaporation were reasonable. Over the 16 year simulation the total model evaporation is within 3% of the total USBR evaporation estimate. In individual years the model evaporation is at most 16% greater or less than USBR estimated evaporation values. The model values are reasonable considering the USBR values are estimates. Table 3-1 shows the annual evaporation volumes from the USBR and the W2 model.

Table 3-1: Annual evaporation volumes in Acre-Feet, USBR and W2 Model

Year	USBR	W2 Model	W2 % of USBR
1990	464,809	453,827	97.6%
1991	420,198	416,110	99.0%
1992	403,360	412,306	102.2%
1993	483,699	474,872	98.2%
1994	504,284	500,196	99.2%
1995	560,150	508,232	90.7%
1996	582,091	576,871	99.1%
1997	592,707	504,939	85.2%
1998	605,297	528,914	87.4%
1999	605,738	529,715	87.4%
2000	576,898	561,412	97.3%
2001	532,968	518,809	97.3%
2002	436,496	451,854	103.5%
2003	352,779	395,129	112.0%
2004	278,349	322,362	115.8%
2005	308,850	338,076	109.5%
Total	7,708,672	7,493,625	97.2%

3.4.2 Temperature

Calibration results of the previous Lake Powell model included a temperature AME of 1.02°C as an average of all vertical profiles stations (Table 3-2). For reference, observed water temperatures near the dam range from approximately 8°C to 28°C. The previous model did not, however, maintain observed temperatures over extended periods of time (Miller, 2007). In the older models the reservoir epilimnetic temperature profiles were consistently too warm in the fall, too cold in the spring, or some combination of both, depending on model heat exchange parameter settings. The model was reproducing annual evaporation volumes within 16% or less but the monthly heat budget was not balanced.

Table 3-2: Previous Lake Powell model temperature calibration

Station	Years	AME	#
Hite	91-05	1.64	52
Scorup	91-05	1.36	54
Good Hope	92-05	1.19	52
Knowles	94-05	1.05	40
Moki	94-04	0.89	38
Bullfrog	91-05	1.02	53
Lake	94-05	0.92	42
Iceberg	94-05	0.82	42
Escalante Confluence	91-05	0.88	54
San Juan Confluence	95-05	0.86	38
Oak Canyon	91-05	0.85	58
Crossing of the Fathers	91-05	0.77	60
Forebay	90-93	0.87	18
Lower Zahn	91-03	1.62	38
Upper Piute	91-05	1.25	49
Lower Piute	91-05	1.10	44
Cha Canyon	91-05	0.89	51
Wahweap	91-05	0.85	180
Average		**1.02**	

An attempt to correct the heat exchange at the reservoir surface involved replacing Page cloud cover observations with observations from Hanksville, Utah (Figure 1-1). Cloud cover observations, as recorded at Hanksville and Page, are estimated by a person who examines the sky and selects one of four possible values, from lowest to highest cloud cover intensity: clear, scattered, broken, and overcast. To convert the categorical value to a numerical value each cloud cover observation was given a numerical value from 0 to 10. From 1990-2005 the average numeric value of Page cloud cover was 2.65 and Hanksville was 4.45. Both datasets were tested in separate simulations in the Lake Powell model holding all other variables constant. Temperature results were compared and the overall temperature AME was 0.08°C better using the Hanksville dataset. Cloud cover observations from Hanksville then replaced the Page cloud cover values in model simulations.

Substituting the cloud cover data did result in a better overall temperature calibration but it did not correct the heat exchange problems at the water surface. CE-QUAL-W2 computes the heat budget through a term-by-term accounting of heat exchange. An investigation into the heat exchange terms was done to determine which terms were influenced most by user-defined model parameters. Two of the terms include an equation with user-defined coefficients, the evaporative heat loss and surface heat conduction terms. The model gives the user freedom to modify the heat exchange of these terms through an evaporative wind-speed formulation (Equation 3-1):

$$f(W) = a + bW^{c} \qquad \textbf{(3-1)}$$

where:

$f(W)$ = wind speed function, $W\ m^{-2}\ mmHg^{-1}$
a = empirical coefficient, 9.2 default
b = empirical coefficient, 0.46 default
c = empirical coefficient, 2.0 default
W = wind speed measured at 2 m above the ground, $m\ s^{-1}$

Some different combinations of empirical coefficients used in other models are given in the user's manual (Cole and Wells, 2003). These combinations represent empirical determinations for systems of different size, in different locations, and for different periods of time. Several of these, as well as custom combinations, were tested in the Lake Powell model. Some corrected either the spring or the fall epilimnion temperatures but none of the combinations solved the temperatures for both time periods. During the spring too much evaporation caused the epilimnion to lose heat and in the fall too little evaporation caused the epilimnion to excessively store heat. The evaporative wind speed equation did not provide enough flexibility to resolve this issue.

A modification to the CE-QUAL-W2 code, specific to the Lake Powell model, added the option of using time-varying empirical coefficients instead of a single coefficient in heat flux computations. This modification was done by Environmental Resources Management (ERM) under contract to the Bureau of Reclamation (Buchak and Prakash, 2007). Coefficients were set at monthly values based on patterns seen in the previous evaporation tests. Coefficient values varied from highs in August/September to lows in February/March. To simplify the process only the "a" coefficient was adjusted. The result of this change was an AME improvement of 0.06°C in the overall temperature calibration. This also changed the distribution of monthly evaporation volumes while annual evaporation volumes remained relatively similar. Summer and fall evaporation volumes increased while winter and spring evaporation volumes decreased (Figure 3-9).

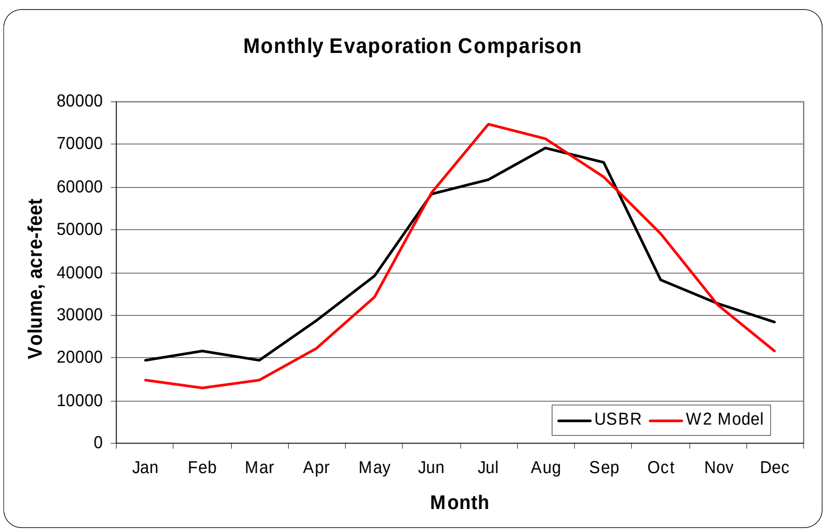

Figure 3-9: Monthly evaporation comparison, USBR (black) and Lake Powell model (red)

Calibrations statistics for temperature are shown for each monitoring site in Table 3-3. For each monitoring site the range of years monitored and number of measured profiles are also shown in the table. The calibration of the Lake Powell model resulted in an AME of vertical temperature profiles of 0.88°C. The AME at individual monitoring sites ranged from a maximum of 1.45 to a minimum of 0.66. Figure 3-10 shows modeled and observed release temperatures as measured in the tailwater. The modeled and observed results for reservoir discharges are displayed as daily mean averages. The AME of observed versus modeled reservoir discharge temperatures is 0.46°C.

Table 3-3: Temperature calibration statistics

Station	Years	AME	#
Hite	91-05	1.45	52
Scorup	91-05	1.23	54
Good Hope	92-05	1.09	52
Knowles	94-05	0.96	40
Moki	94-04	0.83	38
Bullfrog	91-05	0.95	53
Lake	94-05	0.88	42
Iceberg	94-05	0.81	42
Escalante Confluence	91-05	0.77	54
San Juan Confluence	95-05	0.69	38
Oak Canyon	91-05	0.66	58
Crossing of the Fathers	91-05	0.68	60
Forebay	90-93	0.81	18
Lower Zahn	91-03	1.20	38
Upper Piute	91-05	0.83	49
Lower Piute	91-05	0.78	44
Cha Canyon	91-05	0.73	51
Wahweap	91-05	0.76	180
Average		**0.88**	

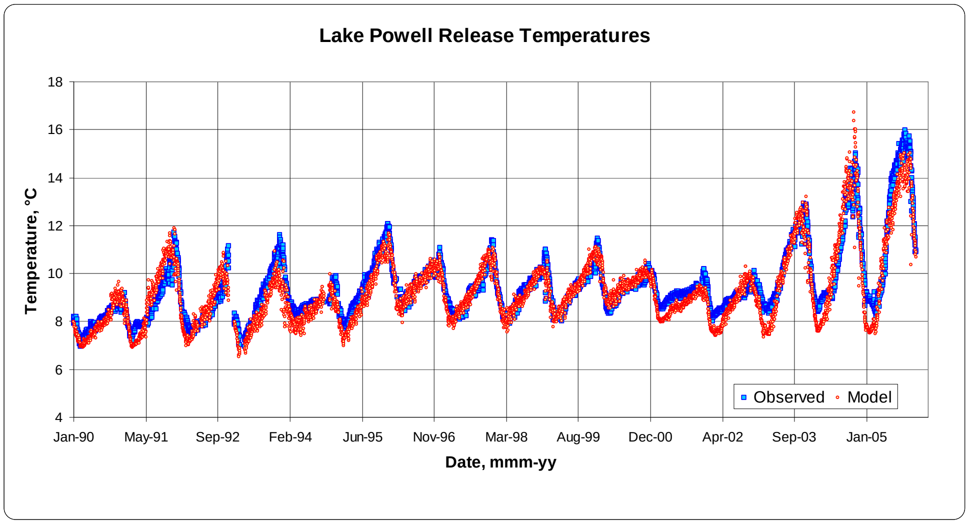

Figure 3-10: Reservoir discharge temperature calibration

3.4.3 Total Dissolved Solids

TDS concentrations in Lake Powell's inflows range from about 200 to 1000 mg/L or higher. Concentrations near the dam range from about 300 to 700 mg/L. Calibration results of the previous Lake Powell model included a TDS AME of 33.3 mg/L for the vertical profile data from monitoring sites (Table 3-4). The most noticeable and consistent errors were seen in the Wahweap vertical TDS profiles. Bottom concentrations were too low by 50-100 mg/L in several consecutive monitoring profiles. The next upstream monitoring site, Crossing of the Fathers, did not show the same difference between observed data and model results except in a few, nonconsecutive profiles which indicated model TDS content was correct upstream. It was then presumed that the hydrodynamics in the model, particularly near the dam, were not accurately representing actual conditions. Several parameters were adjusted to try and improve the model's hydrodynamic accuracy.

Table 3-4: Previous Lake Powell model TDS calibration

Station	Years	AME	#
Hite	91-05	63.92	52
Scorup	91-05	51.78	54
Good Hope	92-05	37.57	42
Knowles	94-05	37.09	40
Moki	94-04	32.98	38
Bullfrog	91-05	28.11	53
Lake	94-05	31.14	42
Iceberg	94-05	29.26	42
Escalante Confluence	91-05	25.36	54
San Juan Confluence	95-05	25.33	38
Oak Canyon	91-05	25.18	58
Crossing of the Fathers	91-05	20.63	60
Forebay	90-93	31.27	18
Lower Zahn	91-03	46.77	38
Upper Piute	91-05	34.37	49
Lower Piute	91-05	30.17	44
Cha Canyon	91-05	30.54	51
Wahweap	91-05	29.36	180
Average		**33.3**	

One possible contributing factor was determined to be a physical restriction limiting the bottom of the intake's withdrawal zone. Engineering drawings show a concrete base which supports the trashracks covering each penstock. The bases protrude into the reservoir and are located directly beneath the penstocks. These bases may restrict flow beneath the penstock. Restricting the bottom withdrawal had been tested previously in temperature calibrations but without any significant differences. The change did, however, affect the TDS calibration, improving the overall TDS AME by 2.7 mg/L. The improvements were most pronounced at the Wahweap monitoring site with an AME reduction of 7.3 mg/L. Vertical profile results from the model comparing TDS concentrations before and after the change illustrate the improvement (Figure 3-11). The change increased TDS concentrations near the reservoir bottom by about 50 mg/L.

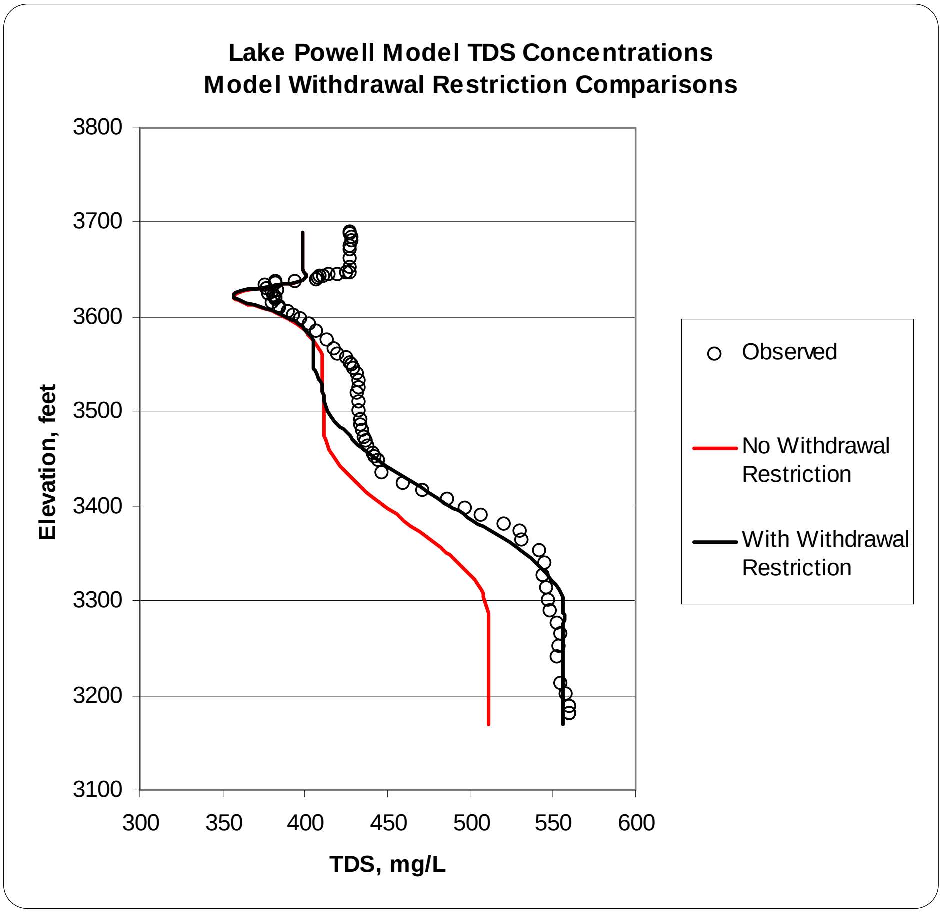

Figure 3-11: TDS profiles at Wahweap before (red) and after (black) withdrawal depth restriction

Calibration statistics and the number of profiles for TDS at each station are shown in Table 3-5. The AME of the vertical TDS profiles is 30.6 mg/L. Figure 3-12 compares modeled and observed TDS concentrations in reservoir releases. The AME of the release TDS is 16.1 mg/L.

Table 3-5: TDS calibration statistics

Station	Years	AME	#
Hite	91-05	61.73	52
Scorup	91-05	48.40	54
Good Hope	92-05	34.30	42
Knowles	94-05	34.14	40
Moki	94-04	29.97	38
Bullfrog	91-05	26.60	53
Lake	94-05	28.83	42
Iceberg	94-05	26.82	42
Escalante Confluence	91-05	23.46	54
San Juan Confluence	95-05	24.72	38
Oak Canyon	91-05	24.15	58
Crossing of the Fathers	91-05	19.50	60
Forebay	90-93	30.07	18
Lower Zahn	91-03	46.75	38
Upper Piute	91-05	33.99	49
Lower Piute	91-05	31.04	44
Cha Canyon	91-05	29.82	51
Wahweap	91-05	22.1	180
Average		**30.6**	

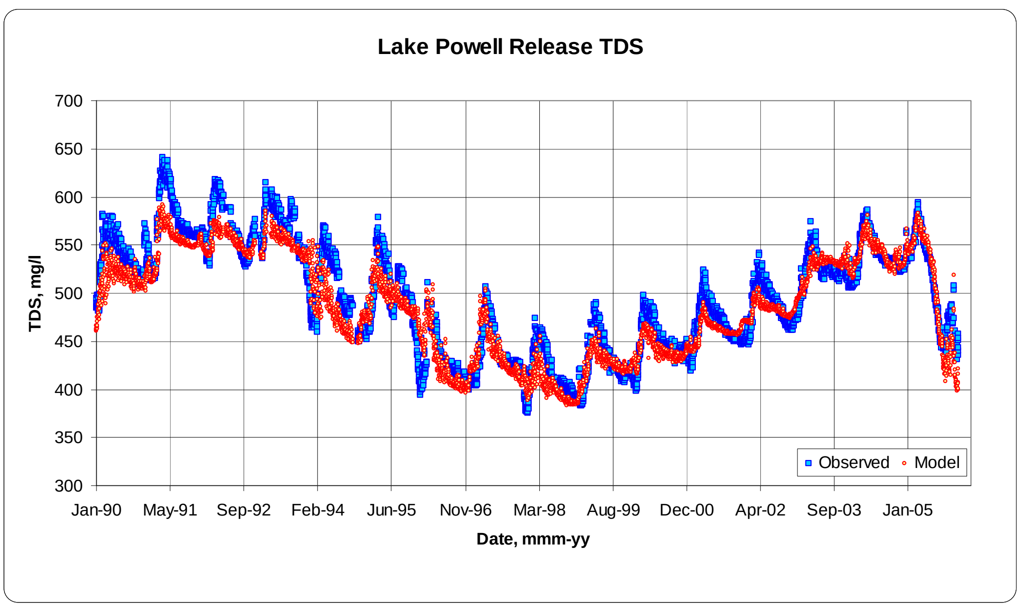

Figure 3-12: Reservoir discharge TDS calibration

3.5 Calibration Summary

The adjustments to the model calibration were done iteratively with DO simulations. The DO simulations revealed many issues with the temperature and TDS calibrations. These results are consistent with statements cited earlier from Hutchinson (1957) and the CE-QUAL-W2 manual (Cole and Wells, 2003) about the value of understanding and representing DO in a system and in hydrodynamic calibration of a model. Additional improvements likely could have been made but time and resource constraints limited calibration efforts to the current calibration. Future improvements and revisions will likely occur as the CE-QUAL-W2 model code is modified, as more data becomes available, and as the U. S. Bureau of Reclamation continues using the model for reservoir water quality planning and management.

4 Dissolved Oxygen in Lake Powell

This chapter summarizes some general characteristics of DO and important considerations in understanding patterns and processes as a way of introducing the characteristics and considerations as they apply to Lake Powell. It will also review some of the previous research of DO depletion patterns and sources. Linking these patterns and sources to the mechanisms in Lake Powell is an important step in developing a model of DO for the reservoir.

4.1 Solubility

The solubility of oxygen in water is determined by temperature, pressure, and salinity. Temperature and salinity both have inverse relationships to oxygen solubility: increases in temperature and salinity lead to decreases in the solubility of oxygen, although the relationship with salinity is exponential and is generally only considered in saline and brackish waters (Wetzel, 2001). DO solubility increases with pressure. This is true for both atmospheric and hydrostatic pressure. The solubility of oxygen in water for temperatures between 0-40°C at an atmospheric pressure of 660 mm Hg is shown in Table 4-1.

The maximum possible concentration of DO in Lake Powell near the dam is approximately 10.4 mg/L based on: Lake Powell's minimum surface water temperature near the dam of 7-8°C and an atmospheric pressure measuring 660 mm HG which corresponds to an elevation of 3700 feet – full-pool water surface. Salinity or TDS in this case, does not appreciably affect the DO concentrations because of relatively low levels. Although 10.4 mg/L DO is roughly the maximum possible level, observed concentrations are usually less because of the mechanisms affecting oxygen replenishment and consumption.

Table 4-1: Solubility of oxygen in water for various temperatures at 660 mm Hg

Temp, °C	DO, mg/L
0.0	12.7
4.0	11.3
8.0	10.2
12.0	9.3
16.0	8.5
20.0	7.8
24.0	7.3
28.0	6.7
32.0	6.3
36.0	5.9
40.0	5.5

4.2 Sources & Sinks

DO concentrations are affected by several processes including turbulence, photosynthesis, respiration of aquatic organisms, and decomposition of organic matter. Oxygen is replenished by wind turbulence and saturated inflows as well as photosynthesis by plankton and macrophytes and it is consumed by respiration of aquatic organisms and by decomposition of organic matter.

All of these mechanisms contribute to the reaeration or consumption of DO in Lake Powell. While it is important to understand these mechanisms in the reservoir, it would be difficult to monitor them in detail sufficient enough to be used in a DO model. This type of monitoring is limited by Lake Powell's size, remote location, and by the resources required to continuously monitor parameters such as DO, plankton, organic matter, and others. It is more productive to recognize patterns in the distributions of DO and relate them to replenishment and consumption processes in the reservoir. Before examining those distributions, the interactions which dominate the DO dynamics in Lake Powell will be discussed.

4.3 Limnology

The distributions of water and its constituents in aquatic systems are influenced by the interactions of physical, chemical, and biological components. As stated by Wetzel (2001) "…limnology correctly encompasses an integration of physical, chemical, and biological components of inland aquatic ecosystems…" The specific limnological components of interest for this particular study of Lake Powell are hydrology, water density, stratification, reservoir circulation, reservoir zonation, and reservoir productivity. The next few sections discuss the interactions between the components and then relate these interactions to DO.

4.3.1 Hydrology

Inflow to Lake Powell from the Colorado River Basin above the reservoir is primarily surface runoff carried by rivers and creeks. The Colorado and San Juan rivers account for 88% and 10% respectively of the total inflow (Department of the Interior,

1995) with 60% of the total inflow occurring between May and July (Irons et al., 1965; Evans and Paulson, 1983). Annual inflow volumes are widely variable from a high of 21.6 million acre-feet in 1984 to a low of 4.1 million acre-feet in 2002 since the reservoir began filling in 1963 (Figure 4-1).

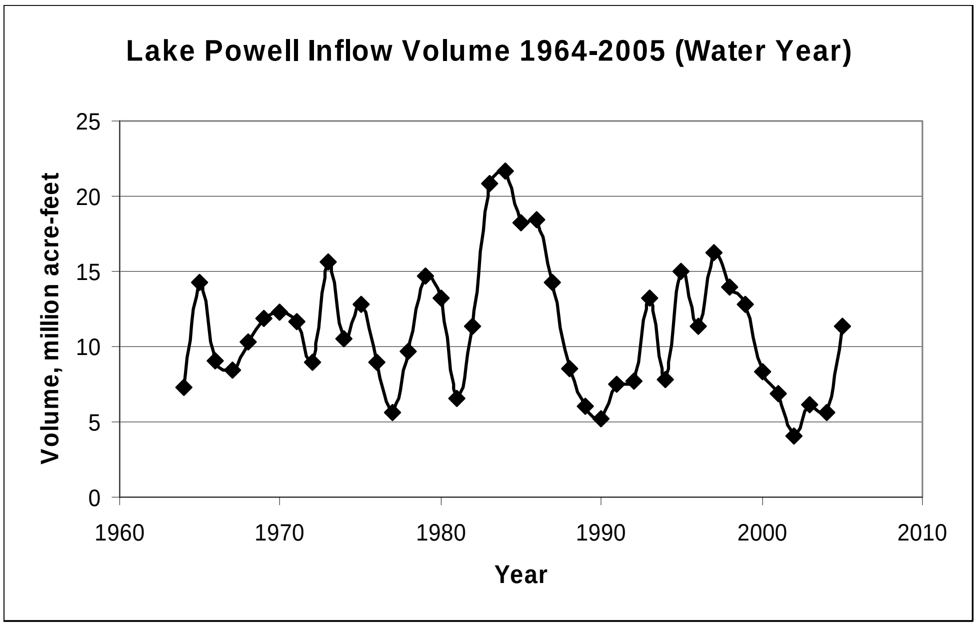

Figure 4-1: Annual Lake Powell inflow, 1964-2005

Outflow from Lake Powell is regulated by Glen Canyon Dam and release volumes are determined by downstream requirements, flood control, and equalization with Lake Mead (Appendix, Section 0). Water is primarily released from the power plant for which the intakes are located at an elevation of 3470 feet. Since 1965 the annual release volume has been at least 8.23 million acre-feet (Department of the Interior, 1995). Seasonal variability in the outflow has been reduced and release volumes are the result of scheduled releases and power demand.

As shown in Figure 4-1, the inflow hydrology commonly cycles between wet periods (1983-1987 and 1993-1999) and dry periods (1988-1992 and 2000-2004). These inflow volume cycles, coupled with regulated releases, create large fluctuations in reservoir elevations and water residence time.

Reservoir elevations typically rise during spring runoff and fall during the remainder of the year as illustrated in Figure 4-2. During a wet cycle, such as 1983-1987 or 1993-1999, the reservoir fills and then elevations fluctuate within the 20 or 30 feet of elevation 3700 feet, or full pool. During drought cycles, such as 1988-1992 or 2000-2004, reservoir elevations gradually drop except during spring runoff where a short increase may be seen. The total drop in reservoir elevation is determined by the severity of a drought. The largest drop observed in Lake Powell was 145 feet from a full reservoir in 1999 to just before spring runoff in 2005. The proximity of the water surface to the dam intakes is determined by reservoir elevations and plays a large role in reservoir currents and in the water quality of reservoir releases.

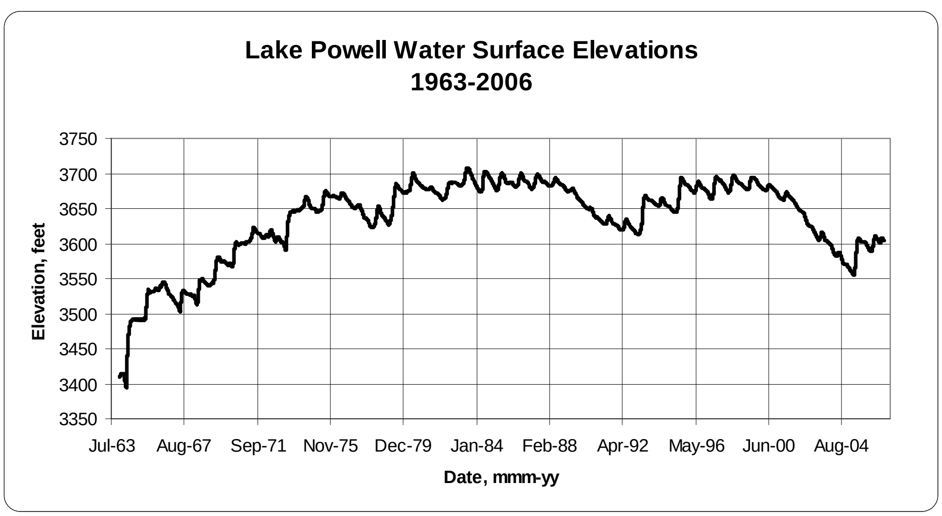

Figure 4-2: Lake Powell reservoir elevations, 1963-2006

Residence time, or hydraulic retention, is the average time it takes for water to move through a reservoir. Retention time in Lake Powell is about 2 years based on an active reservoir capacity of about 24 million acre-feet and an average inflow volume of about 11 million acre-feet (Vernieu et al., 2005). From year to year the retention time of the reservoir has ranged between about 1 and 5 years, though the retention time in localized areas can be much longer or shorter. Local variations are discussed in more detail in the stratification and zonation sections.

4.3.2 Water Density

The density of water regulates the dynamics of aquatic systems and is related to temperature, salinity, and pressure (Wetzel, 2001). As shown in Figure 4-3 density is greatest at 4°C. The density difference due to one degree is greater at higher temperatures than at lower temperatures. Also, density increases with increasing pressure and salinity (TDS). Density in Lake Powell is primarily controlled by water temperature, but TDS also play an important role in currents and mixing.

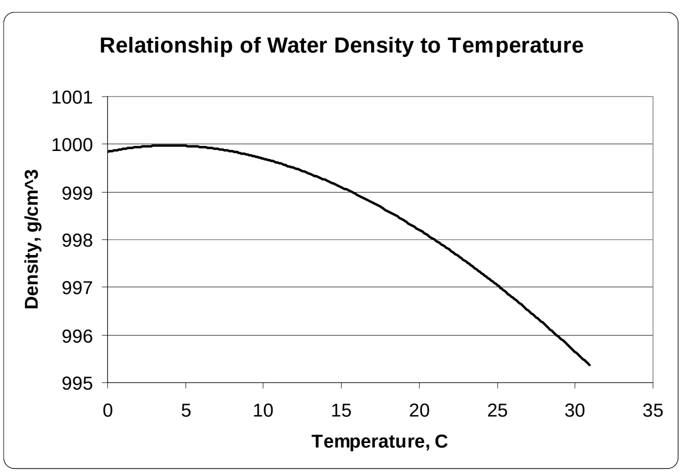

Figure 4-3: Relationship of water density to temperature

4.3.3 Stratification

Due to the temperature dependant density characteristics of water, warmer water overlies colder water creating vertical layers of different temperatures. When these layers become pronounced, as they do in the summer, it is known as thermal stratification and is divided into three layers. The warmer upper layer is termed the epilimnion and temperatures within it are mostly isothermal. The middle layer is termed the metalimnion and it marks the transition from the warmer epilimnion to the colder hypolimnion, or lowest layer. In the colder hypolimnion temperatures are isothermal and remain relatively constant during the course of a year. Figure 4-4 shows thermal stratification in Lake Powell. The approximate locations of the different thermal layers are marked.

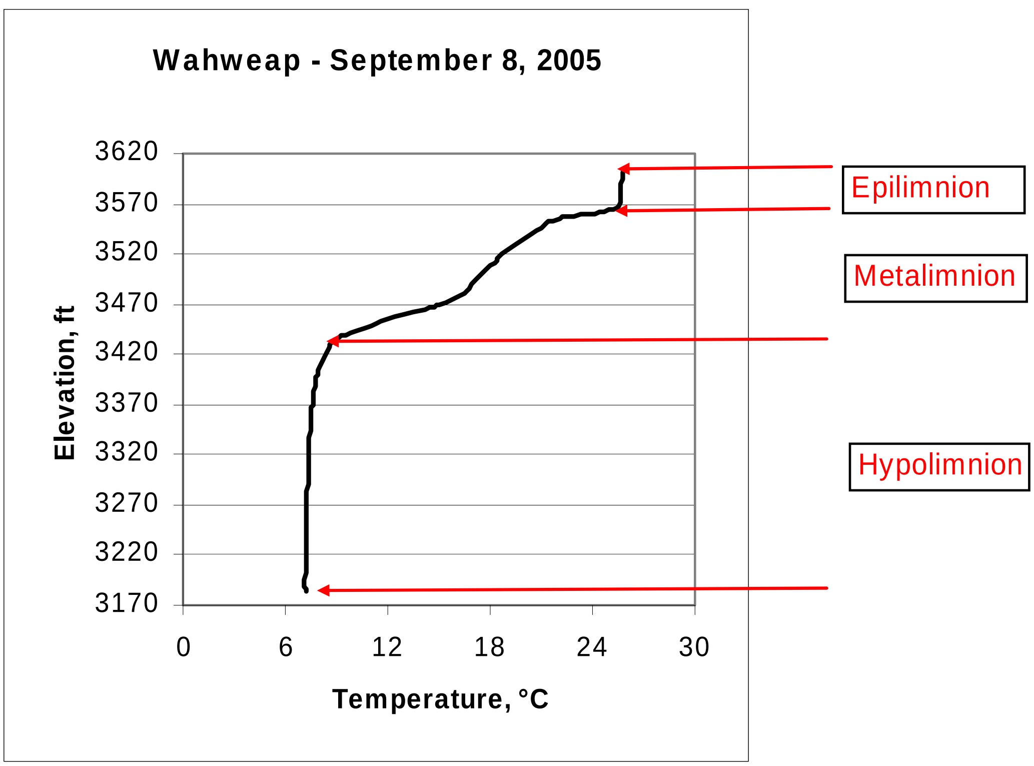

Figure 4-4: Thermal stratification at Wahweap, September 2005

In Lake Powell thermal stratification begins in the spring and is typically stable by July. Stratification persists until air temperatures drop in the autumn. During this time the reservoir surface cools and the cooler water mixes downward. The size of the epilimnion increases while the metalimnion decreases. This continues until temperatures in Lake Powell are vertically isothermal, or very close. At this time temperatures are close to those found in the hypolimnion during summer stratification. This cycle then repeats itself as air temperatures warm in the spring.

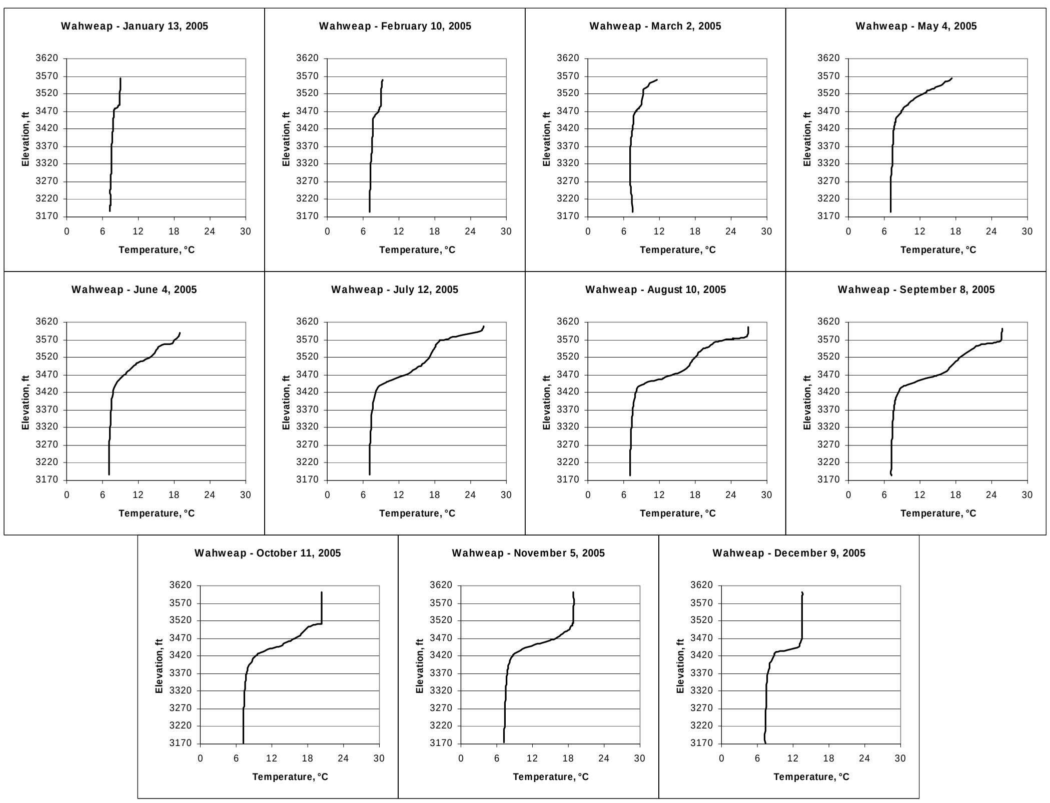

Figure 4-5: Development of thermal stratification at Wahweap, January-December, 2005

Besides stratifying thermally, Lake Powell also stratifies chemically. Chemical stratification involves less dense water overlying denser water and is caused by salinity gradients. It is most obvious in the hypolimnion near the dam where denser water accumulates because of locally higher residence times. Figure 4-6 illustrates vertical TDS concentrations at the Wahweap station from 1964-2006. Homogeneous concentrations from top to bottom only occur a few times such as 1987 and 1999.

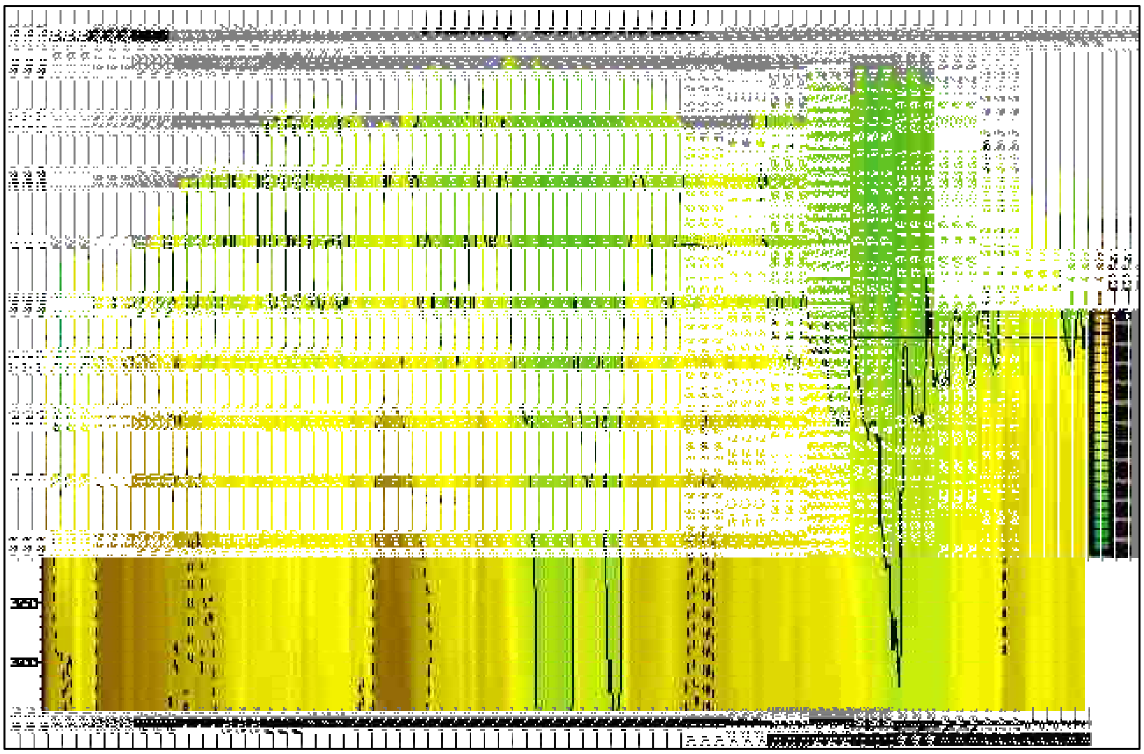

Figure 4-6: Time-depth graph of TDS at Wahweap

4.3.4 Density Currents

Density currents in Lake Powell occur due to density differences between the inflow and reservoir water and vary by season. The three types of density currents are overflow, underflow, and interflow currents (Wunderlich, 1971). The inflow hydrology and reservoir stratification determine the vertical location of these currents.

When the inflow water is warmer and TDS concentrations are lower than the reservoir water the inflow moves across the reservoir surface creating an overflow current. This typically occurs during spring. The volume of the inflow affects the thermal stratification structure. During wet years, the larger inflow volume creates a thicker metalimnion while the smaller inflow volume from dry years forms a thinner metalimnion. This is illustrated in Figure 4-7 which compares thermal stratification in August 1997, a 147% water year, and August 2000, a 75% water year. Another effect hydrology has on the overflow current is the distance it travels along the surface of the reservoir. A large inflow volume will extend farther towards the dam than a small inflow volume.

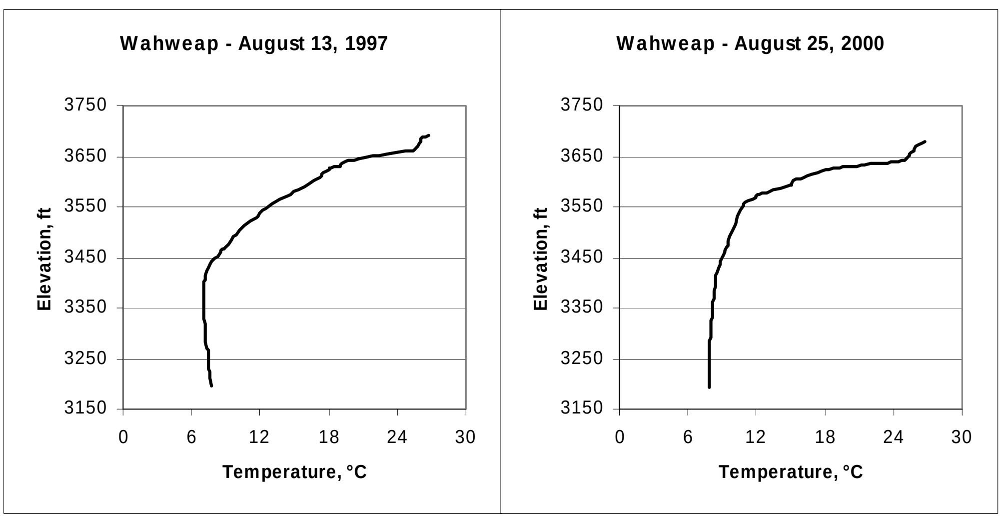

Figure 4-7: Reservoir stratification: larger inflow volume (left) and smaller inflow volume (right)

When the inflow is denser than the receiving water of the reservoir the water moves along the bottom of the reservoir creating an underflow current. This occurs during the winter when both temperatures are colder and TDS concentrations are higher.

The underflow often sweeps along the entire length of the reservoir displacing hypolimnetic water. In other years it sweeps the bottom in upper reaches but as it nears the dam it flows over the in-place hypolimnetic water. This mechanism is best illustrated by a sequence of DO profiles. Figure 4-8 shows DO at the Wahweap monitoring site from January to March of 1999. The first profile shows the DO concentrations before the underflow arrives. By February the underflow sweep has replaced the original water and moved it up. The last profile, March, shows the final location of the hypolimnetic water.

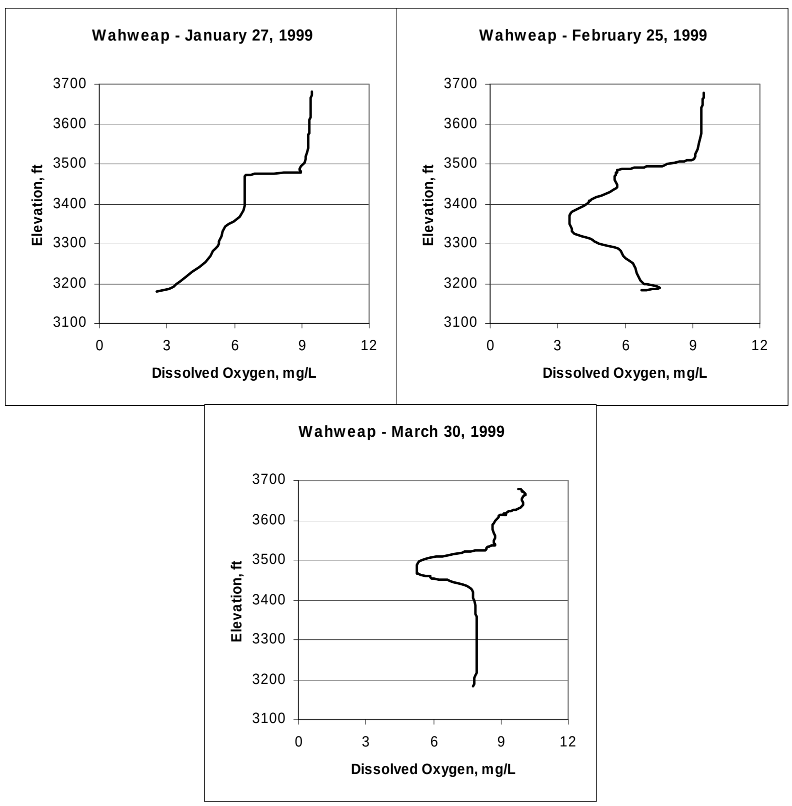

Figure 4-8: DO profiles at Wahweap, January – March, 1999

The last type of density current, an interflow current, occurs when the inflow water is denser than water in the epilimnion and less dense than water in the hypolimnion. In the summer, after spring runoff, the TDS concentrations of the inflow increase, creating enough of a density difference that the inflow moves underneath the epilimnion and through the metalimnion. As the season progresses and summer turns into fall the interflow location drops vertically due to cooler inflows. This same type of current also occurs for a brief time in the early spring when inflows warm but are still less dense than reservoir surface waters. Figure 4-9 is a graph of TDS concentrations that shows an interflow current forming at the upstream end of the reservoir and traveling towards the dam.

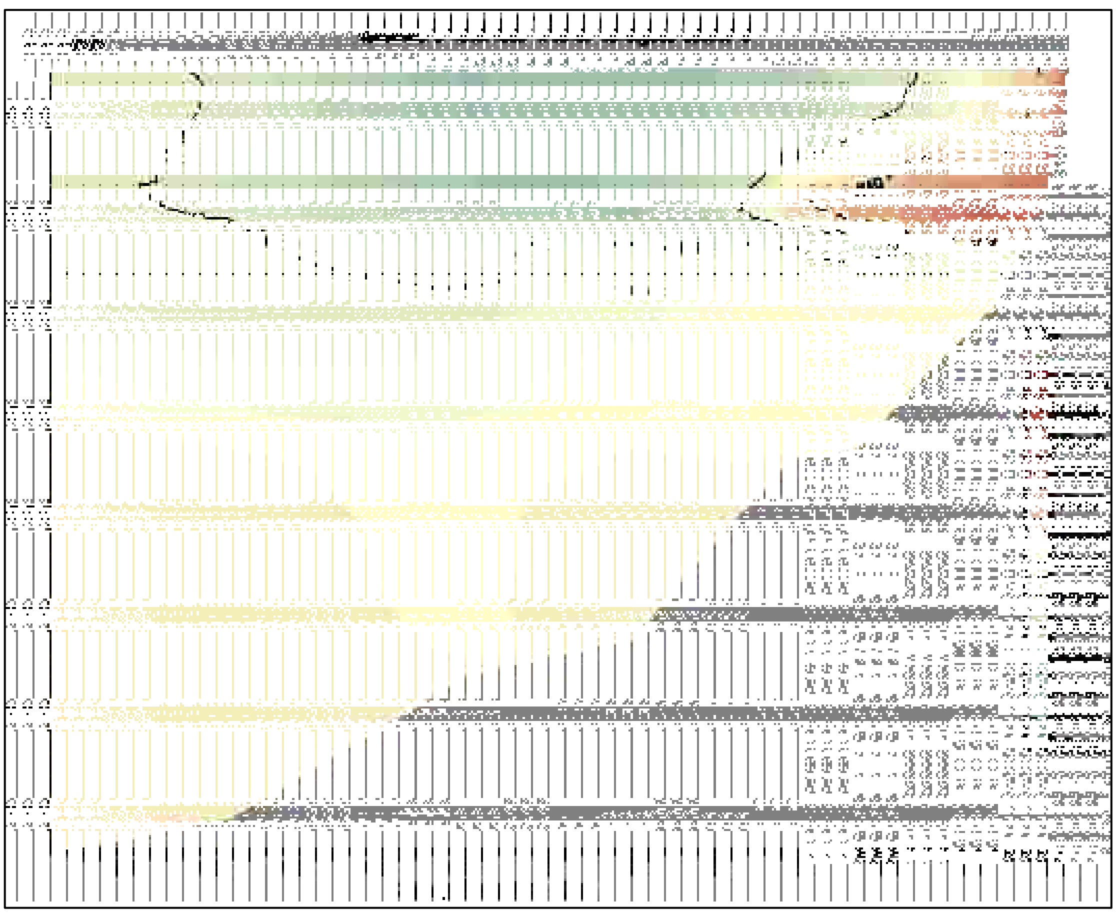

Figure 4-9: Reservoir TDS concentrations, September 2004

4.3.5 Longitudinal Zonation

The discussion of stratification and density currents is typical of the deeper portions of Lake Powell but it is not applicable to the reservoir as a whole. As the water travels longitudinally towards the dam it passes through different zones known as the riverine, transition, and lacustrine zones. Figure 4-10 is a schematic of typical longitudinal zonation in large reservoirs. The approximate location of the zones changes with reservoir storage. Each zone possesses unique physical, chemical, and biological characteristics (Thornton, 1990).

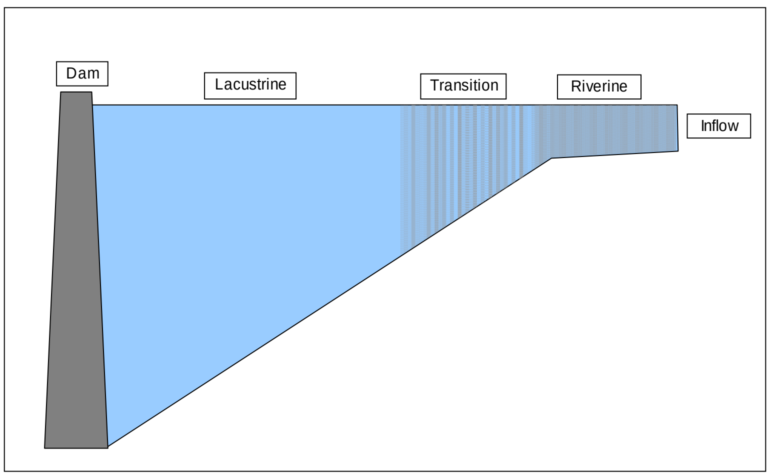

Figure 4-10: Longitudinal zonation (adapted from Thornton, 1990)

Riverine Zone

The riverine zone is more similar to a river than to a lake. In Lake Powell this zone is shallow and the water is well-mixed with low residence times. The exact location of the riverine zone changes as the reservoir is drawn down and the size of the riverine zone changes with inflow volume. Temperature or density gradients do not exist so stratification and density currents do not occur in this zone. Significant deposition of sediment occurs in this zone although smaller particles such as clay do not readily settle and result in turbid water. Large sediment deltas have accumulated in the Colorado and San Juan riverine zones of Lake Powell. During periods of reservoir draw down these sediment deltas are scoured and deposited further downstream.

Transition Zone

The transition zone is characterized by the transitions from a riverine environment to a more lacustrine, or lake environment. It is marked by the point at which density currents begin to form and thermal stratification sets up. When the density current is an underflow or interflow it creates a plunge line or a point where denser river water plunges beneath less dense reservoir water. This is seen in Figure 4-11 as turbid water from the Colorado River enters the transition zone and plunges beneath the less dense reservoir water. Thermal stratification is weak due to the shallow depth and as the summer progresses temperatures along the bottom continue to rise leaving the transition zone void of a hypolimnion as shown in Figure 4-12. Retention time here is longer than the riverine zone but shorter than the lacustrine zone.

Lacustrine Zone

The lacustrine zone is similar to a lake system and most of Lake Powell is classified as this type of zone. Thermal and chemical stratification are more evident in the vertical direction in this zone. Density currents continue from the transition zone and move over, under, or through the lacustrine zone. Retention time in this zone varies by vertical layer and is longest in the hypolimnion. The properties of water released downstream of the dam are determined by the characteristics of the lacustrine zone and the depth of withdrawal.

Figure 4-11: Colorado River plunge line near Hite Marina, March 2003

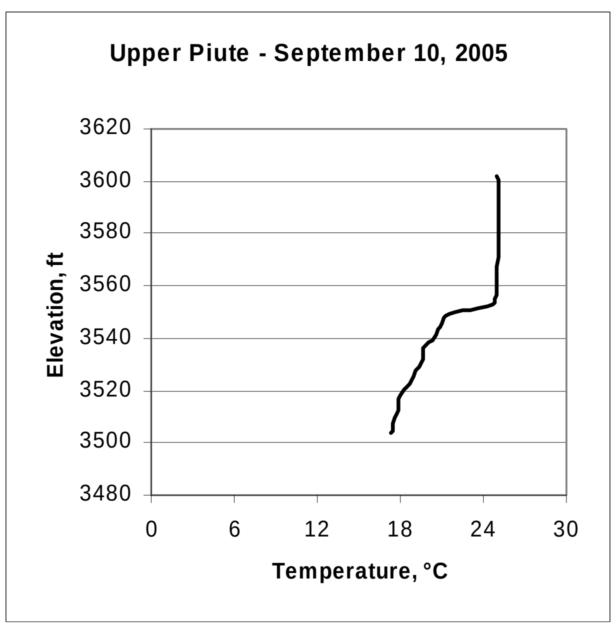

Figure 4-12: Temperature profile, Upper Piute Bay, Lake Powell, September 10, 2005

4.3.6 Circulation Patterns

Transport mechanisms in a reservoir can be separated into many categories including advection, convection, turbulence, diffusion, dispersion, shear, entrainment, mixing, and settling (Ford, 1990). In Lake Powell the forces governing circulation vary by location and season. Three primary mechanisms found in Lake Powell are advection, convection, and turbulence.

Advective circulation patterns in Lake Powell were documented in detail by Merritt and Johnson (1977). The thermal and chemical gradients, known respectively as the thermocline and chemocline, are controlled by advection of relatively warm or saline water. In some parts of the reservoir advection is the primary mechanism which causes water circulation. For example, circulation in the hypolimnion is caused by winter underflow currents which replenish water at the bottom of the reservoir (Johnson and Merritt, 1979).

Convection in Lake Powell occurs when higher density water is located above lower density water, creating instability and forcing mixing. One type of convection occurs during fall turnover when surface waters cool and mix with underlying water due to density differences. Convection in the riverine and transition zones effectively mixes the water column from top to bottom. In the lacustrine zone complete convection of the water column is prevented by the chemocline (Merritt & Johnson, 1979).

Turbulence, in the context of this discussion, refers to mixing created by wind. This occurs at the surface of Lake Powell and is the primary mechanism of aeration for much of the reservoir. The extent to which turbulent mixing is effective depends on several factors including the wind speed, wind direction, and the thermal and chemical composition of the reservoir. Areas of the lake which are isothermal, such as the riverine zone, the epilimnion during summer stratification, and most of the reservoir after fall turnover are subject to wind-induced mixing. At these locations and times there are no density gradients (thermal or chemical) which are resistant to turbulent mixing.

4.3.7 Productivity

The productivity of a system is measured by many factors including nutrients, plankton growth, and transparency. Trophic status classification systems are used to measure different levels of productivity in a system. A commonly used system is the Carlson Trophic Status Index (TSI) which calculates a separate index for total phosphorous, chlorophyll, and secchi disk depth, a measurement of transparency (Carlson, 1977). The three different indexes can be used to determine the trophic level of the system. Briefly, in decreasing order of productivity, four commonly used trophic levels are hypereutrophic, eutrophic, mesotrophic, and oligotrophic.

In terms of phytoplankton productivity, Lake Powell has been classified as an oligotrophic system (Paulson and Baker, 1983). The reservoir trophic state is determined from a single, average value; due to the length and geometric variations in Lake Powell some locations are more eutrophic than others (Utah DEQ, 2007). On the basis of total phosphorous loading alone Lake Powell would be classified as hypereutrophic, however, most of the phosphorous is absorbed to sediments which settle to the bottom of the reservoir and is not available to plankton growth (Gloss et al., 1981).

Plankton growth, density, and distribution are important to the DO dynamics within Lake Powell. They both produce and consume oxygen through photosynthesis, respiration, and decay. Limited monitoring of plankton is done in the reservoir through phytoplankton and zooplankton counts and chlorophyll concentrations.

4.4 Oxygen Distribution

Oxygen distribution in a reservoir is controlled by diffusion, mixing, and saturation (Wetzel, 2001). Vertical profiles of DO from monitoring data in Lake Powell show seasonal and spatial distribution variations. The following sections discuss these patterns in the context of the limnological characteristics from the preceding sections. Patterns and processes seen in the profiles are important in understanding oxygen depletion and then developing a model of DO in the reservoir.

The DO profiles and data selected are from Wahweap, Bullfrog, Scorup, Colorado River inflow, Cha Canyon, Upper Piute Bay, and San Juan River inflow (Figure 3-7). Both the Colorado and San Juan channels are shown because of the different distribution of DO in each. To simplify the presentation of oxygen distribution through the reservoir, only data from 2005 is used. 2005 was chosen because it was a nearly average water year (105%) and the depletion patterns are pronounced compared to other years. Four months are shown for each profile. The months shown are March, June, September, and December. The profiles were also selected to represent each of the reservoir longitudinal zones. The riverine zone data are from the inflow, the transition zone profiles are from Scorup in the Colorado and Upper Piute Bay in the San Juan, and the lacustrine profiles are Bullfrog in the Colorado, Cha Canyon in the San Juan, and Wahweap just upstream of the dam. In addition to DO, temperature data are presented to show oxygen solubility and TDS is shown to identify density currents.

4.4.1 Riverine Zone

DO in the inflows to Lake Powell is typically at saturated levels from turbulent mixing in the rivers. Average DO values from USGS samples in the Colorado River near Cisco, Utah; the Green River at Green River, Utah; and the San Juan River near Bluff, Utah (Figure 3-1) for 1970-2000 are shown in Table 4-2.

Table 4-2: DO average saturation %, Lake Powell inflows, 1970-2000

Gauging Station	Average % Saturation
Colorado R. near Cisco, Utah	99%
Green R. at Green River, Utah	98%
San Juan R. near Bluff, Utah	99%

Riverine zones of reservoirs are shallow and generally considered well-mixed, or quickly aerated. In observations collected near the Lake Powell inflow from 1991-2005 (Figure 4-13) DO concentrations are near saturation except for a decline from about 2001-2005. The decline in saturation levels is noticeable in both riverine zones and coincides with reservoir drawdown. The cause may be associated with biological and chemical oxygen demand introduced from scouring of sediment delta materials.

4.4.2 Transition Zone

As mentioned in the longitudinal zonation section, the transition zone of the reservoir moves up or downstream with changing reservoir elevations and inflows. The two profiles presented here as part of the transition zone, Scorup and Upper Piute Bay, may be located in different zones as the reservoir is filled or drawn down or as other changes occur. During the year 2005 both monitoring sites were located approximately in the transition zone.

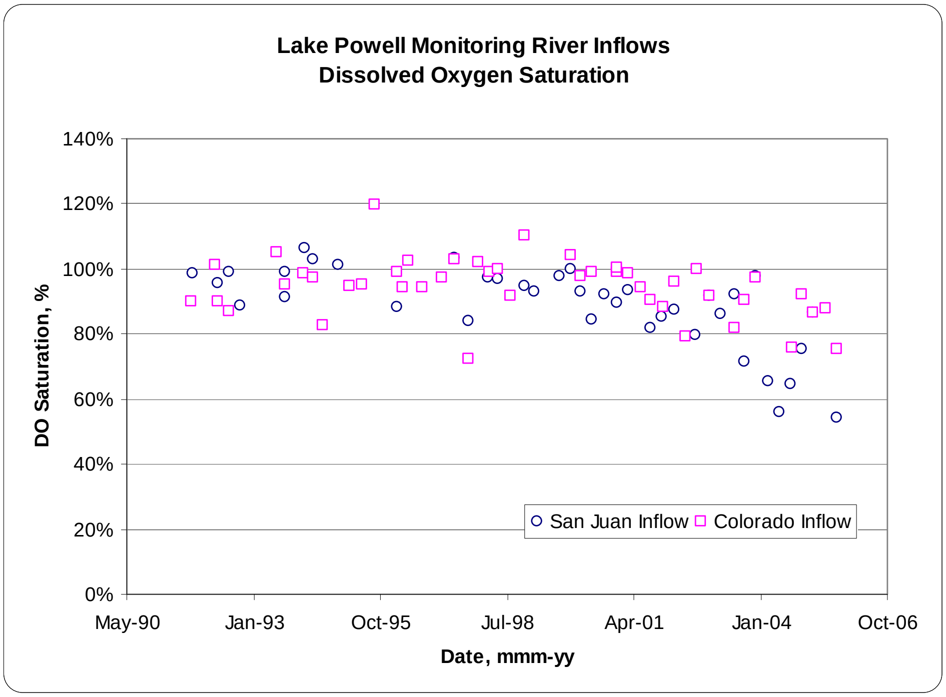

Figure 4-13: Lake Powell riverine zone DO saturation %, 1991-2005

At Scorup, in the Colorado channel of the transition zone, DO concentrations reflect solubility levels except during the September profile (Figure 4-14). Thermal stratification is weak and does not develop into three distinct vertical layers. Below the epilimnion, or active mixing zone, temperatures and DO concentrations decline to the bottom. By the winter DO, temperatures, and TDS are isothermal to near the bottom where an underflow density current is apparent from higher DO and TDS and lower temperatures.

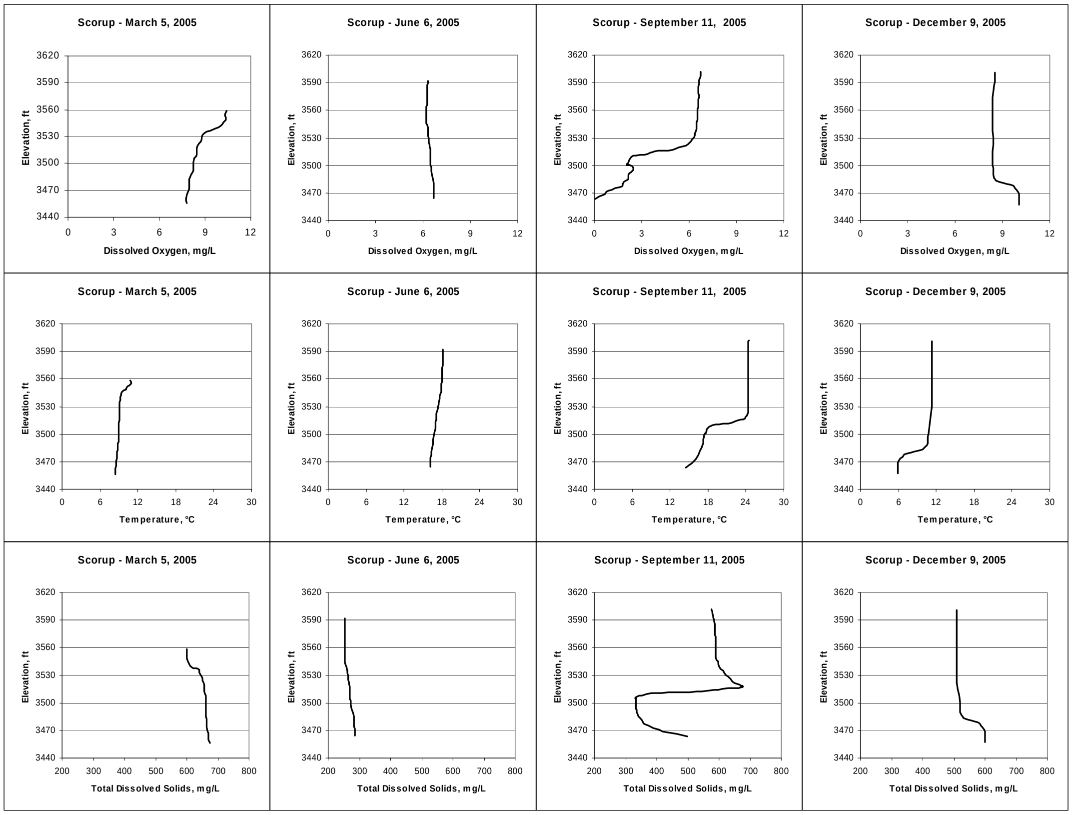

Figure 4-14: Scorup DO, temperature & TDS profiles, 2005

Upper Piute Bay, in the transition zone of the San Juan channel, behaves differently than the transition zone in the Colorado channel (Figure 4-15). A small metalimnetic minimum develops in June and by September the bottom 50 feet of water have turned anoxic. The minimum, which was not evident in the Colorado channel, may be able to develop here because of the lower flows and longer retention time in the San Juan channel. Another difference here from the main channel is a much larger oxygen deficit in the fall than what was measured in the main channel. By winter an underflow density current similar to that at Scorup is seen here.

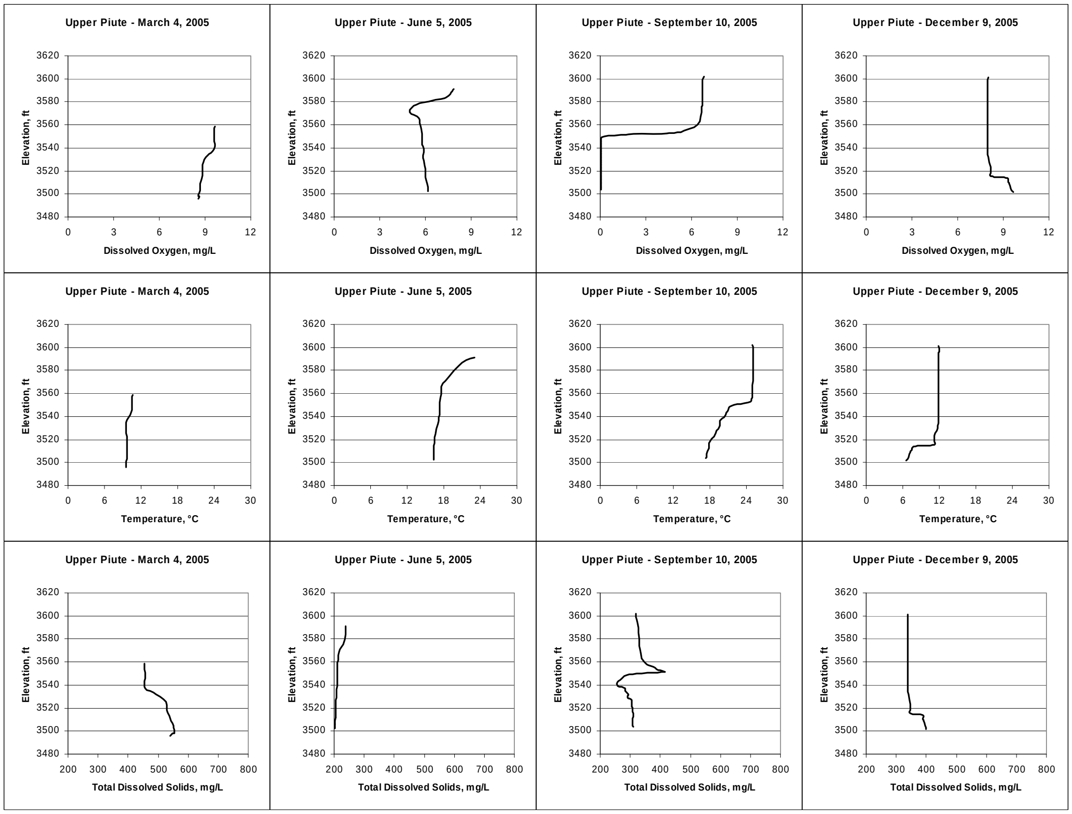

Figure 4-15: Upper Piute Bay DO, temperature & TDS profiles, 2005

4.4.3 Lacustrine Zone

DO content in the lacustrine zone in Lake Powell is not uniform from the upstream end to the downstream end. For this reason, profiles representing the downstream (Wahweap) and upstream (Bullfrog and Cha) lacustrine zone are presented. The upstream lacustrine zone discussion includes profiles from two locations, one in the Colorado channel and the other in the San Juan channel.

Upstream

At the Bullfrog monitoring site, as thermal stratification forms and aeration to layers below the epilimnion is reduced, a metalimnetic minimum is seen (Figure 4-16).

Comparing the September DO profile with the September TDS profile shows the TDS concentrations in this minimum are low. This indicates this water was from spring runoff. By winter, turnover has cooled and aerated the water column down to the chemocline. The winter underflow current has not yet reached this point.

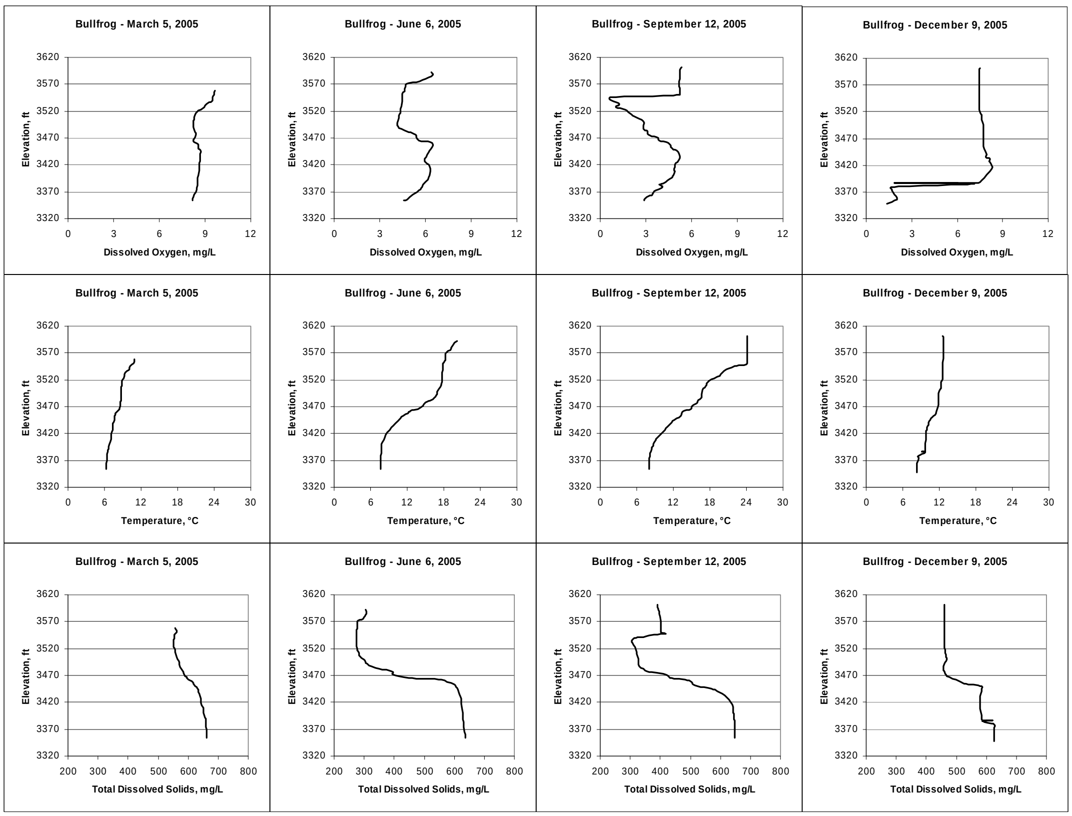

Figure 4-16: Bullfrog DO, temperature & TDS profiles, 2005

At Cha in the San Juan the metalimnetic minimum develops quicker and is more pronounced than that seen at Bullfrog (Figure 4-17). Other seasonal distribution and circulation patterns are similar to those at Bullfrog.

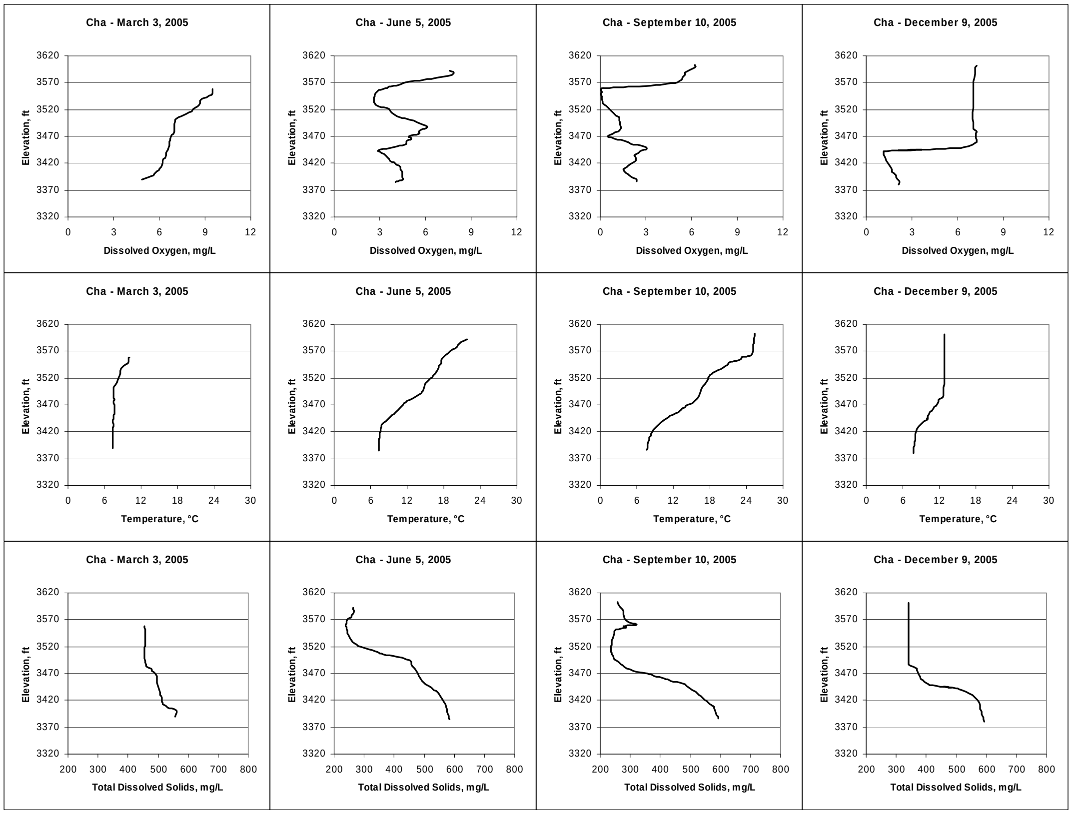

Figure 4-17: Cha DO, temperature & TDS profiles, 2005

Downstream

The distribution of DO at Wahweap (Figure 4-18) acts differently than the lacustrine zone upstream of this location. Circulation is restricted by the dam except at the withdrawal intake. This causes a buildup of oxygen depleted water in the hypolimnion as seen in the first DO profile. These profiles also illustrate an underflow density current moving along the bottom, identified by the higher DO, temperatures, and TDS at the very bottom. The underflow replenishes the bottom water and creates an upwelling of the oxygen-poor water. By June most of this oxygen-poor water has either been diluted by mixing or exported through the dam. By September the metalimnetic minimum seen at Bullfrog (Figure 4-16) and Cha (Figure 4-17) is also seen at Wahweap. By December it has been aerated by convective mixing during turnover.

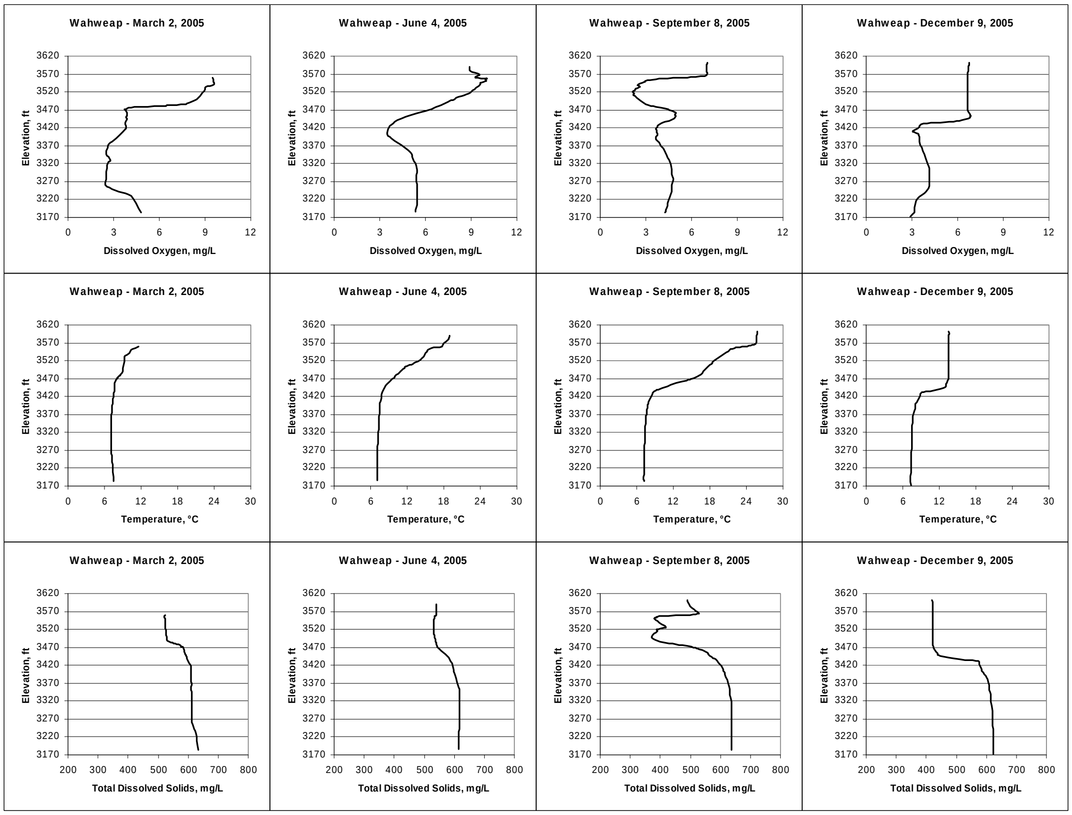

Figure 4-18: Wahweap DO, temperature & TDS profiles, 2005

The two dominant patterns seen in the lacustrine zone oxygen distribution are metalimnetic and hypolimnetic depletion of oxygen. These patterns reappear seasonally although the magnitude of the depletion is not consistent from year to year. This is best seen in time-depth profiles such as those shown at Bullfrog (Figure 4-19) and Cha (Figure 4-20) monitoring sites. The time-depth profiles show DO concentrations from 1991-2005. Field data is collected approximately every four months and interpolated between measurements. The metalimnion minimum appears to increase in size as the reservoir is drawn down and then refilled (2000-2005). The hypolimnetic concentrations also reflect a similar pattern at both sites. These patterns suggest a relationship between oxygen depletion and reservoir elevation. The larger magnitude of depletion in 2005, the first year of substantial inflow volume following a five-year drought, suggests hydrology is a factor.

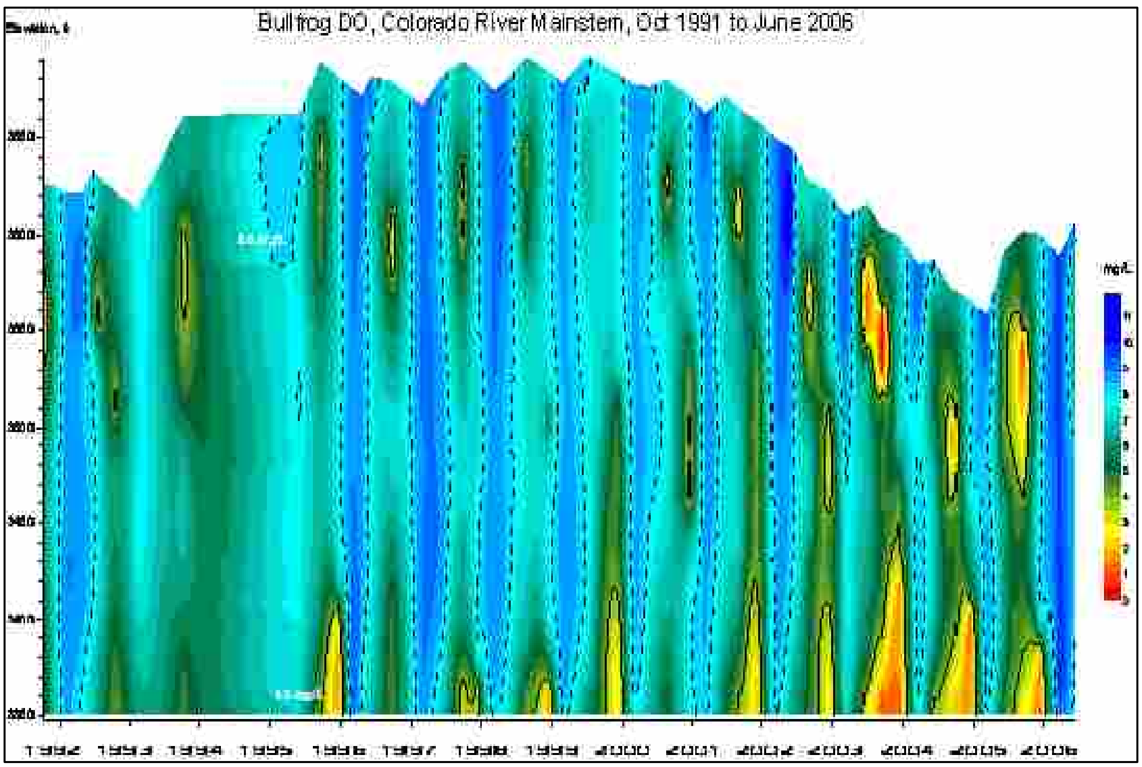

Figure 4-19: Bullfrog time-depth DO profiles, 1991-2006

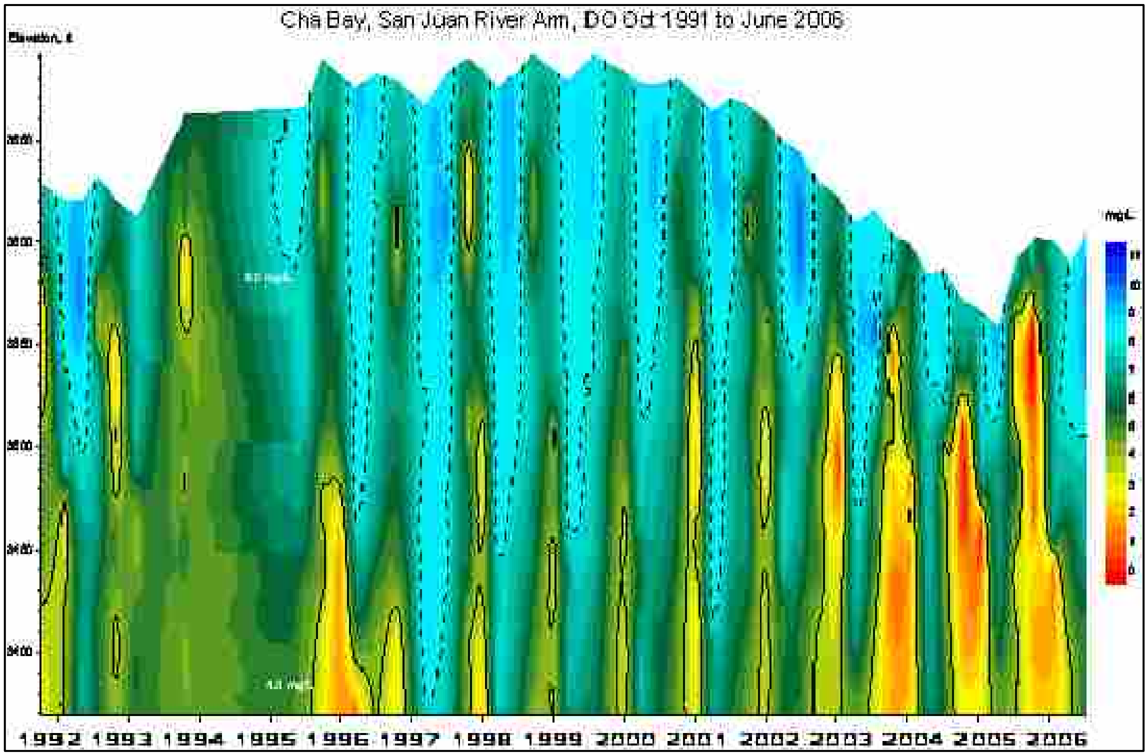

Figure 4-20: Cha time-depth DO profiles, 1991-2005

4.4.4 Metalimnetic Minimum

Metalimnetic oxygen depletion is characteristic of many reservoirs and is an important process in deep reservoirs (U.S. Army Corps of Engineers, 1987). In Lake Powell the minimum typically develops in the transitional zone following spring runoff. Advective currents transport the oxygen depleted water downstream towards the dam. In some years it reaches the dam and in others aeration during fall turnover prevents it from reaching the dam. The 2005 event that led to this research and study is an example of a metalimnetic DO minimum

The development of a minimum DO concentration in the metalimnion is common in Lake Powell. It typically forms below the major inflows following spring runoff, moves longitudinally through the reservoir, and dissipates as the reservoir mixes vertically in the fall and winter. Time-depth profiles at Bullfrog (Figure 4-16) illustrate this pattern. A zone of lower DO water is seen approximately 50 feet below the water surface each year. The size of the depletion varies from year to year depending on several factors. In most years reservoir discharges are not affected because of higher water surface elevations because the location of the metalimnion is far enough above the penstocks (3470 feet) that little to no oxygen depleted water passed through the dam. In 2005 discharges were affected because reservoir elevations were lower than at any other time since initial filling, as shown in Figure 4-21, and low DO water in the metalimnion was located just above the penstock elevation (Figure 1-2).

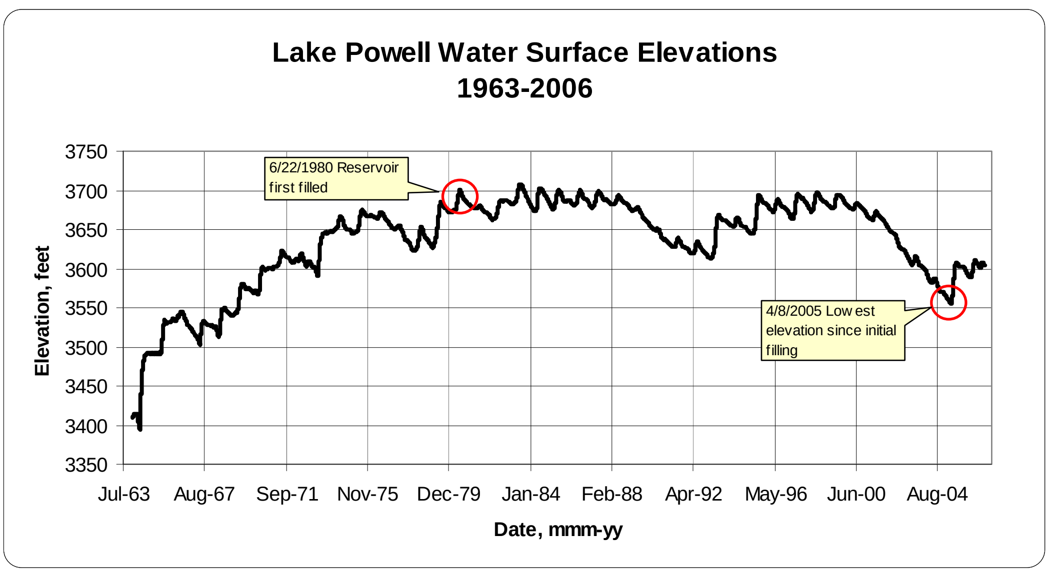

Figure 4-21: Lake Powell water surface elevations, 1963-2006

Johnson and Merritt (1979) presumed that biologic respiration of organic matter was the source of oxygen depletion in Lake Powell's metalimnion. This is likely a source but due to the low productivity of Lake Powell it may not be the sole cause of oxygen depletion.

Another possible source may be created by re-suspension of sediments from the sediment delta which could release nutrients, decomposing organic matter, or reduced iron and manganese. However, these processes have not been well documented in Lake Powell. Some research of the inflow and sediment delta geochemistry is being done by Rich Wildman, PhD candidate at California Institute of Technology, at the time of this writing and is scheduled to be completed sometime in 2007 (Wildman, 2007).

Any of these possible sources may contribute to all or part of the oxygen depletion. The literature reviewed for this study found little research has been done on the source of this type of oxygen depletion in Lake Powell. In order to find additional information on metalimnetic oxygen depletion studies of reservoirs and lakes with similar DO issues were reviewed.

Metalimnetic Oxygen Depletion in Deep Reservoirs & Lakes

Minimum DO concentrations in the metalimnion are more common in the lacustrine zone of deep reservoirs (Cole and Hannan, 1990). Studies of metalimnetic oxygen depletion in different systems include details of the development on the minimum and explanations of possible causes. Lake Washington, Washington; Pisgah Quarry of Kentucky Lake, Kentucky; Lake Mead, Nevada-Arizona; and Flaming Gorge Reservoir, Utah-Wyoming are deep reservoirs or lakes where the occurrences of metalimnetic minimums have been documented and some work has been done to understand the causes.

Shapiro (1960) worked to establish explanations of the occurrences of metalimnetic minimum DO concentrations by relating earlier hypotheses with field observations and analysis. He related these minimums to three possible causes: 1) oxygen uptake by sediment on a mid-water shelf transported horizontally, 2) low oxygen density currents moving through the water body, and 3) in situ consumption of oxygen from biological decomposition or respiration. His study involved Lake Washington, a deep (66 m), natural lake near Seattle. As the metropolitan areas nearby grew Lake Washington became increasingly eutrophic. A metalimnion minimum of DO develops in early June and persists until late October. The study examined whether the minima were caused by interposition of low and high oxygen water, large oxygen uptake from sediments, or in situ processes such as bacteria decomposition. The study concluded that in situ processes were creating the metalimnetic minimum and determined that these processes were related to respiration of zooplankton (Shapiro, 1960).

Pisgah Quarry is a rectangular, deep embayment (33 m) which is connected to Kentucky Lake by a shallow channel. Metalimnetic minimum DO concentrations developed in April of the study year and lasted through September. Schram and Marzolf (1994) examined each of the possible causes of the metalimnetic minimum given by Shapiro (1960). They determined depletion of oxygen could only be caused by in situ processes since the embayment lacked mid-water shelves of sediment and they found no evidence of any inflows which are attributed to the other possible causes. They monitored zooplankton productivity and the flux of particulate organic carbon (POC) in the metalimnion. They concluded POC decomposed by bacteria and used for food by zooplankton resulted in the minimum (Schram and Marzolf, 1994).

Several studies of Lake Mead, a deep-storage reservoir on the Colorado River, have found evidence of minimum DO concentrations in the metalimnion. A study by Baker et al. (1977) considered the possible causes given by Shapiro (1960) to determine the source in the reservoir. In Lake Mead the metalimnetic minimum only occurs in Boulder Basin, the basin furthest downstream. The primary reason is the inflow of wastewater effluent from the city of Las Vegas, which enters Boulder Basin. Productivity is high in this area of the lake and the metalimnetic depletion is attributed to respiration of plankton. Lower pH values coincided with low DO concentrations in the vertical profile. This information was used to confirm that respiratory activity was decreasing both the oxygen and pH levels (Baker et al., 1977).

The three previous cases each attributed oxygen depletion to an in situ process, specifically respiration of plankton. In the final case examined for this report, Flaming Gorge Reservoir, Bolke (1979) attributes the depletion in the metalimnion to interflow currents. Below the two major inflows to the reservoir oxygen depletion occurs in the hypolimnion, likely by the decomposition of organic matter. Downstream of these locations DO concentrations were lowest in the metalimnion. Analyses of phytoplankton and seston taken during the study determined they were not the cause of the minimum. Interflowing density currents appeared to transport the minimum as they moved horizontally through the reservoir (Bolke, 1979).

4.4.5 Hypolimnetic Depletion

At Lake Powell depletion of oxygen in the hypolimnion is observed annually at locations in the transition zone (Figure 4-14 and Figure 4-15) and lacustrine zone (Figure 4-19). This water is refreshed by the underflow density current each winter. At the downstream end of the lacustrine zone near the dam hypolimnetic oxygen depletion also occurs but the pattern differs from that observed upstream. The depletion is not as rapid and mixing or transport caused by the underflow density current does not occur seasonally. This is illustrated by a time-depth profile of DO at Wahweap for the time period 1965-2006 (Figure 4-22). In one sequence oxygen depleted water accumulates beginning in about 1994 and persists without complete mixing until 1999. A different sequence beginning in 1999 and continuing through 2005 shows seasonal replenishment of the hypolimnion by the underflow density current. Although the advective underflow refreshes waters at the bottom of the reservoir its DO content is typically below saturation. This may be caused by mixing with reservoir water, from oxygen demanding material it is carrying, or both.

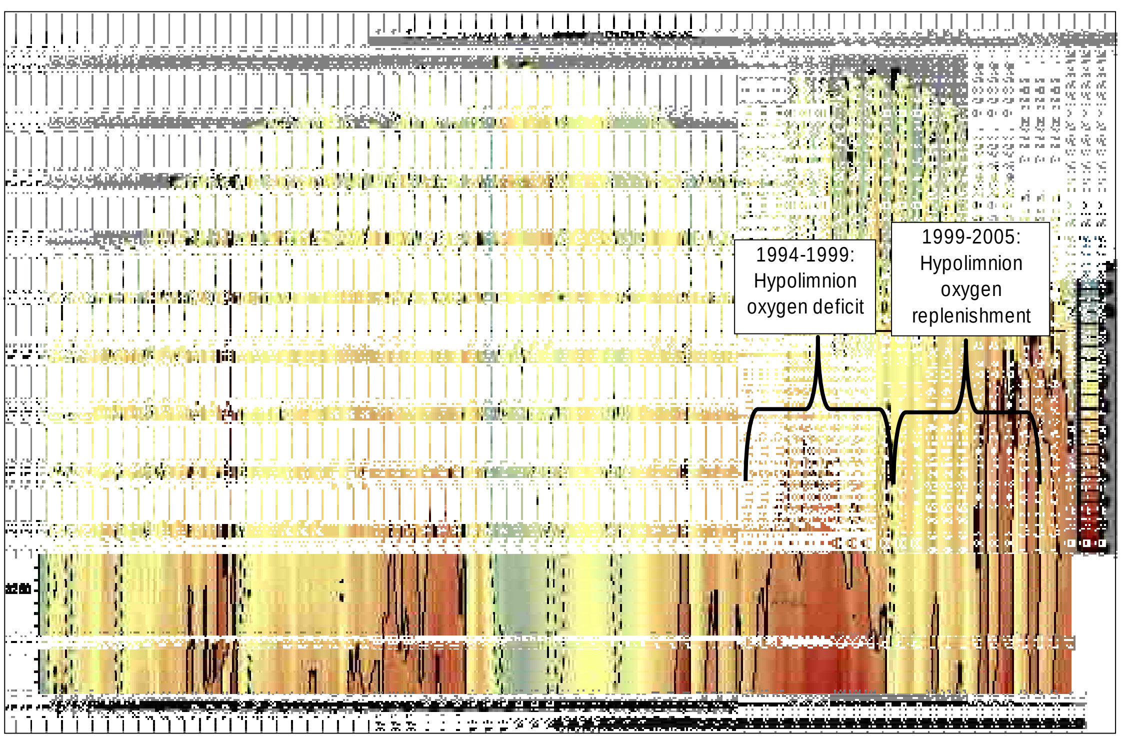

Figure 4-22: Wahweap time-depth DO, 1965-2006

Hypolimnetic depletion, like metalimnetic depletion, occurs because the consumption rate is greater than the aeration rate. As stated previously, the source of replenishment to the hypolimnion is the underflow density current. The remainder of the year, oxygen in the hypolimnion is consumed. The profiles show that this typically begins at the water-sediment interface in the transition zone and spreads into the lacustrine zone.

Oxygen depletion in the hypolimnion typically does not affect DO concentrations below the dam as the withdrawal is located above the depleted water. The exception is an upwelling caused by an underflow current. The depleted water is pushed up towards the withdrawal location and released from the dam. The upwelling in 1999 created such an event and DO in the tailwater dropped for a brief period (Figure 4-23).

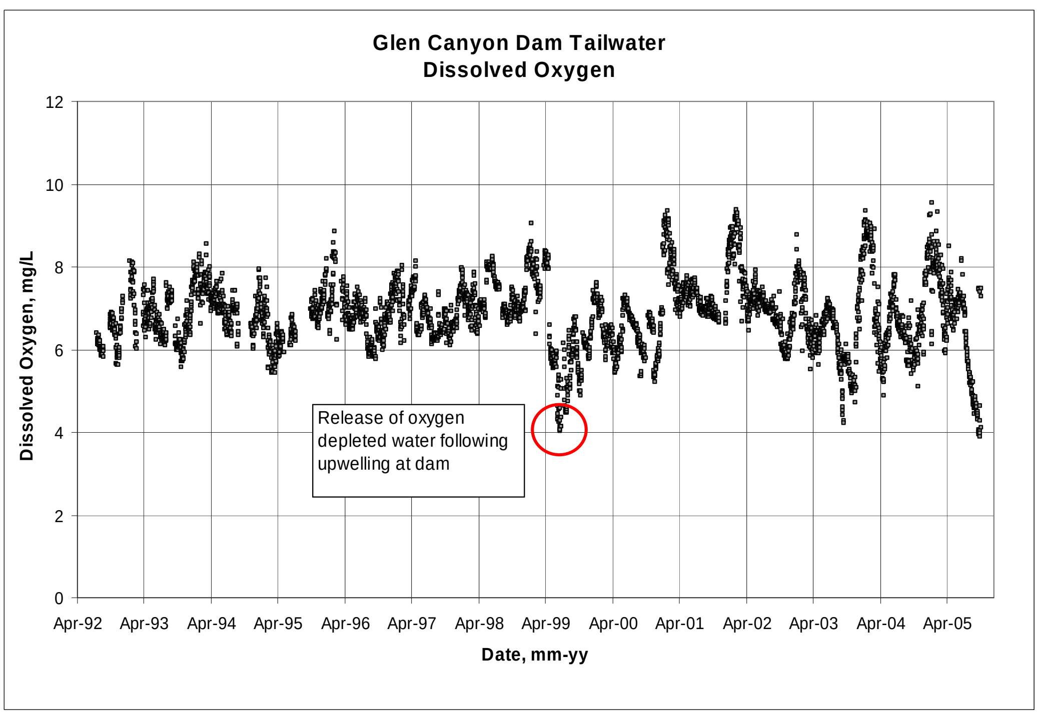

Figure 4-23: Tailwater DO concentrations

Hypolimnetic Depletion Patterns in Reservoirs

Reservoirs which experience hypolimnetic DO depletion have a common cycle of depletion (Cole and Hannan, 1990). The depletion begins at the sediment-water interface in the transition zone of a reservoir with the onset of thermal stratification. Thermal stratification isolates the hypolimnion from reaeration. From this point it progresses through the reservoir. The rate at which it spreads depends on decomposition of organic matter, the amount of DO available, and the temperature of the hypolimnion. The cycle ends when either the hypolimnion is exported through the dam or fall turnover reaerates the deep hypolimnion. Fall turnover in Lake Powell rarely aerates the reservoir to saturation from top to bottom (Johnson and Merritt, 1979).

There are numerous examples of this type of depletion in reservoirs. Oxygen depletion among the different cases can be generalized into the decomposition of organic matter found in the hypolimnion and sediments (Wetzel, 2001). The source of organic matter in the water columns and sediments varies depending on the reservoir and its drainage basin. In certain reservoirs organic matter loading from inflows dominates hypolimnetic depletion while in others plankton and bacterial respiration can dominate DO dynamics (Cole and Hannan, 1990).

5 Modeling Dissolved Oxygen

Modeling DO in Lake Powell requires representing the physical, chemical, and biological processes discussed in the previous section using the capabilities of CE-QUAL-W2. Representing the processes and simulating DO is an iterative process where the required changes are determined from results of previous simulations. This chapter summarizes the modeling methods used to represent processes which influence DO and the progression of the DO simulation.

5.1 Simulating Oxygen Demand using CE-QUAL-W2

To simplify this discussion the physical, chemical, biological processes which influence DO in Lake Powell will be grouped into three types: transport, replenishment, and consumption. The capabilities of the CE-QUAL-W2 model to represent each type of process will be explained as well as the methods for verifying the accuracy of model results.

Transport

Transport of DO is primarily influenced by reservoir hydrodynamics. In natural lake systems it is common not to consider flow dynamics when describing DO distribution but in reservoirs, flow dynamics are the driving force in DO distribution (Cole and Hannan, 1990). As described in the CE-QUAL-W2 model introduction, hydrodynamics are simulated in the longitudinal and vertical directions and are included in the model by default. Verifying hydrodynamic calibration is done iteratively by comparing observed and modeled values of temperature, TDS, and water quality constituents (Cole and Wells, 2003).

Replenishment

Replenishment of DO in the reservoir is caused by wind-induced reaeration, inflow DO concentrations, and photosynthesis. The model includes reaeration by wind which is calculated using a reaeration equation. There are 14 different lake or reservoir appropriate reaeration equations to choose from (Cole and Wells, 2003). In all of the equations reaeration is a function of wind speed and water depth. Equation 5-1 is the default formulation suggested by the user's manual and is used in these simulations (Cole and Wells, 2003). Inflowing DO concentrations are user inputs in a time-series format. Photosynthesis is included in processes associated with algae. Verifying the accuracy of DO replenishment is combined with verification of DO consumption because the two types of processes occur simultaneously and are not easily separated.

$$K_a = \frac{K_L}{H} = \frac{0.5 + 0.05W^2}{H} \qquad \textbf{(5-1)}$$

where:

K_a = reaeration rate, day^{-1}
K_L = reaeration velocity, m s^{-1}
H = depth, m
W = wind speed at 10 m height, m s^{-1}

Consumption

The sources of DO consumption include solubility changes from temperature, organic matter respiration, and decay in the reservoir as discussed in the previous chapter. The organic matter may be brought into or originate in the reservoir. Solubility, as affected by temperature, was included in model simulations of DO. The specific sources of organic matter that are represented in the model include nitrification of ammonia to nitrate-nitrite, algal respiration, organic matter decomposition, carbonaceous biochemical oxygen demand (CBOD), and sediment oxygen demand (SOD). As stated in the replenishment discussion, verifying the consumption of DO is combined with verifying the replenishment and is best achieved by comparing model results of DO with each parameter associated with consumption. Each process or parameter is briefly explained below.

Consumption by nitrification is included when ammonia and nitrate-nitrite are simulated. Including this process in the CE-QUAL-W2 model is necessary to simulate algae. External loading of ammonia and nitrate-nitrite is represented by inflow data. Internal cycling is calculated by model algorithms. Different temperature rate multipliers and decay rates for ammonium and nitrate can be adjusted in the model. The model results can be verified by ammonia and nitrate-nitrite measurements.

As with photosynthesis, respiration is included with algal processes in the CE-QUAL-W2 model. Several different parameters can be adjusted to control algal growth, respiration, excretion, mortality, and settling. Algal growth preferences for different nutrients and temperatures are user-defined. Other user-defined parameters include stoichiometric equivalences for determining nutrient concentrations in algae, and organic matter and chlorophyll-a conversion ratios. Any number of different algal species can be simulated by CE-QUAL-W2. Algae growth is verified using chlorophyll-a concentrations and algal counts or bio-volumes.

The CE-QUAL-W2 model includes four types of organic matter: refractory and labile dissolved organic matter, and refractory and labile particulate organic matter. The labile component represents organic matter which readily decays while the refractory component is slow to decay. The primary source of labile organic matter within the model is algal excretion and mortality. A portion of the labile organic matter is converted to refractory organic matter. User adjusted coefficients and values allow each of the different organic matter compartments to have a separate decay rate as well as a labile to refractory decay rate; the particulate compartments to include a settling rate; and temperature rate multipliers and stoichiometric equivalents which apply to all organic matter compartments.

CBOD is used within the model to represent organic matter in the inflows only and not within the reservoir itself. This distinction is made because the loading of oxygen demand from inflows is often measured using a biochemical oxygen demand (BOD) test and the results from this test are not easily broken down between the different organic matter compartments. It also keeps inflowing oxygen demand separate from in situ oxygen demand in the model. The user-defined coefficients associated with the CBOD compartment include a 5-day decay rate, a coefficient to adjust for temperature effects, a ratio of 5-day to ultimate CBOD, and stoichiometric equivalents for nutrients. The model can simulate any number of CBOD groups. The accuracy of CBOD concentrations is verified by DO concentrations within the reservoir.

SOD is represented by a sediment compartment with zero-order and first-order SOD. Values for the zero-order SOD are specified by segment and typical values range from 0.1 to 1.0 gO_2 m^{-2} day^{-1} (Newbold and Liggett, 1974). The manual recommends use of this parameter in initial calibration as it is essentially a pure calibration parameter which can be used to back calculate DO uptake rates. The drawback to using this to simulate oxygen demand is it remains constant over time and is only sensitive to changes in temperature. The first-order SOD tracks organic matter delivery to the sediments meaning an increase in organic matter delivery will affect the SOD. This method is more predictive than the zero-order SOD. Accuracy of the two SOD compartments is confirmed by DO measurements.

5.2 Dissolved Oxygen Models

Several model simulations were made to reproduce DO dynamics in Lake Powell for the years 1990-2005. Each successive simulation built upon progress made in the previous one. Many of the changes discussed in the temperature and TDS calibrations resulted from the iterative DO simulations. The following is a description of the simulations, categorized by major changes or additions. The results of these models are presented in the following chapter.

5.2.1 Nutrients & Plankton Simulation

The initial DO model attempted to simulate DO dynamics beginning with the original Lake Powell temperature and TDS model. The depletion of oxygen was simulated using recognized depletion sources such as the decomposition of algae (Hansmann et al., 1974; Johnson and Page, 1981). Water quality processes represented in that simulation included DO consumption and replenishment, algal processes, organic matter decomposition, nutrient cycling, and first-order SOD. Algae were represented by one group in the model because of a lack of detailed information on the different algal species in Lake Powell. The user-defined kinetic coefficients and rates were set to default values as recommended in the user's manual (Cole and Wells, 2003) because no data relating to any of the processes had been collected to suggest otherwise.

Input data requirements for this model included phosphorus, nitrate-nitrite, ammonia, and DO concentrations. Nutrient concentrations from water quality monitoring measurements were used for model inflow concentrations. These data are collected quarterly near the inflow locations. Linear interpolation in time between the samples was done to generate a continuous dataset. DO concentrations were assumed to be near saturation based on USGS data in the inflows. The same assumption was also used in the Lake Powell BETTER model (Bureau of Reclamation, 1999).

Calibration data include DO concentrations measured at several monitoring sites (Figure 3-7) taken at depth intervals of 1 to 4 meters from the water surface to the reservoir bottom. The high vertical resolution of the DO data provided information about DO dynamics which was valuable to model calibration.

Nutrient and chlorophyll-a concentrations at selected sites were also available but measurements were made at only a few select depths. The low vertical and longitudinal resolution made it difficult to compare results from the model with the field observations. There were also questions about quality control and quality assurance of the phytoplankton measurements (Miller, 2007). For these reasons these datasets were not used in model calibration.

5.2.2 Zero-order SOD Simulation

In order to increase the oxygen demand in the sediments the zero-order SOD computation was included in the simulation. An SOD value was set for each individual segment. For all simulations the closer the segment was to the dam the smaller the value. Several simulations with varying SOD values were made. Kinetic coefficients were initially set to default values. Temperature rate multipliers were adjusted in later simulations to increase the decay rate at lower temperatures.

5.2.3 Measured BOD Concentrations Simulation

Conclusions from previous simulations indicated the inflows needed additional oxygen demand. A search of available databases found the results of several BOD tests in the Colorado River inflow area and upstream of the San Juan River inflow area performed by the State of Utah. These tests, however, were taken between 1976 and 1979, well before the model simulation period. As a sensitivity experiment average values from the results of those BOD tests were used for inflow CBOD concentrations in the model. Associated CBOD kinetic coefficients were set to default values.

5.2.4 Empirical Oxygen Demand Loading Simulation

An empirical method of loading oxygen demand to the reservoir was also tested building from the nutrient, plankton, and zero-order SOD simulations. This method began based on observations of the DO distribution throughout the. In summary these observations include:

- A seasonal metalimnetic minimum in the upper lacustrine zone (Figure 4-19);

- The location of the metalimnetic minimum coincides with the location of the summer/fall interflow density current;
- An apparent increase in the magnitude of metalimnetic and hypolimnetic depletion during reservoir drawdown event (2000-2004) and subsequent average hydrologic year (2005) (Figure 4-19); and
- Replenishment of hypolimnion water by the underflow density current still left concentrations below saturation

Using these observations as a guide for timing and magnitude, an oxygen demand was introduced to the reservoir via the inflows using CE-QUAL-W2's CBOD compartments. Two CBOD groups were established and used to simulate this oxygen demand. The first (CBOD1) was designed to simulate the metalimnetic oxygen depletion by increasing concentrations as flow increased. The second (CBOD2) simulated the depletion in the underflow density current by increasing concentrations as inflow temperatures decreased. The CBOD kinetic coefficients were adjusted to represent the two different types of oxygen demand as given in Table 5-1. These values include the 5-day decay rate at 20°C ($KBOD_{20}$) and the temperature coefficient (TBOD).

Table 5-1: CBOD kinetic coefficients

Kinetic Coefficient	CBOD Group 1	CBOD Group 2
$KBOD_{20}$, day^{-1}	0.25	0.10
TBOD	1.0147	0.98

The CBOD group 1's higher decay rate and temperature coefficient allow faster decay at relatively warm temperatures with minimal decay at relatively cold temperatures. Group 2's lower decay rate and temperature coefficient create a slower decay but still allow it to decay at cold temperatures.

The actual decay rate (KBOD) was calculated from Equation 5-2 using values for $KBOD_{20}$ and TBOD. Adjusting these values was part of the calibration process.

$$KBOD = KBOD_{20} * TBOD^{T-20} \tag{5-2}$$

Calibration of the DO model was done iteratively by varying the concentrations of the two different CBOD groups. Equations were developed to load CBOD concentrations in the reservoir inflows and were based on reservoir inflow rate and water surface elevation. The CBOD loading equations developed for the Colorado (Equations 5-3 & 5-4) and San Juan (Equations 5-5 & 5-6) rivers are:

$$CBOD1_{CR} = 6 * \frac{Q_{CR}}{70,000} * F_{ELEV} \tag{5-3}$$

$$CBOD2_{CR} = 6 * \frac{4}{T_{CR}} * F_{ELEV} \tag{5-4}$$

$$CBOD1_{SJR} = 6 * \frac{Q_{SJR}}{12,000} * F_{ELEV} \tag{5-5}$$

$$CBOD1_{SJR} = 6 * \frac{4}{T_{SJR}} * F_{ELEV} \tag{5-6}$$

$$F_{ELEV} = 1.05 - (\frac{WSE - 3550}{150}) \tag{5-7}$$

where:

$CBOD1_{CR}$ = Colorado River CBOD1 concentrations, mg/L
$CBOD2_{CR}$ = Colorado River CBOD2 concentrations, mg/L
$CBOD1_{SJR}$ = San Juan River CBOD1 concentrations, mg/L
$CBOD2_{SJR}$ = San Juan River CBOD2 concentrations, mg/L
Q_{CR} = Colorado River inflow rate, cfs
T_{CR} = Colorado River inflow temperature, °C
Q_{SJR} = San Juan River inflow rate, cfs
T_{SJR} = San Juan River inflow temperature, °C
F_{ELEV} = Elevation factor
WSE = Lake Powell water surface elevation, feet

The coefficients used in the above equations were determined by iterative simulations but also were based on some physical factors. CBOD loading from all equations increases with decreasing elevation. An elevation factor (Equation 5-7) is included as part of each of the CBOD equations. It is intended to reproduce the increased oxygen depletion magnitudes observed during reservoir drawdown. The further the reservoir is drawn down the greater the elevation factor and the CBOD concentrations.

The CBOD1 equations (Equations 5-3 and 5-5) for the Colorado and San Juan inflows were designed to increase CBOD loading as daily mean flow rates increased. In each CBOD1 equation a parameter for flow is included, represented by the symbol Q. Annually this value is highest during spring runoff and simulates the increased organic loading from the watershed and from increased scour of the sediment delta.

The CBOD2 equations (Equations 5-4 and 5-6) for both inflows were designed to increase loading with increasing water density. This was done by including water temperatures in the equations. In computing the daily CBOD2 concentrations all temperatures less than 4°C were set to a minimum 4°C. The oxygen demand from the CBOD2 equations simulates consumption in the underflow density current. This source of the oxygen consumption may be sediment oxygen demand, biological decomposition, or chemical oxidation.

6 Results

Results from DO simulations are presented here. Temperature calibration results were presented in Section 3.4.2 and TDS calibration results were presented in Section 3.4.3. The DO calibration results are presented in tables showing the AME at the different reservoir monitoring sites. Particular attention was paid to the Wahweap monitoring site where the most data exists. To put model errors in perspective, DO concentrations in Lake Powell can range from 0 to 10 mg/L. Profiles illustrating model results and field data are shown for the results of the empirical CBOD simulation only. The profiles shown are from the 2005 quarterly data from the following monitoring sites: Scorup, Bullfrog, Wahweap in the Colorado River channel, and Upper Piute Bay and Cha in the San Juan River channel.

6.1 Nutrients & Plankton Simulation

Results from the nutrients and plankton simulation are shown in Table 6-1. The overall AME is 2.38 mg/L. The error at Wahweap (3.04 mg/L) is significantly greater than the overall error. In all locations the model DO concentrations are higher than the concentrations in the field data. Given what nutrient concentrations were available the oxygen demand associated with phytoplankton was not large enough to reproduce oxygen depletion in the reservoir. The error is largest at locations furthest from the riverine and transition zones.

Table 6-1: Nutrients & plankton simulation - DO calibration results

Station	Years	AME	#
Hite	91-05	1.67	52
Scorup	91-05	1.78	54
Good Hope	92-05	1.82	51
Knowles	94-05	1.90	40
Moki	94-04	1.94	38
Bullfrog	91-05	2.13	54
Lake	94-05	2.16	42
Iceberg	94-05	2.23	42
Escalante Confluence	91-05	2.30	54
San Juan Confluence	95-05	2.35	38
Oak Canyon	91-05	2.24	58
Crossing of the Fathers	91-05	2.85	60
Forebay	90-93	2.22	19
Lower Zahn	91-03	2.07	38
Upper Piute	91-05	2.34	49
Lower Piute	91-05	2.81	44
Cha Canyon	91-05	2.92	51
Wahweap	91-05	3.04	180
Average		**2.38**	

6.2 Zero-Order SOD Simulation

Results from the zero-order SOD simulation are shown in Table 6-2. The overall AME is 1.52 mg/L. The error at Wahweap (1.91 mg/L) is still greater than the overall error. This simulation improved upon results from the previous simulation, particularly in the Colorado River channel sites. Including SOD in the model adds a large fraction of the hypolimnetic oxygen depletion. The SOD is not able to simulate the oxygen demand in the metalimnion, however. This is apparent by the locations in the lacustrine zone having the largest errors. The minimal mixing in this zone prevents the simplistic zero-order SOD from generating the total oxygen demand.

Table 6-2: Zero-order SOD simulation - DO calibration results

Station	Years	AME	#
Hite	91-05	1.33	52
Scorup	91-05	1.28	54
Good Hope	92-05	1.22	51
Knowles	94-05	1.33	40
Moki	94-04	1.27	38
Bullfrog	91-05	1.24	54
Lake	94-05	1.36	42
Iceberg	94-05	1.37	42
Escalante Confluence	91-05	1.42	54
San Juan Confluence	95-05	1.52	38
Oak Canyon	91-05	1.37	58
Crossing of the Fathers	91-05	1.68	60
Forebay	90-93	1.52	19
Lower Zahn	91-03	1.64	38
Upper Piute	91-05	1.46	49
Lower Piute	91-05	1.62	44
Cha Canyon	91-05	1.71	51
Wahweap	91-05	1.91	180
Average		**1.52**	

6.3 Measured BOD Concentrations Simulation

Results from using past measured BOD concentrations in the inflow are shown in Table 6-3. The overall AME is 1.23 mg/L. Again, the error at Wahweap (1.38 mg/l) is greater than the overall error. This simulation increased the total oxygen demand and improved on results from the SOD simulation. Noticeable improvements are seen at the lacustrine zone monitoring sites. Oxygen demand in the metalimnion was partially represented by the BOD loading added to the reservoir inflows.

Table 6-3: BOD simulation - DO calibration results

Station	Years	AME	#
Hite	91-05	1.20	52
Scorup	91-05	1.09	54
Good Hope	92-05	1.13	51
Knowles	94-05	1.25	40
Moki	94-04	1.13	38
Bullfrog	91-05	1.06	54
Lake	94-05	1.13	42
Iceberg	94-05	1.14	42
Escalante Confluence	91-05	1.12	54
San Juan Confluence	95-05	1.19	38
Oak Canyon	91-05	1.09	58
Crossing of the Fathers	91-05	1.26	60
Forebay	90-93	1.09	19
Lower Zahn	91-03	1.51	38
Upper Piute	91-05	1.49	49
Lower Piute	91-05	1.28	44
Cha Canyon	91-05	1.31	51
Wahweap	91-05	1.38	180
Average		**1.23**	

6.4 Empirical Oxygen Demand Loading Simulation

Final results of the empirical oxygen demand loading simulation are shown in Table 6-4. The overall AME was 1.12 mg/L. The error at Wahweap (1.15 mg/L) is comparable to the overall error. This simulation improved upon results of the BOD simulation at most monitoring sites. The empirical CBOD loading added to the inflows followed the patterns of metalimnetic and hypolimnetic depletion more closely.

Table 6-4: Empirical oxygen demand loading simulation - DO calibration results

Station	Years	AME	#
Hite	91-05	1.14	52
Scorup	91-05	1.02	54
Good Hope	92-05	1.04	51
Knowles	94-05	1.12	40
Moki	94-04	0.98	38
Bullfrog	91-05	1.01	54
Lake	94-05	1.07	42
Iceberg	94-05	1.12	42
Escalante Confluence	91-05	1.07	54
San Juan Confluence	95-05	1.13	38
Oak Canyon	91-05	1.00	58
Crossing of the Fathers	91-05	1.05	60
Forebay	90-93	0.94	19
Lower Zahn	91-03	1.41	38
Upper Piute	91-05	1.32	49
Lower Piute	91-05	1.26	44
Cha Canyon	91-05	1.29	51
Wahweap	91-05	1.15	180
Average		**1.12**	

Profiles of the DO calibration are shown for the transition and lacustrine zones in both river channels (Figures 6-1 to 6-5). The figures are included to illustrate the model's ability to reproduce complex profile shapes as well as areas where improvement is needed. In March the profiles show the model does not have enough DO in the hypolimnion except at Wahweap where the model has too much DO. In June the model still does not have enough DO though it captures the pattern of metalimnetic depletion at Cha. By September the model is following the patterns of metalimnetic and hypolimnetic depletion at most locations. Finally, during winter turnover in December the model approximately reproduces the DO curves seen at each location.

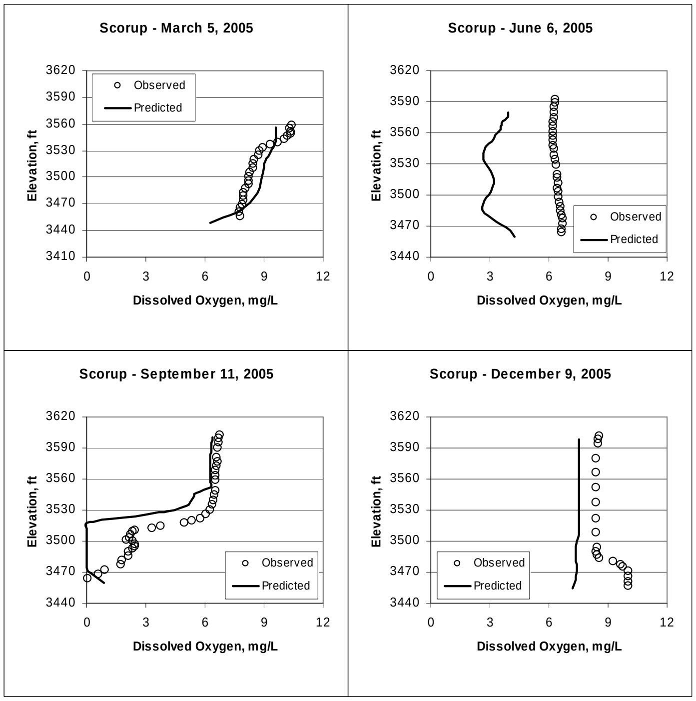

Figure 6-1: Predicted and observed DO concentrations, Scorup, 2005

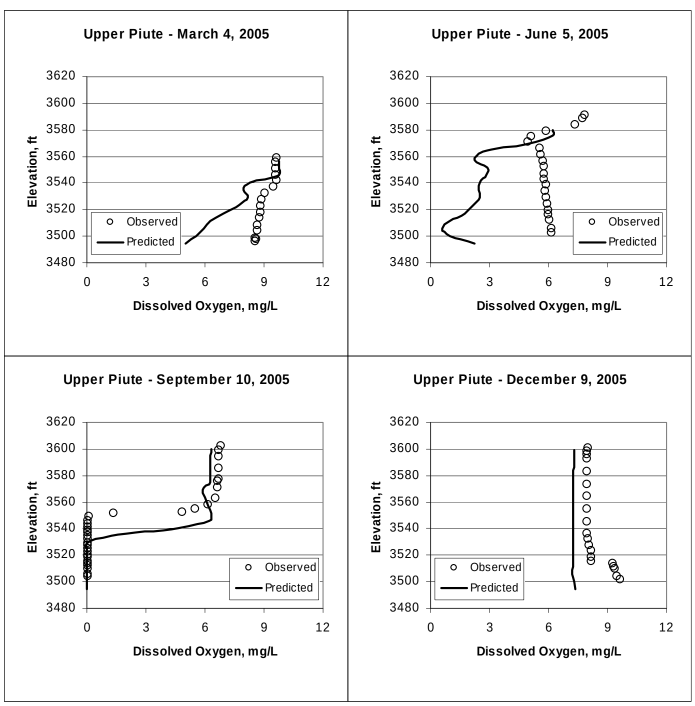

Figure 6-2: Predicted and observed DO concentrations, Upper Piute Bay, 2005

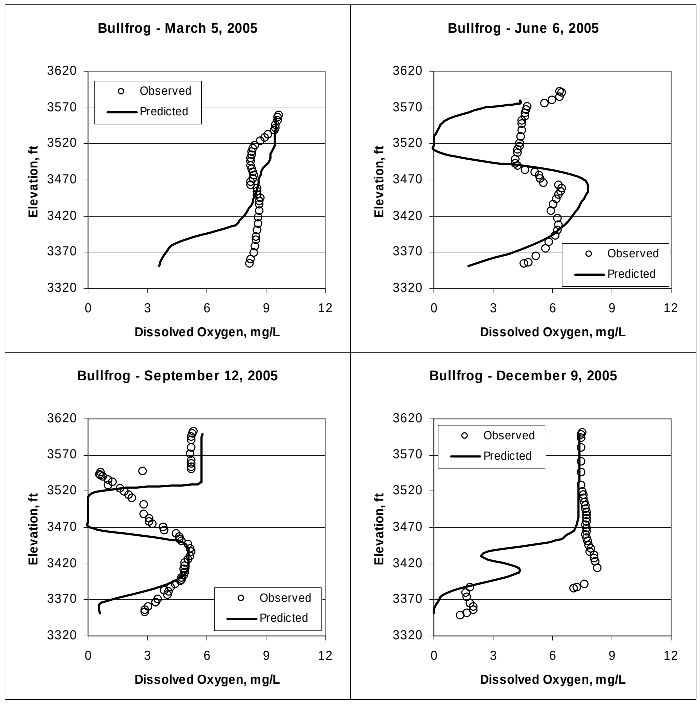

Figure 6-3: Predicted and observed DO concentrations, Bullfrog, 2005

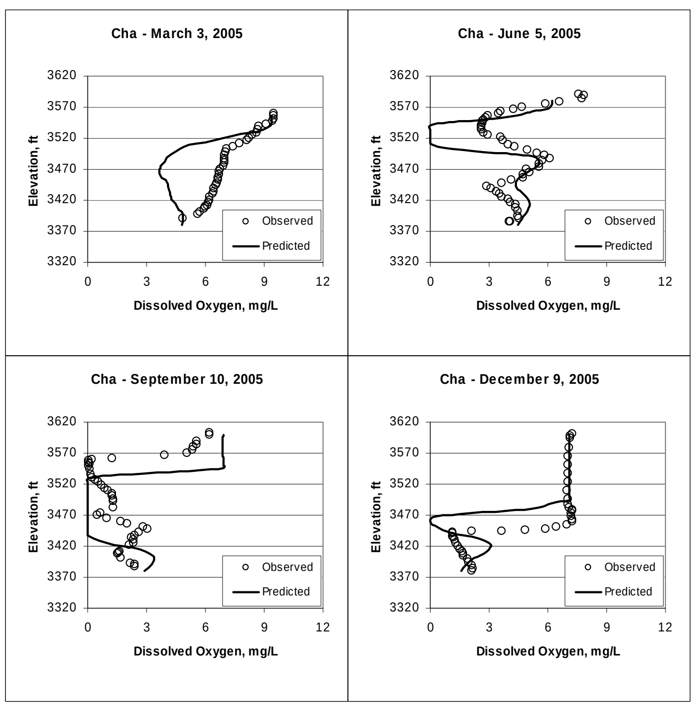

Figure 6-4: Predicted and observed DO concentrations, Cha, 2005

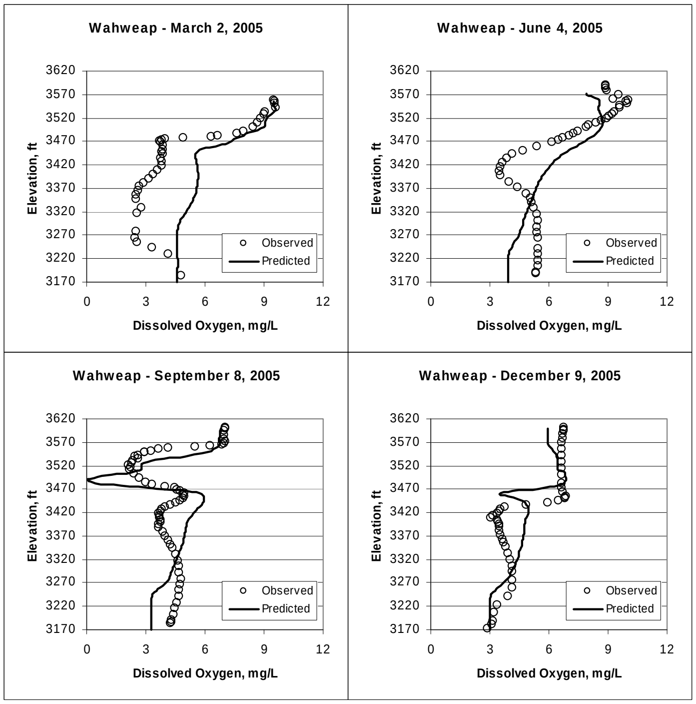

Figure 6-5: Predicted and observed DO concentrations, Wahweap, 2005

7 Conclusions

The empirical CBOD method used to simulate DO dynamics is a significant advancement in modeling water quality and hydrodynamics in Lake Powell. This method allows for useful simulations of DO without knowing or specifically simulating the complex interactions which deplete oxygen in Lake Powell. Discussion of more specific conclusions relating to the results of the DO modeling as well as recommendations follows.

7.1 Dissolved Oxygen Simulations

Statistical results from the DO simulations (Tables 6-1 to 6-4) show the empirical CBOD loading simulation resulted in the lowest AME. The largest improvement between the simulations is shown by the AME of the monitoring site just above the dam at Wahweap. Since this site is measured monthly it represents the most continuous dataset making it an important site in calibration. The AME results at Wahweap for each simulation are shown in Table 7-1.

The results presented show the simulations progressively improving the general DO calibration, but only results comparing the calibration at different monitoring sites over the entire simulation period have been shown. Other important indicators of the DO calibration are shown by examining the changing magnitude of depletion and the seasonal reproduction of the DO distribution.

Table 7-1: DO simulations, Wahweap monitoring site AME

Simulation	Wahweap AME
Nutrient-plankton	3.04
Zero-order SOD	1.91
Inflow BOD	1.38
Empirical CBOD	1.15

7.1.1 Oxygen Depletion Magnitude

The first three DO simulations progressively grew more complex in simulating DO dynamics in Lake Powell by including oxygen demand based on algal processes, then model SOD calculations, and finally approximate inflow BOD loads. The nutrient concentrations in the algal processes, segment SOD values, and BOD loads used in the simulations were relatively constant over time. As a result they do not reproduce the greater oxygen depletion seen during reservoir drawdown. The empirical methods used to calculate the CBOD loading were designed to compensate for this by increasing oxygen demand during reservoir drawdown. The results of this improvement are illustrated by examining AME values at the Wahweap monitoring site by year. The results of the third simulation of plankton-SOD-BOD are compared to the empirical CBOD simulation results in Table 7-2. The empirical CBOD simulation generally has better results in each year. The difference is most pronounced in 2004 and 2005, the years of lowest reservoir elevations. The magnitude of oxygen depletion is largest during these years and the empirical CBOD simulation best approximates the increased depletion.

Table 7-2: Wahweap AME results for BOD and empirical CBOD simulations, 1991-2005

Year	BOD	Empirical CBOD
1991	1.851	1.841
1992	1.111	0.956
1993	1.167	0.842
1994	1.155	0.996
1995	0.902	0.772
1996	0.951	0.786
1997	1.565	0.992
1998	0.928	0.685
1999	0.757	1.023
2000	0.987	0.868
2001	1.147	1.072
2002	1.532	1.579
2003	2.259	2.079
2004	2.044	1.614
2005	2.228	1.323

7.1.2 Seasonal DO Distribution

Capturing the seasonal distribution of metalimnetic and hypolimnetic depletion was among the first steps in developing the DO model. Once the pattern was properly replicated subsequent simulations were used to refine the results. The seasonal pattern, as reproduced by the model is illustrated in Figure 7-1 (Bullfrog) and Figure 7-2 (Cha). These depict DO over depth and time. The results are output from the model every 5 days. The elevations are shown in meters and the time scale is Julian days where 1 =

January 1, 1990. Comparing these with similar figures illustrating field data for Bullfrog (Figure 4-19) and Cha (Figure 4-20) shows similarities in the pattern of metalimnetic and hypolimnetic depletion.

Though the magnitude of depletion is more pronounced in some years than in others, a seasonal pattern of metalimnetic and hypolimnetic depletion is apparent in each figure. The magnitude of metalimnetic depletion is greatest when large inflow volumes follow consecutive years of reservoir drawdown, such as in 2005. The timing and location of DO depletion during this event was approximated using the empirical CBOD equations. Other metalimnetic minimums were also approximated throughout the 16 year simulation.

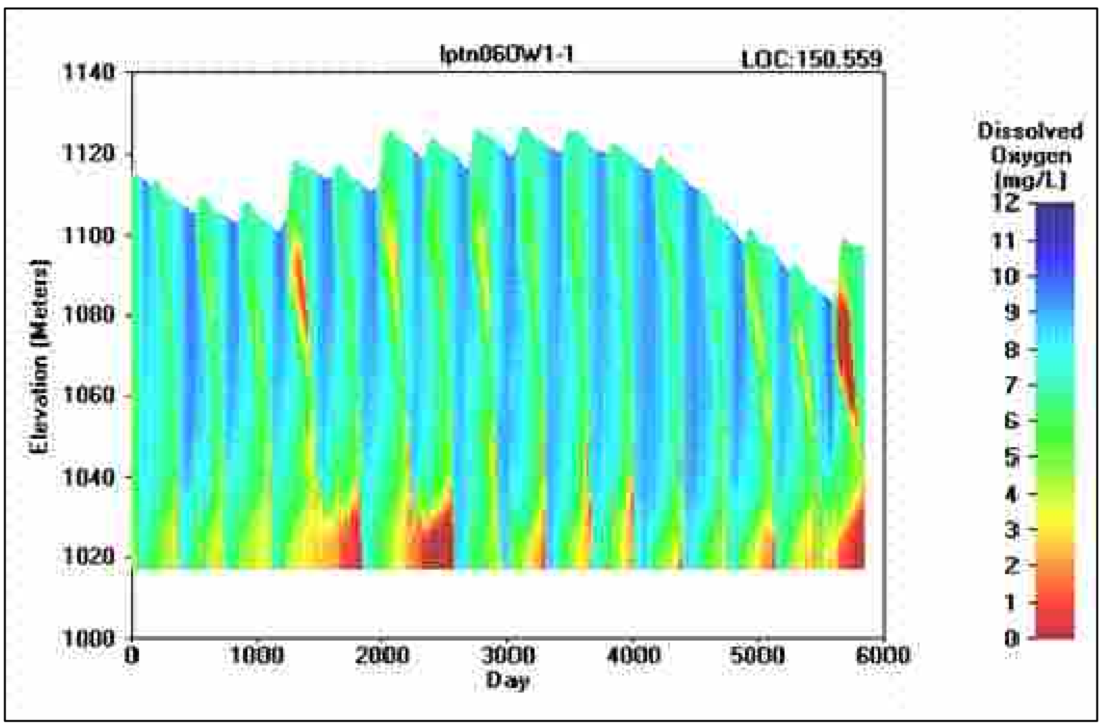

Figure 7-1: Modeled time-depth profile, Bullfrog monitoring site, CE-QUAL-W2 results

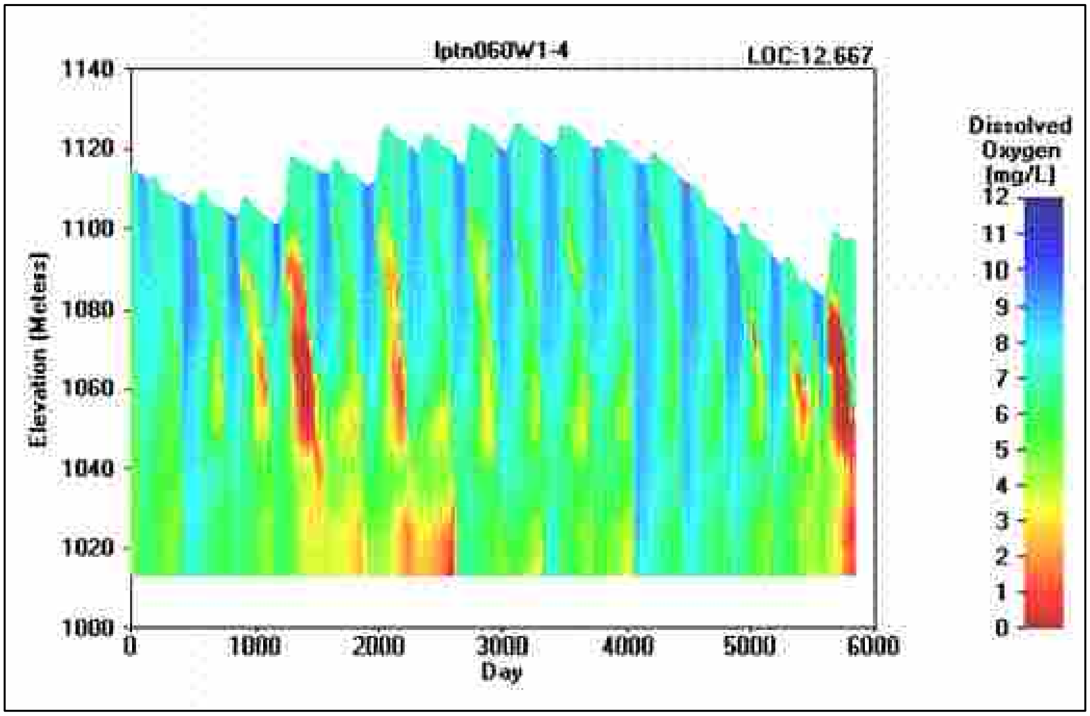

Figure 7-2: Modeled time-depth profile, Cha monitoring site, CE-QUAL-W2 results

7.1.3 Hydrodynamic Calibration

Hydrodynamic accuracy of the model is determined by the accuracy of temperature, TDS, and DO. The calibration results of the temperature and TDS (Sections 3.4.2 and 3.4.3) have improved from previous models suggesting an improvement in hydrodynamics. Also, several specific hydrodynamic problems were resolved as part of the DO simulations.

The heat budget imbalance was noticed in part because of discrepancies in surface DO content which were related to similar discrepancies in surface temperatures. The changes in cloud cover and evaporation corrected these errors.

Problems in the underflow density current were noticed when it was apparent there was too much advective mixing at the bottom of the reservoir upstream of the dam. Both DO and TDS concentrations were diluted seasonally by a “sweep” of the underflow density current in the model. Field data for the two parameters suggested the “sweep” only occurred under certain conditions. This led to limiting the withdrawal zone of the dam intake and served to partially correct the frequency of the underflow “sweep”.

7.1.4 Assumptions & Uncertainty

Several assumptions went into the development of the empirical CBOD loadings and associated equations and influence the results of the model. First, its development was based on a hypothesis that oxygen depletion is increased by scouring of the major tributaries’ sediment deltas. As the reservoir elevations drop, the area of sediment delta exposure increases and as the inflowing rivers travel through the exposed delta they scour and transport sediments. The release of organic matter from the sediments and the oxidation of reduced metals (Lee and Lee, 2005) may contribute to oxygen depletion. The magnitude of depletion would be a function of the exposed delta area and the amount of scouring which presumably increases as flow rates increase. While organic matter is present in the sediments (Vernieu et al., 2005) and the preliminary results of a geochemical study of the sediments indicate an increase in reduced metals as the inflow travels across the delta (Wildman, 2007), more research into these interactions is necessary.

The equations used in the calibration also may not be valid in other simulations of DO in Lake Powell. The equations were calibrated for a specific time period (1990-2005) and the events that drive DO may change over time. The equations were also based on specific elevations and flow rates. Flows or elevations outside of the ranges experienced between 1990 and 2005 may also make the equations invalid.

7.2 Recommendations

7.2.1 Dissolved Oxygen Calibration

The modeling results presented here provide a starting point for calibrating the DO in the reservoir. Generating oxygen demand with the empirical CBOD is a similar method to the model's zero-order SOD algorithm. It is a calibration parameter which is useful for calibrating and then back calculating oxygen demand loads and sources. This will narrow the list of possible oxygen demand sources which can then be verified using field measurements.

The Upper Colorado Region of the Bureau of Reclamation will continue to refine the calibration of DO using the empirical methods developed in this study. Future work on the model will include representing more of the physical, biological, and chemical processes which influence DO. Research on sediment delta interactions will be incorporated into the simulations. This will result in more accurate hydrodynamic, temperature, TDS, and DO calibrations.

7.2.2 Planning and Management

Planning and management at Lake Powell and Glen Canyon Dam relating to reservoir water quality or hydrodynamics will benefit from the use of the Lake Powell model. The reservoir water quality monitoring program can use the model to determine the measurement frequency and location of water quality parameters. This will improve understanding of the reservoir as well as improve data used in the model. The model will also aid in analyzing modifications to the dam such as the temperature control device. Proposed or anticipated modifications can be included in the model and simulated over a historical time period. Modeled results in and below the reservoir compared with observed data can be used in determining the impacts of modifications.

7.2.3 Other Systems

The results and conclusions from this study are not intended for use on Lake Powell alone. The concepts of model development can potentially be applied to many other systems. The model development began with researching the principles of limnology and flow dynamics of reservoirs in general and Lake Powell specifically. The Upper Colorado Region of the Bureau of Reclamation anticipates using the methods developed here and applying them to studies and models of other systems within their region such as Flaming Gorge Reservoir. Results from other systems will supplement the methods, results, and conclusions of this study.

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Appendix A

Glen Canyon Dam and Lake Powell Reservoir Background

In the arid southwestern United States the Colorado River is vital to the water supply of nearly 33 million peoples and irrigates nearly 4 million acres of land (Department of the Interior, 2005). Water allocations within the system are governed by several public laws and treaties. The heavy demands on the river and its tributaries led to the need for reservoir storage. Among the many dams and reservoirs constructed were Glen Canyon Dam and Lake Powell.

Colorado River Allocations

Colorado River water was allocated by the Colorado River Compact of 1922, the Boulder Canyon Project Act of 1928, the Water Treaty of 1944, the Upper Colorado River Basin Compact of 1948, and others. The Colorado River Compact geographically divided the Colorado River Basin into the Upper and Lower Basins. The Upper Basin includes the states Colorado, New Mexico, Utah, and Wyoming and the Lower Basin includes Arizona, California, and Nevada. The dividing point is Lee's Ferry in northern Arizona (Figure A-1). Each basin was allocated 7.5 million acre-feet of water annually. In the Upper Basin the 7.5 million acre-feet was divided between the states by the Upper

Colorado River Basin Compact of 1948. This gave 50,000 acre-feet of water to Arizona with the remaining water divided as follows (Department of the Interior, 2005):

- Colorado – 51.75%
- New Mexico – 11.25%
- Utah – 23%
- Wyoming – 14%

Water in the Lower Basin was allocated by the Secretary of the Interior between the states as follows (Department of the Interior, 2005):

- Arizona – 2,800,000 acre-feet
- California – 4,300,000 acre-feet
- Nevada – 300,000 acre-feet

Additional allocation came with the Water Treaty of 1944 which obligated the United States to deliver 1.5 million acre-feet to Mexico annually. This obligation was divided evenly between the two basins.

Colorado River Storage Project

The Colorado River Storage Project (CRSP) was authorized by Congress in the year 1956 to provide the storage necessary for the upper basin states to meet water delivery obligations to the lower basin states. The long-term storage provided by the project allows the upper basin states to develop their apportioned shares of the Colorado River. The project consists of four units, Glen Canyon on the Colorado River, Flaming Gorge on the Green River, Navajo on the San Juan River, and the Wayne N. Aspinall Storage Unit on the Gunnison River. The Glen Canyon unit is the key feature of the

CRSP and accounts for almost 80% of the 34 million acre-feet of storage provided by the project.

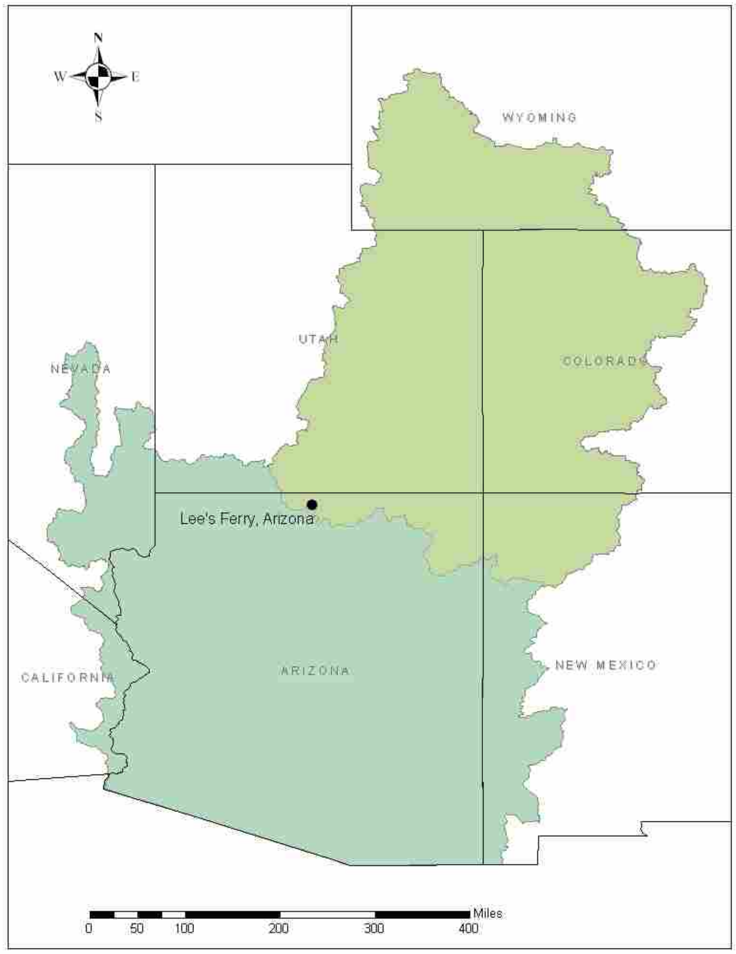

Figure A-1: Upper and lower basins of the Colorado River, also showing Lee's Ferry, Arizona

Glen Canyon Dam

Glen Canyon Dam is located 15 miles upstream of Lee's Ferry on the Colorado River. Construction commenced in 1957 and was completed in 1964. The dam is a thin arch concrete structure, 710 feet in height. The normal operating water surface is 3700 feet and the maximum water surface is 3710.6 feet. At normal pool the hydraulic height is 583 feet. Water is released from the dam from the powerplant, outlet works, or spillway or a combination of the above. Eight penstocks carry water to the powerplant, each having a centerline elevation of 3470 feet. The total capacity of the powerplant at normal pool is 33,200 cfs. The outlet works consist of four 96-inch diameter pipes at centerline elevation 3376 feet. The combined capacity of the outlet works at normal pool is 15,000 cfs. Two spillways, one in each abutment, are used for flood control. Each spillway is controlled by radial gates at the intake entrance. The combined capacity of the spillways at normal pool is 208,000 cfs.

Lake Powell Reservoir

The reservoir formed by Glen Canyon Dam, Lake Powell, backs up the Colorado River from a few miles south of the Utah-Arizona border to well into southeastern Utah. At normal pool the reservoir is 186 miles long with a surface area of 161,390 acres. The reservoir has a total shoreline of 1,960 miles (Ferrari, 1988). Numerous side canyons which branch off from the main channel give Lake Powell its highly irregular shape.

The reservoir first began storing water in March 1963. Power production first began in 1964 when the reservoir reached the minimum power pool elevation, 3490 feet. The reservoir filled to elevation 3700 for the first time in June 1980. The lowest recorded elevations since initial filling occurred in April, 2005 at 3555 feet.

Tributaries

The principal tributaries to Lake Powell are the Colorado River, the Green River – of which its confluence with the Colorado River is upstream of Lake Powell – and the San Juan River. Minor tributaries include the Dirty Devil and Escalante rivers as well as many smaller creeks, springs, and washes. These tributaries drain a combined area of 108,000 square miles. The Colorado, Green, and San Juan rivers and their tributaries form high in the mountains where precipitation can exceed 60 inches annually, mainly in the form of snow. These rivers flow down from high elevations and across the Colorado Plateau, where precipitation can be as little as 6 to 8 inches annually, before entering the waters of Lake Powell.

Flow in the Colorado River is highly variable. Annual flow volumes have ranged from 4 to 22 million acre-feet. Since the reservoir first began filling in 1963 annual average inflow to Lake Powell was 11.1 million acre-feet. The Colorado, Green, and San Juan rivers, on average, account for 95% of the total inflow to Lake Powell. Of this flow 60% occurs from the months May through July during spring snowmelt (Irons et al., 1965; Evans and Paulson, 1983).

Reservoir Release and Storage Guidelines

Releases at Glen Canyon Dam are required to be at least 8.23 million acre-feet annually, reservoir storage permitting. Monthly and hourly release volumes are the result of scheduled releases. Releases may exceed this volume in the event of flood flows or reservoir equalization with Lake Mead. Flood flows result from extreme hydrologic events that exceed the storage of Lake Powell. Another component of this is flood control which does not allow reservoir storage on January 1 to exceed 22.6 million acre-feet. Reservoir equalization requires maintaining, as practicable as possible, equal reservoir storage between Lakes Mead and Powell when active reservoir storage in the Upper Basin exceeds the quantity of storage set forth by the Secretary of the Interior in Public Law 90-537, Section 602(a) (U.S. Bureau of Reclamation, 2007b).

Future Operations and Water Use

As the upper basin states move closer to developing their full allotment of Colorado River water the projected inflow to Lake Powell will continue to decrease. Since initial filling (1980) the average storage of the reservoir on September 30th, the end of the water year was 19.1 million acre-feet. Over the next 50 years the projected September 30th average storage is 17.5 million acre-feet (Department of the Interior, 1995).

Appendix B

Glen Canyon Dam Temperature Control Device

Seasonal temperatures in the Colorado River ranged from 0°C to 30°C prior to the construction of Glen Canyon Dam. Since the construction of Glen Canyon Dam temperatures vary little seasonally and are typically between 7-12°C. These cold releases have impacted native fish through the Grand Canyon according to a biological opinion issued by the Fish and Wildlife Service (FWS) (Department of the Interior, 1995). The FWS opinion also recommended that the Bureau of Reclamation evaluate methods to control temperatures and implement controls, if possible. The preferred method for controlling temperature releases is by adding a selective level withdrawal structure to the dam (U.S. Bureau of Reclamation, 2005). The selective level withdrawal structure is also known as a temperature control device (TCD).

Two TCD structures will be added over two of the eight existing penstocks at the dam. They will be capable of selectively withdrawing water from elevations above the current penstock elevation. Withdrawals from the epilimnion during the summer will warm reservoir discharges (U.S. Bureau of Reclamation, 2005).