Projecting Temperature in Lake Powell and the Glen Canyon Dam Tailrace

By Nicholas T. Williams[1]

Abstract

Recent drought in the Colorado River Basin reduced water levels in Lake Powell nearly 150 feet between 1999 and 2005. This resulted in warmer discharges from Glen Canyon Dam than have been observed since initial filling of Lake Powell. Water quality of the discharge also varied from historical observations as concentrations of dissolved oxygen dropped to levels previously unobserved. These changes generated a need, from operational and biological resource standpoints, to provide projections of discharge temperature and water quality throughout the year for Lake Powell and Glen Canyon Dam. Projections of temperature during the year 2008 were done using a two-dimensional hydrodynamic and water-quality model of Lake Powell. The projections were based on the hydrological forecast for the Colorado River Basin and initial conditions from limnological field surveys. Results from the projection simulations are presented and compared with 2008 field observations. Post-simulation comparisons of projected results with field data were done to assess the accuracy of projection simulations.

Introduction

Drought in the Colorado River Basin from 1999 to 2005 greatly reduced the inflow to Lake Powell and brought about changes to temperature and water quality of the river below the dam. Reservoir elevations steadily dropped to an elevation of 3,555 feet in April 2005, just before the snowmelt runoff of that year. The powerplant intakes, which were then only 85 feet below the reservoir water surface, withdrew warmer water from the reservoir, and river temperatures below the dam peaked at 61 °F (16 °C) in October 2005 (fig. 1). While it was expected that temperatures in the river below the dam would warm with decreasing reservoir elevations, it was not the only factor contributing to warmer temperatures. Spring runoff volume and the local climate were also significant factors affecting the magnitude of warming in dam discharges (Bureau of Reclamation, 2007).

During the period of warmest river temperatures, the dissolved oxygen content of discharges from the dam declined to concentrations lower than any previously observed (fig. 1). Operations at Glen Canyon Dam were modified by running turbines at varying speeds, which artificially increased the dissolved oxygen content of discharges; however, these changes also resulted in decreased power generation and possibly damaged the turbines (Bureau of Reclamation, 2005). The processes in the reservoir creating the low dissolved oxygen content in the reservoir had been observed in previous years, but before 2005 the processes had never affected the river below the dam to this magnitude (Vernieu and others, 2005). As with the warmer temperatures, the low dissolved oxygen concentrations could not be explained solely by the reduced reservoir elevations. Other contributing factors include interactions with exposed sediment delta and spring runoff volume (Wildman, 2009).

The low dissolved oxygen content of Glen Canyon Dam discharges during 2005 resulted in increased efforts to provide better information on potential water-quality issues in the reservoir and on changes to temperature or water quality of dam discharges. Studying the conditions of the drought and

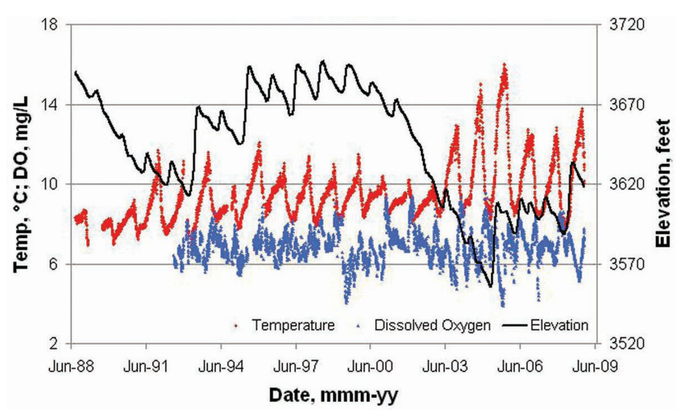

Figure 1. Daily water temperature and dissolved oxygen concentration below Glen Canyon Dam with Lake Powell water-surface elevations, 1988–2008 (adapted from Vernieu and others, 2005).

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reservoir processes has increased understanding of the causes of warmer temperatures and other water-quality changes in discharges from the dam (Vernieu and others, 2005; Williams, 2007; Wildman, 2009). Quarterly lake-wide monitoring of the reservoir provides information about conditions in the reservoir in advance of such events, but projecting the routing of water through the dam to the river below is difficult to determine from the reservoir monitoring data alone. A computer model has been developed and tested to reproduce historical hydrodynamics and water-quality characteristics of Lake Powell and the discharges from Glen Canyon Dam (Williams, 2007). Using this model in combination with monitoring data and hydrological forecasts allows for projection simulations of temperature in and below Lake Powell several months in advance. The objective of this report was to use the existing model and develop methods for simulating reservoir and dam discharge temperatures that can be replicated for repeated simulations at later dates.

Glen Canyon Dam and Lake Powell

Glen Canyon Dam is located in north-central Arizona just south of the Utah-Arizona border near the town of Page, Arizona (fig. 2). The dam was constructed between 1957 and 1964 and formed the reservoir known as Lake Powell. At full capacity the lake's elevation is 3,700 feet, the volume is 26.5 million acre-feet, and its deepest point is more than 500 feet. Water is released from the dam through the hydroelectric powerplant. The intake for the powerplant is at elevation 3,470 feet, 230 feet below the water surface of a full reservoir. The large lake and deep intake for the powerplant altered the temperature and water quality of the Colorado River below the dam. Large seasonal fluctuations from 32 °F to 80 °F (0 °C to 27 °C) in river temperatures were replaced with temperatures ranging from 44 °F to 54 °F (7 °C to 12 °C) after the reservoir filled and stayed within this range while reservoir water-surface elevations were maintained above approximately 3,600 feet (Vernieu and others, 2005).

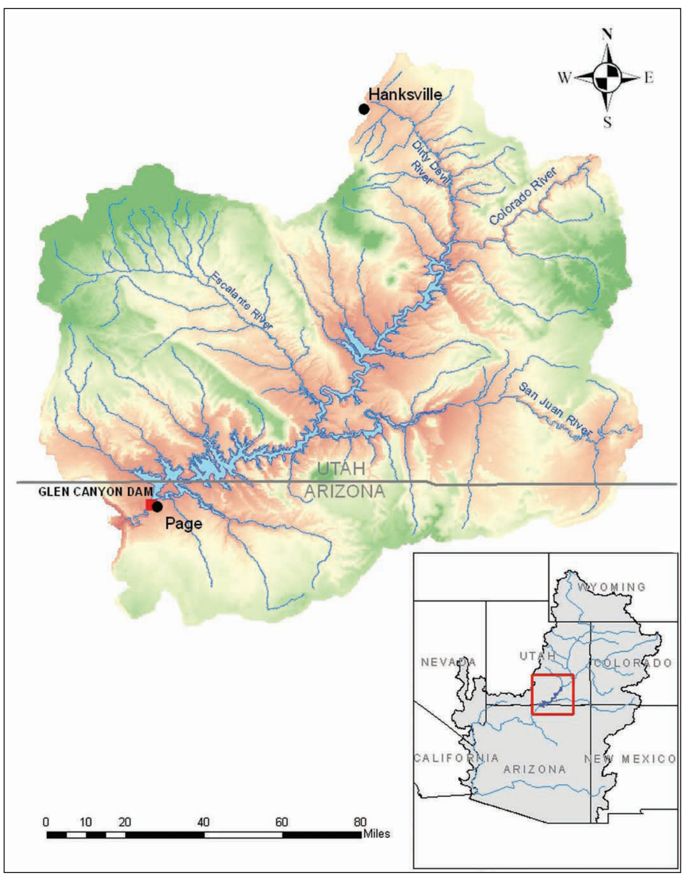

Figure 2. Lake Powell and immediate watershed showing location of Glen Canyon Dam; inset shows the location of Lake Powell in reference to the Colorado River Basin

Methods

Hydrologists and meteorologists develop forecasts to project runoff and weather that are intended to be an educated guess at what the future might bring. These forecasts are based on current conditions and assumptions of future conditions. Forecasts are not 100 percent accurate in their predictions, but the information they provide is still useful for planning purposes. Similarly, current conditions in Lake Powell and assumptions about future inputs to the reservoir during 2008 were simulated in a model to project characteristics of Lake Powell and the Colorado River below Glen Canyon Dam. Detailed results from the simulations were used to support quarterly monitoring and provide information for dam operations and resource management.

Hydrodynamic and Water-Quality Model

Temperature in and below Lake Powell is simulated using the two-dimensional hydrodynamic and water-quality model, CE-QUAL-W2, version 3.2 (Cole and Wells, 2003). CE-QUAL-W2 is currently developed by the U.S. Army Corps of Engineers and Portland State University and has evolved over three decades. It assumes lateral homogeneity and is ideal for long, narrow waterbodies such as Lake Powell. The model is capable of predicting water-surface elevations, velocities, temperatures, and a number of water-quality constituents. Water is routed through cells in a computational grid where each cell acts as a completely mixed reactor in each time step. Geometrically complex waterbodies are represented through multiple branches and cells. Multiple inflows and outflows are represented through point/nonpoint sources, branches, precipitation, and other methods. Output from the model provides options for detailed and convenient analyses.

Lake Powell Model Description

The Lake Powell CE-QUAL-W2 model was developed and tested by the Bureau of Reclamation, Upper Colorado Regional Office (Williams, 2007). The particular model discussed here simulated hydrodynamics, temperature, salinity, dissolved oxygen, phytoplankton, and organic matter decay in Lake Powell from January 1990 through December 2005. It is hereafter referred to as the calibration model so as to distinguish it from the projection simulation models of Lake Powell. The calibration model uses a geometric, computational grid and various input data to simulate these processes. The model computational grid, inputs, and calibration process and results are briefly discussed in the sections below.

Lake Powell Bathymetry

The bathymetry of Lake Powell is represented in the CE-QUAL-W2 model as a two-dimensional computational grid. The two dimensions represented are the length and depth, which are divided into longitudinal segments and vertical layers. The lateral dimension, or width, is not represented in the grid, but an average width is computed and used to determine volume. Because the model grid is two-dimensional, all modeled parameters, such as temperature, velocity, and water-quality constituents, can only vary in the longitudinal and vertical directions. This assumes that modeled parameters do not vary significantly in the lateral direction, and this assumption is considered appropriate for Lake Powell.

The Lake Powell CE-QUAL-W2 computational grid consists of nine branches that represent the following channels and bays: Colorado River or main channel, Bullfrog and Halls Creek Bay, Escalante River channel, San Juan River channel, Rock Creek Bay, Last Chance Bay, Warm Creek Bay, Navajo Canyon, and Wahweap Bay (fig. 3). The nine branches are further subdivided into 90 segments between 800 and 17,000 meters in length. Each segment consists of up to 97 layers, which are each 1.75 meters in height. Figure 4 is an image of the computational grid showing a plan view of the entire reservoir, a side view of the segment above Glen Canyon Dam, and a profile view of the Colorado River or main channel. In the computational grid, the color green indicates the upstream segment of a branch, blue indicates the downstream segment of a branch, and red indicates the segment where one branch connects to another branch.

Model Inputs

Model inputs are time sequences of data that describe meteorological conditions, inflows, outflows, and water-quality parameters at Lake Powell. The time sequence inputs also provide the model boundary conditions. Meteorological data measured and recorded at the Page Municipal Airport were obtained through the National Climate Data Center (NCDC). Inflow records for all gaged tributaries of Lake Powell were obtained from the U.S. Geological Survey (USGS) National Water Information System (NWIS) for the Colorado River. The number and location description of these stream sites are presented in table 1. For inflows where little or no data are available, estimates are made to approximate base flows. Data for outflow from Lake Powell through Glen Canyon Dam were obtained from historical reservoir data recorded by the Bureau of Reclamation (Reclamation). Water-quality data for tributary inflows, including temperature, total dissolved solids (TDS), dissolved oxygen, and nutrients, were obtained from measurements collected by several different agencies, including USGS, Reclamation, and the Utah Division of Water Quality (Utah DWQ).

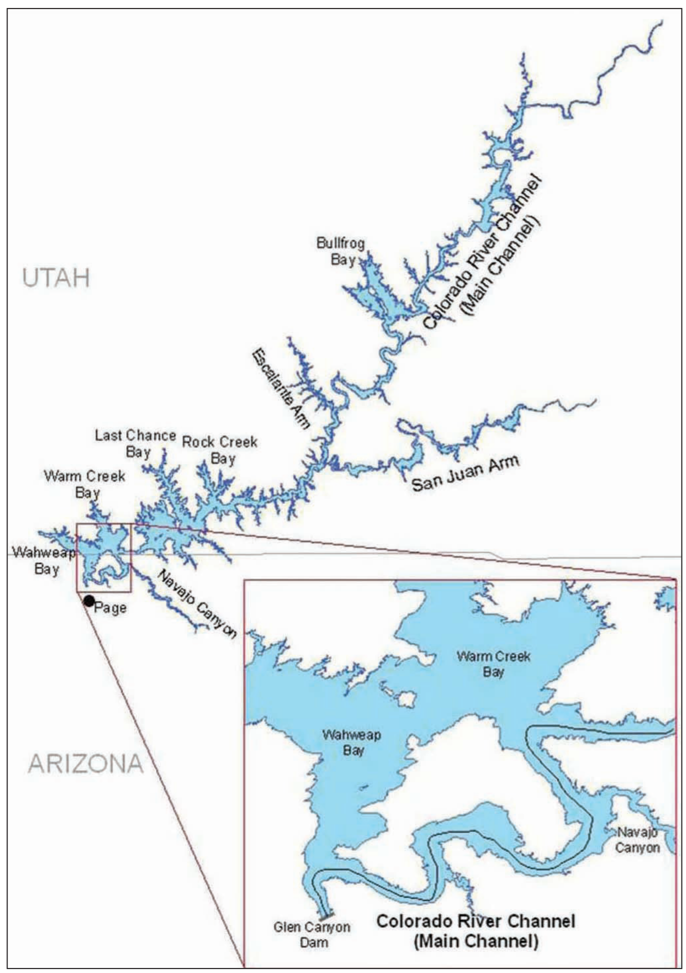

Figure 3. Lake Powell channels and bays.

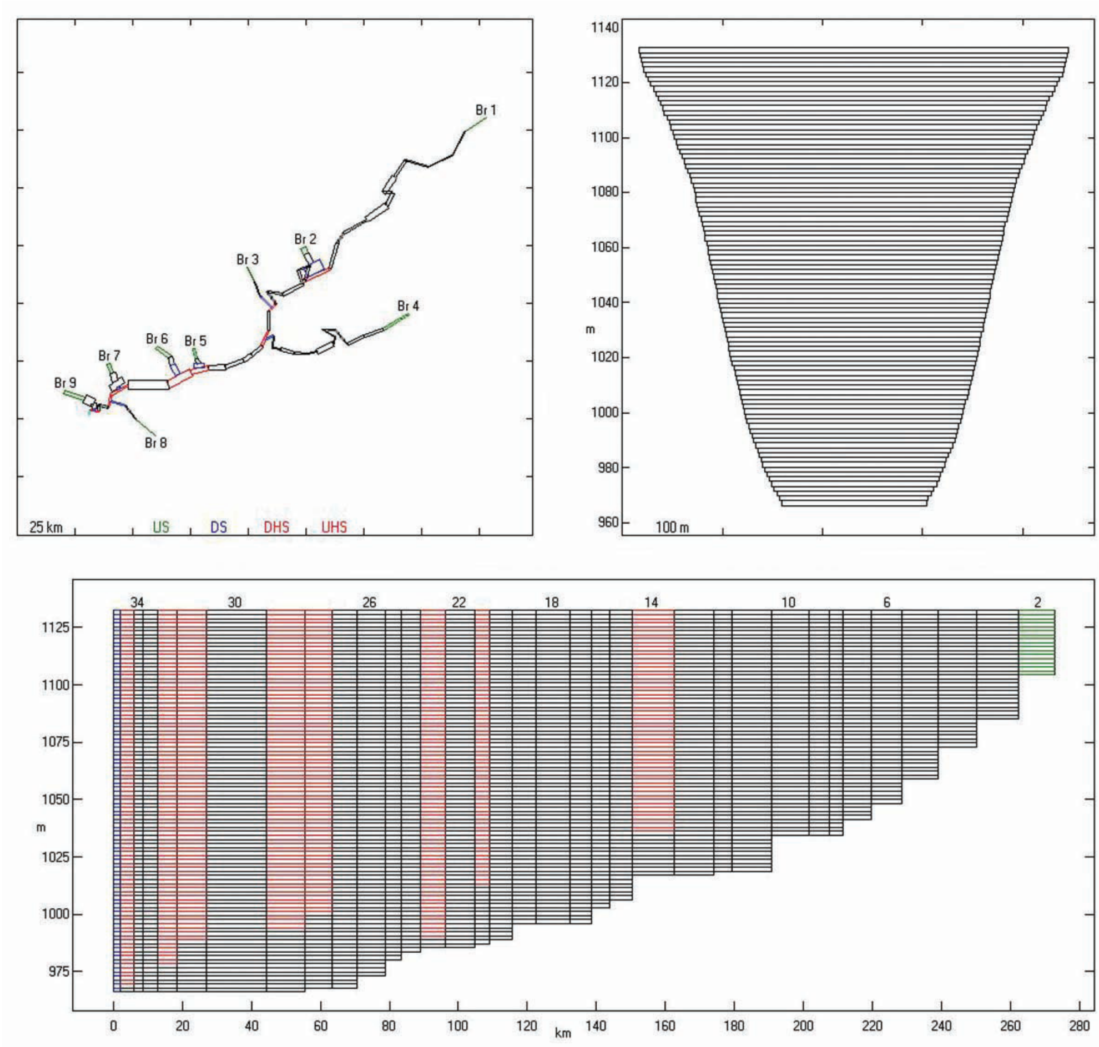

Figure 4. Lake Powell computational grid displaying plan, side, and profile views of the grid.

Table 1. U.S. Geological Survey (USGS) National Water Information System streamgages on tributaries of Lake Powell.

USGS streamgage number	Location description
09180500	Colorado River near Cisco, UT
09315000	Green River at Green River, UT
09328500	San Rafael River near Green River, UT
09379500	San Juan River near Bluff, UT
09333500	Dirty Devil River above Poison Springs Wash near Hanksville, UT

The word "Predicted" in the equation is part Roman and part italic. Should it all be italic?

Need reference to table 4.

Calibration

The calibration model was calibrated for the historical period 1990–2005 by comparing field observations of reservoir water-surface elevation (WSE), temperature, TDS, and dissolved oxygen with simulated model results. The quality of model calibration was measured by using the absolute mean error (AME) statistic (eq. 1). Model calibration statistics are presented in table 2 for the reservoir and in table 3 for the dam discharge. The mean of discharge temperatures and TDS are also presented in table 3. Statistics of dissolved oxygen concentration for dam discharges are not included because power generation increases dissolved oxygen in the river below the dam slightly depending on several factors (Williams, 2007). The model does not account for those factors; therefore, a comparison of dissolved oxygen content of the discharge with model results would not reflect actual processes.

$$AME = \frac{\sum \left| \mathrm{Pr}\,edicted - Observed \right|}{NumberofObservations} \qquad (1)$$

Projection Model

Four projection simulations were run during 2008, which simulated reservoir and discharge temperatures. The projection simulation models were based on the calibration model, meaning kinetic coefficients and parameters determined by the 1990–2005 calibration were used in the projection simulation. The first step in setting up the projection simulations was determining the model simulation period. The starting date of model simulation was determined by the quarterly lake-wide monitoring surveys that provided data for the model initial conditions. The ending date of all simulations was December 31, 2008. Next, input data were added to the model. The inputs included reservoir initial conditions, forecasted hydrology including inflows and outflows, meteorology, and inflow temperatures and water quality.

Reservoir initial conditions were obtained from quarterly lake-wide monitoring surveys conducted by the USGS Grand Canyon Monitoring and Research Center (GCMRC). Surveys used for initial conditions were conducted from February 26 to March 2, 2008, and from June 14 to June 18, 2008. During the surveys, data were collected for physical, chemical, and biologic characteristics of the reservoir at more than two dozen locations throughout the reservoir. The temperature, TDS, and dissolved oxygen data collected during the surveys were used as reservoir initial conditions and were interpolated across the model computational grid to create the input for the model.

Next, reservoir inflows and outflows for the projected period of time were obtained from the 24-Month Study reports (Bureau of Reclamation, 2009) that are hydrological forecasts of inflows to and operations of major reservoirs in the Colorado River Basin for a period of 24 months beginning with the month the report was issued. The reports provide monthly projections of Lake Powell inflow, outflow, and water-surface elevations. Inflow and outflow data in the reports are given as monthly volumes in acre-feet. Elevation data are given as end-of-month elevations in feet. The 24-Month Study provided total monthly inflow, but the Lake Powell projection simulation models require that the total inflow volume be allocated among the major tributaries. The allocation to the major tributaries was based on historical average ratios of tributary inflow to total reservoir inflow, which were 79 percent for the Colorado River, 13 percent for the San Juan River, <1 percent for the Dirty Devil River, and 2 percent for ungaged inflows.

Meteorological data required by the model include air and dewpoint temperature, wind speed and direction, and cloud cover recorded at the Page Municipal Airport. Typically hourly or sub-hourly observations of these parameters are used, but detailed forecasts of meteorology were not available; therefore, an hourly average of meteorological data for 1990–2005 from the Page Municipal Airport was used for the corresponding model simulation dates and times.

The inflow temperature and water-quality inputs to the projection simulations were developed from empirical and statistical relations. The program W2Met, developed by Environmental Resource Management, Inc. (ERM), was used to develop inflow temperatures on the basis of meteorological inputs (Buchak and others, unpub. data, 2004). The same method was used to derive the inflow temperatures for the calibration model of Lake Powell (Williams, 2007). Inflow TDS was developed from power regressions with streamflow

Table 2. Lake Powell CE-QUAL-W2 model, reservoir calibration statistics, 1990–2005 (Williams, 2007).

[m, meters; °C, degrees Celsius; mg/L, milligrams per liter]

Parameter	Absolute mean error
Water-surface elevation	0.08 m
Temperature	0.74 °C
Total dissolved solids	31.3 mg/L
Dissolved oxygen	1.09 mg/L

Table 3. Lake Powell CE-QUAL-W2 model, dam discharge calibration statistics, 1990–2005 (Williams, 2007).

[°C, degrees Celsius; mg/L, milligrams per liter]

Parameter	Mean		Absolute mean error
	Observed	Modeled	
Temperature	9.69 °C	9.22 °C	0.46 °C
Total dissolved solids	501 mg/L	492 mg/L	16.1 mg/L

It would be helpful if Buchak's initials could be included and his affiliation.

Table 4. Projection simulation name and associated dates for the 24-Month Study report, starting date, lake-wide survey, period of observed data input to the model, and period of projected data input to the model.

Projection name	24-Month Study	Model starting date	Lake-wide survey used for initial conditions	Period of actual data inputs	Period of projected data inputs
April 2008	April 2008	2/29/2008	February/March 2008	2/29/2008 to 4/15/2008	4/16/2008 to 12/31/2008
June 2008	June 2008	2/29/2008	February/March 2008	2/29/2008 to 6/4/2008	6/5/2008 to 12/31/2008
July 2008	July 2008	6/16/2008	June 2008	6/16/2008 to 7/28/2008	7/29/2008 to 12/31/2008
October 2008	October 2008	6/16/2008	June 2008	6/16/2008 to 10/16/2008	10/17/2008 to 12/31/2008

for the major tributaries to Lake Powell (Liebermann and others, 1987). The dissolved oxygen content of the inflows was assumed to be at saturation levels based on data collected by the USGS (Williams, 2007). Other water-quality inputs to the model were developed similar to the inputs of the calibration model (Williams, 2007).

Four projection simulations were run during the spring and summer of 2008. These simulations are referred to as the April, June, July, and October 2008 projection simulations and are named on the basis of the month from which the 24-Month Study data were used. For example, the April 2008 projection simulation used hydrological forecast data from the April 24-Month Study. The model starting date of each projection simulation depended on the initial condition data collected during the quarterly lake-wide surveys. Each simulation had a period of time between the model starting date and the actual calendar day when the model was executed. During this period, observed data for inflow, outflow, and meteorology, rather than forecasted or average data, were used for the model inputs.

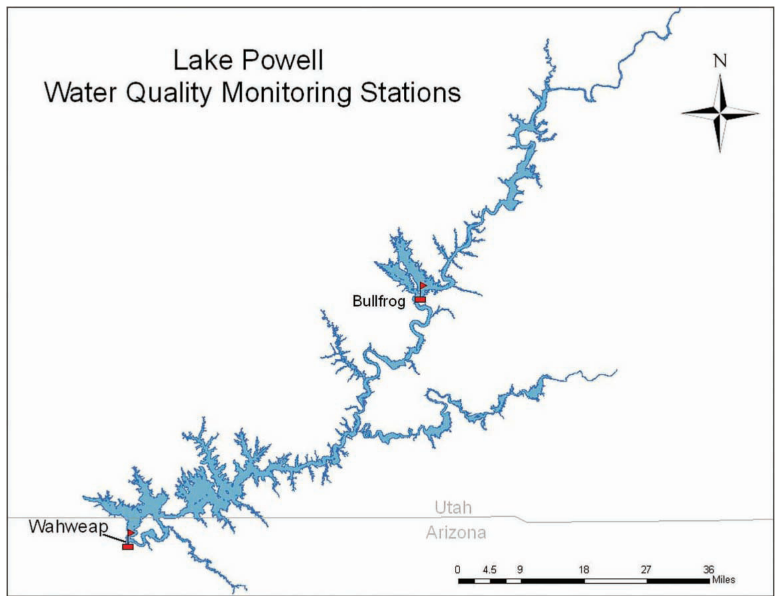

Figure 5. Lake Powell showing Wahweap and Bullfrog monitoring locations.

Results

The results of reservoir temperatures from the projections simulation models are presented as depth profiles of temperature and are compared with actual reservoir temperature profiles measured during monitoring surveys during June 2008 and October-November 2008. Two reservoir monitoring locations were selected to present simulation and observed temperatures—Wahweap and Bullfrog (fig. 5). The June profiles for Wahweap (fig. 6) and Bullfrog (fig. 7) compare temperature results from the April 2008 and June 2008 projection simulations with the observed reservoir temperatures. The accuracy of the projections is determined from the AME statistic (eq. 1). The AME statistics of the projection simulations compared with the June observed data are shown in table 5.

The October-November profiles for Wahweap (fig. 8) and Bullfrog (fig. 9) compare temperature results from each projection simulation with the observed reservoir

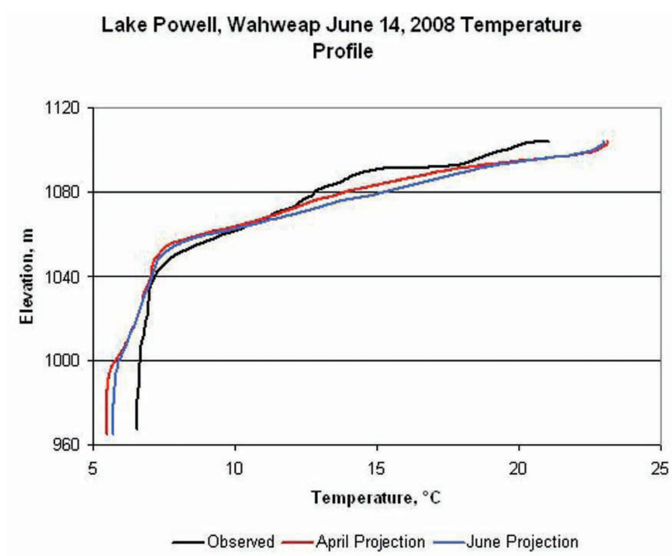

Figure 6. Wahweap, Lake Powell, June 14, 2008, temperature profile comparing projection simulation and observed temperatures.

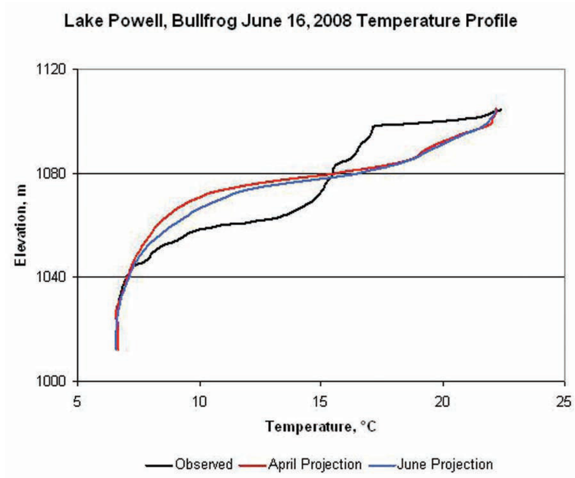

Figure 7. Bullfrog, Lake Powell, June 16, 2008, temperature profile comparing projection simulation and observed temperatures.

Table 5. Reservoir temperature profile absolute mean error statistics for 2008 projection simulations.

[°C, degrees Celsius; NA, not available (or not applicable?)

Projection simulation	Wahweap profile June 14, 2008	Bullfrog profile June 16, 2008	Wahweap profile October 29, 2008	Bullfrog profile November 1, 2008
April 2008	0.99 °C	1.85 °C	0.84 °C	1.06 °C
June 2008	1.17 °C	1.64 °C	0.56 °C	1.04 °C
July 2008	NA	NA	0.48 °C	0.77 °C
October 2008	NA	NA	0.57 °C	0.83 °C

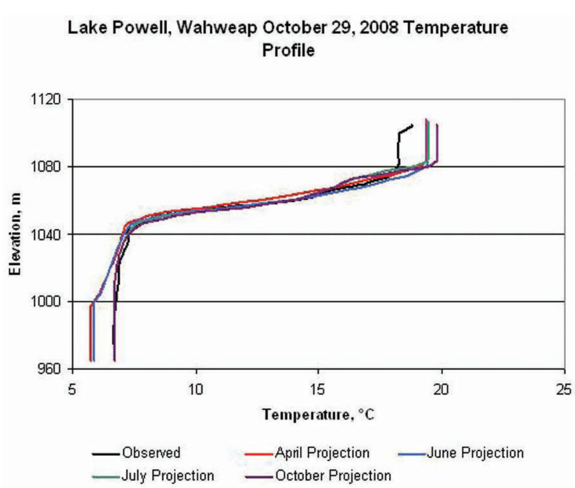

Figure 8. Wahweap, Lake Powell, October 29, 2008, temperature profile comparing projection simulation and observed temperatures.

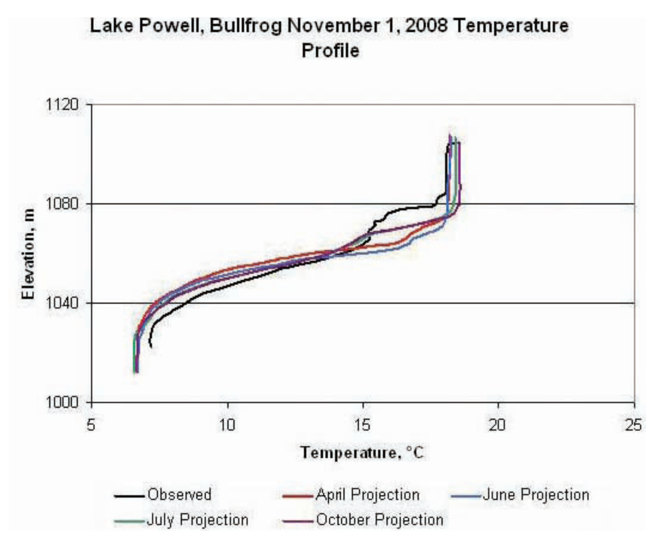

Figure 9. Bullfrog, Lake Powell, November 1, 2008, temperature profile comparing projection simulation and observed temperatures.

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temperatures. The AME statistics of the projection simulations compared with the October-November observed data are shown in table 5.

The results of dam discharge temperatures from the projection simulation models are presented as daily average temperatures and compared with actual water temperatures from Glen Canyon Dam discharges between April and December 2008. The actual water temperatures are labeled “Below Dam DCP” (Data Collection Platform) in the figures displaying results. Results from the April 2008 projection simulation are presented in figure 10, results from the June 2008 projection simulation are presented in figure 11, results from the July 2008 projection simulation are presented in figure 12, and results from the August 2008 projection simulation are presented in figure 13.

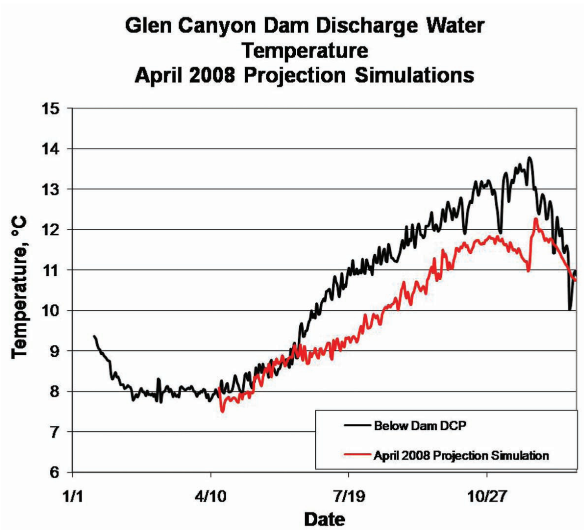

Figure 10. Glen Canyon Dam discharge water temperature, April 2008 projection simulation temperatures compared to Below Dam DCP temperatures.

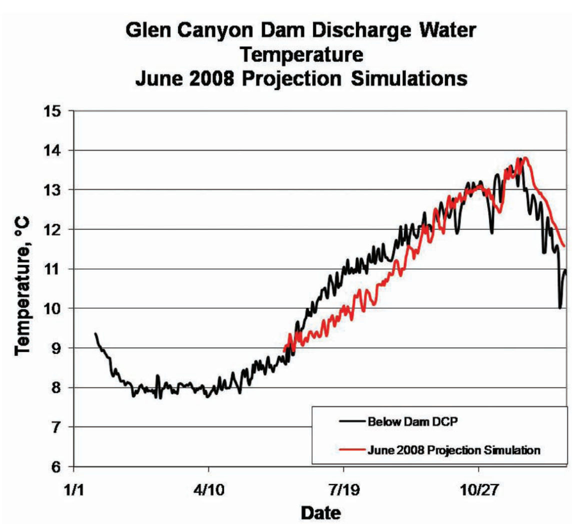

Figure 11. Glen Canyon Dam discharge water temperature, June 2008 projection simulation compared to Below Dam DCP temperatures.

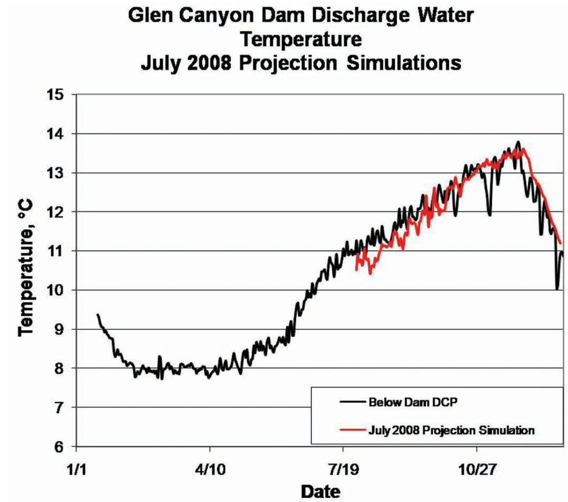

Figure 12. Glen Canyon Dam discharge water temperature, July 2008 projection simulation compared to observed Below Dam DCP temperatures.

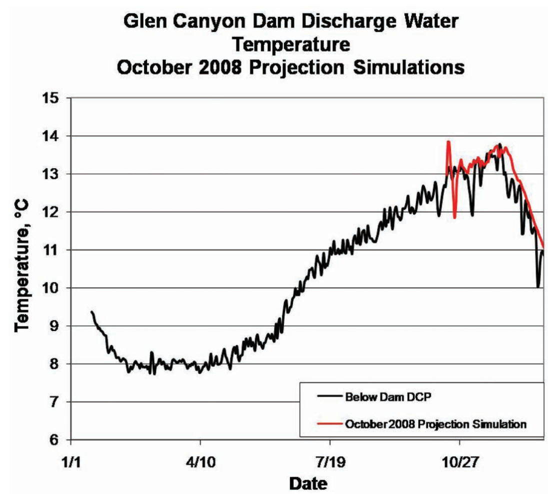

Figure 13. Glen Canyon Dam discharge water temperature, October 2008 projection simulation compared to Below Dam DCP temperatures.

Discussion

The results of water temperature in Glen Canyon Dam discharges using projection simulations are encouraging. As expected, projections are more accurate in the late season simulations as can be seen by comparing the April and June results with the July and October results. The April projections, in particular, do not adequately project the warmest discharge temperatures. The differences in the projections can be explained by several factors.

Warming is variable during spring months at Lake Powell and in the inflows. The July and October simulations capture this warming through the June initial conditions and actual meteorology between June and the date of the projection simulation (July or October). The April and June simulations rely on assumptions during the most critical time of reservoir warming, which is the spring runoff period.

Hydrological forecasts are subject to assumptions for snowpack accumulation, melting patterns, and other hydrologic factors. The forecasts are most variable during the periods of highest inflows, which are April through July. Base flows during the other months do not have as much variability. The April and June simulations use forecasts of spring runoff into the lake while the July and October simulations are done after spring runoff thereby removing the uncertainty associated with runoff assumptions.

The projection simulations did not capture the development of stratification, especially in the upper reservoir as is illustrated by the June Bullfrog temperature profile. Based on the differences between the modeled results and the observed temperatures, the use of average meteorological data to represent meteorological conditions in the projection simulations may not be an appropriate assumption. Future projection simulations could explore alternate methods of representing meteorological conditions. Methods to disaggregate inflow volumes from monthly average flow rates to daily average flow rates could also be investigated.

Implications for Management

Reliable forecasts of water temperatures below Glen Canyon Dam are important to scientists and natural resource professionals involved in aquatic habitat studies in Grand Canyon. Results from the Lake Powell CE-QUAL-W2 model are input to a model of the Colorado River in Grand Canyon maintained by GCMRC. The results from this model include water temperatures at several key locations along the river. The data from the two models allow professionals to know of temperatures conditions in advance and adapt studies accordingly. Accurate results from the CE-QUAL-W2 model are crucial to the Colorado River model and to resource management planning. Because the application of the model for projection simulations is still being developed and refined, a value of +/– 1 °C has been arbitrarily used to define accurate results. Continued development and experience with the projection simulations are expected to reduce that value.

It is anticipated that the model simulation results will continue to be used concurrently with the Colorado River model. Future uses will build on the knowledge and experience gained from this first year of model projections. Specifically, the early spring model projection will be considered qualitative, and recommendations to the GCMRC will include delaying detailed analysis and planning until a projection can be made in June or July. Subsequent projections in a given year will be used to confirm previous projection results or provide information in the event projections differ significantly.

Acknowledgments

I would like to thank Mr. Jerry Miller, retired Reclamation water-quality scientist, for his mentoring, input on the modeling, and insight into Lake Powell processes; Mr. Robert Radtke, Reclamation physical scientist, who supplied several images that were used during the presentation to illustrate reservoir water quality and processes; Mr. Rich Wildman for sharing his knowledge and insight into geochemical processes at Lake Powell; and finally, Mr. Bill Vernieu, USGS hydrologist, for providing monitoring data from Lake Powell limnological surveys that were used to calibrate the model and compare results.

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