ALGAL SUSCESSION AND NUTRIENT DYNAMICS IN ELEPHANT BUTTE RESERVOIR

by

Eric J. Nielsen

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering

Brigham Young University

April 2005

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Eric J. Nielsen

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

Date	E. James Nelson, Chair
Date	A. Woodruff Miller
Date	Gus P. Williams

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the dissertation/thesis of Eric J. Nielsen in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date	E. James Nelson Chair, Graduate Committee

Accepted for the Department

A. Woodruff Miller
Department Chair

Accepted for the College

Douglas M. Chabries
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

ALGAL SUSCESSION AND NUTRIENT DYNAMICS IN

ELEPHANT BUTTE RESERVOIR

Eric J. Nielsen

Department of Civil and Environmental Engineering

Master of Science

A water quality model was created for Elephant Butte Reservoir, New Mexico to understand nutrient dynamics and algal response during a three year period. The model chosen for this study was CE-QUAL-W2 because of its proven ability to accurately represent hydrodynamics and the ability to represent multiple algal groups. Elephant Butte has been subject to large algal blooms. This study examined the phosphorus loading into the reservoir to see if it could sustain the observed algal growth. Data showed that the amount of bioavailable phosphorus was more than enough to support large blooms. This study was also an initial attempt to model multiple groups of algae. The information obtained will later be used in other water quality models built and maintained by the US Bureau of Reclamation. Four algal species were modeled; diatoms, dinoflagellates, cyanobacteria and greens. Research

into literary values of kinetic parameters for multiple algal species was conducted and the results were compiled in this paper to assist future modeling efforts. Because Elephant Butte was often nitrogen-limited, the calibration of algal growth was difficult. Algal growth was very sensitive to the adjustment of kinetic parameters for nitrogen half-saturation, light requirements, growth rates and temperature rate multipliers.

ACKNOWLEDGMENTS

I wish to thank the members of my graduate committee, Dr. Miller and Dr. Williams for their insight and especially thank my advisor Dr. Nelson for his constant support and encouragement. I thank Jerry Miller, Nick Williams and Amy Cutler from the Bureau of Reclamation for offering their expertise in the field of modeling and their knowledge concerning this area of research. I wish to express appreciation to the Bureau of Reclamation and EMRL for funding this research.

I also wish to thank the one who should be thanked most of all, my wife Anna-Lena for being my best friend and supporting me through all of life's endeavors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

Water quality is becoming a more integral part of the management process of water resources. These water sources are vital for domestic water use, irrigation, power generation, revenue from recreational activities and as habitat for wildlife. The question of supply is now directly tied with the question of the quality of that supply. Federal standards are established and enforced by states to maintain and protect the water quality of lakes and rivers. The water quality of lakes and rivers are often stressed by population growth, industry, farming, natural pollutants and other activities.

These sources can degrade the quality of waterbodies miles away from their immediate location. Watersheds, by definition, are areas that drain to a control point. They are complex systems that can house several of the previously mentioned sources of potential impact to water quality. Reservoirs are often a control point of watersheds. Reservoirs are excellent indicators of the overall health of a watershed because they are receptacles of all watershed activities. Over a timeframe of many years reservoirs age; meaning that they become more biologically productive. Because pollutants from a watershed are concentrated in reservoirs, the reservoirs age at an accelerated rate. This process of accelerated growth is called eutrophication.

Eutrophication of reservoirs occurs when nutrient levels are high and the productivity of plant species, specifically algae, increases.

Elephant Butte Reservoir, the modeling site of this study, is situated on the Rio Grande River and is the largest reservoir in the state of New Mexico. It serves as a recreational area, a source of irrigation and drinking water and it is used for power generation. (Elephant Butte, 2004) Recently Elephant Butte Reservoir has suffered decreasing levels of water quality, including large algal blooms. The state of New Mexico's Water Quality and Water Pollution Control (305d) report for 2002 states "nuisance algae (is one of) the major casual agents of use impairment." Recent algal blooms in Elephant Butte have been toxic, which presents a hazard to livestock, pets and wildlife in the area. The presence of floating algae also discourages recreation and causes various problems in water treatment processes downstream such as clogged filters and taste and odor in drinking water. Large algal blooms further degrade water quality by depleting dissolved oxygen in surface waters, which is detrimental to aquatic animal populations. Elephant Butte Reservoir is an excellent case study for the purposes of this research.

1.1 Model Selection

With the increasing concern over water quality, decision makers want to know what drives the eutrophication process so that they can identify limiting nutrients and improve water quality. Numeric models are being used to better understand the degradation of water quality and the eutrophication of reservoirs. Numeric models are useful as interpretative tools to better understand the prototype or as predictive tools to investigate the impact of prescribed changes. There are many numeric models available for simulating water quality in reservoirs. WASP6 (Water Quality Analysis Simulation Program) is an EPA supported water quality model that has many state variables to model natural and manmade pollutants. WASP6 can model multiple CBOD sources, chemicals and solids, but it models algae as one assemblage. (WASP, 2005) BASINS (Better Assessment Science Integrating point and Nonpoint Sources) is another widely-used water quality model. It is a multi-purpose environmental analysis system that integrates many models and databases for water quality studies. (BASINS, 2004) Another numeric model, CE-QUAL-W2 is a two-dimensional laterally-averaged hydrodynamic and watery quality model. Recent versions of CE-QUAL-W2 can model many constituents including multiple algal groups. (Cole, 2002)

CE-QUAL-W2 was chosen for this modeling study for a few important reasons. CE-QUAL-W2 is widely used and accepted, and was the model selected for this study by the Bureau of Reclamation Upper Colorado Water Quality Group who funded this research. CE-QUAL-W2 is well suited for this study because it allows algae to be modeled as multiple groups. Modeling algae in multiple groups is important because modeling algae as one conglomerate is only a general approximation of actual conditions because kinetic rates are highly species dependent. (Zison, 1978) A more accurate representation is possible by modeling algae as groups based on different species.

1.2 Previous Research

Modeling multiple algal groups is a relatively new endeavor. Investigation into previous studies using multiple algal groups found few examples. This is likely due to the fact that most models do not support multiple algal groups and that simulating multiple groups adds more uncertainty and difficulty into a model. Bowen (1999) investigated the effect of nutrient reduction on the estuarine portion of the Nuese River in North Carolina. He found that the model poorly predicted the timing and location of algal blooms and that calibration to observed values depended on adjusting multiple parameters. These same problems were encountered during this research. The setting of Bowen's paper differs from that of this thesis because different algae are found in estuarine environments than those found in freshwater reservoirs. Applicable research was also conducted on Lake Waco (Flowers, 2001) and is proposed on Lake Spokane (Cusimano, 2004).

Deer Creek Reservoir on the Provo River in Utah is a freshwater system that was successfully modeled by the Bureau of Reclamation. (PSOMAS, 2002) In the 1980's Deer Creek experienced high nutrient loadings and became eutrophic. The Deer Creek water quality model was conducted to better understand past problems with algal blooms associated with this eutrophic period and as a guide to improve management decisions. Water quality levels improved dramatically through the recommendations made by this study on Deer Creek. (Miller, 2005) The conditions in Deer Creek were similar to the conditions now witnessed in Elephant Butte. This study attempts to investigate the situation in Elephant Butte so that the same positive results experienced in Deer Creek can be attained in Elephant Butte. The Deer Creek water quality model represented algae as one mass in the model. The Elephant Butte water quality model represents various species of algae as multiple groups. This research is the next step in the process of more completely modeling reservoirs using multiple algal groups.

1.3 Objectives

The objectives of this study are to:

- Determine whether the external phosphorus loading is sufficient to sustain the observed amount of algal growth or is internal loading of phosphorus also required;
- Represent algae in CE-QUAL-W2 with multiple groups and correctly model their seasonal succession;
- Research literature values for algal growth and create a reference document for others using CE-QUAL-W2 to model reservoirs using multiple algal groups; and
- Assist the Bureau of Reclamation in managing water quality of Elephant Butte Reservoir by contributing this model and its results as part of a continuing study.

In an attempt to better understand and develop management methods to limit the appearance and extent of these algal blooms, this study will examine the effect different loadings of phosphorus have on algal growth and attempt to model the seasonal succession of these algae.

The limiting nutrients of algal growth will also be examined, specifically phosphorus. The source of phosphorus can be broken down into two compartments: 1) Phosphorus can enter the reservoir externally through rivers or tributaries and 2) phosphorus sorbs onto iron-containing sediments under aerobic conditions and is released and made internally available when the water column becomes anoxic. This distinction between external and internal phosphorus loading is important because it is a determining factor in the choice of remediation. For example, if the primary source of phosphorus is internal (phosphorus desorbing from sediments), then treatment of external sources such as improved wastewater treatment in cities upstream will have little effect on the water quality of Elephant Butte Reservoir. It is vital to know that proposed remediation steps will be successful when making management decisions.

CE-QUAL-W2 allows the investigation of characteristics that drive reservoir behavior and predict future behavior given certain situations. For this study, CE-QUAL-W2 was used to model Elephant Butte Reservoir over a five-year period from 1998-2002. This period was chosen because of the range of conditions experienced by the reservoir in these four years. Elephant Butte Reservoir storage was near storage capacity in 1998 and 1999. By the end of 2002 the reservoir was drained to 15% of capacity. By including both wet and dry years, the validity of the model results is increased. (Cole, 2002)

1.4 Scope

This study is part of an ongoing U.S. Bureau of Reclamation, U.S. Geological Survey, and State of New Mexico Study to assess the water quality impacts in

Elephant Butte Reservoir. The scope of this study was to set up the CE-QUAL-W2 model and calibrate it hydrodynamically, evaluate the nutrient dynamic within the reservoir, and to initially test the new algal compartment of the latest version CE-QUAL-W2. This model is also part of an ongoing study to determine the relationship between internal and external phosphorus loading and the algal bloom dynamics within the reservoir. This work was in part supported by funding from the U.S. Bureau of Reclamation. It is anticipated that additional work with this model, beyond the scope of this thesis, will be done by the U.S. Bureau of Reclamation, and the State of New Mexico. The purpose of this thesis was to set up the model, complete initial calibration, assemble the database to begin testing the new algal compartment of Version 3.2, and complete a preliminary calibration of the unique algal succession in Elephant Butte Reservoir.

2 Model Background

2.1 Site Characterization

Elephant Butte Reservoir is situated on the Rio Grande River in southwestern New Mexico near the city of Truth or Consequences (see Figure 2.1), 125 miles northwest of El Paso, Texas. Elephant Butte Dam (originally Engle Dam) was completed in 1916 by the Bureau of Reclamation. It is a concrete gravity dam that stands 301 feet high and 1,674 feet long. The conservation capacity of the reservoir is 2.2 million acre-feet of water. At the time it was built, Elephant Butte Reservoir was the largest structure built in the United States, creating the largest manmade reservoir in the world. (Elephant Butte, 2004) At full capacity Elephant Butte Reservoir stretches back 40 miles along the Rio Grande River. Elephant Butte Reservoir is a long and narrow reservoir, no more than 3 miles at any point when filled to capacity. It is divided in two sections by an even narrower section of the reservoir called the "Narrows". The width of the reservoir through the Narrows ranges from 950 feet to 2000 feet. After the Narrows, Elephant Butte Reservoir quickly becomes significantly deeper than the portion of the reservoir above the Narrows.

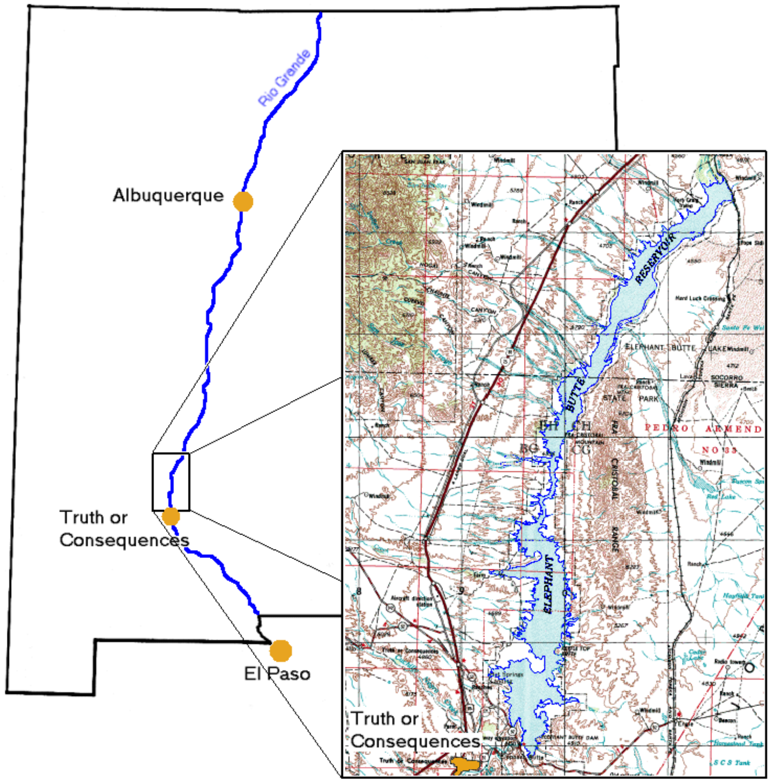

Figure 2.1 Map of Elephant Butte Reservoir.

2.1.1 Water Uses

Water from Elephant Butte Reservoir is used for irrigation and as a municipal water supply for the city of El Paso, Texas. Besides the importance of preserving the water quality of Elephant Butte for drinking and irrigation purposes, it is also important for the recreational use of the reservoir. As the largest water body in New Mexico, Elephant Butte has always been a recreation destination. Elephant Butte attracts an average of 1.7 million visitors a year which is nearly 40% of all state park visits. (UNM, 2005) This constitutes a substantial portion of the estimated $100 million brought into the state's economy through tourism. Water from the reservoir is also used to power a hydroelectric plant at the base of the dam. This hydroelectric plant contains three generators each producing up to 10.3 MW of electricity. Elephant Butte Reservoir is a valuable resource and a worthy candidate of a water quality study.

2.2 Model Characterization

2.2.1 History

CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality numerical model. The term “laterally-averaged” means that the computed values (temperature, concentration, etc.) for each cell are constant across the width of that cell. CE-QUAL-W2 is a finite difference model which uses a grid to numerically solve the governing equations. CE-QUAL-W2 has been under continuous development since 1975. It was originally known as the Laterally Averaged Reservoir Model (LARM), which was authored by Edinger and Buchak. Water quality algorithms were added in 1986 by the Water Quality Modeling Group at the US Army Engineer Waterways Experiment Station (WES) and the model was renamed CE-QUAL-W2 Version 1.0. CE-QUAL-W2 has evolved from that time to include new algorithms to improve accuracy and stability. (Cole, 2002)

2.2.2 Capabilities and Limitations

It is important to understand the capabilities and limitations of CE-QUAL-W2 in order to understand its application to Elephant Butte and the model results. CE-QUAL-W2 has many capabilities which make it applicable for this study. Since Elephant Butte is a long and narrow reservoir, a laterally-averaged model like CE-

QUAL-W2 can be used because changing concentrations across the width of the reservoir are assumed to be insignificant. CE-QUAL-W2 allows for long term simulations and water quality responses which are also important for this study. Version 3.1 allows for modeling of multiple algal groups and output of kinetic fluxes for multiple constituents including phosphorus. The limitations of CE-QUAL-W2 which affect this study are that it does not explicitly include zooplankton and their effects on recycling of nutrients. The model also uses a simplistic algorithm to simulate sediment oxygen demand. "It does not model kinetics in the sediment and at the sediment-water interface. This places a limitation on long-term predictive capabilities of the water quality portion of the model." (Cole, 2002) Despite these limitations CE-QUAL-W2 has accurately modeled the behavior of many water bodies. (Cole, 2002)

2.2.3 Previous Applications

CE-QUAL-W2 has been used by modelers around the world. To date the number of waterbodies modeled by CE-QUAL-W2 is more than 250. Models using multiple algal groups like this study include Nuese River, Lake Spokane and Lake Waco. Lake Waco was one of the first to use the ability of CE-QUAL-W2to model multiple algal groups. (Flowers, 2001) Lake Spokane had been modeled using CE-QUAL-W2 and expressed interest and the need to develop the model further by including multiple algal groups. (Cusimano, 2003) Nuese River investigated the sensitivity of calibration of multiple algal groups and found that prediction of time and place of algal blooms is problematic. (Bowen, 1999)

The Deer Creek TMDL study investigated the level of eutrophication in the reservoir and as part of that study involved the use of CE-QUAL-W2 to model the effects of nutrients on algal growth. Although the scope of the Deer Creek is larger than the scope of this study, it is similar in many respects. Deer Creek is an important source of drinking water to the Salt Lake and Utah counties and it is a popular recreation area. During the 1970s and 1980s Deer Creek Reservoir was highly eutrophic suffering from low hypolimnetic dissolved oxygen concentrations, large toxic algal blooms and high levels of nutrient concentrations. CE-QUAL-W2 was used to better understand reservoir processes and to predict results of proposed management practices. The results of the predictive modeling were instrumental in reducing the nutrients in the reservoir by 70 percent and improving the overall water quality. Because CE-QUAL-W2 Version 2 was used in the modeling of Deer Creek Reservoir, the algae had to be represented as a single conglomerate. (PSOMAS, 2002) This study uses CE-QUAL-W2 Version 3, which allows the modeling of several algal groups.

3 Model Generation

The purpose of this chapter is to describe the process of creating the Elephant Butte Reservoir CE-QUAL-W2 model, to give supportive background information relevant to the problem statement, and to validate the model results. The following sections discuss the various components required for the Elephant Butte model, which are bathymetry, boundary conditions, meteorological data, evaporation, constituent data and algal composition. The section on bathymetry explains how the physical description of the reservoir was represented. The boundary conditions of the model which will be discussed include inflow, outflow and surface relationships. The meteorological data section illustrates the use and importance of weather conditions on the model. Evaporation is an important concern in the Elephant Butte model. The section on evaporation details how it was represented in the model. The constituent data used to describe the nutrients, organic matter, suspended solids and other parameters are described. The final section discusses the data and methods used to characterize the different species of algae in Elephant Butte Reservoir. CE-QUAL-W2 files used for the Elephant Butte model are found on the attached CD.

3.1 Bathymetry

Bathymetry data was the starting point for the CE-QUAL-W2 model. Bathymetry is the measurement of depths of a body of water and describes the shape and volume of that waterbody. It quantifies the height, length, width and orientation of each cell used in a grid to describe the reservoir. Important qualities such as the storage-capacity curve are derived from the bathymetric data. Because the bathymetry is vital to obtaining accurate model results (Cole, 2002), a significant amount of time was spent generating and verifying a bathymetry file for CE-QUAL-W2. Many months can be spent estimating widths of reservoir sections, formulating a bathymetry file and calibrating it to a storage-capacity curve. In the case of Elephant Butte this process was expedited by the use the software program, Watershed Modeling Systems (WMS), developed by the Environmental Modeling Research Laboratory (EMRL), a part of the Civil and Environmental Engineering Department at Brigham Young University. Among its many capabilities, WMS can use various forms of spatial data to create bathymetry inputs files suitable for use in CE-QUAL-W2. Similar to a Geographic Information System (GIS) format, spatial data are read into WMS and processed. Ideally a three-dimensional digital elevation set would be used, but because Elephant Butte Reservoir was impounded so long ago, this information was not available. Instead, a Triangulated Irregular Network (TIN) created from cross sectional data was used as spatial data used for Elephant Butte (see Figure 3.1).

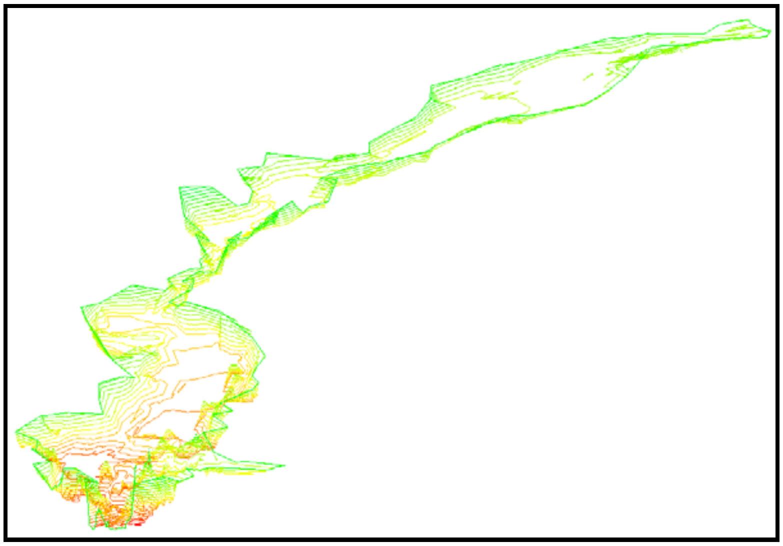

Figure 3.1 Bathymetry created From TIN.

The next step was to discretize the reservoir into model segments. This was done by creating polygons longitudinally along the reservoir. Elephant Butte was divided into segments each roughly 1500 meters long. After specifying a layer height of 1 meter for all cells, the cell widths were automatically calculated from the TIN developed for Elephant Butte. The segment lengths and layer heights were chosen based on values used in previous models and to achieve a sufficiently refined grid. With this information WMS generated a CE-QUAL-W2 bathymetry file. A storage-capacity curve was then created from the bathymetry file and compared to an observed storage-capacity for Elephant Butte. The observed storage-capacity curve was created in 1997 from capacity equations derived by the Bureau of Reclamation Technical Service Center using the least squares method of curve fitting. (Miller, 2005) Figure 3.2 shows the calibrated storage-capacity curve from the CE-QUAL-W2 bathymetry file plotted against the derived storage-capacity curve from the Bureau of Reclamation. Notice how well the calibrated model compares to the actual data.

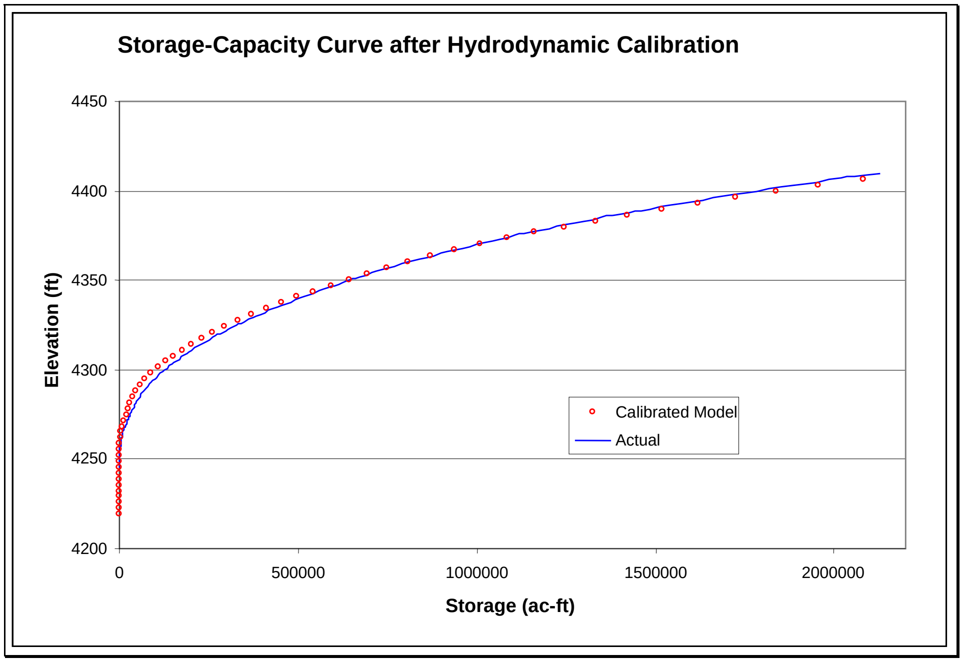

Figure 3.2 Results from calibration of bathymetry.

The use of WMS was advantageous because creating bathymetry files for Elephant Butte took hours instead of weeks. WMS also expedited modification of the bathymetry to ensure that results were not adversely affected by grid resolution. The final bathymetry of the model is shown in Figure 3.3. The minimum cell width in the bathymetry was limited to 30m to increase model stability and decrease model run times.

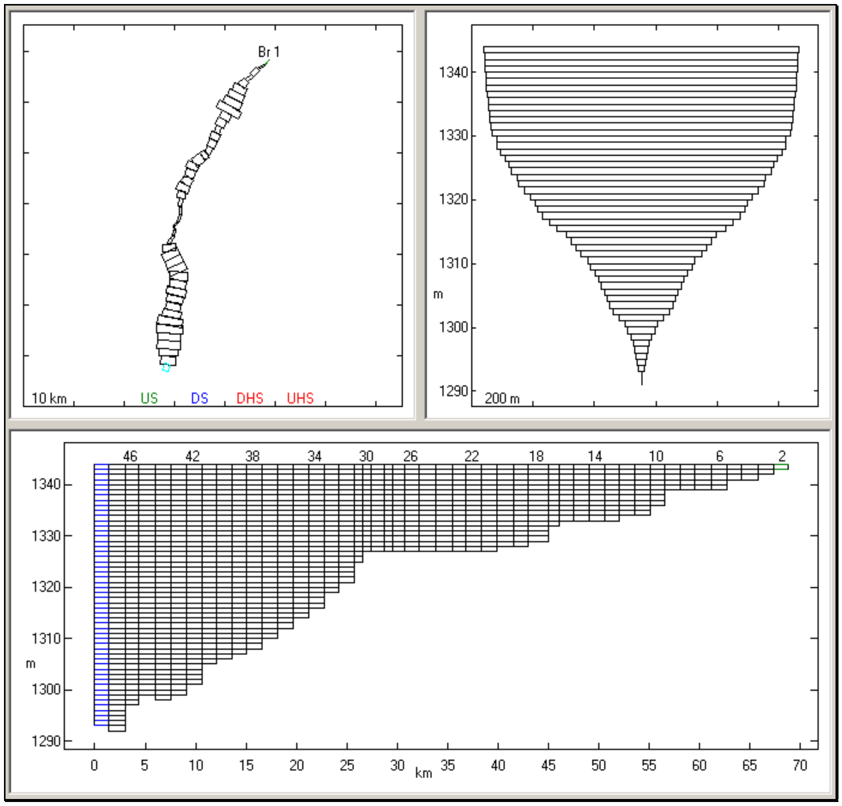

Figure 3.3 Elephant Butte bathymetry (clockwise: plan, front, and side views).

3.2 Boundary Conditions

Accurate boundary conditions are essential to properly represent a process with a computer model. Incomplete or faulty boundary conditions are often the source of error found in modeling efforts. Boundary conditions used for the Elephant Butte model are shown in Table 3.1.

Table 3.1 Elephant Butte boundary conditions.

Inflow	Upstream (flow, temperature, constituents)
	Distributed tributary (flow, temperature, constituents)
	Precipitation (amount, temperature)
Outflow	Downstream (flow)
	Evaporation (amount is computed by model)
Surface	Surface heat exchange
	Solar radiation absorption (computed by model)
	Wind Stress (computed from meteorological data)
	Gas Exchange (computed from meteorological data)

Data for the boundary conditions were provided by various sources including records of the United States Bureau of Reclamation (USBR) El Paso office and the United States Geological Survey (USGS). The upstream boundary conditions included daily inflow data, monthly water temperature measurements (section 3.2.1), and monthly water quality values (section 3.5). Other inflow boundary conditions included distributed tributary inflow, temperature and constituent data and precipitation amounts. The downstream boundary conditions used in the model were daily flows at the reservoir outlet and evaporation. Surface boundary conditions can be adjusted; however default values were used in the Elephant Butte model.

Initial conditions for the model were assigned uniformly to every cell in the model. This is not an exact representation of real conditions because variations in temperature and concentrations exist longitudinally down the reservoir. For this reason the model was started in 1998, a year earlier than the first set of calibration data in 1999. The boundary conditions for 1998 were as accurate and frequent as the remaining years of data. Running the model one year before output was collected

(1998) lessened any effect from the lack of accuracy in the initial conditions. In effect this allows the model to generate accurate initial conditions for the first year of calibration (1999) on its own.

3.2.1 Equilibrium Temperatures

The fluctuation of inflowing water temperature can have a pronounced effect on the heat budget of a water body. (Cole, 2002) This fluctuation in temperatures throughout the day and night affect the characteristics of the thermocline. The data provided for this model only contained average daily temperatures. After preliminary model runs it was decided that more frequent inflow water temperatures were needed in order to accurately capture the behavior of the thermocline throughout the simulation. Thus, equilibrium water temperatures were calculated using meteorological data and a software package called W2Met. (Edinger, 2005)

3.3 Meteorological Data

Meteorological data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Data Centers. Table 3.2 shows the required meteorological data and units for CE-QUAL-W2.

Table 3.2 Required meteorological data.

Required Data	Units
Air Temperature	° C
Dewpoint Temperature	° C
Wind Speed	m / sec
Wind Direction	rad
Could Cover	0 – 10

Meteorological data are one of the primary forcing functions of CE-QUAL-W2, so it is vital that it be as frequent as possible. The data for Elephant Butte are input hourly over the five year period. Hourly data provided sufficient resolution to represent the heat budget of Elephant Butte Reservoir. This was evident in the hydrodynamic calibration process which will be discussed in section 4.1. The NOAA station used was station 722710 KTCS Truth or Consequences. The station location with respect to the reservoir can be seen in Figure 3.4. The proximity of the station to the reservoir lessened the need to adjust the meteorological data for relevance and thus lessened calibration time and should result in increased accuracy of the results.

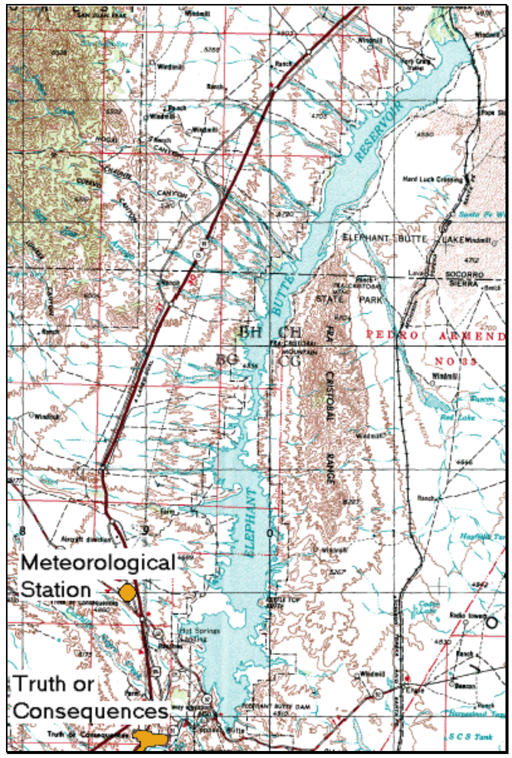

Figure 3.4 Location of meteorological station.

Other than the cloud cover data, which required a transformation from the original values, the meteorological data obtained were used directly in the model. CE-QUAL-W2 requires cloud cover as a scale of 0 to 10 (0 meaning no cloud cover and 10 meaning total cloud cover). Because the cloud cover date was not recorded in this format, a conversion was required. The cloud cover data obtained from this station was recorded as clear, scattered, broken or overcast. Table 3.3 shows the fraction of cloud cover associated with each designation for conversion to model requirements.

Table 3.3 Cloud cover.

Type	Fraction	Scale 1 -10	Model value
Clear	0	0	0
Scattered	1/8 – 4/8	1.25 – 5.0	3
Broken	5/8 – 7/8	6.25 – 8.75	7
Overcast	8/8	10	10

Cloud cover in the meteorological data file was entered using the designations and the associated fractions. Because each designation spans a range of possible values, an analysis was conducted on the sensitivity of the model to cloud cover. A time series of water surface elevations were used to determine the sensitivity of the model because of the impact cloud cover has on evaporation. Figure 3.5 shows that the model is not sensitive to the change of cloud cover values within the specified ranges because the water surface elevations over time are not affected by their change. Results from model runs with different cloud cover data are essentially identical, as seen in Figure 3.5. This is most likely because the skies were clear over Elephant Butte Reservoir around 80% of the simulation, according to the data.

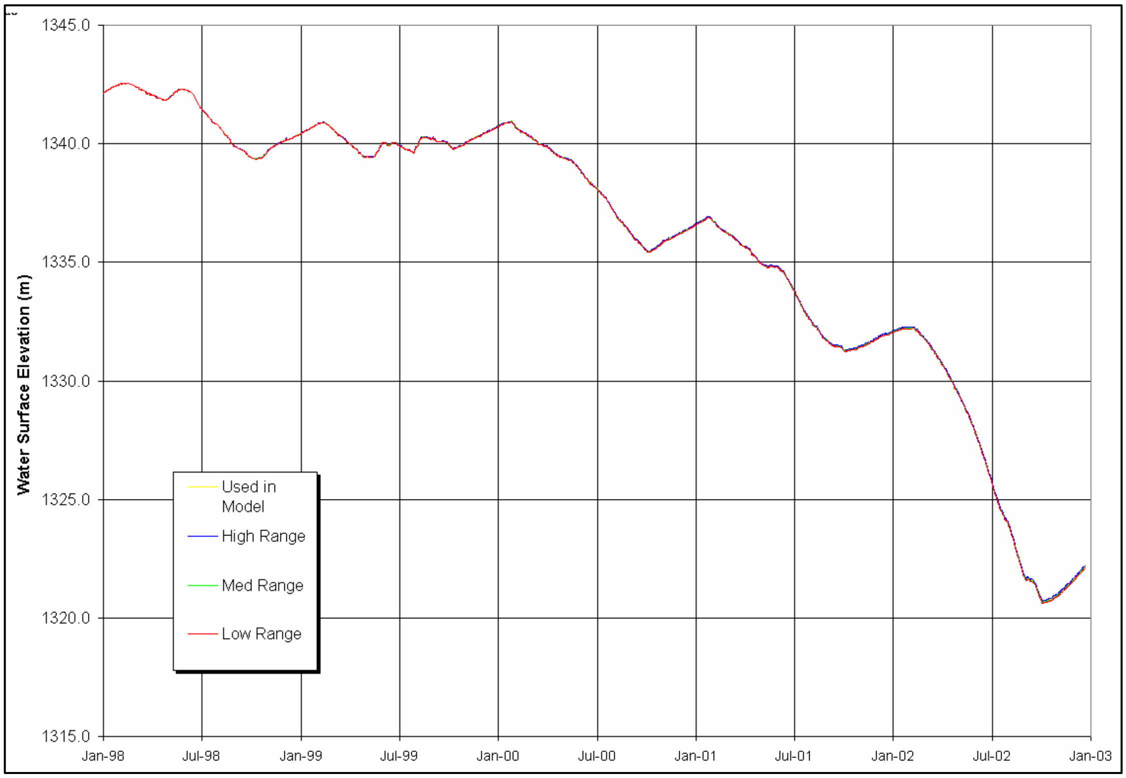

Figure 3.5 Results from cloud cover sensitivity analysis.

Precipitation was modeled for this study. Hourly precipitation data were collected over the five year period of study from the NCDC website (NCDC, 2003) for the Municipal Airport in Truth or Consequences, New Mexico. These data were converted to the correct units and formatted as an input file for use in CE-QUAL-W2. At first it was not certain whether the inclusion of precipitation had a significant impact on the model because it is modeled as water directly entering the reservoir, not runoff. After investigation it was discovered that precipitation was a significant contributor to the water budget. For this reason precipitation was included in the Elephant Butte model.

3.4 Evaporation Coefficients

Elephant Butte is located in one of the driest regions of the United States. Annual evaporation at the reservoir ranges between 50,000 ac-ft and 250,000 ac-ft. (S.S. Papadopulos, 2000) Evaporation is an important mechanism for the Elephant Butte model in two ways. First, evaporation plays an important role in the water budget and thus has a large effect on the reservoir volume over time. Second, the rate of evaporation also greatly influences the water temperatures of the reservoir. For these reasons it was important that the rates describing evaporation were appropriate for the reservoir. CE-QUAL-W2 utilizes an evaporation equation of the form

$$E = k * f(u) * (e_s - e_a)$$

Where:

E = evaporation

k = coefficient

$f(u) = a + bW^c$

e_s = saturation vapor pressure

e_a = air vapor pressure

CE-QUAL-W2 allows specification of the coefficients (a, b, and c) of the wind function, f(u). By proper use of these coefficients, evaporation can be adjusted constantly, linearly and exponentially in relation to the wind. The vapor pressures are calculated internally and the wind speed is provided from data in the meteorological input file. The wind function requires wind speeds taken two meters from the ground. The height for the ASOS wind tower used for this study is 10 meters, CE-QUAL-W2 allows the specification of the height of the wind measurements to adjust for this. Adjustment of the wind measurement height affects the rate of evaporation. The El

Paso office of the USBR provided monthly data for evaporation. This evaporation data was used during calibration to verify the amount of water being evaporated.

3.5 Constituent Data

CE-QUAL-W2 has eighteen constituent state variables such as total dissolved solids, orthophosphate, nitrite-nitrate, dissolved oxygen, etc. Four of the eighteen constituent state variables represent groups that can consist of various divisions. These four constituents are generic zero or first order constituents, inorganic suspended solids, carbonaceous biochemical oxygen demand loadings, and algal groups. The use of multiple algal groups in this model will be discussed in further detail in the following section. Table 3.4 shows all of the constituent state variables available that were used in the Elephant Butte model. All state variables were modeled because “constituent kinetics are strongly coupled and failure to include one or more constituents can have far reaching effects” (Cole, 2002). It can be seen that although phosphorus is the nutrient of concern, it is important to include and accurately model all nutrients to effectively represent the system and achieve meaningful results.

Table 3.4 Constituent state variables in CE-QUAL-W2.

Total dissolved solids	Labile dissolved organic matter
Any 0- or 1-order constituents	Refractory dissolved organic matter
Inorganic suspended solids	Labile particulate organic matter
Dissolved inorganic phosphorus	Refractory particulate organic matter
Ammonium	CBOD groups
Nitrate-nitrite	Algal groups
Dissolved silica	Dissolved oxygen
Particulate biogenic silica	Total inorganic carbon
Dissolved iron	Alkalinity

Constituents enter Elephant Butte Reservoir from the Rio Grande or from non-point sources. Nutrients are present in many different forms in an aquatic environment. Matter can be dissolved or in particulate form. Nutrients can be organic or inorganic. In this study the nutrients of concern are the bioavailable or dissolved inorganic nutrients. The constituent data that enters as external input into the Elephant Butte model from the Rio Grande were obtained from two sources. The USGS gaging station #08358400 "Rio Grande Floodway at San Marcial, NM" and data collected by the Bureau of Reclamation were combined to make a file that provides bimonthly constituent data into the reservoir.

The inflow constituent data alone hinted that Elephant Butte was a unique reservoir. Inflow concentrations of bioavailable orthophosphate averaged 0.27 mg/L over the simulation period. The average inflow concentration of nitrate-nitrite over the simulation was 0.48 mg/L. Stoichiometric ratios of compounds needed for algal cell growth specify that the ratio of nitrogen to phosphorus is around 14:1. (Miller, 2005) The ratio of nitrogen to phosphorus in the inflow concentrations for Elephant

Butte was only 2:1. This indicates that Elephant Butte Reservoir is nitrogen-limited during the course of this simulation. Because Elephant Butte is nitrogen-limited during the timeframe of this study, the algal growth and algal succession in the model was unique and interesting. Section 3.6 describes in more detail the condition of the reservoir with respect to algae.

Constituent data entering the reservoir as a non-point source were estimated and included in the model using the distributed tributary constituent file. Development of a more accurate non-point source loading to a waterbody is an area of possible future research and will be discussed later in the study.

3.6 Algal Groups

Algae play an important role in the internal cycling of nutrients within a reservoir. For this reason and others it was advantageous to include algae in the model to accurately represent the nutrient dynamics. Algal growth is a function of temperature, light and nutrients. The abundance or scarcity of these factors determines the rate of growth. As algae grow they incorporate various nutrients into their structure during photosynthesis. These nutrients, including phosphorus, are returned to the water column as excretions from the algae, during decomposition after the algae have died, and from algal respiration.

Of the constituents discussed in the previous section, carbon, phosphorus, nitrogen and silicon are the major nutrients in algal growth. (Cole, 2002) And as mentioned in section 3.5, the ratio of each nutrient needed for algae to grow is based on stoichiometric relationships. Because Elephant Butte is nitrogen-limited during the timeframe of this study, it is an interesting case of algal growth and algal succession. This situation is unique because a majority of eutrophic reservoirs are phosphorus-limited. In a nitrogen-limited reservoir such as Elephant Butte, it is easy to assume that nitrogen-fixing algae would dominate this reservoir because they are able to obtain unlimited amounts of nitrogen from the atmosphere. This is alarming because nitrogen-fixing cyanobacteria are often the major cause of toxic blooms. However, contrary to what would be expected from the collected algae data, cyanobacteria are not the dominant species of algae in Elephant Butte. This makes Elephant Butte a unique case study and a challenge to model. Calibration of the algal succession is described in section 4.2.

A strength of CE-QUAL-W2 is that it allows for the modeling of multiple algal groups. Because different species of algae have different characteristics, it is possible to better define the nutrient cycling caused by the algae using multiple groups. The Elephant Butte model includes four algal groups, representing the dominant species throughout the period of study, which are diatoms, cyanobacteria, green algae, and dinoflagellates. Figure 3.6 shows the seasonal succession of these four algal species during 1999 and 2000.

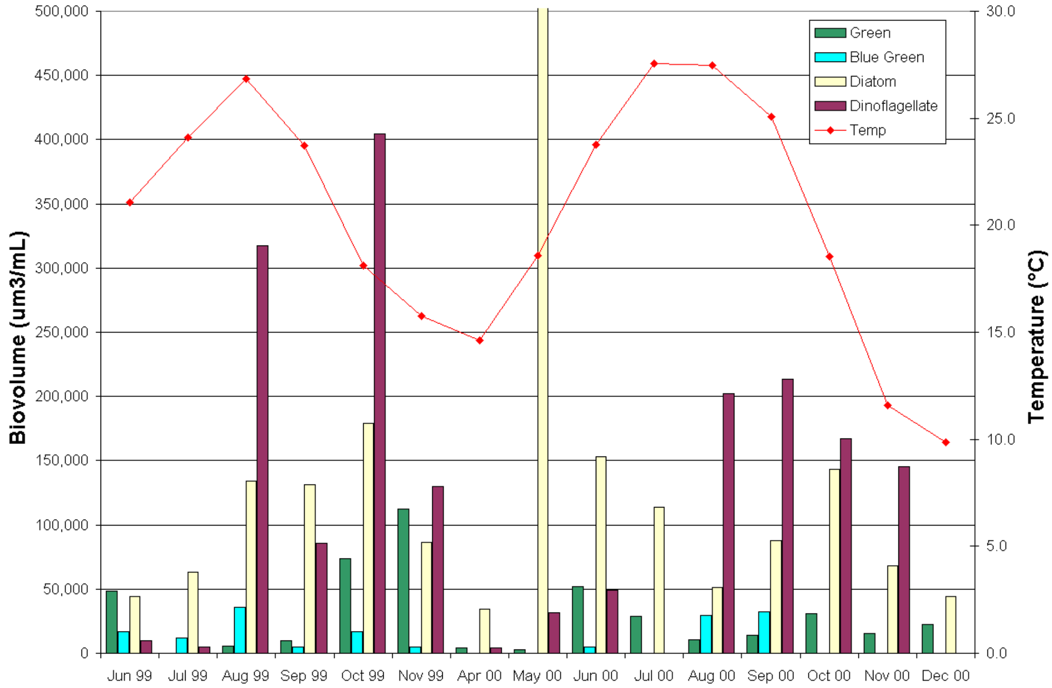

Figure 3.6 Monthly Algal Data.

The dominant species for Elephant Butte were determined based on data collected which detailed biovolume and biodensity of every species found in the reservoir. Ranges of values for growth, respiration, excretion, settling, and mortality rates as well as the half-saturation constants used for each algal compartment were obtained from the EPA's handbook "Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (2nd Edition)" and are reported in Table 3.5.

Table 3.5 Typical values of algal kinetic coefficients.

	Diatoms	Greens	Cyanobacteria	Dinoflagellates
AG	1.1 - 5.0	0.7 - 4.1	0.4 – 2.5	0.2 – 2.1
AR	0.04 – 0.08	0.03 – 0.07	0.03 – 0.065	0.047
AS	0.05 – 0.4	0.05 – 0.4	0.0 – 0.15	2.8 – 6.1
AT1	0	10	15	15
AT2	10	25	20	20
AT3	30	35	30	30
AT4	32	40	40	35
ASAT	70 - 140	30 - 50	20 - 100	40 – 90
AHSP	0.001–0.009	0.003 - 0.02	0.01 – 0.02	0.06
AHSN	0.015 - 0.03	0.03 – 0.035	0.0 – 0.001	0.005 – 0.08

Notice that the half-saturation for nitrogen limited growth for cyanobacteria can be zero. This means that cyanobacteria in the Elephant Butte can be modeled as nitrogen-fixing.

4 Model Calibration

This chapter describes the process of calibrating the Elephant Butte Reservoir CE-QUAL-W2 model to observed data. Calibration is a vital step in the modeling process. The intent of the following discussion is to enumerate and justify the decisions made during the calibration process to add clarity to the conclusions made later in the study.

4.1 Hydrodynamic Calibration

Hydrodynamic calibration can be accomplished in many ways. Because there is no one ideal method (Cole 2002), three steps were taken to calibrate the hydrodynamics of the Elephant Butte model. These steps were 1) balancing the water budget, 2) thermal calibration, and 3) dissolved oxygen calibration, which are described in the followings sections.

4.1.1 Water Budget

Although balancing the water budget is not technically part of hydrodynamic calibration, accurately accounting for the water budget is the most fundamental part of calibrating a model. If a model is not correctly predicting the amount of water moving through and remaining within the reservoir then there is little hope that any other predictions made by the model can have validity.

The components of the water budget for Elephant Butte Reservoir are depicted in Figure 4.1 below.

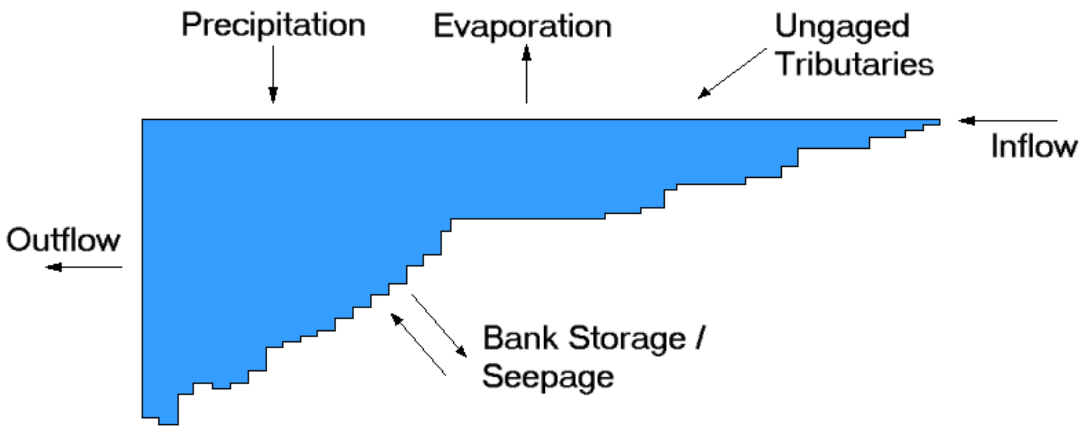

Figure 4.1 Components of Elephant Butte water budget.

As mentioned previously (section 3.2) the inflow and outflow data were provided by the El Paso office of the USBR. Monthly evaporation and seepage data were also included in this data set and all were accounted for in the water budget. Daily precipitation data were obtained from the Truth or Consequences Municipal Airport. The only unaccounted source to the Elephant Butte water budget is the ungaged tributary flow from storm events. These ungaged flows were determined using a computer program provided by Tom Cole and Scott Wells (Cole, 2004), authors of the CE-QUAL-W2 model. This program helps to complete the water budget by solving for the unaccounted flows by forcing the computed water surface elevation to match the observed water surface elevation. The program outputs a file of flows that can be used by CE-QUAL-W2 as a distributed tributary inflow file (essentially spreading the difference over the entire reservoir). This file was included in the Elephant Butte model to represent the ungaged tributary inflows and the effects of bank storage. Figure 4.2 shows the flows from the distributed tributary file over the course of the simulation. Figure 4.2 also shows the correlation between increased ungaged flows and major storm events in the area (> 0.5 in. precipitation / day). This further justifies the inclusion of the file created by the water balance program.

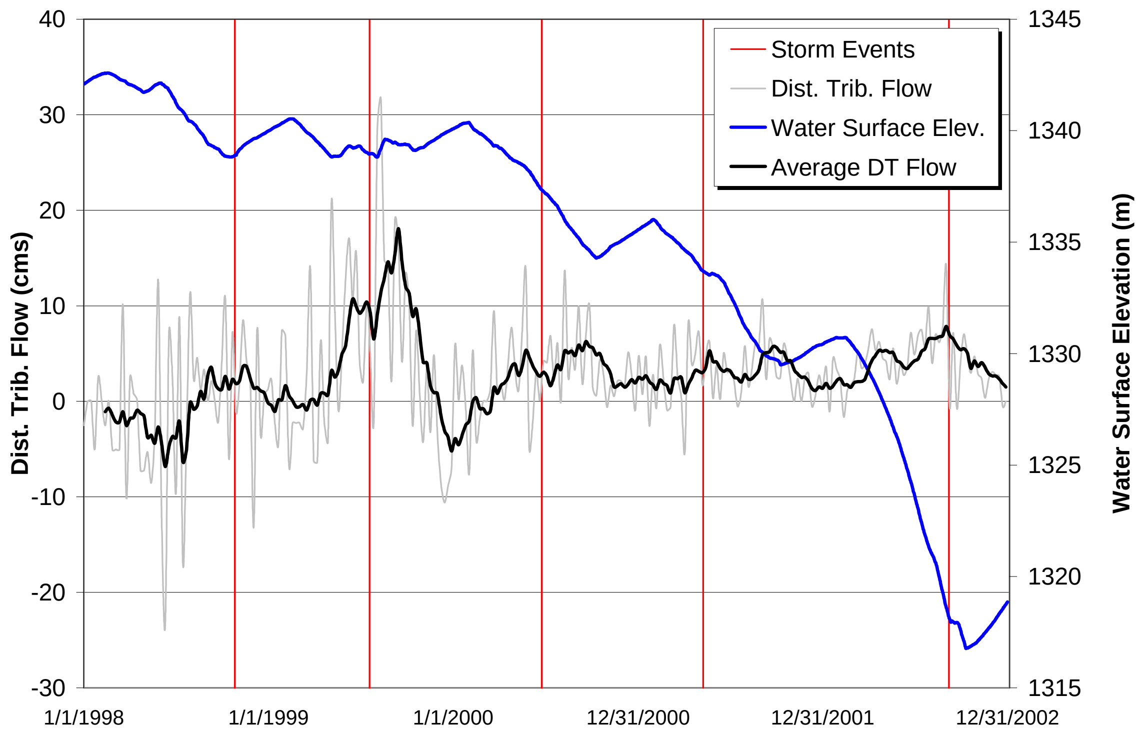

Figure 4.2 Distributed tributary flow 1998-2002

During the process of calibration it was evident that bank storage was an important mechanism in the Elephant Butte water budget. In the early years of the simulation (1998-2000) when the reservoir was near capacity, the water balance program shows an increase of water leaving the reservoir. In the later years of the simulation (2000-2003) when the reservoir was significantly drawn down, the water balance program shows an increase of water entering the reservoir. This can be explained through significant bank storage as the water surface elevation fluctuates. When the water elevation rises, water leaves the reservoir and seeps into the ground or banks. As the water surface recedes, the water stored in the bank flows back out into the reservoir.

Because Elephant Butte Reservoir is located in one of the most arid regions of the United States increasing the default evaporation coefficients (see section 3.4) were required for model calibration. CE-QUAL-W2 models of other reservoirs in the region used a similar increase of the evaporation coefficients in an attempt to best represent this process. The US Bureau of Reclamation Upper Colorado Water Quality Group is currently calibrating CE-QUAL-W2 models for Lake Mead and Lake Powell using altered evaporation coefficients. (Miller, 2005) A sensitivity analysis was conducted for the Elephant Butte model on the effect of each evaporation coefficient, as well as on various combinations of coefficients. The sensitivity analysis examined how combinations of coefficients performed based on the volume of evaporation, effect on water temperature and model runtimes. The volume of evaporation was evaluated after each run by comparing the amount of evaporation computed by the model against monthly pan data provided by the USBR El Paso office. After each run the temperature profiles were also inspected to ensure that the heat budget was not being adversely impacted as a result of the evaporation calibration. The last factor, although not vital to the integrity of the model results, was still important in the decision of which evaporation coefficients to use. This factor affected the speed at which the model ran. Certain combinations of coefficients seemed to cause run times to increase dramatically. Finally it was decided to use the default evaporation coefficients with the exception of a slight increase in base evaporation. The results using these coefficients provided an accurate amount of evaporation and accurate temperature profiles. The evaporation coefficients used are shown in Table 4.1 compared to their corresponding default values.

Table 4.1 Calibrated evaporation coefficients.

Coefficient	Model Value	Default
a	10.0	9.2
b	0.46	0.46
c	2.0	2.02

All of these components of the water budget were balanced until computed water surface elevations over the duration of the simulation had an average mean error of less than 10 cm compared to observed water surface elevations.

4.1.2 Temperature

After the water budget of Elephant Butte was balanced, the next step was to thermally calibrate the model. Thermal calibration of Elephant Butte was closely tied to the previous step of balancing the water budget because of the calibration of the evaporation coefficients. Thermal calibration proved useful during the calibration of the evaporation coefficients as was discussed in section 4.1.1. Some combination of evaporation coefficients were able to balance the water budget but did not accurately capture the behavior of observed temperature data. Evaporation calibration was complete when the water budget was balanced and the thermal characteristics (thermocline depth and shape) were reasonable.

Thermal calibration for Elephant Butte was fairly simple and straightforward. The coefficients that affect thermal calibration suggested in the CE-QUAL-W2 users manual (Cole 2002) and the values used in the Elephant Butte (EB) model are shown in Table 4.2.

Table 4.2 Coefficients affecting thermal calibration.

Coefficient	EB	Default
Longitudinal eddy viscosity [AX]	1 m^2 sec^{-1}	1 m^2 sec^{-1}
Longitudinal eddy diffusivity [DX]	1 m^2 sec^{-1}	1 m^2 sec^{-1}
Chezy coefficient [FRICT]	70 m^2	70 m^2
Wind Sheltering coefficient [WSC]	1.0	Parameter
Solar radiation absorbed in surface layer [BETA]	0.45	0.45
Extinction coefficient for pure water [EXH2O]	0.30 m^{-1}	0.45 m^{-1}
Extinction coefficient for inorganic solids [EXINOR]	0.10 m^{-1}	0.01 m^{-1}
Extinction coefficient for organic solids [EXORG]	0.10 m^{-1}	0.2 m^{-1}
Coefficient of bottom heat exchange [CBHE]	7.0E-8	7.0E-8
Sediment (ground) temperature [TSED]	16.12	-
Heat loss to sediments that is added back to water [TSEDF]	1.0	0.0 - 1.0
Interfacial friction factor [FI]	0.0	0.01

One of the main calibration parameters in CE-QUAL-W2 is the wind sheltering coefficient. A wind sheltering coefficient is assigned to each segment of the reservoir model. Adjusting these coefficients allows the modeler to compensate for wind sheltering caused by terrain and to compensate for large distances from weather stations. In the case of Elephant Butte it was not justifiable to use the wind sheltering coefficients as a calibration parameter since Elephant Butte Reservoir is located in a flat, open area and the recording station for meteorological data is less than two miles from the reservoir. This is somewhat unique because wind sheltering coefficients are often used as a primary calibration parameter. The temperature profiles generated by the model using default values for calibration parameters accurately matched observed temperature profiles. Figure 4.3 shows an example of calibrated temperature profiles. Statistical accuracy is also shown for each profile in the figure. Profiles from other years and locations were also calibrated as accurately.

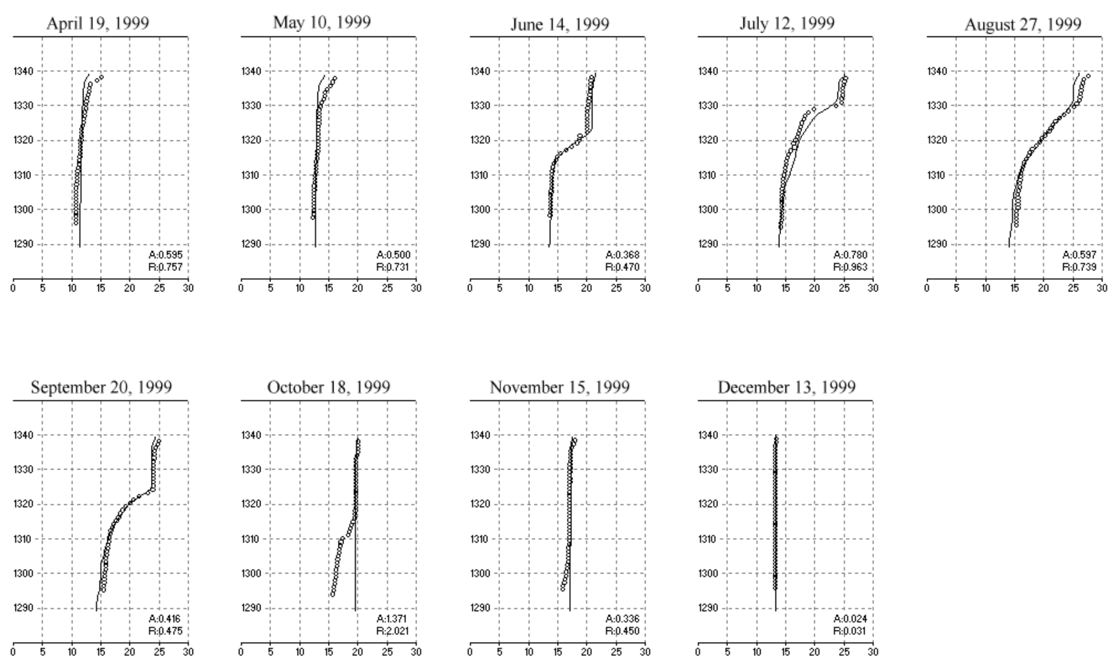

Figure 4.3 Calibrated Temperature Profile near the Dam for 1999.

4.1.3 Dissolved Oxygen

Calibration of the dissolved oxygen in a reservoir is an important step in obtaining a useful model. When the dissolved oxygen is properly modeled it provides additional evidence that the hydrodynamics of the reservoir are modeled correctly. "Experience has shown that dissolved oxygen and phytoplankton are often much better indicators of proper hydrodynamic calibration than temperature or salinity" (Cole, 2002). Cole goes on to explain that dissolved oxygen is a better indicator for two reasons. First, dissolved oxygen has gradients at different locations in the water column than temperature. Second, dissolved oxygen is much more dynamic than temperature and responds quickly to sudden changes in hydrodynamics. Dissolved oxygen calibration was conducted on the Elephant Butte model to ensure more accurate modeling of the hydrodynamics. This calibration was conducted before the algal groups were added. A sediment oxygen demand was applied to the water column and calibrated against observed profiles. Ideally this dissolved oxygen calibration would be done again after the algal groups had been added. Because the algal growth was not able to be calibrated, the dissolved oxygen was not calibrated either.

4.2 Algal Succession

As mentioned previously in section 3.5, the nutrient budget and the behavior of algal growth in Elephant Butte Reservoir present a challenging situation to model. From the nutrient data it was determined that Elephant Butte is nitrogen-limiting throughout the simulation. This fact was confirmed during the calibration of algal growth. CE-QUAL-W2 can output the limiting factors for each of the four algal groups and this data also showed that nitrogen or light was often the limiting constituent. It would be suspected that under these conditions nitrogen-fixing algae would outcompete other species and dominate the reservoir. As mentioned in section 3.6, the dominant algal species in Elephant Butte are dinoflagellates and diatoms, not the nitrogen-fixing cyanobacteria. This posed a problem in modeling because there was not enough nitrogen available for observed algal growth without enough nitrogen-fixing algae in the reservoir. To overcome this, the dinoflagellates were modeled as nitrogen-fixing so that they would be dominant and still provide enough nitrogen into the water column. This improved results but the dinoflagellate modeled could not be proved with a literature review as a nitrogen-fixing algae.

The process of correctly calibrating multiple groups of algae was challenging. In the CE-QUAL-W2 manual Cole (2002) states that, "When including multiple algal groups, the temperature rate coefficients are one of the most important parameters determining algal succession." This statement was strikingly evident in the calibration of the four algal groups in Elephant Butte. Results from model runs were extremely sensitive to practically any adjustment of the temperature rate coefficients. Allowing one algal group to grow too early or too late negatively interfered with the growth of other algal groups. Other possible calibrating parameters included are shown in Table 3.5. However, most of these parameters were not used in calibration, assuming that literary values were correct. Parameters that were adjusted besides the temperature rate coefficients were settling velocities, saturating light intensities, and phosphorus and nitrogen half-saturation constants. Of all of the calibrating parameters, temperature rate multipliers were the most important in the Elephant Butte model. The model was not able to be calibrated for algal growth. It was impossible to achieve enough nitrogen in the water to drive the observed growth while keeping the kinetic parameters within the researched ranges. Further research into the specific species of algae in the reservoir and additional algal data will help future calibration attempts. As the Bureau of Reclamation continues to use multiple algal groups in this model and other models, a better understanding of representing multiple algal groups will be achieved.

5 Summary and Conclusions

5.1 Realization of Objectives

The objectives outlined in the introduction were resolved in the following ways:

- External phosphorus loading alone is sufficient to support observed algal blooms in the reservoir;
- Qualitatively modeled seasonal algal species succession although many problems were experienced;
- Use of this document and the researched literature values will hopefully expedite future efforts to model multiple algal groups;
- The Bureau of Reclamation will continue to investigate algal blooms using this CE-QUAL-W2 model of Elephant Butte Reservoir along with models of other reservoirs.

5.1.1 Phosphorus Loading

The initial assumption of this study was that the external loading of phosphorus to the reservoir was not sufficient to produce the amount of algae observed in Elephant Butte Reservoir. This assumption was made based on other large reservoirs in the region. Reservoirs in the southwest usually have high suspended sediment loadings which tie up available phosphorus. Lake Powell which lies on the Colorado River in Utah can have similar inflow concentrations of total phosphorus as Elephant Butte but the concentrations of bioavailable phosphorus vary significantly between reservoirs. The percentage of bioavailable phosphorus to total phosphorus average over 30% in Elephant Butte but in Lake Powell it is only 0.5 – 1.0% (Miller, 2005). This means that there is a lot more phosphorus available to drive algal growth. This also means that the sediments entering Elephant Butte probably have a low affinity for phosphorus sorbtion. This poses a problem because phosphorus sorbtion onto iron-containing sediments usually acts as a buffer protecting reservoirs from large spikes entering the system. Without this sort of buffer Elephant Butte is susceptible to large nutrient spikes that produce large algal blooms.

5.1.2 Algal Succession

Previous water quality models have represented algal growth as a single assemblage. The kinetic coefficients used to describe this type of assemblage were an average of all of the species of algae present in the water column. This type of representation of the algae in a reservoir is only an approximation. (Zison, 1978) Representing each species of algae as a different group in a model allows for a more accurate representation of their behavior. Because of this capability, seasonal growth and decline of the dominant algal species could be represented in the Elephant Butte model. Once this succession of algal species was properly captured, it was then possible to determine why certain species dominate and what would happen if conditions were to change. This was of interest because in Elephant Butte it was not apparent why nitrogen-fixing blue-green algae do not dominate the reservoir during the period of study instead of the observed diatom and dinoflagellate species. The reservoir is nitrogen-limited during the modeled time period, which would make nitrogen-fixing algae able to outcompete other algae. If blue-green algae were to flourish many problems would be expected such as toxic algal blooms and taste and odor problems in drinking water.

5.1.3 Literature Values

Literature values were collected from the EPA document on surface water quality modeling (Bowie, 1985) and grouped in a format that useful for application into CE-QUAL-W2 models. These ranges represent a wide range of values and questions into the validity of possible values should be investigated further by referring to the EPA document. These values are guidelines and should not be considered absolute. As Elephant Butte showed, sometimes the algae behave differently than laboratory results would predict. Correlation between laboratory results and field observations will be better defined through further application of models using multiple algal groups.

5.1.4 Further Investigation by USBR

Studies like this one on Elephant Butte are useful. It is important that our water sources are protected from degrading levels of water quality. Management of reservoirs in the southwest can be improved by understanding the workings of evaporation, algal succession, and the effects of phosphorus learned from this study on

Elephant Butte Reservoir. The Elephant Butte water quality model is accurately calibrated hydrodynamically and will be used for further research. The results of this research along with the literature data collected will hopefully help future modelers better represent and protect these valuable resources.

5.2 Additional Findings

CE-QUAL-W2 has been used on over 250 water quality studies in reservoirs located worldwide (www.ce.pdx.edu/w2). This shows that CE-QUAL-W2 is capable of accurately modeling waterbodies subject to many different climates. The results of this model add to the reliability of CE-QUAL-W2 by capturing the behavior of Elephant Butte which lies in the arid southwest.

An interesting additional finding during this study was the effect of evaporation on calibration. Because Elephant Butte is located in the arid Southwest Desert, evaporation was closely examined. A sensitivity analysis was performed to investigate the effect of adjusting the coefficients tied to evaporation in the model. This study found that based on three factors, 1) volume of evaporation 2) effect on temperature and 3) effect on model run times, coefficients similar to the default coefficients worked best. This adds further evidence to the fact that CE-QUAL-W2 is able to accurately represent waterbodies in various conditions with little or no adjustment to default coefficients. The evaporation coefficients were adjusted slightly by increasing the base rate of evaporation. This was anticipated due to the location and climate of Elephant Butte.

5.3 Potential Application of Results

There are many TMDL studies being conducted on reservoirs throughout the country. Vast amounts of data are collected and organized in this process to determine how to best protect designated water uses. When large sets of data are available it becomes more feasible to construct a computer model. Using a model such as CE-QUAL-W2 with multiple algal groups in conjunction with other studies can add depth to the results of a TMDL report.

5.4 Potential Future Research

The results from this research have opened up many options for research that can be investigated or developed more fully. Proposed options for future research include the following topics.

This model used a rudimentary representation of non-point source flow to the reservoir. The non-point source (or distributed tributary file) in the Elephant Butte model represented bank storage to and from the reservoir and seasonal storm runoff. This simple representation was applied because these flows were comparatively small to the inflow over the course of the simulation. Future research could consist of using a runoff model to develop and calibrate storm hydrographs and assign the flows as seasonal tributaries to the reservoir. Tributaries enter the model at one point instead of being distributed according to surface area over the entire model. Another opportunity for research involves refining how constituents are introduced through non-point sources. Currently the use of HSPF (Hydrological Simulation Program – Fortran) is being explored to more reliably create non-point source loadings to be used in CE-

QUAL-W2 based on hydrologic conditions, land use, soil type and other parameters. The results from HSPF can then be introduced into the model through the distributed tributary constituent inflow file. Adding these refinements to the non-point sources in the model will allow for more accurate results by further minimizing the error that enters the model.

The results achieved on understanding the behavior of algae in this research can be investigated further. The succession of algae in this study was done qualitatively not quantitatively. A quantitative analysis can be conducted by developing relationships between chlorophyll-a concentrations and the dry weight of biomass calculated by the model. This will allow the calibration of biomass as well as timing and relative bloom size.

6 References

BASINS (2004). "EPA Fact Sheet: Better Assessment Science Integrating point and Nonpoint Sources, Version 3." Retrieved February 2005, from Environmental Protection Agency, Water Science Web site: http://www.epa.gov/waterscience/basins/v3-1fs.pdf

Bowen, J.D. (1999) "Calibration Performance of a Two-Dimensional, Laterally-Averaged Eutrophication Model of a Partial Mixed Estuary." Part of *Proceedings of the 6th International Estuarine and Coastal Modeling Conference, Reston, VA:ASCE*, 0-7844-0504-2, pg. 1299.

Bowie, G.L., et al. (1985). "Rates, Constants and Kinetic Formulations in Surface Water Quality Modeling (Second Edition)." *EPA/600/3-85-040*, US Environmental Protection Agency, Washington, D.C.

Cole, T.M., and S.A. Wells (2002). "CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.1," Instruction Report EL-2002-1, US Army Engineering and Research Development Center, Vicksburg, MS.

Cole, T.M (2004). "Water Balance Utility." Download provided along with CE-QUAL-W2 model. Retrieved September 2004, from CE-QUAL-W2 Web site: http://www.ce.pdx.edu/w2/

Cusimano, B. (2003). "Response to comments on Draft Report: Spokane River and Lake Spokane (Long Lake) Pollutant Loading Assessment for Protecting Dissolved Oxygen." Washington State Department of Ecology.

Edinger, J.E. (2004). "W2Met" Retreived July 2004, from J.E. Edinger Assosicates, Inc. Web site: http://www.jeeai.com/Software-W2.htm#W2Met

Elephant Butte (2004) "Elephant Butte Lake" Retrieved May 2004, from the Truth or Consequences Web site: http://www.truthorconsequencesnm.net/eb_lake.htm

Flowers, J.D., et al. (2001) "Water Quality Modeling of Lake Waco Using CE-QUAL-W2 for Assessment of Phosphorus Control Strategies." Texas Institute for Applied Environmental Research. Tartleton State University.

NCDC (2003). Precipitation data was retrieved July 2003 from the NCDC Web site: http://www.ncdc.noaa.gov/servlets/ULCD

New Mexico Water Quality Control Commision. (2002). "Water Quality and Water Pollution Control in New Mexico". Prepared for submission to the Congress of the United States pursuant to Section 305(b) of the Federal Clean Water Act.

Miller, Jerry (2005). United States Bureau of Reclamation, Salt Lake City Office, Water Quality Group. Personal communication.

PSOMAS. (2002). "Deer Creek Reservior Drainage TMDL Study". Prepared for Utah Department of Environmental Quality – Division of Water Quality. By PSOMAS, Salt Lake City, UT.

S.S. Papadolulos & Associates, Inc. (2000). "Middle Rio Grande Water Supply Study". Prepared for US Army Corps of Engineers Albuquerque District and New Mexico Interstate Stream Commision. By S.S. Papadopulos & Associates, Inc., Boulder, CO.

UNM (2005), "New Mexico Statistical Abstract Summaries" Retrieved February 2005, from The University of New Mexico Web site: http://www.unm.edu/~bber/statabst/toursumm.htm

WASP (2005). "Water Quality Analysis Simulation Program." Retrieved February 2005, from Environmental Protection Agency, Water Science Web site: http://www.epa.gov/athens/wwqtsc/WASP.pdf

Zison, S.W., et al. (1978). "Rates, Constants and Kinetic Formulations in Surface Water Quality Modeling." *EPA/600/3-78/105*, US Environmental Protection Agency, Washington, D.C.