Brigham Young University
BYU ScholarsArchive

Theses and Dissertations

2011-03-16

Developing Methods to Assess the Potential Effects of Global Climate Change on Deer Creek Reservoir Using Water Quality Modeling

Reed Earl Chilton
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Civil and Environmental Engineering Commons

BYU ScholarsArchive Citation
Chilton, Reed Earl, "Developing Methods to Assess the Potential Effects of Global Climate Change on Deer Creek Reservoir Using Water Quality Modeling" (2011). *Theses and Dissertations*. 2468.
https://scholarsarchive.byu.edu/etd/2468

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.

Developing Methods to Assess the Potential Effects of Global Climate Change on Deer Creek Reservoir Using Water Quality Modeling

Reed Chilton

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Gustavious P. Williams, Chair
E. James Nelson
M. Brett Borup

Department of Civil and Environmental Engineering

Brigham Young University

April 2011

Copyright © 2011 Reed Chilton

All Rights Reserved

ABSTRACT

Developing Methods to Assess the Potential Effects of Global Climate Change on Deer Creek Reservoir Using Water Quality Modeling

Reed Chilton
Department of Civil and Environmental Engineering, BYU
Master of Science

To evaluate the potential impacts of future climate change on a temperate reservoir, I used a calibrated water quality and hydrodynamic model validated using three years of data (2007-2009) from Deer Creek Reservoir (Utah). I evaluated the changes due to altered air temperatures, inflow rates, and nutrient loads that might occur under Global Climate Change (GCC). I developed methods to study GCC on reservoirs. I produced Average Water Temperature Plots, Stratification Plots, and Total Concentration Plots. Average Water Temperature Plots show the sensitivity of the water temperature to various parameters. Stratification Plots quantify stratification length and strength as well as ice-cover periods. Total Concentration Plots analyze the reservoir as a whole concerning water quality parameters. Increasing air temperature increased the water temperature, lengthened stratification time, increased stratification strength, decreased the ice-cover period, decreased the total algae concentration, decreased the flows, and caused peak nutrient concentrations to occur earlier. Decreasing flows caused increased water temperature, shorter stratification periods, weaker stratification, and increased nutrient concentrations. Increasing phosphate concentrations caused increases in total algae, dissolved oxygen, and phosphate concentrations. Variations in Nitrate-Nitrite concentrations did not influence the tested parameters. I found that the reservoir is only sensitive to these changes during the spring and summer. The tools which I developed were used to run the model scenarios, organize the data, and plot the results. They can be used on other reservoirs and for other water quality parameters.

Keywords: climate change, water quality, temperate reservoir, CE-QUAL-W2

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Gustavious P. Williams, for helping me learn throughout my thesis. I would also like to thank Brigham Young University for providing a great learning atmosphere. Also, I would like to thank Oliver Obregon and the other members of the Deer Creek Research group for all of their help collecting and analyzing data. I am thankful for the U.S. Bureau of Reclamation for providing funds for this project. Finally, I would like to thank my parents and most of all, my wife and son, for supporting me and helping me reach my goals.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

Global Climate Change (GCC) is of concern for many areas, including the potential impact on drinking water sources. Air temperature and inflow changes could change the quality and treatability of drinking water sources. I studied Deer Creek Reservoir, which is located in a temperate region in Utah, to determine what impacts GCC could have on the reservoir and its internal processes. I had a unique opportunity to calibrate a Deer Creek water quality model as the reservoir was both filled to capacity and during reconstruction efforts, drawn down to levels not experienced since the 1930s when the dam was built. I obtained data during this three-year period and developed a water quality model that accurately reproduced these extreme reservoir conditions. I used this extreme period, from maximum fill to maximum recorded drawdown, as the base-case for evaluating GCC impacts. This study, while specific to Deer Creek, can be generalized to include other reservoirs. I have confidence in the ability to generalize these findings to other areas because of the extreme range I used to develop and validate the model used for the analysis.

A number of environmental changes could significantly impact Rocky Mountain Reservoirs mostly dealing with temperature and precipitation levels. The Intergovernmental Panel on Climate Change (IPCC) has projected an increase in average annual temperature of 1 to 3 °C from 2010 to 2039 (Field et al. 2007). The annual-mean precipitation is projected to decrease in the Central Rocky Mountain region of the United States where Deer Creek Reservoir is located, even though most of the continent has a projected precipitation increase (M.L. Parry 2007). Stream flow over the last century has decreased about 2% per decade in the Rocky Mountain region (Rood et al. 2005). A combination of higher temperatures and lower precipitation resulting in lower stream flows could have larger impacts on water processes due to the synergistic effects of these variables. This study was designed to determine what types of impacts could occur and their potential magnitude.

Increased water temperature, changes in water chemistry, and biological activity are some of the water quality effects that could result from climate change (Means 2010). Thermal stratification in Deer Creek occurs during the summer months every year and is one of the dominant physical characteristics of the reservoir. As the air temperatures increase, the thermal stratification may become stronger which will produce anoxia in deep layers of the reservoir. The reservoir could also mix (lose stratification) earlier or later significantly impacting biological and physical processes. Others have studied these general effects, Bartholow et al. (2001) reported potential reservoir impacts due to variability in water temperature, producing chemical, physical, and biological effects. Paerl and Huisman (2009) concluded that algae blooms can also be affected by the physical and hydrologic changes to a reservoir environment caused by climate changes and varied nutrient loading.

I designed a modeling study to analyze the influence and potential impacts of climate change on Deer Creek Reservoir. The model was based on field data during a period of uncharacteristic change in the reservoir conditions due to construction. My model was based on these extreme data and replicated the observed reservoir conditions during this period which gives us more confidence in the model results. I used this extreme period as the base case for evaluating the impacts of GCC on Deer Creek. I also studied of the impacts of various potential changes against very different base case values. To study GCC, I developed an approach to quantify potential impacts and to determine which reservoir processes are sensitive to the changing environment. I evaluated potential impacts due to changes in temperature, inflow, and inflow nutrient loadings to see which environmental changes caused the largest impacts. I developed analysis approaches that looked at the integrated reservoir and in temporal changes. This approach allowed comparison of large, high-resolution water quality model results across the various change scenarios.

Water quality models have been used to implement best management practices (BMP’s) and simulate water quality and hydrothermal conditions in water bodies worldwide (Bartholow et al. 2001, Debele et al. 2008). One common model used for these studies is CE-QUAL-W2 which is a two-dimensional water quality and hydrodynamic model that has been used in several cases to analyze reservoir changes and processes (Bartholow et al. 2001, Gelda et al. 1998).

We developed a CE-QUAL-W2 model based on three years of data from 2007 through 2009. To evaluate GCC impacts, I modified the model by changing the model boundary conditions representing air temperature, inflow, and nutrient loading to simulate GCC changes.. I based the magnitude of these boundary condition changes on projected GCC impacts from the IPCC report (M.L. Parry 2007).

Specifically, I modified four model boundary condition time series: air temperature, inflows, inflow phosphate concentration, and inflow nitrate concentration. In each case, I developed new three-year long time series to evaluate impacts from these changes compared to the base case model. Most of these time series contained daily data, though some: meteorological, inflow, and outflow contained hourly data. These boundary conditions were selected based on projected GCC changes and my basic understanding of which changes might have the greatest impact on reservoir processes. This study gives a better understanding of the sensitivity of the reservoir processes to GCC by identifying and quantifying the impacts of potential environmental changes.

GCC impacts have been studied on multiple reservoirs (Bartholow et al. 2001, Fang and Stefan 1999, Hondzo and Stefan 1996, Livingstone 2003, Stefan 1998). This Deer Creek Reservoir study is important because of the opportunity I had to calibrate and validate the model using measured field data over extremely large changes in the reservoir conditions. This calibration and validation effort provides confidence that I can accurately predict and evaluate impacts to reservoir processes from potential changes in the environment. This study, including the developed methods and tools, provides information that can be generalized to other temperate reservoirs in the Rocky Mountain region and will allow resource managers to plan for potential changes. In addition, Deer Creek Reservoir is a primary drinking water source for Salt Lake and Utah counties which comprise a large percentage of the population of Utah. A changed environment could have large impacts on water supply and treatment for this area. Understanding potential impacts can provide water managers with information that can be used to mitigate the harm these impacts could cause.

1.1 Study Area

Deer Creek Reservoir is a dimictic-temperate reservoir located on the Provo River in Wasatch County, Utah. It is classified as a dimictic reservoir because of the two complete mixing (top to bottom) periods that occur each year in the water column (Kalff 2002, Wetzel 2001). It is located below the Heber Valley approximately 30 km above Utah Lake. When the reservoir is full is covers 10.85 km^2, is approximately 9.7 km long, and an average of 0.6 km wide. Deer Creek's main inflow is Provo River while other inflows come from Main Creek, Snake Creek, and Daniel's Creek. The reservoir has a capacity of 152,700 ac-ft (PSOMAS 2002). The watershed that flows into the reservoir is approximately 171,663 acres. Annual Precipitation ranges from 41 to 102 cm (16 to 40 in) and the frost-free season ranges from 80 to 100 days (Casbeer 2009). Changes in temperature and flow, and nutrients are the changes that I evaluated to determine potential impacts from GCC.

Deer Creek Reservoir is used for municipal and industrial power and irrigation flows to more than 195 km^2 of farmland (Anderson et al. 1976). It is the main water supply for approximately 485,000 people in Utah and Salt Lake Counties including the Salt Lake City, American Fork, Lehi, Lindon, Pleasant Grove, Orem, and Provo water districts (Casbeer 2009, Reservoir 2002). Deer Creek also functions as a storage area for Provo River floodwater and as surplus for Weber River water. The Metropolitan Water District of Salt Lake City receives water from Deer Creek Reservoir through a 67.6 km aqueduct (Anderson et al. 1976). Other uses of Deer Creek Reservoir include swimming, boating, and fishing (BOR 2009). Figure 1.1 shows Deer Creek Reservoir.

The limiting nutrient for plant and algal growth in Deer Creek Reservoir is phosphorus (Casbeer 2009). In the 1970's Deer Creek Reservoir was found to be strongly eutrophic near the Provo River inflow and undesirable blue-green algae were dominant. These algae caused tastes and odors in the drinking water which were difficult to remove in the treatment plants. In partial response to this problem (and as part of a larger storage plan), Jordanelle Reservoir was constructed upstream. Jordanelle Reservoir traps phosphorus with retention and sedimentation, reducing the nutrient inflows to Deer Creek (PSOMAS 2002).

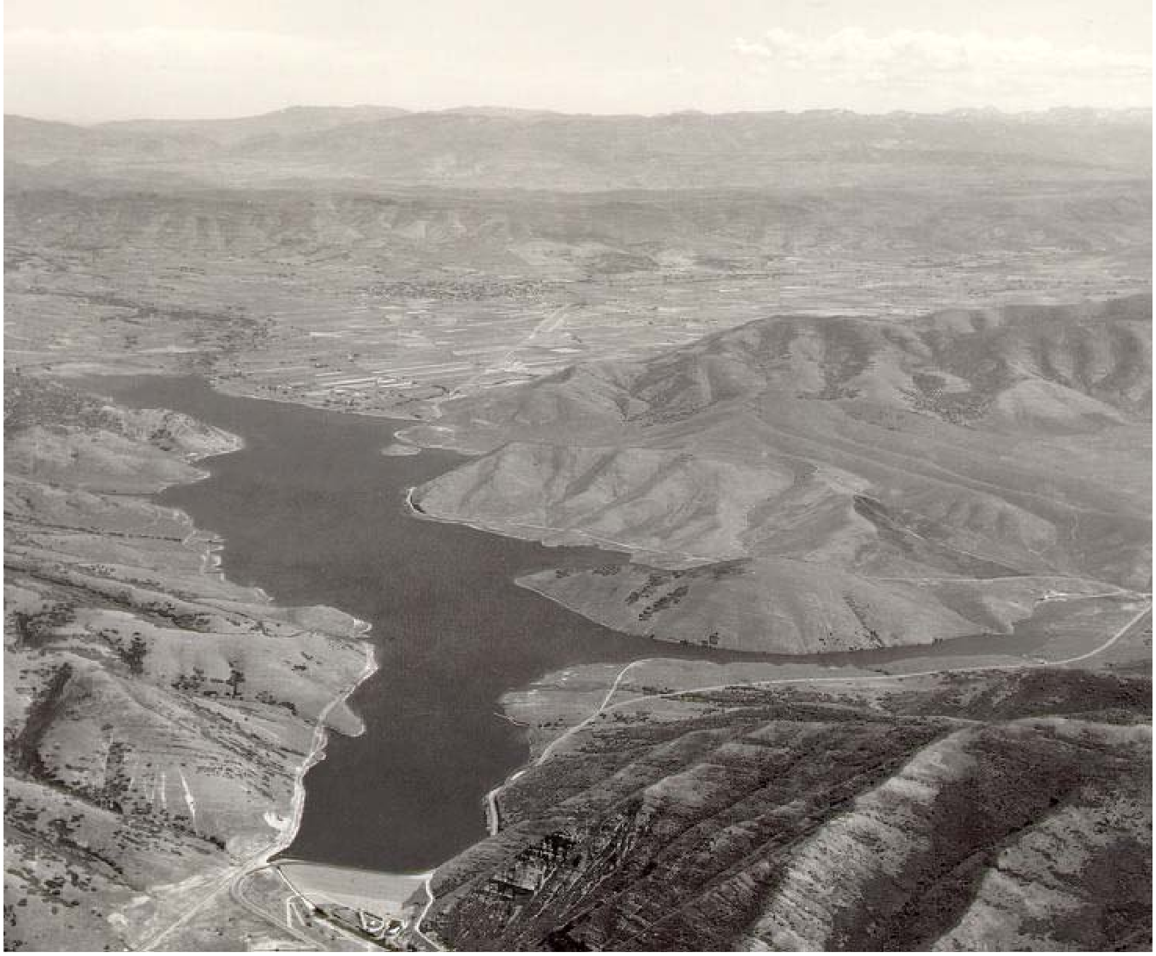

Figure 1.1: Deer Creek Reservoir (BOR 2009)

By 1996, Jordanelle Reservoir was completely filled and since that time there has been a reduction in phosphorus loads to a current range of 2200 kg/yr to 3500 kg/yr in Deer Creek Reservoir. This project and other BMP’s in the Heber Valley between Jordanelle and Deer Creek Reservoir have helped to reduce the algae blooms in Deer Creek Reservoir and improve the water quality, although the algae blooms are still present. The causes for these blooms are unknown as the phosphorus reduction was expected to have larger impacts. These blooms may be due to sediment movement and re-suspension which provides nutrients to the water column from the sediments (Casbeer 2009, Childers 2009).

In 2007, Deer Creek dam was in the final phase of the Safety of Dams project. The spillway gate structure was stabilized and updated with an emergency generator, electrical controls, and SCADA equipment. The crest elevation of the dam was raised approximately 1.8 meters. Compacted engineering fill replaced material from the downstream toe of the dam to prevent liquefaction in the event of an earthquake. The Safety of Dams work prepared Deer Creek Dam for fifty years of service (PRWUA 2008).

During construction, the water surface elevation of the reservoir was changed dramatically from historical conditions. Figure 1.2 shows the total volume of Deer Creek Reservoir from 2007 through 2009 along with the historical minimum, maximum, and average volumes. According to the Provo River Water Users Association (2008) the reservoir matched the historic maximum fill levels in 2006. Starting in the middle of August 2007, the water volume of the reservoir approached the historic minimum volume for the reservoir, and in 2009, the summer reservoir volume once again was at an historic maximum. This large shift in reservoir storage conditions over a very short period of time was due to a combination of construction and weather conditions. In 2008 the water levels were below average for the whole year. In 2009, the water volume reached and surpassed average and the reservoir was full from May to July with water going over the spill way. During model calibration, I was able to reproduce the reservoir processes over these extreme fluctuations in reservoir volume and have confidence that I can use the model to study changes from GCC on the reservoir.

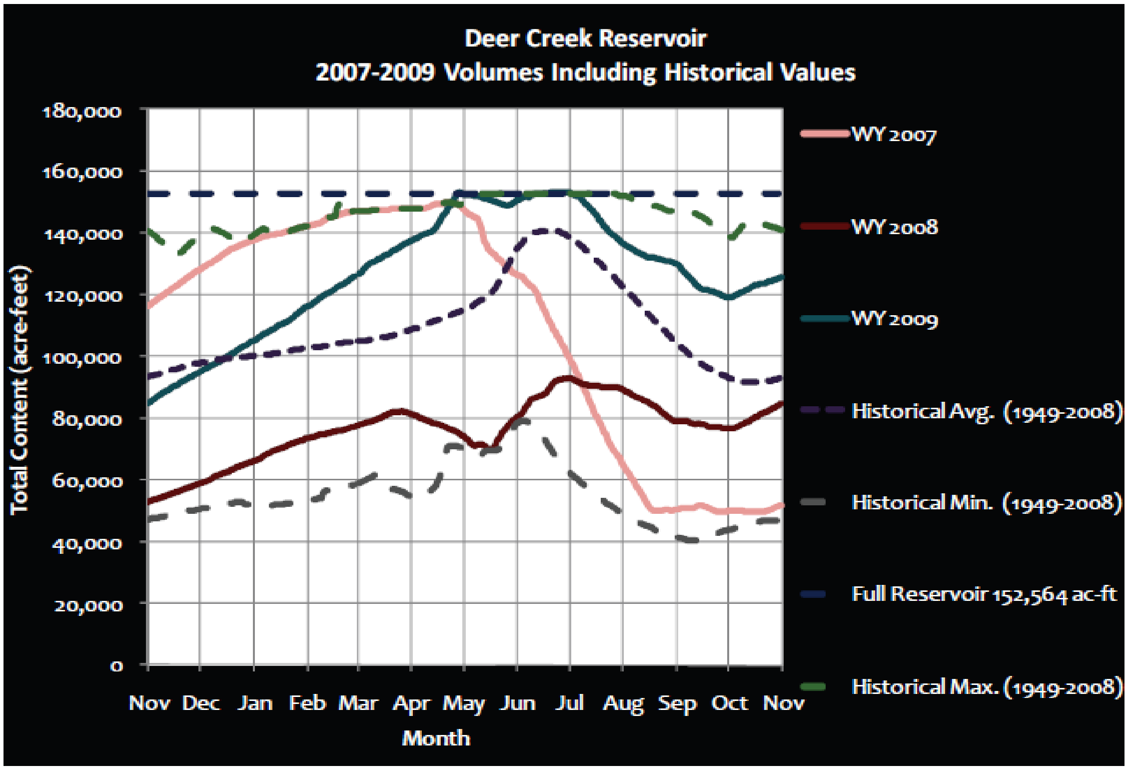

Figure 1.2: Deer Creek Reservoir volumes from 2007-2009 (PRWUA 2009)

2 GLOBAL CLIMATE CHANGE

GCC is an area of concern and study in water management to determine present and future impacts and changes to the drinking water supply. The IPCC was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to assess the scientific, technical and socio-economic information required to understand the risk of human-induced climate change. Governments acknowledge the IPCC as a policy-neutral and balanced scientific stand on the issue and use its reports for decision making. The IPCC has released a number of studies that baseline potential changes in temperature, rainfall, and other climatic variables (Bates et al. 2008, M.L. Parry 2007). I used these values as the basis for my study.

Impacts of GCC are being studied on water bodies. Stefan (1998) and Livingstone (2003) have concluded that the summer stratification of lakes and reservoirs will last longer and be stronger than in the past. Ice cover duration is also expected to decrease due to longer stratification and increasing air temperature (Mooij et al. 2005). Livingstone (2003) analyzed lakes in Central Europe from the 1950s to the 1990s. He observed increasing epilimnion and metalimnion temperatures of 0.24K/decade. 2-3 weeks of longer stratification were also observed (Livingstone 2003). Paerl and Huisman (Paerl and Huisman 2009) concluded that the nutrient-algal bloom threshold relationships can be affected by physical and hydrologic changes caused by climatic changes, not only by high concentration of nutrients. Bartholow et al (2001) and Means (2010) have concluded that increased water temperatures, changes in water chemistry, and biological activity are some of the water quality effects produced by climate change.

2.1 Modeling GCC Impacts on Lakes and Reservoirs

Schindler (1997) used observational data from 1970 to 1990 in Ontario, Canada. He stated that models are unproven and unpredictable. He observed temperature increases of 1-2^{o} C over this time period. He observed changes to the physical, chemical, and biological characteristics and attributed these changes to climatic warming on terrestrial catchments. The changes that he observed may have also been due to human stresses and land-water interactions. He observed increases in evaporation, evapotranspiration, atmospheric CO_2, chemical concentrations, ice-free season length, and water temperature for lakes and streams. He concluded that an average air temperature increase of 2^{o}C would cause a greater decrease in stream flow than a 10% decrease in precipitation (Schindler 1997).

Stasio and Hill (1996) used a 10 year physics-based 1-dimensional model called DYRESM to evaluate the impacts of doubling CO_2. They modeled cold, intermediate, and warm years of meteorological data in four Northern United States temperate lakes. Their goal was to determine how physical, chemical, and biological components of lakes may respond simultaneously to GCC. The simulations showed an earlier onset of stratification, increase of summer epilimnetic temperatures, and longer stratification duration with increased intensity. They noted that physical responses to climate change are consistent among all climate scenarios, but biological responses are more variable and depend on the ecosystem (Stasio et al. 1996).

Stefan (1998) also used a 1-dimensional model in Northern United States temperate lakes and used climate models with a doubling of atmospheric CO_2 over an 18 year period. He used the output from the Canadian Climate Center General Circulation Model and the Goddard Institute of Space Studies General Circulation Model. Secchi depth was used to correlate changes to lake geometry and stratification. Stefan observed shorter ice cover periods and lake temperature variations from the base model throughout the year (Stefan 1998).

Bartholow (2001) used a CE-QUAL-W2 model to simulate the effects of a temperature control device on the reservoir output on Shasta Lake in California. This allowed for the release of water from various dam elevations which would vary the water temperature. Although this study was not related to GCC, in-reservoir temperature effects were studied. As the chemical and thermal characteristics of the discharge changed, the reservoirs characteristics were relatively unchanged. Simulations showed an earlier onset and shorter duration of summer stratification due to the temperature control device. Nutrient composition was unchanged. He found that hydrologic and meteorological variables influenced the model predictions more than the temperature control device (Bartholow et al. 2001).

2.1.1 GCC on Deer Creek

This study focused on the effects of GCC on Deer Creek Reservoir. Located in the Rocky Mountain Region of the United States, this region is predicted to undergo various climate changes in the future. In the 4th Assessment Report (2007) the IPCC reported an estimated temperature change for Utah of about 1°C from 1955 to 2005. The warming trend is expected to continue and increase from 1 to 3°C from 2010 to 2039 with late century warming of 2 to 3°C. Although GCC predictions are uncertain, this study will analyze the magnitude of potential future changes and how these changes would affect the water of Deer Creek Reservoir and other water supply reservoirs in temperate regions.

The annual-mean precipitation is predicted to increase in most of the North American continent, except for the Southwest United States, including Utah, which is expected to decrease. Increasing temperatures and decreasing precipitation will lead to longer and more intense drought conditions for this region. Stream flow over the last century has decreased about 2% per decade in the Rocky Mountain region (Rood et al. 2005). The simulated future surface and bottom water temperature of lakes, reservoirs, and rivers in North America are predicted to increase from 2 to 7^{o}C as a result of GCC (Stefan 1998).

3 METHODS

This chapter discusses the objectives of my thesis. The study was done on Deer Creek Reservoir which is a dimictic temperate reservoir. The purpose of this study is to simulate potential climate change on Deer Creek Reservoir and develop methods and tools to analyze the potential changes on in-reservoir water quality of Deer Creek Reservoir. I did this by calibrating and validating a water quality model using field data from a period with large fluctuations in volume, then changing the model boundary conditions to correspond with predicted climate change for the studied region.

We used collected data, made a 2-dimensional CE-QUAL-W2, calibrated the model, developed methods to quantify and analyze results, and developed tools and programs to extract and plot the results.

3.1 Data Collection

I gathered meteorological and water quality data from the Environmental Protection Agency, Central Utah Water Conservancy District (CUWCD), United States Geological Survey, and the BYU Deer Creek Research Group to create model input files to use for model calibration and validation. I extracted the data from databases from 2007 through 20009.

I developed the input files to represent the meteorological boundary conditions that contained hourly air temperature, dew point temperature, wind speed, speed direction, and solar radiation data. I obtained these data for the 2007-2009 time period from the Central Utah Water Conservancy District data collection site near Snake Creek.

We gathered water quality and flow data from the EPA STORET, USGS, and the Central Utah Water Conservancy District databases (Figure 3.1).

The EPA stations I used were:

- UTAHDWQ 4997250 N/A N/A Spring Ck Ab CNFL / Provo R Nr Heber
- UTAHDWQ 5910160 N/A N/A Snake Ck Ab CNFL / Provo R at USBOR Guage
- UTAHDWQ 5910020 N/A N/A Lower Charleston CNL Ab CNFL / Daniels Ck
- UTAHDWQ 5913520 N/A N/A Daniels Ck Ab Deer Creek Res
- UTAHDWQ 5913450 N/A N/A Deer Creek Res Midlake Up Wallsberg Bay Off Creek Inlet 08
- UTAHDW1 5913460 N/A N/A Main Ck Ab Deer Ck Res at US 189 Xing

The USGS stations I used were:

- USGS 10156000 SNAKE CREEK NEAR CHARLESTON, UT
- USGS 10157500 DANIELS CREEK AT CHARLESTON, UT
- USGS 10155500 PROVO RIVER NEAR CHARLESTON, UT

3.2 CE-QUAL-W2

Water managers can effectively use water quality models to design, study, and assess changes in a reservoir over time. Water quality models have been used to simulate water quality and hydrothermal conditions in worldwide water bodies (Bartholow et al. 2001, Debele et al. 2008, Kim and Kim 2006, Kuo et al. 2006).

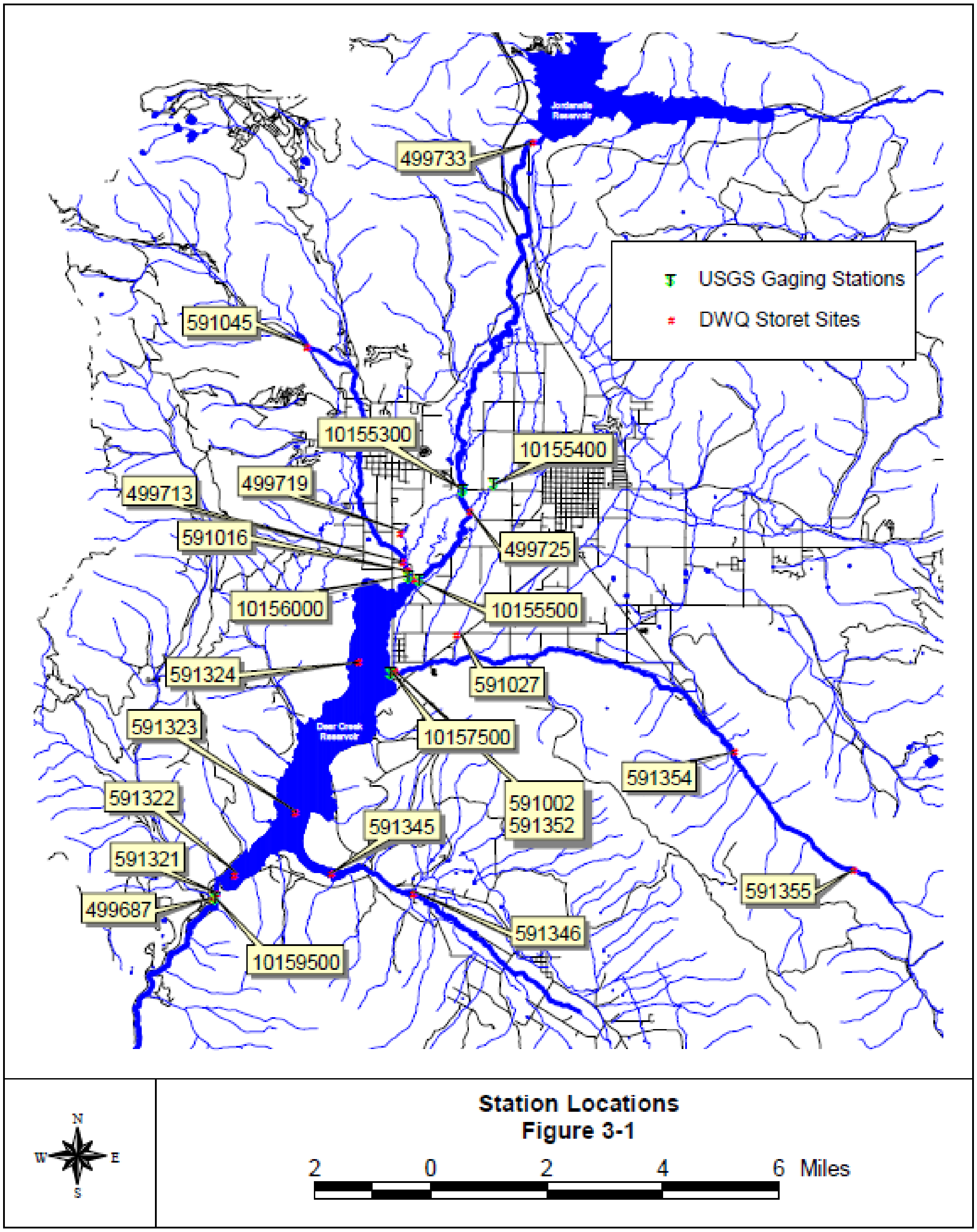

Figure 3.1: USGS and DWQ station locations (PSOMAS)

CE-QUAL-W2 is a finite difference, two-dimensional hydrodynamic and water quality model which was developed by the US Army Corps of Engineers to better manage water supply reservoirs (Bartholow et al. 2001, Gelda et al. 1998). CE-QUAL-W2 works best for relatively long and narrow lakes and reservoirs because it assumes lateral homogeneity (Cole and Wells 2006). The model has undergone various changes to improve the computational efficiency and accuracy, transport and mixing schemes, and has expanded to model hydraulic structures and multiple water-body capabilities (Williams 2007).

3.3 Deer Creek Model

We chose to use the CE-QUAL-W2 model because it is one of the most commonly used models worldwide to simulate reservoirs and is the model that the Upper Colorado US Bureau of Reclamation (BOR 2009) currently uses to evaluate water quality in reservoirs of the Rocky Mountain States.

In 1995 the Central Utah Water Conservancy District developed a CE-QUAL-W2 model to simulate water quality in Deer Creek Reservoir. They used this model to evaluate the impacts of decreasing long-term trends in total phosphorous and total nitrogen on the reservoir. Also, this model was developed to understand past problems associated with algal blooms that clogged water treatment plant filters causing odor and taste problems (PSOMAS 2002).

I evaluated potential GCC by simulating meteorological, hydrological, and nutrient changes in the Deer Creek Reservoir system and studying the resulting impacts. This study will aid in analyzing future changes that may be necessary to keep the water of Deer Creek Reservoir drinkable and healthy.

Previous modeling efforts on Deer Creek have not been used to evaluate potential GCC impacts. There have been studies that looked at the impacts of various changes that were designed to limit nutrient loads. PSOMAS (2002) discussed the use of BMP’s that have been implemented to improve the reservoir from eutrophic to its current mesotrophic state. My study can help them continue to improve the water quality of the reservoir by understanding how future environmental changes could impact the reservoir.

The Deer Creek Reservoir CE-QUAL-W2 model is a simplified representation of the reservoir. I considered changes to inflow volumes, which indirectly include runoff and precipitation in the drainage basin. I analyzed the results by comparing trends that occur in the reservoir due to GCC rather than precise values. This approach shows how various changes could impact reservoir processes compared to a baseline model. I had more confidence in this approach, rather than trying to evaluate specific predictions.

I am confident that my model can evaluate a wide range of changes, and that relative changes in the reservoir predicted by the model are credible. However, I do not view these as predictive of the future state of the Deer Creek reservoir, because I did not try to accurately present all the changed boundary conditions that could occur in the future. I evaluated various aspects of those changes, e.g., flow, air temperature, etc. could change the reservoir and how sensitive the reservoir was to those changes.

3.3.1 Geometric Representation

Deer Creek Reservoir was represented by a geometric computational grid (Figure 3.2). Branch 1 of Deer Creek Reservoir is the main branch which goes from the Provo River inflow to the Dam. It is divided into eighteen segments. Branch 2 is Wallsburg Bay and Main Creek inflow from the east, flowing into Branch 1. Branch 2 is divided into nine segments.

3.3.2 Meteorological Inputs

We developed the meteorological input file with hourly air temperature, dew point temperature, wind direction, wind speed, and solar radiation data from the climatological station located in Snake Creek. I obtained these data from the CUWCD from 2007-2009. The data reflect the daily ranges in temperature over the three year period.

3.3.3 Initial Conditions

The initial conditions used to create the model were defined by the characteristics of Deer Creek Reservoir as described in PSOMAS (2002) and observed values. These conditions were based on data from 4 sampling locations. The main sampling location is called “Near Dam”, which is the southern-most section. The sampling location near the Provo River inflow is called “Upper” and “Midlake” was between Upper and Near Dam. The fourth sampling point was called “Wallsburg”, which is located in Wallsburg Bay. Figure 3.3 shows a map of Deer Creek with the sampling locations. The distance between “Near Dam” and “Midlake” is approximately 3.9 km. The distance between “Midlake” and “Upper” is approximately 3.4 km. “Wallsburg” is approximately 1.2 km from where Wallsburg Bay opens up into the Main Branch of the reservoir.

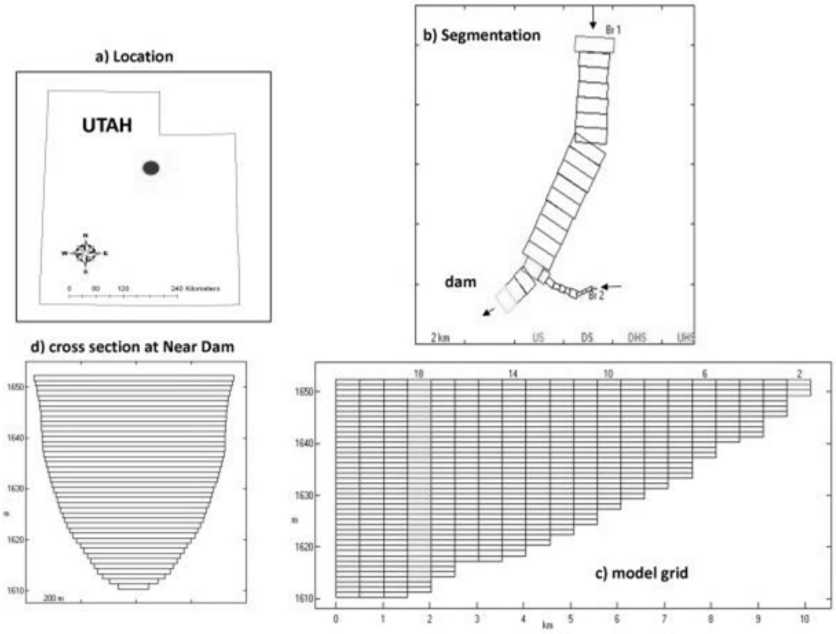

Figure 3.2: a) Deer Creek Reservoir location; b) Reservoir segmentation; c) model geometric grid-branch 1, and d) Deer Creek model cross section

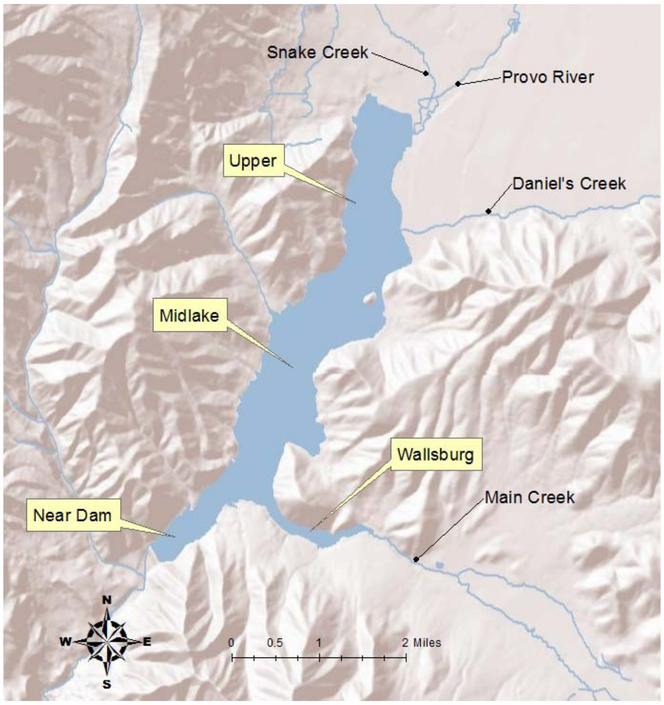

Figure 3.3. Sampling points for Deer Creek Reservoir

3.3.4 Boundary Conditions

The boundary conditions included water temperature, hydrologic inputs, inflow water quality, and their distributed files. Boundary conditions were based on observed data and computed values where required. The distributed files represent the un-gauged data along the reservoir from sources beside the main inflows. This would include overland flow, seepage, direct precipitation, etc.

3.4 Model Calibration

3.4.1 Background on Calibration

I used water balance, temperature, total dissolved solids (TDS), dissolved oxygen (DO) and Chlorophyll-a measured data to calibrate the Deer Creek Reservoir W2 model. The accuracy of the calibration was measured by the statistical global absolute mean error (AME) of temperature, TDS, DO and Chlorophyll-a. The AME considers the absolute total sum of the predicted minus the observed values, divided by the number of observations. Equation 3-1 is the equation for AME.

$$\text{AME}=\frac{\sum|\text{Predicted-Observed}|}{\text{number of observations}} \tag{3-1}$$

3.4.2 Calibration Results

I calibrated the model using water balance data. I used water surface elevation data from the CUWCD to calibrate with the model produced data. Figure 3.4 shows the calibration for water balance.

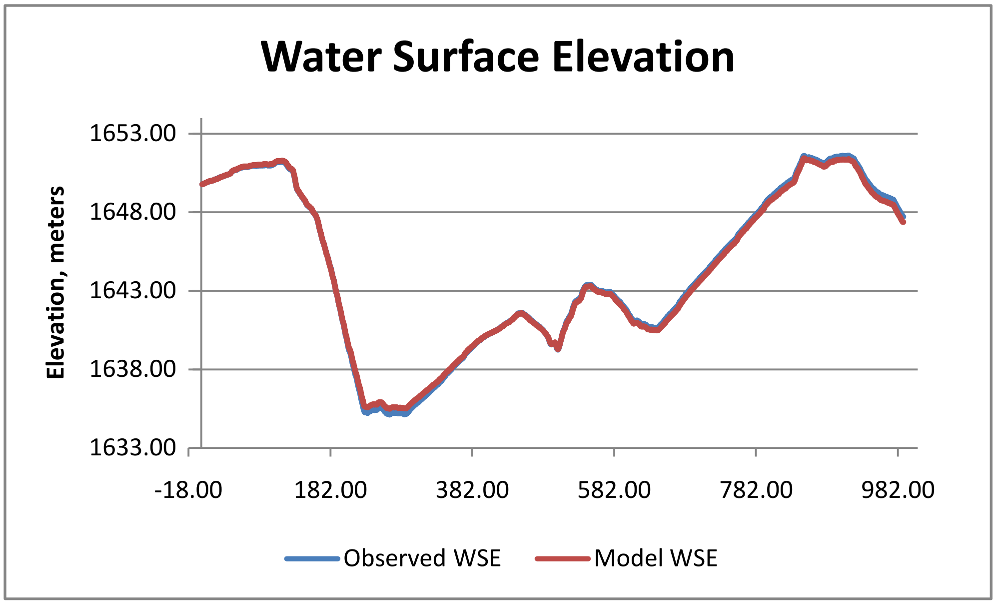

Figure 3.4: Water surface elevation calibration

Next, I calibrated for hydrothermal conditions by adjusting the coefficients recommended by Cole and Wells (2006) to match model thermal profiles to field measured data. After this calibration, the AME was 0.96 which means the average model value is within 0.96^{o}C of the observed value for the thermal calibration. Figure 3.5 shows a sample of the thermal calibration of the complete vertical profile at the Near Dam sampling point on five different dates. On the calibration plots, the circles are the observed data and the line is the model output.

I calibrated the model to the DO measurements. The AME obtained for DO was 1.5. This means that there is an average of 15% error between the observed data and the model produced data. Example plots are shown in Figure 3.6.

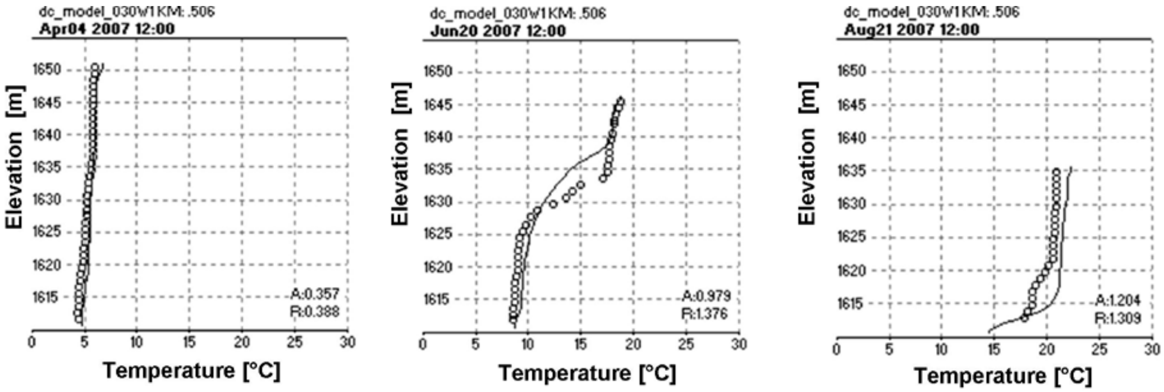

Figure 3.5: Thermal calibration results for the Near Dam sampling point for various days

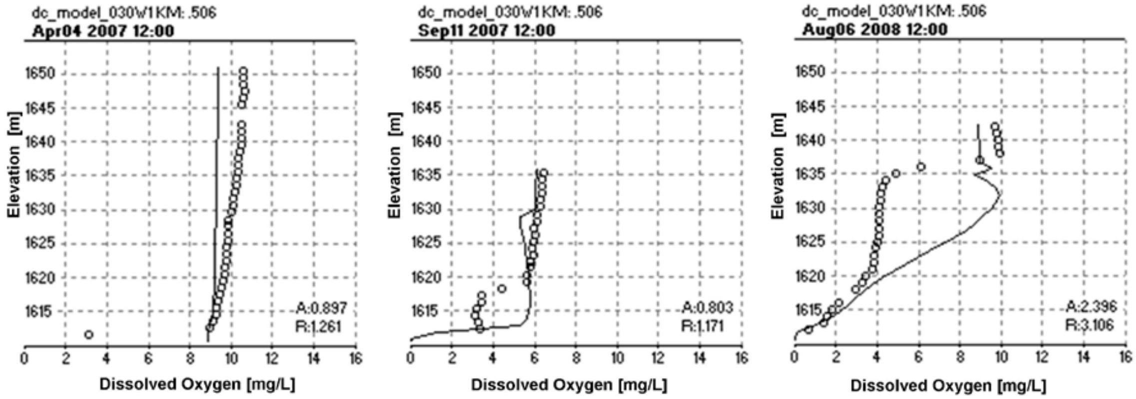

Figure 3.6: DO calibration for the Near Dam sampling point for various days

Next, I calibrated the model to the TDS measurements. Even though TDS is not as conservative as salinity to calibrate a W2 model, I used it because TDS was the only available data with similar characteristics to salinity. The AME for TDS was 9.6. This means that the average model value is within 9.6 mg/L. Since these values range from 0 to 500 mg/L, the AME represents about 5% error. Figure 3.7 shows the calibration for vertical profiles of TDS data measured and modeled in the reservoir at the Near Dam sampling point.

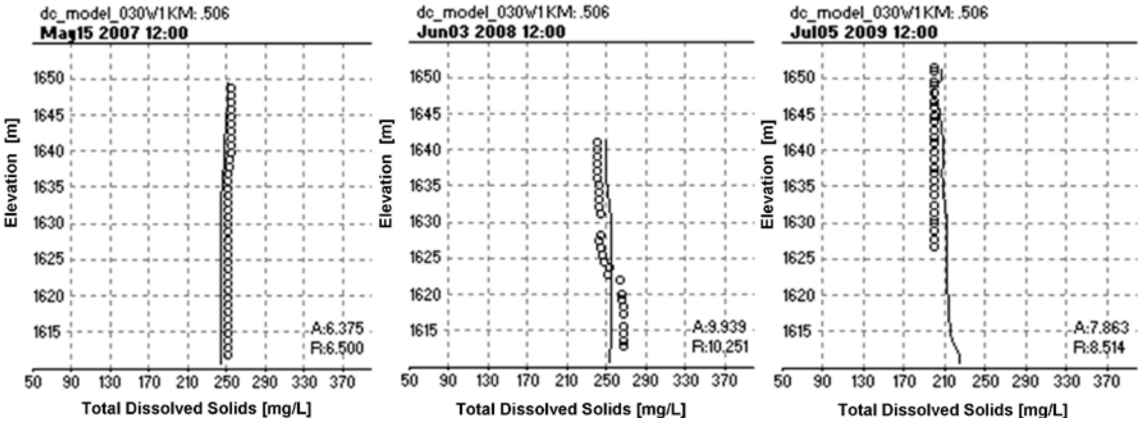

Figure 3.7: TDS calibration results for the Near Dam sampling point for various days

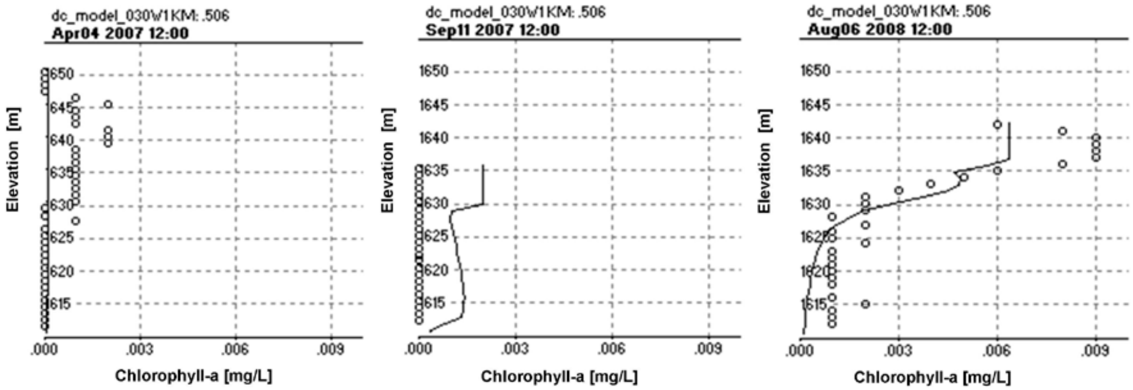

Figure 3.8: Chlorophyll-a calibration results for the Near Dam sampling point for various days

I ended the calibration with Chlorophyll-a calibration. The AME for Chlorophyll-a was 3.24 which is a about a 35% error (Figure 3.8). Error in the chlorophyll calibration is present for a variety of reasons and is expected. Algae are spatially diverse in reservoir and single profiles or measurements change quickly with reservoir conditions. Algae and some other data were only available for limited time periods. Hourly data were not available for each parameter, and even daily data was unavailable for some time periods.

3.5 Data Management and Representative Plots

The data management and plot development is a major contribution of my thesis. I developed methods that allow quantifiable results for reservoir modeling studies. Traditionally, visual animations are produced through programs such as AGPM to view the changes over time. These animations include data from the entire model, but are presented as a time-varying two-dimensional plot of the entire reservoir. While this is a good way of viewing large changes, it is difficult to determine differences between multiple model runs and more importantly to quantify those differences.

To date, the majority of results in similar studies are descriptive. I have developed tools, using scripts that automate the process of performing model runs through a set of scenario changes, formatting the results, performing calculations, and creating plots with little human intervention. These tools can be applied to other working CE-QUAL-W2 models.

3.5.1 Cygwin

Cygwin is a Linux type environment for Windows. I used Cygwin to facilitate automating the modeling and data presentation tasks. Evaluating GCC impacts require a large number of runs, each of which generates hourly information for a three year period at each model grid node. Being able to automate the modeling and initial analysis tasks was imperative to being able to conduct this research. Even the relatively simple task of opening each output file and generating individual plots would have resulted in extreme time requirements.

Using scripts and tools I developed in the Cygwin environment, I was able to change the hourly inputs for the three year period, create new input files, run the model with those inputs, and process the output files automatically. I ran the Deer Creek model through Cygwin to simulate each change using scripts. Then I plotted the data with Gnuplot. Gnuplot is a free, command-driven plotting program which I automated using Cygwin bash scripts.

I needed to determine how to evaluate changes between the baseline and the modeled condition for the entire reservoir and quantify these changes. I developed methods using profiles and total concentration plots to analyze and quantify the impacts that various changes can have on the reservoir compared with the base model.

I created scripts to extract and format necessary data including time with corresponding air temperature, water temperature, inflow, phosphorus concentration, nitrogen concentration, total water volume, algae mass, and chlorophyll-a concentrations. The plots are shown in the Results section.

In Appendix A.1 and A.2 there are full versions of some of the scripts that I used to extract data and plot results. There were basically three scripts that I used. The first was to extract the data from the model output file. The second script was to organize the data into a table, calculate reservoir water volume, and calculate total reservoir concentration. The final scripts are made to plot the data and save them as jpeg files.

3.5.2 Tool Development Methods

As noted, the model creates hourly data over the three-year model period at each grid node. There is no standard method for evaluating global changes to a reservoir and comparing those changes to a baseline condition for a large number of simulations. Traditionally one or two simulations have been compared in significant detail, but I developed methods to facilitate a more general comparison in a quantitative manner. The initial plot that I created using my tools was Chlorophyll-a Profiles. These are not unique profiles but were used as preliminary results and learning to run scripts in Cygwin. I was interested in creating plots that would show variation with time. I created three plots that analyze the reservoir over time: Average Water Temperature Plots, Stratification Plots, and Total Concentration Plots. In this section I will explain the purpose of each plot and how they were calculated.

3.5.3 Chlorophyll-a Profiles

We used vertical profiles of chlorophyll-a concentrations with respect to elevation to understand impacts to vertical distributions at a specific location. I developed a script to automate Gnuplot in Cygwin to plot these profiles.

Chlorophyll-a Profiles require a specific location and time. For comparison, the location and time can be changed. Initially, I plotted various locations of the reservoir for a specific time to compare the chlorophyll concentration trends in the reservoir. I also plotted varying dates and times to compare the chlorophyll concentrations over time. I created a large number of plots and making comparisons became overwhelming. To reduce the number of plots, I chose to plot and analyze vertical profiles at the Near Dam sampling point.

3.5.4 Average Water Temperature

My first plot that shows reservoir changes with time is the Average Water Temperature Plot. I developed a script to extract weekly profiles at the Near Dam sampling point in Deer Creek at noon. This sampling point is located at the deepest area of the reservoir. The script then averages the entire temperature profile values from the surface of the reservoir down to the bottom of the water column. This was done weekly and then plotted with time. The scripts can be modified to extract profiles hourly, daily, or any other resolution that the user desires.

An Average Water Temperature Plot can also be done to analyze the water temperature sensitivity to changes in flow, wind speed, or other parameters of interest. The benefit of this plot is that it is a visual of how the parameter change influences the water temperature and when. For example, this plot can show the months when changes in air temperature influence the average water temperature and by how much.

3.5.5 Stratification Plots

The Stratification Plots require temperature profiles at a specific location. The time-step that I used was weekly profile extraction, and can be modified. The scripts extract top water surface elevation and the bottom water elevation for each time step and calculate the difference. Then the difference is plotted with time to see when the stratification was strongest and when the reservoir turned over.

I defined stratification strength by the magnitude of difference between surface water temperature and the bottom temperature. The higher the difference in temperatures results in stronger stratification. After the reservoir has turned over, the water temperature profile is more uniform so the difference in water temperatures from top to bottom of the water column is very small. When the reservoir is covered in ice, the surface of the reservoir is colder than the bottom of the reservoir so the difference is negative. This analysis does not take into account the shape of the stratification or the thickness of the epilimnion.

I used the Near Dam sampling point in Deer Creek for these plots. I used this plot to analyze the impacts of air temperature and inflow on stratification length and strength. I was also able to determine the impacts on ice-cover periods. Other variable such as wind speed or other water quality parameters could also be used to analyze their impacts on stratification.

3.5.6 Total Concentration Plots

I wanted to evaluate the entire reservoir as a whole for independent model changes. The model output has total mass values for several constituents including algae, dissolved oxygen, phosphate, and nitrate-nitrite. At first I extracted these values weekly and plotted them with respect to time. While this was useful, I observed that the changes in mass was more influenced by the volume of water in the reservoir than by changes in the boundary conditions, making it difficult to separate impacts from GCC from normal variation in the reservoir. An example of this plot is shown in Figure 4.8.

To address this problem, I normalized the mass balance using the total reservoir volume. CE-QUAL-W2 does not provide a method to output total reservoir volume so I wrote a script to compute it using the storage-capacity curve for Deer Creek. I then divided the total mass of each of the constituents by the total reservoir volume to get average total concentration values. I then plotted these total concentrations with respect to time. I called them Total Concentration Plots. This proved to be a useful method to analyze the data over time and compare scenarios with the base case.

I modeled changes in Temperature, Flow, Nitrates, and Phosphates. For each change, I ran a base case, a negative change, and a positive change. The magnitudes of the changes were based on the IPCC predictions (M.L. Parry 2007). For the negative change, I used the same magnitude as the positive change. This allowed me to understand the sensitivity of the model to these potential changes. For evaluation, I extracted total mass concentrations of Algae, Dissolved Oxygen, Phosphate, Nitrite-Nitrate, and reservoir volume for each model run. These values were extracted weekly. This results in 16 temporal average total concentration plots, each showing 3 runs.

Total Concentration Plots allow comparison changes in the entire reservoir rather than specific locations. These global plots help identify trends that occur from GCC and variations from the base case. They are independent of total water volume so difference between the plots is the results of the parameter that was changed based on predicted GCC magnitudes. The plots show the model generated base case, increased parameter results, and decreased parameter results over the modeled period of three years.

The total concentration is a single number that represents conditions over the total reservoir volume. It does not show spatial distributions or indicate where the majority of the mass is located in the reservoir. However, this parameter provides a method to easily compare model results for different scenarios. I evaluated total concentration changes over time to see the seasonal variation of these constituents. These plots showed both magnitude and temporal changes in constituent concentrations for the various scenarios.

3.6 Modeled Climate Changes

3.6.1 Air Temperature

I evaluated potential air temperature changes from GCC by adding and subtracting 3^{o}C to the model input data air temperature. This was a constant delta value applied throughout the year. This value came from the IPCC prediction of increase in temperature for the region by 2039 (M.L. Parry 2007). I simulated a decrease in temperature as well as the increase to observe total concentration sensitivity to air temperature changes. This simulation represents cold, normal, and warm climate trends. I ran the model with each of the three climate change scenarios.

3.6.2 Inflow

I ran the model with changes in inflow of plus and minus 10% of the calibrated model generated data. This simulated potential dry, normal, and wet scenarios. I used 10% change in flow from the IPCC prediction of a 2% per decade decrease in flow. In order to view changes I increased the change in flow to 10%. Runoff and groundwater changes were not considered in this study. The outflow values remained constant, assuming that water needs were unchanging.

3.6.3 Phosphates

I simulated an increase and decrease of inflow phosphate concentrations by 50%. The inflow concentrations of each inflow source were changed by 50%. These runs represent high, low, and normal concentrations of phosphates. The nutrient changes could be caused by the expansion of urban areas into the watershed surrounding the reservoirs, building upstream dams, changes in land use, or farming. The phosphate concentrations are a concern due to correlations with algae blooms.

3.6.4 Nitrates

I simulated an increase and decrease of Nitrate concentration by 50%. The inflow concentrations of each inflow source were changed by 50%. These runs represent high, low, and normal concentrations of Nitrates. Nitrates are important because they are necessary for life and are related with algae blooms (Vesilind 2004).

4 RESULTS

I used the tools which I developed to produce results for Deer Creek Reservoir. I ran simulations to represent potential scenarios due to climate change. I plotted Chlorophyll-a profiles, average water temperature plots, stratification plots, and total algae concentration plots to quantify the potential GCC effects in Deer Creek.

4.1 Chlorophyll Profiles

Chlorophyll-a profiles were used as preliminary indicators of GCC effects in Deer Creek. These Chlorophyll-a profiles are from the Near Dam site corresponding to two sample days. Each of the plots are taken at noon on the given day. Chlorophyll readings are sensitive to the time of day. I evaluated the change in Chlorophyll-a profiles that resulted from changes in each of the four main parameters. These are presented in this section.

4.1.1 Air Temperature Changes

Figure 4.1 shows the profiles for July 28, 2008 and August 3, 2009 at the Near Dam sampling point for changes in air temperature. I observed that the Chlorophyll-a concentrations did not significantly change if air temperature was increased 3°C. Also, I saw that Chlorophyll-a concentrations decreased when air temperature values were colder (-3 °C). These simulations showed us that the Chlorophyll-a concentrations are slightly affected by changing air temperature.

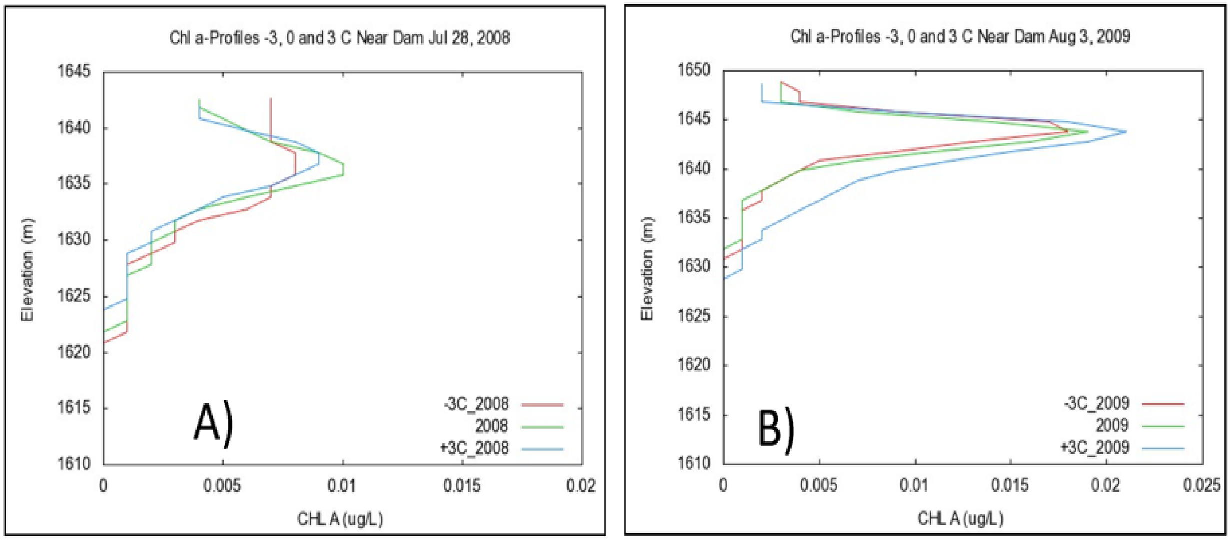

Figure 4.1: Chlorophyll-a profiles at the Near Dam sampling point by adjusting air temperature: A) Summer 2008 and B) Summer 2009

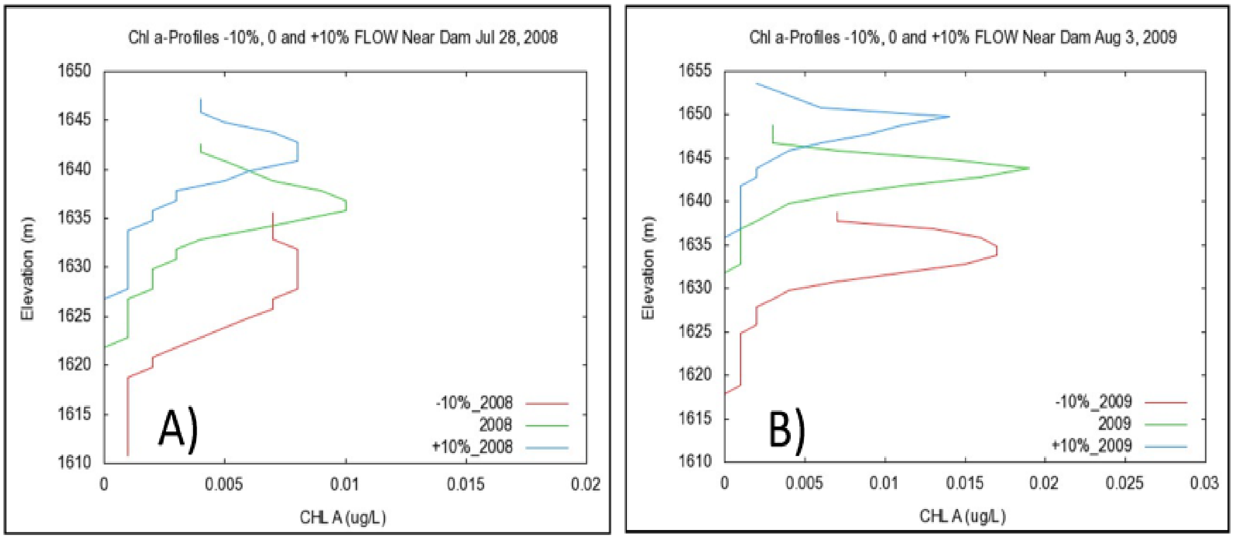

Figure 4.2: Chlorophyll-a profiles at the Near Dam sampling point by adjusting flow: A) Summer 2008 and B) Summer 2009

4.1.2 Inflow

There is no influence on the chlorophyll levels except that the elevation of the water changes. High inflow yields higher elevation of the readings, and lower inflow yields lower elevation of the readings. The elevations at which the chlorophyll readings are zero are also influenced in the same way by the inflow. The chlorophyll only exists about 25 meters below the surface regardless of the flow (Figure 4.2).

4.1.3 Phosphates

Decreasing and increasing the phosphate concentrations has a strong effect on the vertical profile on chlorophyll. The run for the +50% phosphates shows the highest concentration of chlorophyll-a in the reservoir. The concentrations near the thermocline are much higher than the run with no change and the run for -50% phosphates. Increasing amounts of phosphates into Deer Creek would increase the amounts of chlorophyll-a in the reservoir. Figure 4.3 shows the

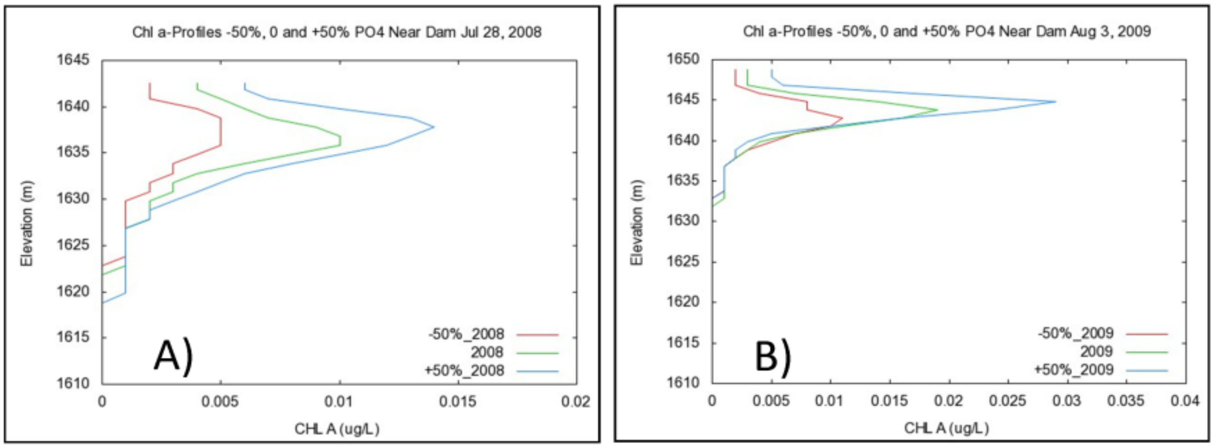

Figure 4.3: Chlorophyll-a profiles at the Near Dam sampling point by adjusting phosphate concentrations: A) Summer 2008 and B) Summer 2009

predicted Chlorophyll-a profiles at the Near Dam sampling point. These predicted Chlorophyll-a profiles proved that there are direct correlations between phosphate concentrations and Chlorophyll-a concentrations. I also simulated increasing and decreasing nitrates concentrations by 50%. However, I did not observe any change in Chlorophyll-a as a result of changing nitrate concentrations.

4.2 Average Water Temperature Plots

4.2.1 Air Temperature

To better analyze these results I have plotted the average water temperature as a result of changing air temperature. Figure 4.4 shows how the air temperature influences the changes in water temperature.

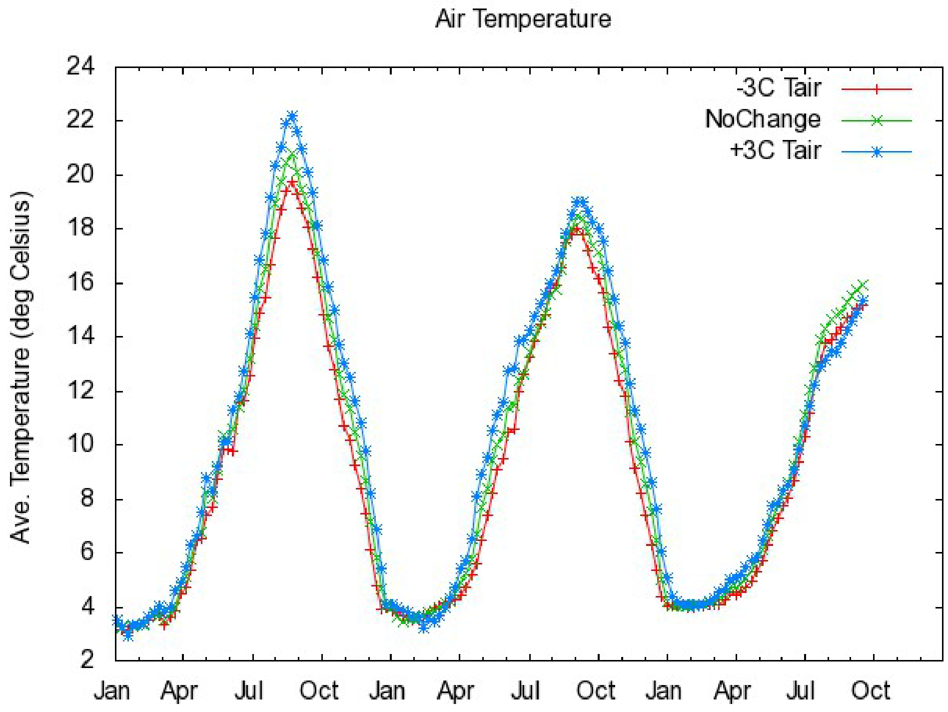

Figure 4.4: Average water temperature at the Near Dam Sampling Point as a result of changing air temperature, -3°C, no change, +3°C

The +3^{o}C run has the highest water temperature which is expected. There is an increase of approximately 1^{o}C in water temperature as the air temperature increases 3^{o}C. Warmer water temperatures can result in increasing chemical and biological processes which are of concern for Deer Creek because of its past issues with algae blooms. Increasing water temperatures would also decrease the dissolved oxygen in the water leading to larger anoxic zones in the bottom layers of the reservoir.

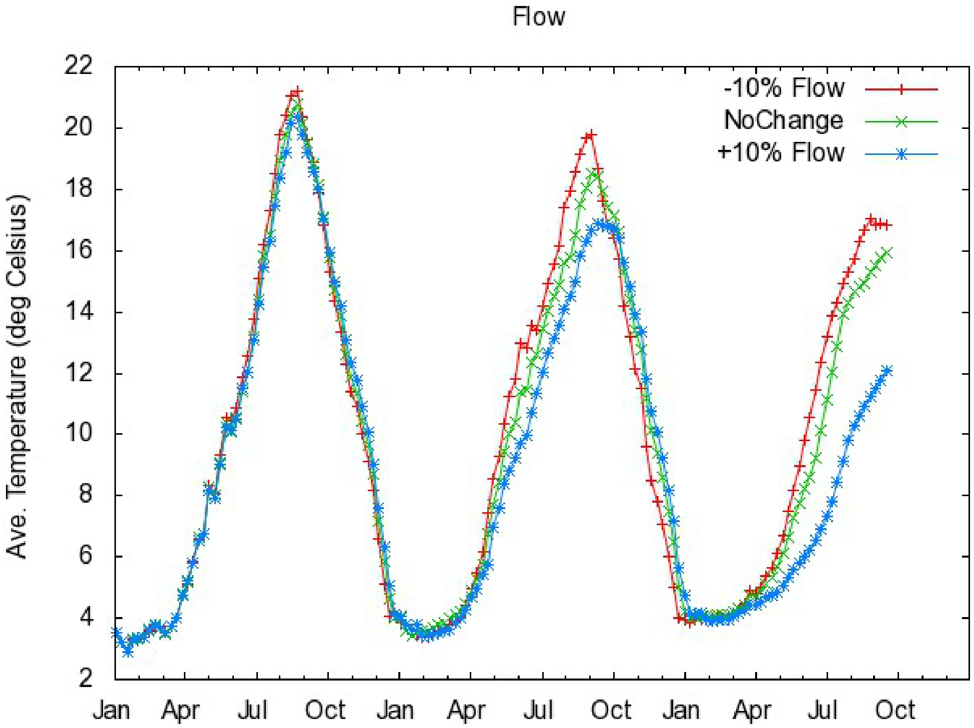

Figure 4.5: Average temperature of Deer Creek as a result of changes in inflow, -10%, No Change, +10%

4.2.2 Inflow

Decreasing inflow is predicted to be a result of GCC. The amount of inflow will influence the water temperature of the reservoir. Figure 4.5 shows that as flows are decreased, the average water temperature in the reservoir will increase. This trend is consistent throughout the model simulation. The projected results of GCC are increased air temperature and decreased flows, which both show increases in water temperature.

4.3 Stratification Plots

4.3.1 Air Temperature

Stratification Plots show the difference between the surface water temperature and the bottom water temperature for the reservoir (Figure 4.6). When the difference between these two temperatures is 0, the reservoir is mixing. As the difference increases, the reservoir stratification is stronger. In the first April shown on the plot, the +3^{o}C simulation increases earlier than the No Change and -3^{o}C simulations. This means that stratification started earlier as the air temperature increased. This is also shown in the following years, but it is less evident. The result is also similar for the end of the stratification period. The +3^{o}C line returns to 0 later in the year in the second and third years. The increased air temperature causes the stratification to start earlier and end later in the year.

The strength of stratification is also shown in Figure 4.6. For every year, the summer stratification is strongest with the increased air temperature. The decreased air temperature has the weakest stratification, which is shown by the lowest difference in top and bottom water temperatures. Increasing the air temperature by 3^{o}C causes the stratification to be about 1^{o}C stronger.

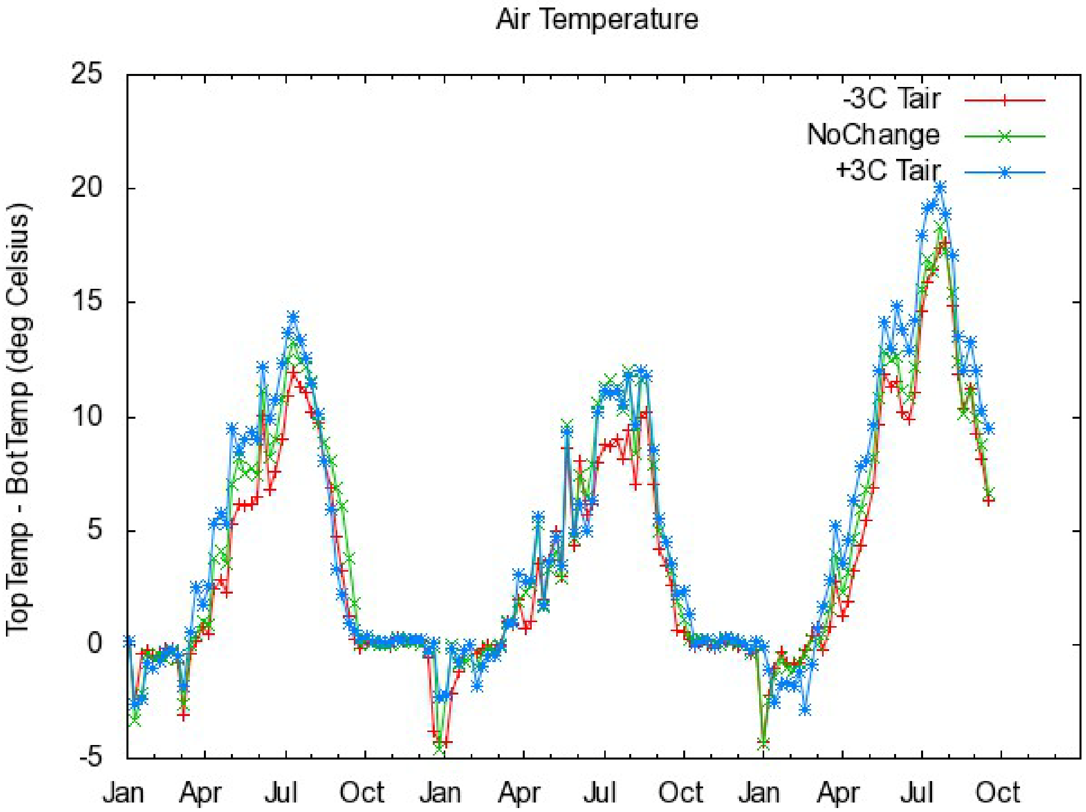

Figure 4.6: The difference between top water temperature and bottom water temperature at the Near Dam sampling point for changes in air temperature, -3^{o}C, no change, +3^{o}C

As expected with longer and stronger stratification, the period when the top of the reservoir is frozen decreases. This is shown in the plot by the times where the lines drop below 0. This happens when the reservoir freezes over, which causes the water on the bottom of the reservoir to be higher than the surface water temperature. This trend is most evident in the second January. The +3^{o}C line drops below 0 later and comes back up to 0 earlier than the other runs. This results in a shorter period of time of ice-cover for the reservoir.

4.3.2 Inflow

The Stratification Plot for changes in inflow is shown in Figure 4.7. The decreased inflow shows weaker and shorter stratification than the higher flows. The changes in inflow do not show a consistent change in the ice-cover period of the year. The summer is the only time of the year that the water temperature is influenced by inflow volume. The lower flows result in higher water temperature but shorter and weaker stratification (Figure 4.7). This occurs because water volume decreases as the inflow decreases. In the model, I kept the outflows constant. The solar radiation was able to penetrate further towards the bottom of the reservoir, heating the

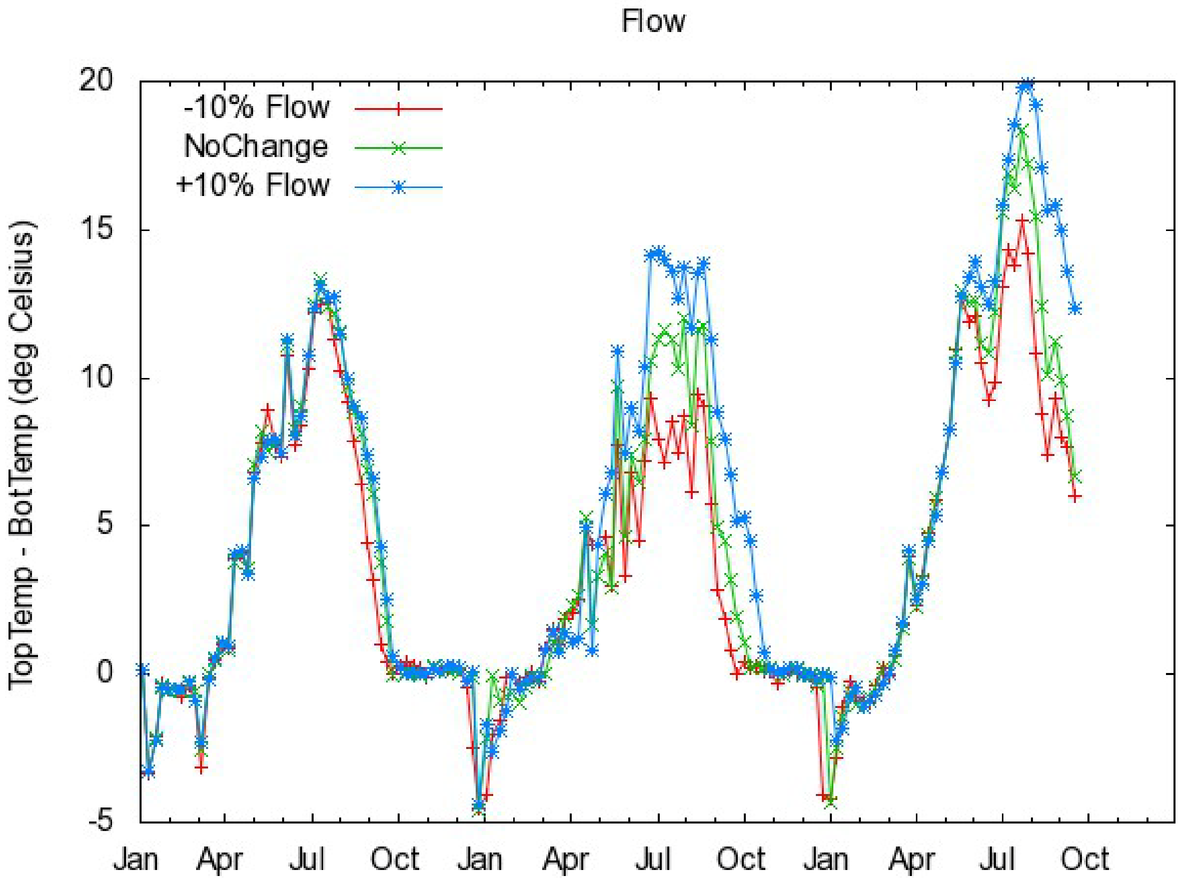

Figure 4.7: The difference between the top and bottom water temperature of Deer Creek as a result of changing inflows, -10%, no change, +10%

bottom layers more than when the reservoir was full. This caused a smaller difference in top and bottom water temperatures and a weaker stratification. However, these trends are more based on the reservoir water volume rather than the inflow so changing the outflow could change these results.

4.4 Total Concentration Plots

4.4.1 Air Temperature

I ran the Deer Creek W2 model three times. I decreased the input air temperature by 3^oC, kept it the same, and increased the input air temperature by 3^oC. I extracted the total algae concentration for the reservoir and plotted it with respect to time (Figure 4.8). Also, I plotted total dissolved oxygen concentrations (Figure 4.9), total phosphate concentrations (Figure 4.10), and total nitrate-nitrite concentrations (Figure 4.11) from each of the three air temperature simulations.

The total algae concentrations increased when air temperature decreased 3°C during the spring and summer seasons of each year. The air temperature influenced the time of the peaks of total algae concentration. The higher the air temperature, the earlier the peak would occur in the season. This is of concern because the stratification of the reservoir will last longer if the air temperature increases. This will produce longer periods of anoxic conditions in the lower levels of the reservoir that can release nutrients from the sediments forming higher concentrations of algae in the water column.

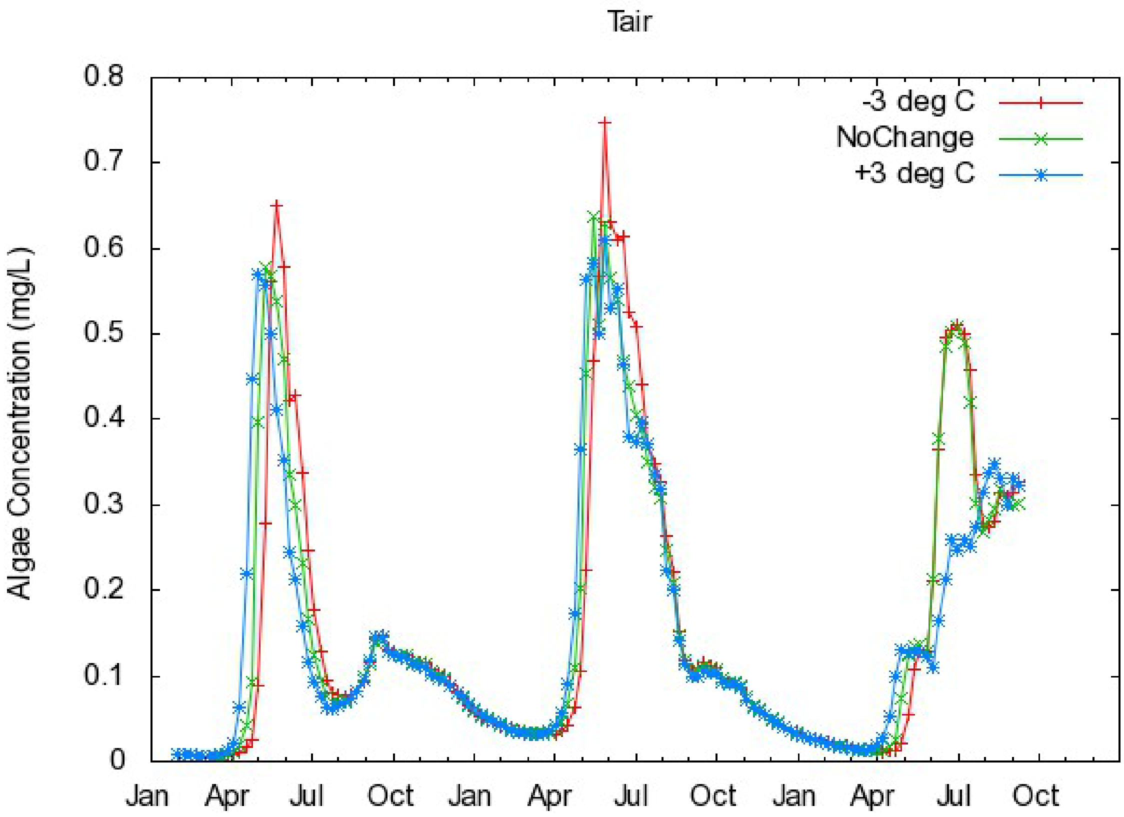

Figure 4.8: Total algae concentrations by simulating air temperature scenarios in Deer Creek, -3°C, no change, +3°C

There were not changes in total algae concentration in the fall and winter seasons in Deer Creek. The greatest change in the total algae concentration plot for Deer Creek occurred during the last May through August. During this period the total algae concentration for +3°C air temperature simulation was much less than the base model and the -3°C simulation. This result was very different than the other years. I ran the model again to simulate +1°C and +2°C. The +1°C and +2°C runs followed the trend of the -3°C and base model simulations. The +3°C simulation was the only run that dropped far below the other curves. This result is due to the temperature being too high for the algae species to survive. Further biological study of algae is required for this aspect of the model.

The increased air temperature decreased the total dissolved oxygen concentration in the reservoir from the first May through the second January and the second October through January (Figure 4.9). According to Vesilind (2004), this is the expected trend for water temperature and dissolved oxygen. From the second February to May, the increased air temperature for dissolved oxygen did not follow the base or the -3^{o}C plots.

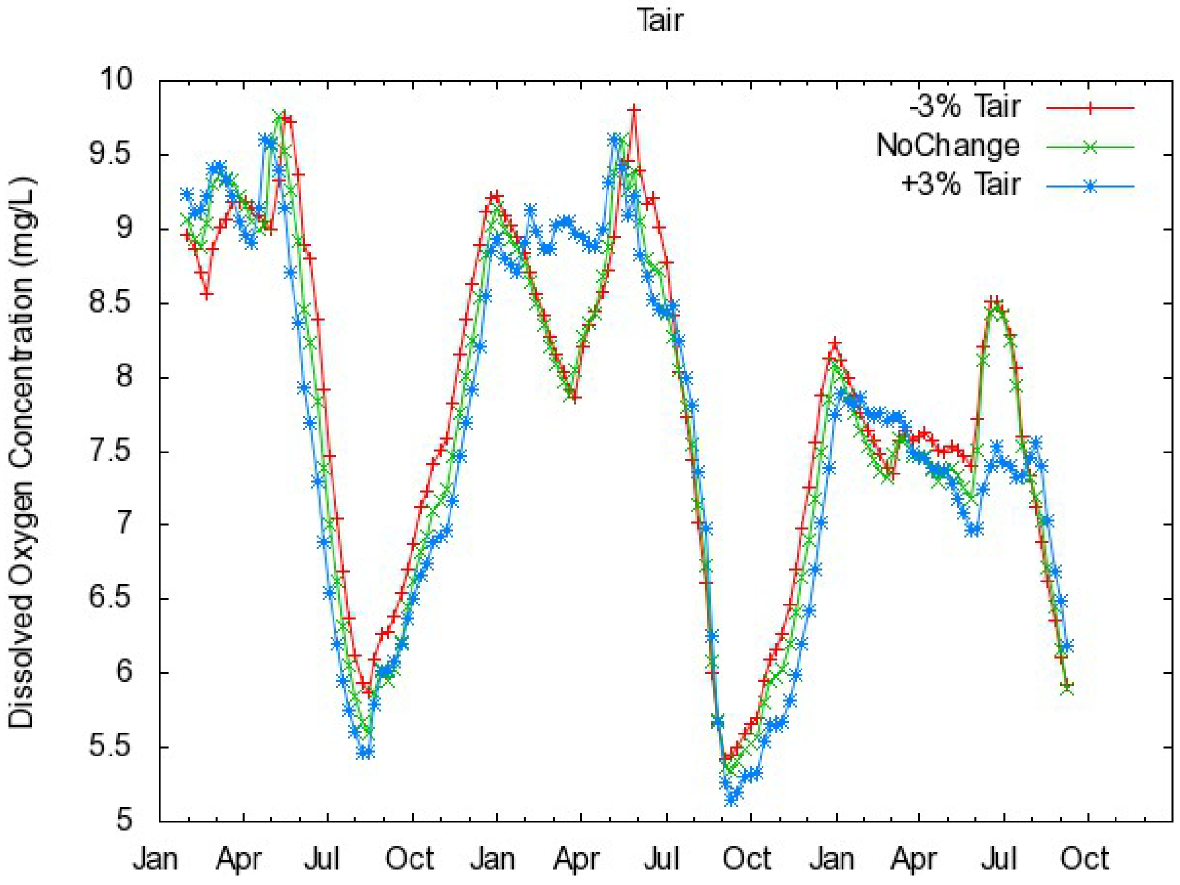

Figure 4.9: Total dissolved oxygen concentrations by simulating air temperature scenarios in Deer Creek, -3^{o}C, no change, +3^{o}C

The peak phosphate concentrations were during the spring and summer seasons of each of the 3 simulated years. The changes in temperature had minimal impact on the phosphate concentrations until the second May where the -3°C simulation was the highest when compared with the base model and +3°C simulation. However, in the third summer, the opposite trend occurred and the total phosphate concentrations lines were much higher for the +3°C simulation than the base and -3°C simulations (Figure 4.10). The fall and winter seasons were not influenced by the changes in temperature. The phosphate concentrations were the lowest during these seasons.

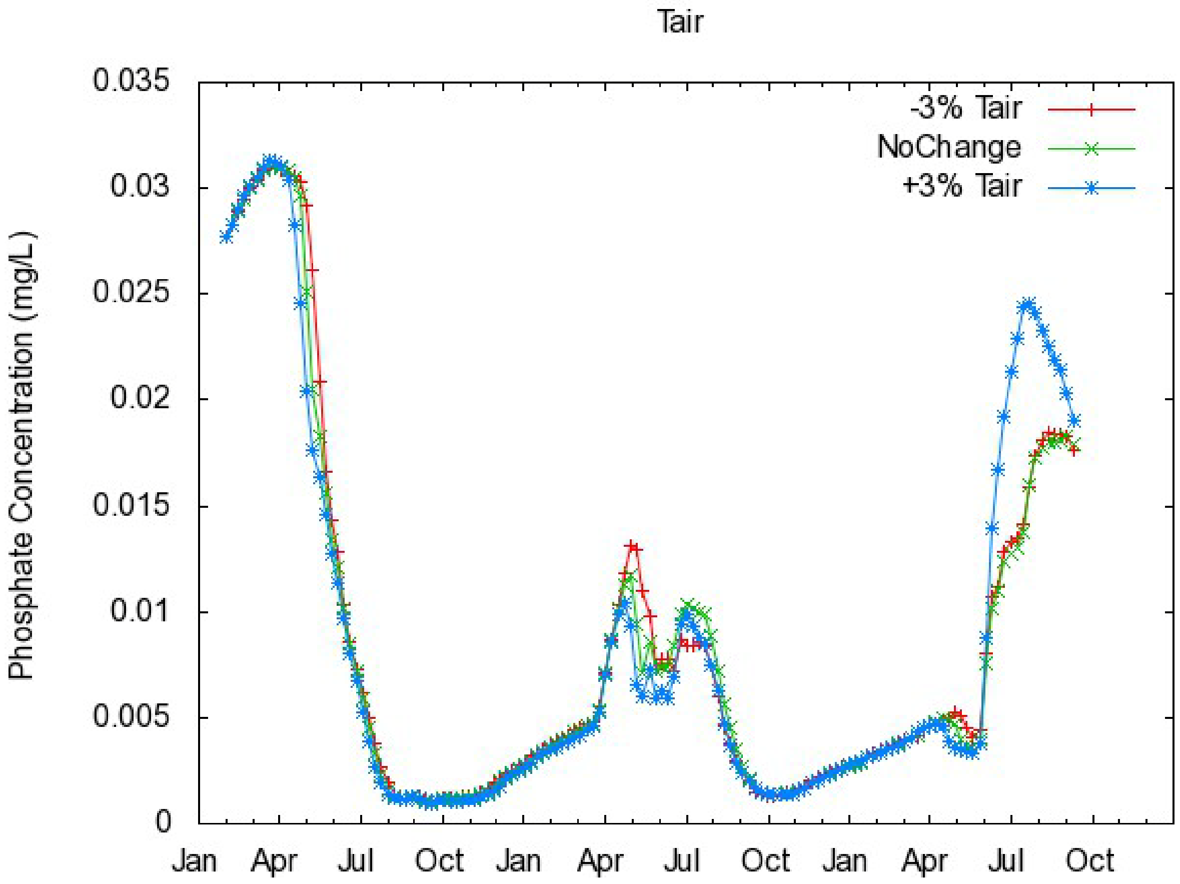

Figure 4.10: Total phosphate concentrations by simulating air temperature scenarios in Deer Creek, -3^{o}C, no change, +3^{o}C

Decreasing and increasing the air temperature had little effect on the Total Nitrate-Nitrite concentrations in the reservoir (Figure 4.11). The three runs have very similar temporal trends and are approximately the same value for most of the simulation. The main impact of temperature change for total nitrate-nitrite concentrations is that the colder air temperature slows down the processes that effect nitrate-nitrite concentrations. For example, in the first May and June, the concentrations for the -3°C simulation do not drop with the No Change and +3°C simulations. The -3°C simulation takes an additional few days to decrease in concentration. This trend is also apparent in the second spring and summer months.

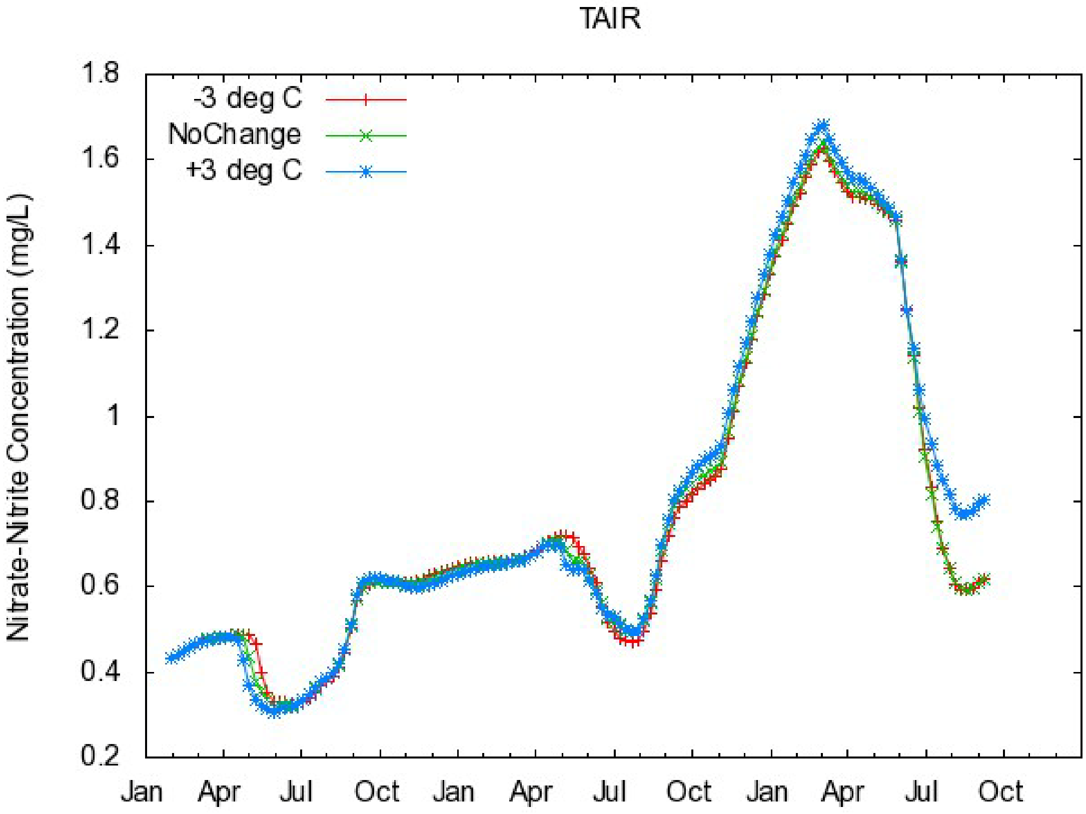

Figure 4.11: Total nitrate-nitrite concentrations by simulating air temperature scenarios in Deer Creek, -3°C, no change, +3°C

4.4.2 Inflow

In order to represent high flows and droughts produced by GCC in Deer Creek, I ran the Deer Creek W2 model three times: I decreased the input inflow by 10%, kept it the same, and increased the inflow by 10%. I extracted the output total algae concentrations of each simulation for the reservoir and plotted them with respect to time. This plot is shown in Figure 4.12.

Also, I extracted total dissolved oxygen concentrations (Figure 4.13), total phosphate concentrations (Figure 4.14), and total nitrate-nitrite concentrations (Figure 4.15) to evaluate the GCC effects in Deer Creek produced by changes in inflows. In each of the figures, the +10% flow line stops in February of the last year. This is because I kept the outflow flow rates constant for all of the runs. With the increased inflow and unchanging outflow, the reservoir overflowed. The model crashed at this point.

Figure 4.12 shows the predicted total algae concentrations after decreasing and increasing the inflows by 10% for Deer Creek. There were not changes between runs until September of the first year. From the first September to the second February the total algae concentration when inflow was decreased by 10% was higher than the base model and the +10% flow lines. The same trend was followed for the next fall-winter season when total algae concentration was decreased for the -10% flow simulation and increased for the +10% flow simulation.

There were changes during the second and third spring and summer seasons where the total algae concentration peak reached maximum values for the -10% inflow simulation. Decreasing flow yielded increasing total algae concentration for Deer Creek Reservoir. Decreasing flow is a projected impact of GCC for the region. In the first year of simulation, when the reservoir volume was low, the changes in flow had no impact on the total algae concentration.

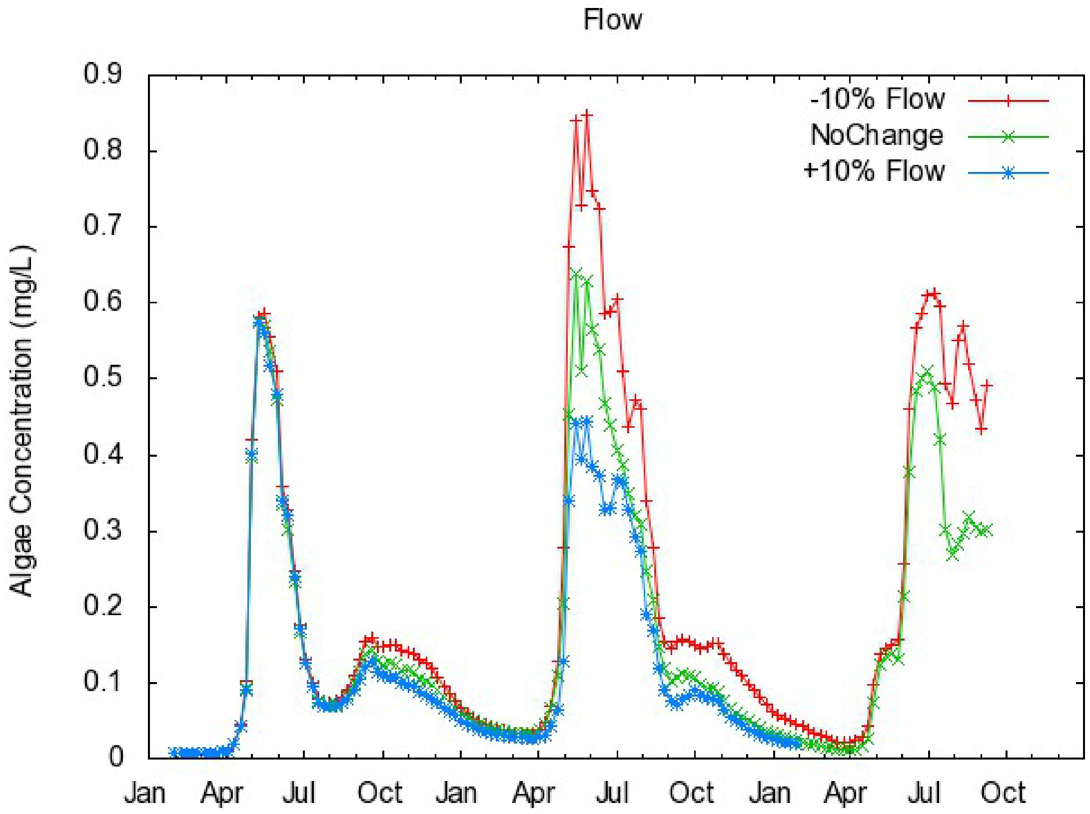

Figure 4.12: Temporal total algae concentrations by simulating inflow scenarios in Deer Creek, -10% inflow, no change, +10% inflow

The changes in inflow into Deer Creek had no effect on the dissolved oxygen concentration for the reservoir during the first winter and spring. Starting in the first August, the decreased flow resulted in a higher concentration of dissolved oxygen compared to the +10% flow and the base model simulations. This indicates that lower inflows produced higher total algae concentrations (Figure 4.12) and these algae concentrations demand more dissolved oxygen during the summer (Figure 4.13). However, in the end of the second August through November, the trend was opposite. The -10% flow resulted in lower dissolved oxygen concentrations. After November the trend reversed to lower flows resulting in higher dissolved oxygen concentrations.

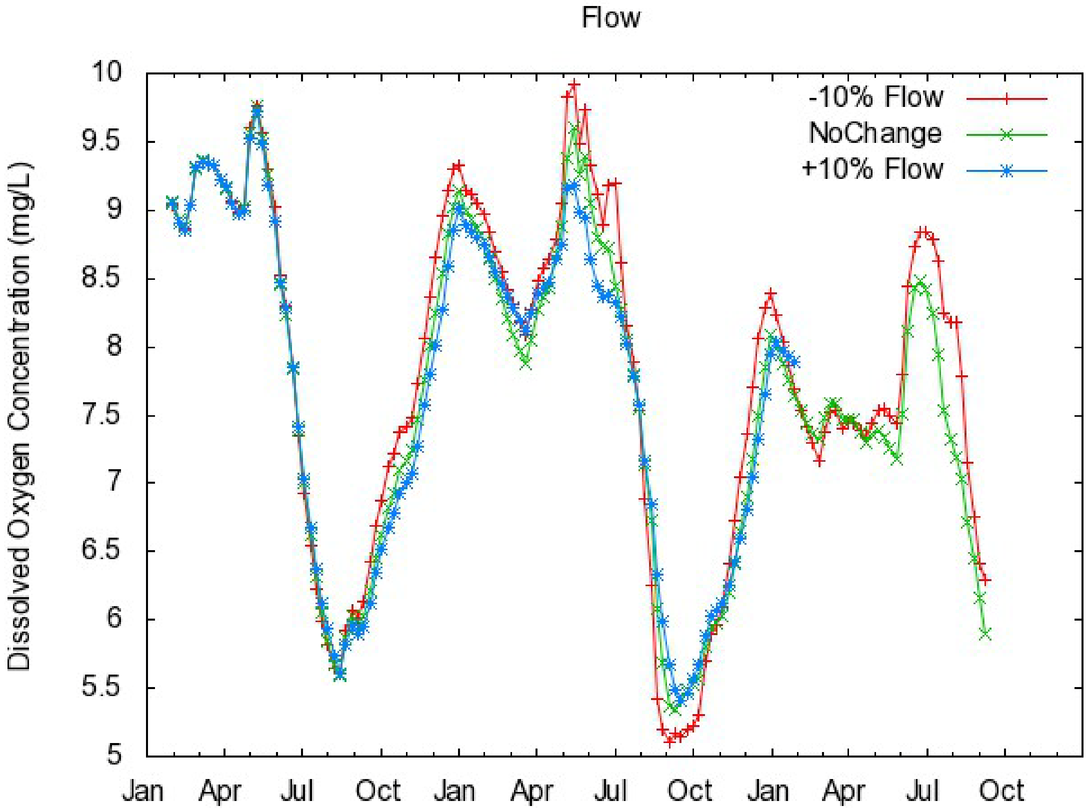

Figure 4.13: Total dissolved oxygen concentrations by simulating inflow scenarios in Deer Creek, -10% inflow, no change, +10% inflow

Decreasing and increasing the flow rates by 10% influenced the phosphate concentration (Figure 4.14). There were no differences between the 3 runs until the second January. The -10% Flow fluctuated from having the highest concentrations to the lowest concentrations in the second May of simulation. The three simulations followed the same general trend and showed greater differences when the reservoir was full in the last two years of simulation. These samples were taken at noon. The dissolved oxygen concentration is sensitive to time so they may be different if taken at night.

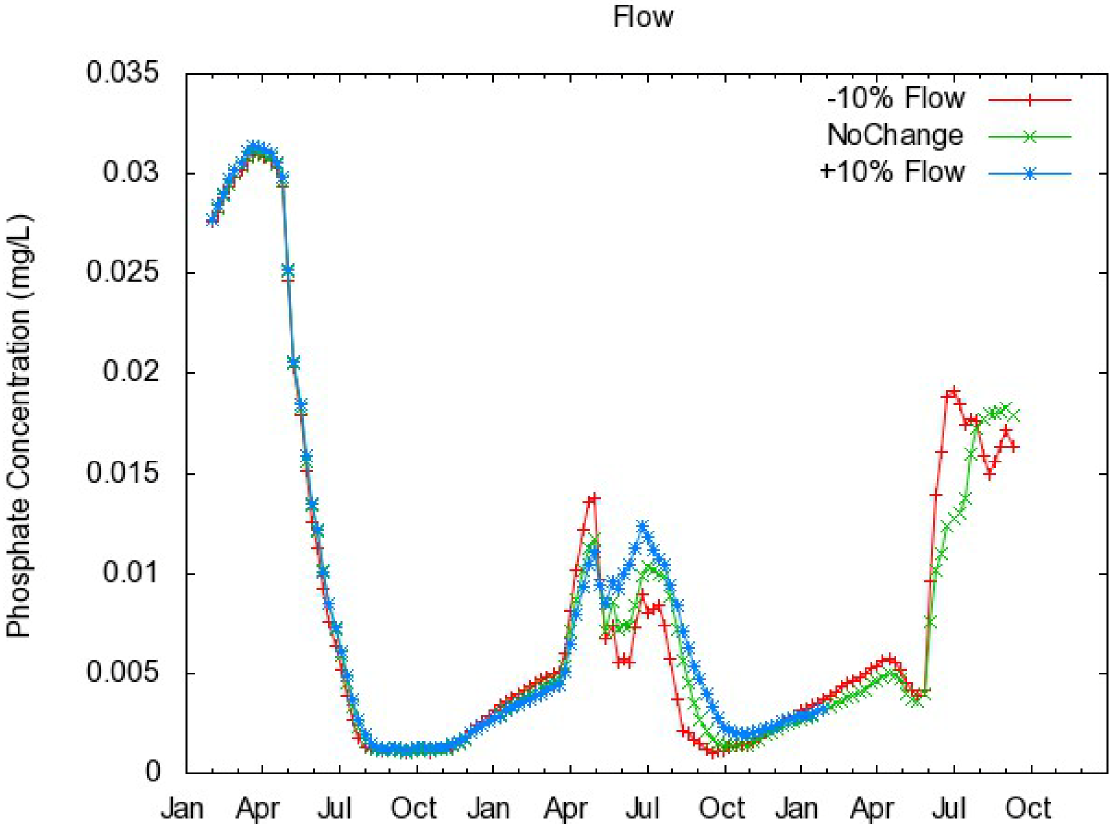

Figure 4.14: Total phosphate concentrations by simulating inflow scenarios in Deer Creek, -10% inflow, no change, +10% inflow

The changes in flow had a very evident impact on Nitrate-Nitrite concentrations (Figure 4.15). However, there was no change in the total concentrations until the second May of simulation. Starting the second September, the -10% flow resulted in higher nitrate-nitrite concentrations than the base and +10% flow simulations. From that point in the model, it showed that as flow decreased, the nitrate-nitrite concentrations increased. When the reservoir levels were low, there was no impact of the changing flow.

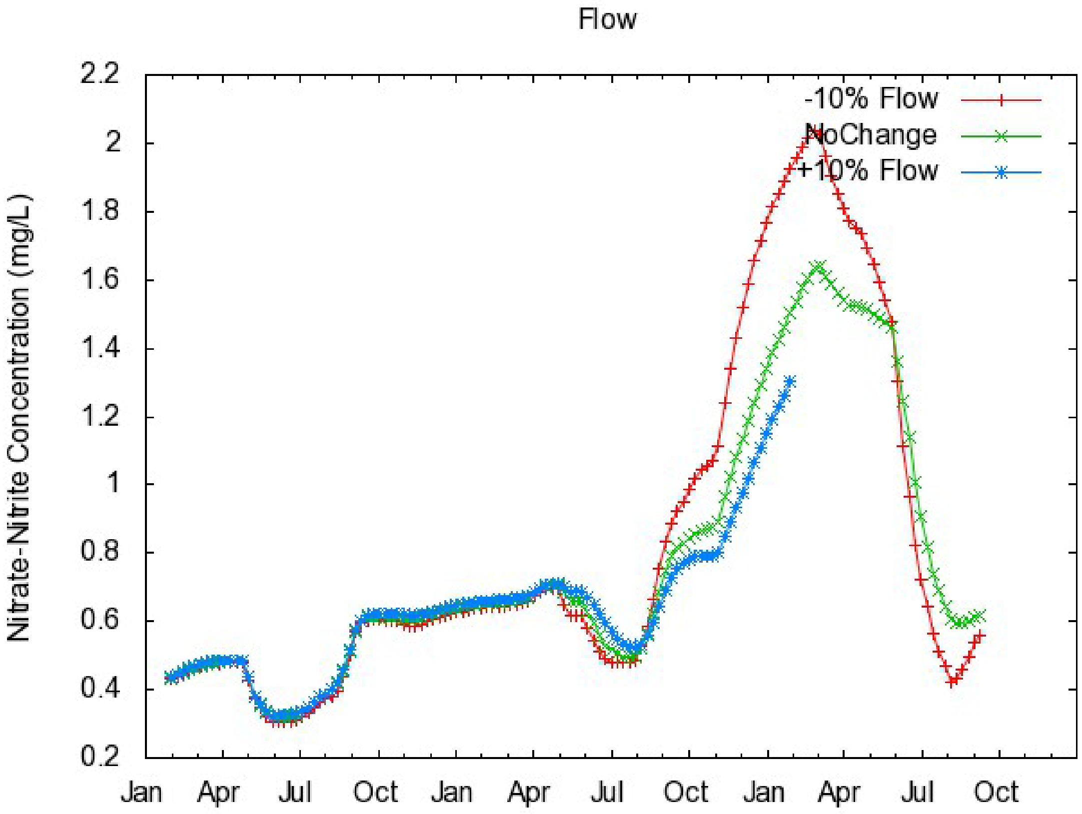

Figure 4.15: Total nitrate-nitrite concentrations by simulating inflow scenarios in Deer Creek, -10% inflow, no change, +10% inflow

4.4.3 Changes in Phosphates

In order to represent nutrients into Deer Creek, I ran the W2 model three times by adjusting phosphates. I decreased the input phosphate concentrations by 50%, kept it the same, and increased the input phosphate concentrations by 50%. I extracted the total algae concentration for the reservoir and plotted it with respect to time (Figure 4.16). Also, I extracted of the temporal total dissolved oxygen concentrations (Figure 4.17), total nitrate-nitrite concentrations (Figure 4.18), and total phosphate concentrations (Figure 4.19) for Deer Creek. I did not plot the average temperature or stratification plots for the nutrients because they do not influence these plots.

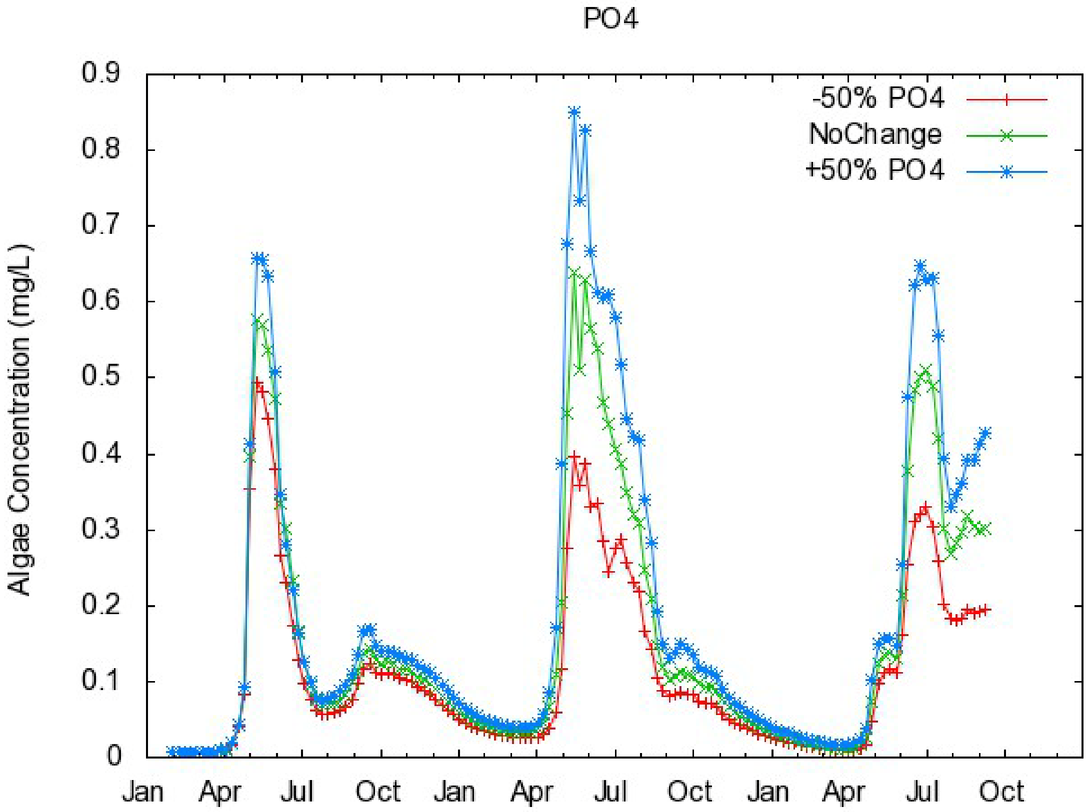

Figure 4.16: Total algae concentrations by simulating phosphate scenarios in Deer Creek, -50% phosphate, no change, +50% phosphate

The most significant change in Deer Creek simulations occurred when I increased and decreased the phosphate concentrations by 50%. The predicted total algae concentrations increased during the spring and summer seasons when inflow phosphate concentrations were increased (Figure 4.16). There was no significant change during the fall and winter months.

Changes in phosphate had little influence on the dissolved oxygen concentration. The +50%, base, and -50% plots are all almost identical until the second spring. For the second spring and summer the +50% PO4 concentrations caused higher dissolved oxygen concentrations. The -50% PO4 caused lower dissolved oxygen concentrations than the base and +50% PO4 simulations (Figure 4.17). This same trend starts again in the third spring. The changing phosphate concentrations have no impact during the fall and winter seasons for the entire simulation. This plot is sensitive to the time of the day. This plot was derived from weekly profiles at noon. The stage of photosynthesis determines when the algae is consuming or decomposing oxygen. This plot could be improved by plotting profiles more frequently than weekly.

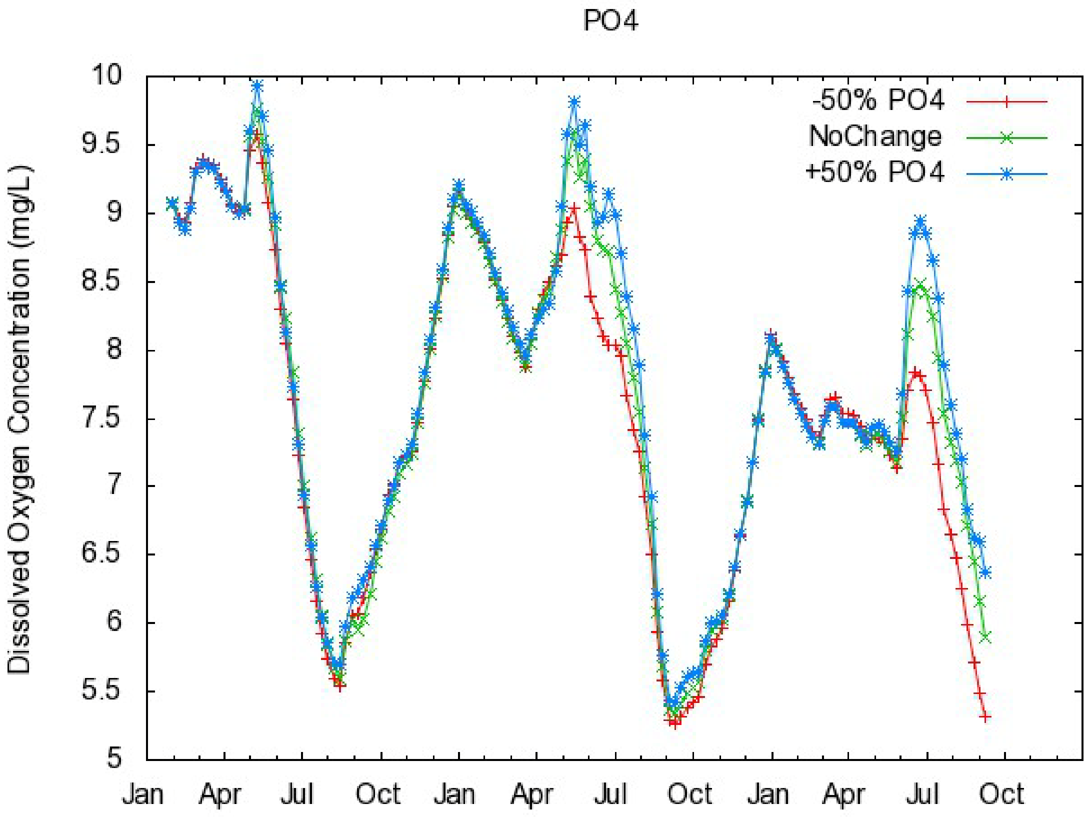

Figure 4.17: Total dissolved oxygen concentrations by simulating phosphate scenarios in Deer Creek, -50% phosphate, no change, +50% phosphate

Decreasing and increasing the phosphate input values impacted the nitrate-nitrite concentrations during May through September of each year (Figure 4.18). The common trend is the lower the input phosphate concentration, the higher the nitrate-nitrite concentration. This trend is consistent for each of the three periods of differing total nitrate-nitrite concentrations for the reservoir. During the other periods of the simulation, there was no influence of phosphate concentrations.

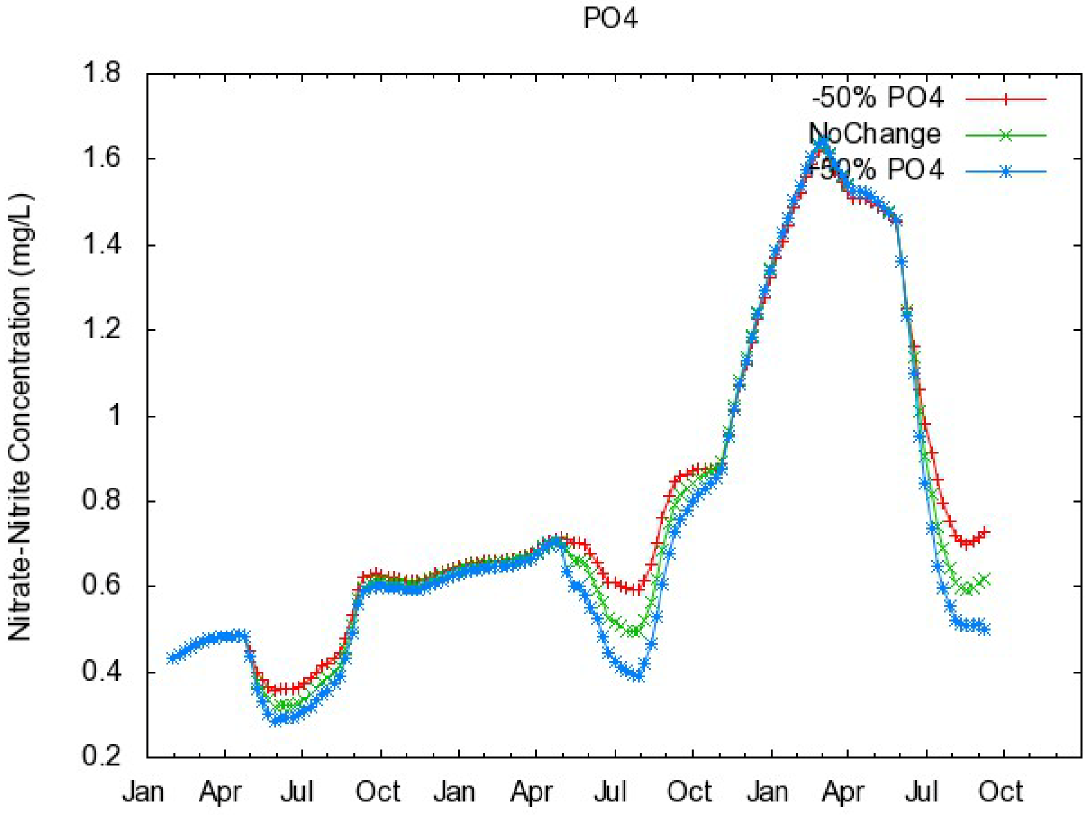

Figure 4.18: Total nitrate-nitrite concentrations by simulating phosphate scenarios in Deer Creek, -50% phosphate, no change, +50% phosphate

Changes in phosphate input concentrations influence the total phosphate concentrations for the reservoir (Figure 4.19). The +50% phosphate concentration caused higher total phosphate concentrations and the -50% run caused lower concentrations. The fall and winter months showed less impact on total concentration than the spring and summer months. This is expected due to increased sunlight, photosynthesis, and algal growth during the spring and summer (Wetzel 2001).

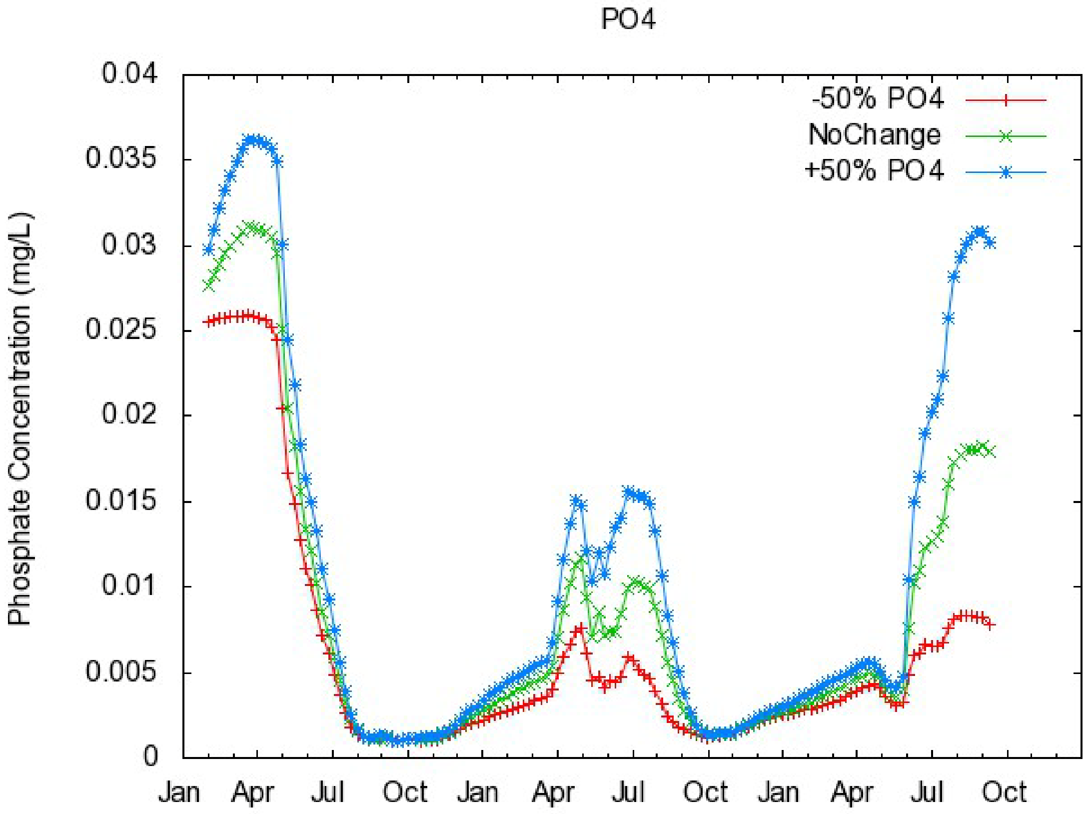

Figure 4.19: Total phosphate concentrations by simulating phosphate scenarios in Deer Creek, -50% phosphate, no change, +50% phosphate

4.4.4 Changes in Nitrates

I ran the Deer Creek W2 model three times by adjusting the nitrate-nitrite concentrations. I decreased the input nitrate-nitrite concentrations by 50%, kept it the same, and increased the input nitrate-nitrite concentrations by 50%. I extracted the total algae concentration for the reservoir and plotted it with respect to time (Figure 4.20). Also, I extracted total dissolved oxygen concentrations (Figure 4.21), total phosphate concentrations (Figure 4.22), and total nitrate-nitrite concentrations (Figure 4.23) to assess the nutrient loading effects in Deer Creek.

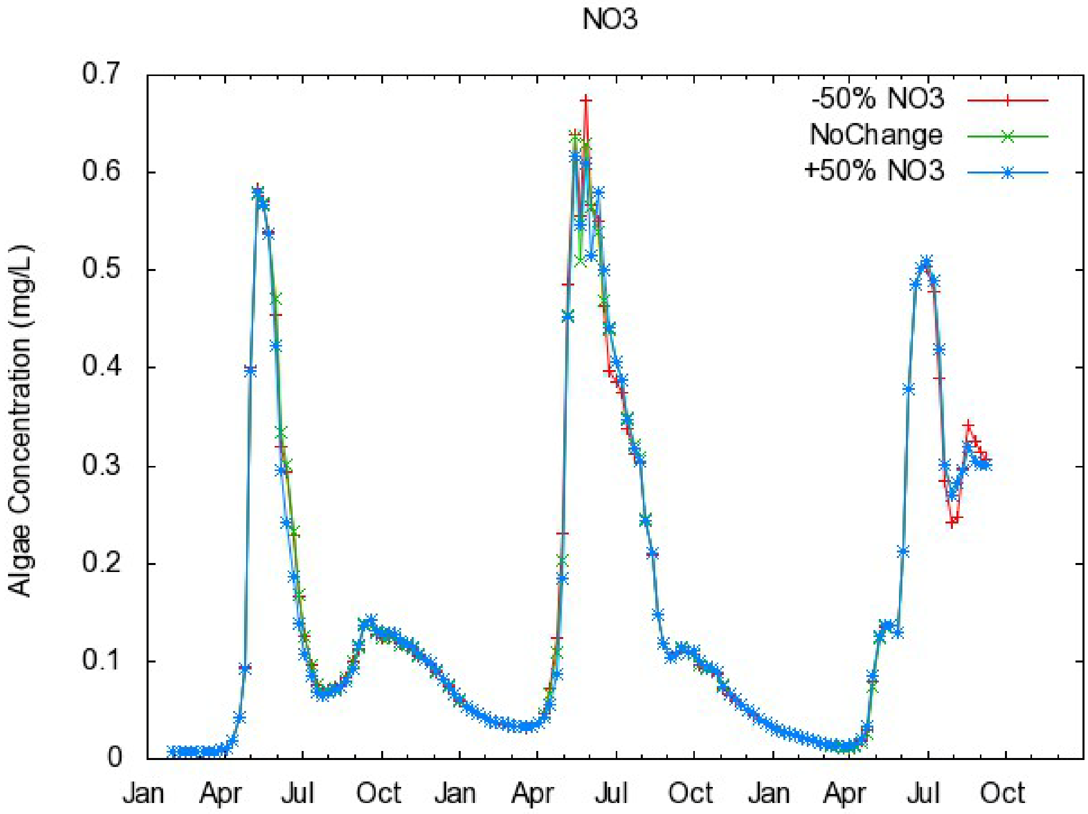

Figure 4.20: Total algae concentrations by simulating nitrate-nitrite scenarios in Deer Creek, -50% nitrate-nitrite, no change, +50% nitrate-nitrite

There were not changes in total algae concentration for the three simulated scenarios of Deer Creek (Figure 4.20). This occurred because the limiting nutrient in Deer Creek is phosphorus so the changing nitrate-nitrite scenarios had no impact on the algae concentrations.

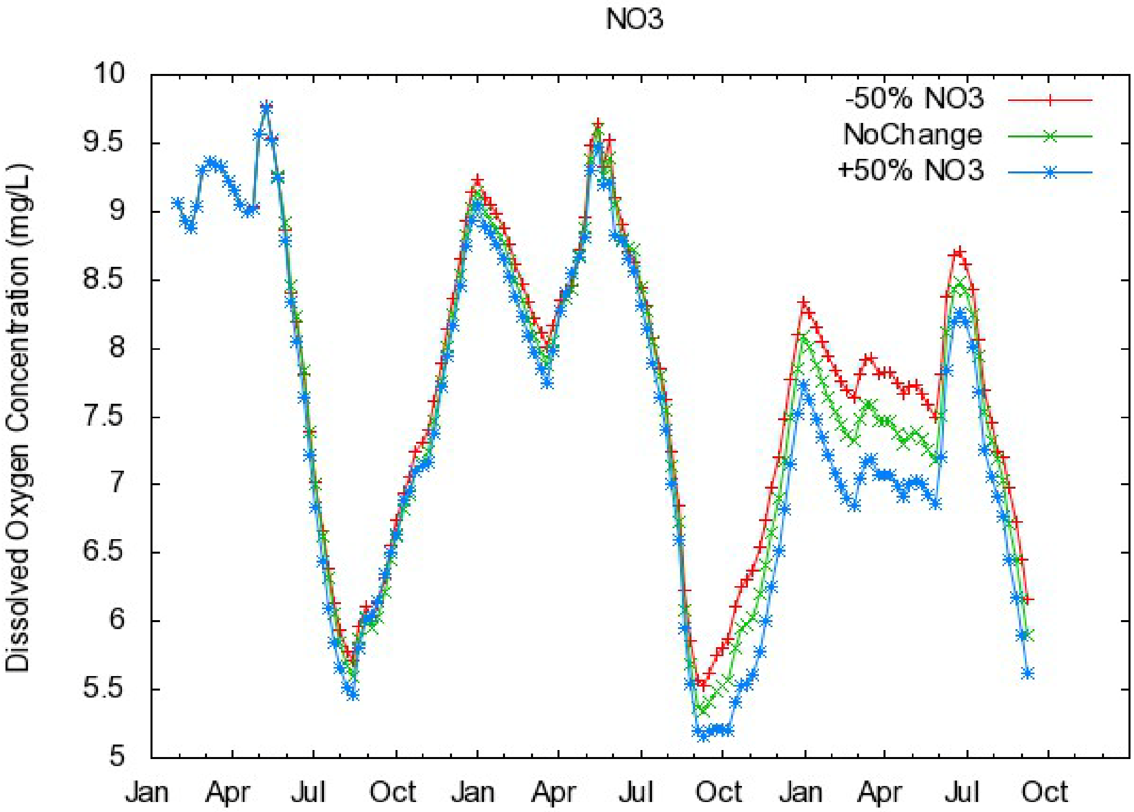

Figure 4.21: Total dissolved oxygen concentrations by simulating nitrate-nitrite scenarios in Deer Creek, -50% nitrate-nitrite, no change, +50% nitrate-nitrite

Changes in nitrate concentrations had no effect on the dissolved oxygen concentrations for the first year of simulation. In the first December there is a slight trend developing which shows the the -50% nitrate-nitrite input gives higher dissolved oxygen concentrations. The +50% nitrate-nitrite input gives the lowest of the three runs. Starting in the second September through the end of the simulation this trend is more evident. The longer the simulation is run the more influence the changes in nitrate-nitrite have on dissolved oxygen. This could be of concern if there are large changes in concentration over a long period of time.

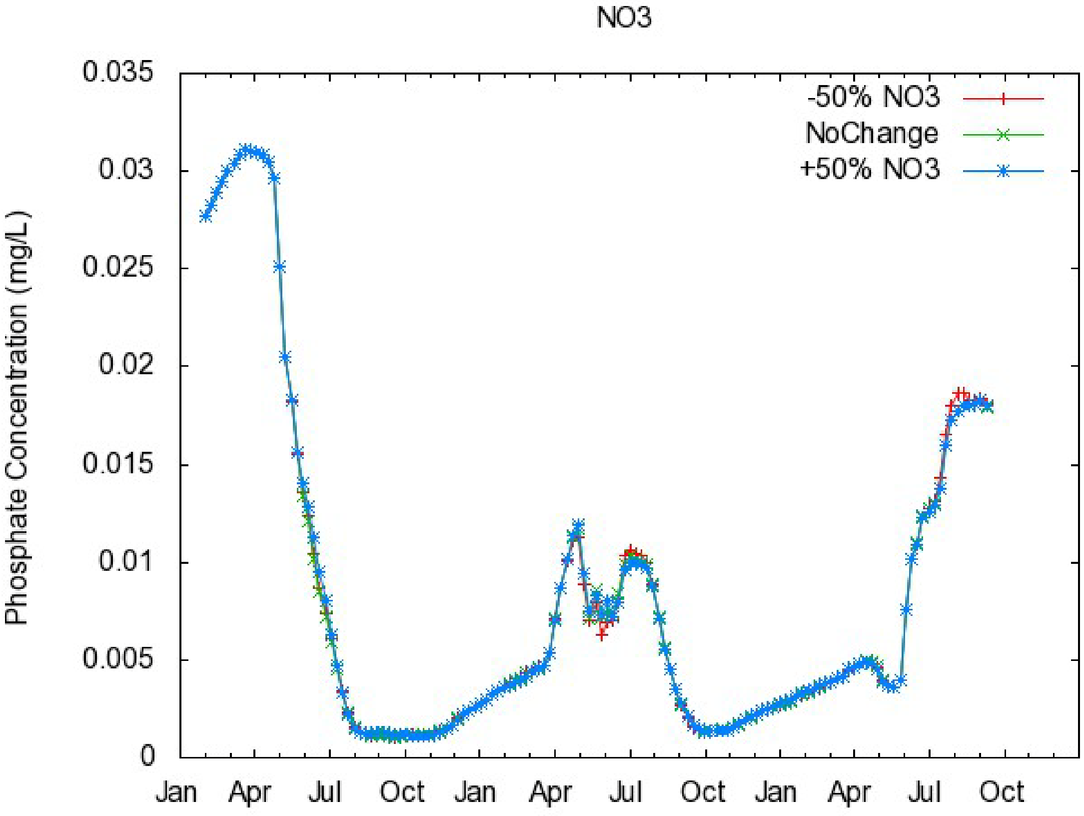

Figure 4.22: Total phosphate concentrations by simulating nitrate-nitrite scenarios in Deer Creek, -50% nitrate-nitrite, no change, +50% nitrate-nitrite

Increasing and decreasing nitrate concentrations 50% resulted in no change in total phosphate concentration for the three simulated scenarios of Deer Creek (Figure 4.22). As expected the strongest change was when I extracted the temporal total nitrates concentrations (Figure 4.23) which followed the same trends of the three simulations. The higher nitrate-nitrite inflow concentration yields the higher the total nitrate-nitrite concentration. The total nitrate-nitrite concentrations increase with time.

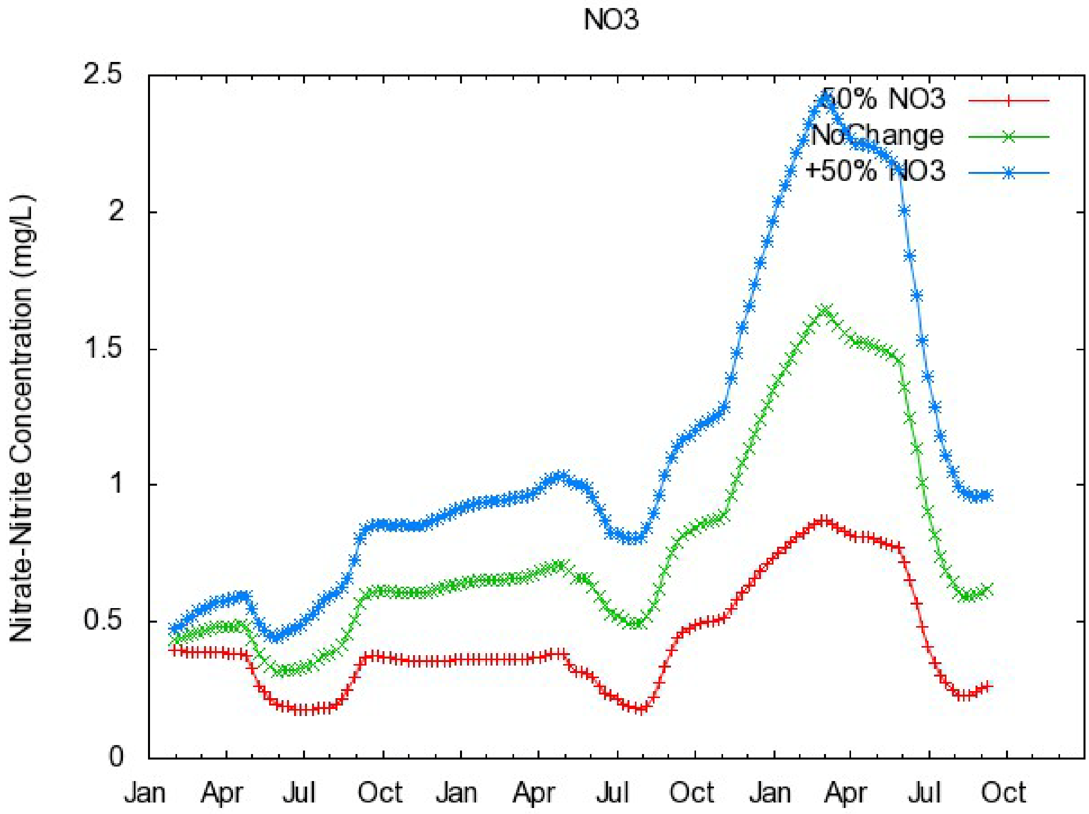

Figure 4.23: Total nitrate-nitrite concentrations by simulating nitrate-nitrite scenarios in Deer Creek, -50% nitrate-nitrite, no change, +50% nitrate-nitrite

5 CONCLUSIONS

We assessed potential climate change effects on Deer Creek Reservoir by using a W2 water quality and hydrodynamic model. my findings indicate that climate changes predicted by IPCC (2007) could impact the Deer Creek system. Changes in air temperature showed significant effects on Deer Creek during the spring and summer months. Increased air temperatures caused higher water temperatures which influenced the stratification of the reservoir. As Stefan (1998) and Livingstone (2003) concluded, increased air temperature will cause longer stratification periods and shorter ice-cover periods. My Deer Creek model showed these results as well as stronger stratification. The increased air temperature also caused decreased total algae concentration, decreased dissolved oxygen concentrations, decreased flows, and earlier peak nutrient concentrations. This will cause larger and more severe anoxic zones in the reservoir which will deplete the health of the water.

Inflows also influenced the reservoir. Decreased inflows caused higher water temperature, but shorter stratification periods, and weaker stratification. This occurs because there is lower water volume in the reservoir when the flows are down. With less water there is going to be less stratification.

The limiting nutrient in Deer Creek is phosphorus. The simulated changes in phosphorus caused increased concentrations of total algae, dissolved oxygen, and phosphate concentrations.

This would increase the probability of Blue-Green algae becoming a problem in Deer Creek again. The increased phosphorus concentrations may be a result of the expansion of urban areas into the watershed surrounding the reservoirs, building upstream dams, changes in land use, or farming. The simulated changes of nitrate did not have a strong impact on the reservoir.

The findings of my model are consistent with other literature for GCC analysis. The tools that I have developed can help to quantify the results of these studies. The tools can be used on other working CE-QUAL-W2 models. The methods which I have developed can be done quickly as the tools automate the majority of the work.

Further study of this topic may include extending the model to a longer time period of 10 years to analyze these trends over a longer period of time. Another GCC parameter of interest is how changes in wind speed would influence these parameters. Also, analysis of different types of algae may help to confirm which types of algae are influenced by GCC. I are confident in my findings and methods as the model was able to replicate dramatic changes in the reservoir during a period of construction and confirm the findings of other literature.

REFERENCES

Anderson, D., Dracup, J., Fogarty, T., and Willis, R. (1976). "Water quality modeling of deep reservoirs." Journal (Water Pollution Control Federation), 48(1), 134-146.

Bartholow, J., Hanna, R., Saito, L., Lieberman, D., and Horn, M. (2001). "Simulated limnological effects of the Shasta Lake temperature control device." Environmental Management, 27(4), 609-626.

Bates, B., Kundzewicz, Z., Wu, S., and Palutikof, J. (2008). "Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 p."

BOR (2009). "Deer Creek Reservoir." <http://www.waterquality.utah.gov/watersheds/lakes/DEERCREK.pdf>. (Jul. 13, 2010).

Casbeer, W. (2009). "Phosphorus Fractionation and Distribution across Delta of Deer Creek Reservoir." Brigham Young University.

Childers, A. (2009). "Quantitative Estimate of Mass Sediment Movement with Sonar in Deer Creek Reservoir." Brigham Young University.

Cole, T. M., and Wells, S. A. (2006). "CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.5." Instruction Report EL-06-1, US Army Engineering and Research Development Center, Vicksburg, MS.

Debele, B., Srinivasan, R., and Parlange, J. Y. (2008). "Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins." Environmental Modeling and Assessment, 13(1), 135-153.

Fang, X., and Stefan, H. G. (1999). "Projections of Climate Change Effects on Water Temperature Characteristics of Small Lakes in the Contiguous U.S." Climatic Change, 42(2), 377-412.

Field, C., Mortsch, L., Brklacich, M., Forbes, D., Kovacs, P., Patz, J., Running, S., and Scott, M. (2007). "North America Climate Change 2007: Impacts, Adaptation and Vulnerability.

Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ML Parry, OF Canziani, JP Palutikof, PJ van der Linden and CE Hanson, Eds." Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson, 617–652.

Gelda, R., Owens, E., and Effler, S. (1998). "Calibration, verification, and an application of a two-dimensional hydrothermal model [CE-QUAL-W2 (t)] for Cannonsville Reservoir." Lake and Reservoir Management, 14(2), 186-196.

Hondzo, M., and Stefan, H. G. (1996). "Dependence of Water Quality and Fish Habitat on Lake Morphometry and Meteorology." Journal of Water Resources Planning and Management, 122(5), 364-373.

Kalff, J. (2002). "Limnology." Prentice-Hall, Inc., 113 Sylvan Ave. Englewood Cliffs NJ 07632 USA. 608, 2002.

Kim, Y., and Kim, B. (2006). "Application of a 2-Dimensional Water Quality Model (CE-QUAL-W2) to the Turbidity Interflow in a Deep Reservoir (Lake Soyang, Korea)." Lake and Reservoir Management, 22(3), 213-222.

Kuo, J., Lung, W., Yang, C., Liu, W., Yang, M., and Tang, T. (2006). "Eutrophication modelling of reservoirs in Taiwan." Environmental Modelling & Software, 21(6), 829-844.

Livingstone, D. M. (2003). "Impact of Secular Climate Change on the Thermal Structure of a Large Temperate Central European Lake." Climatic Change, 57(1), 205-225.

M.L. Parry, O. F. C., J.P. Palutikof, P.J. van der Linden, C.E. Hanson (2007). "IPCC 4th Assessment Report: Climate Change 2007." Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.

Means, E. G., Laugier, M.C., Daw, J.A., and Owen, D.M (2010). "Impacts of climate change on infrastructure planning and design: Past practices and future needs." Journal American Water Works Association, 102(6).

Mooij, W., Hülsmann, S., De Senerpont Domis, L., Nolet, B., Bodelier, P., Boers, P., Pires, L., Gons, H., Ibelings, B., Noordhuis, R., Portielje, R., Wolfstein, K., and Lammens, E. (2005). "The impact of climate change on lakes in the Netherlands: a review." Aquatic Ecology, 39(4), 381-400.

Paerl, H., and Huisman, J. (2009). "Climate change: a catalyst for global expansion of harmful cyanobacterial blooms." Environmental Microbiology Reports, 1(1), 27-37.

PRWUA (2008). "Provo River Water Users Association Annual Report 2008."Provo, 20.

PRWUA (2009). "Provo River Water Users Association Annual Report 2009."Provo, 14.

PSOMAS (2002). "Deer Creek Reservoir Drainage TMDL Study."Salt Lake City, 92.

Rood, S., Samuelson, G., Weber, J., and Wywrot, K. (2005). "Twentieth-century decline in streamflows from the hydrographic apex of North America." Journal of Hydrology, 306(1-4), 215-233.

Schindler, D. W. (1997). "WIDESPREAD EFFECTS OF CLIMATIC WARMING ON FRESHWATER ECOSYSTEMS IN NORTH AMERICA." Hydrological Processes, 11(8), 1043-1067.

Stasio, B. T. d., Jr., Hill, D. K., Kleinhans, J. M., Nibbelink, N. P., and Magnuson, J. J. (1996). "Potential Effects of Global Climate Change on Small North-Temperate Lakes: Physics, Fish, and Plankton." Limnology and Oceanography, 41(5), 1136-1149.

Stefan, H. G. (1998). "Simulated climate change effects on year-round water temperatures in temperate zone lakes." Climatic Change, 40(3-4), 547-576.

Vesilind, P. A. (2004). Introduction to environmental engineering, Thomson/Brook/Cole, Belmont, CA.

Wetzel, R. G. (2001). Limnology : lake and river ecosystems, Academic Press, San Diego.

Williams, N. (2007). "Modeling Dissolved Oxygen in Lake Powell using CE-QUAL-W2." Brigham Young University.

APPENDIX A

There are some example scripts that I used for the analysis. Any sentence that begins with a “#” or “%” is a comment or explanation of what the script is doing, but is not part of the script.

A.1 Data Extraction

```
#!/bin/sh

# Script to extract data from SPR files and create files to plot with

#Algal Mass

#grep Algal mass snp.opt | grep " CMBRS " | awk '{print $2, $3, $4' > PhosMB.dat

grep -A15 'CE-QUAL-W2' snp.opt | grep 'Elapsed time' | awk '{print $5}' > Time.dat

#Searches the snp.opt file for the first 15 lines for the first time that the exact phrase “CE-
QUAL-W2” is found. Once it finds the phrase it will search from that spot for the exact phrase
“Elapsed time”.  Then it will take the next 5 spaces and create the file Time.dat.

grep -A117 'Mass Balance' snp.opt | grep 'Elevation' | awk '{print $4}' > Elev.dat

#Searches the snp.opt file for the first 117 lines for the first time that the exact phrase “Mass
Balance” is found. Once it finds the phrase it will search from that spot for the exact phrase
“Elevation”.  Then it will take the next 4 spaces and create the file Elev.dat.

grep -A93 'Mass Balance' snp.opt | grep -A45 'Branch 1' | grep -A1 Algae | grep CMBRS | awk
'{print $6}' > AlgB1.dat

#Searches the snp.opt file for the first 93 lines for the first time that the exact phrase “Mass
Balance” is found. Once it finds the phrase it will search the next 45 lines from that spot for the
exact phrase “Branch 1”.  Then it will search for the word Algae.  Once it finds Algae it will
search for “CMBRS”.  Then it will take the next 6 spaces and create the file AlgB1.dat.
```

```
grep -A93 'Mass Balance' snp.opt | grep -A45 'Branch 2' | grep -A1 Algae | grep CMBRS | awk '{print $6}' > AlgB2.dat
```

#Searches the snp.opt file for the first 93 lines for the first time that the exact phrase “Mass Balance” is found. Once it finds the phrase it will search the next 45 lines from that spot for the exact phrase “Branch 2”. Then it will search for the word Algae. Once it finds Algae it will search for “CMBRS”. Then it will take the next 6 spaces and create the file AlgB2.dat.

#Repeat this process for the number of branches you have in your model, changing the search name to Branch # and the file name to AlgB#.dat. # being the corresponding branch number.

```
grep -A115 'Mass Balance' snp.opt | grep -A50 'Branch 1' | grep -A1 'Dissolved oxygen' | grep CMBRS | awk '{print $6}' > OxB1.dat
```

```
grep -A115 'Mass Balance' snp.opt | grep -A50 'Branch 2' | grep -A1 'Dissolved oxygen' | grep CMBRS | awk '{print $6}' > OxB2.dat
```

#This is the same process as for the Algae extraction. The important things that may will need to be changed are the number values on the grep –A### commands. Some of the words you are searching for may be farther down in the snp.opt file so the number may need to increased. To avoid this problem you can make count the number of lines for each branch and use the maximum value for all of the grep commands. Also, you will need to change the third grep to correspond with whichever extraction you are doing and make sure that it matches exactly with what is in the snp.opt file. Finally, change the file name to correspond with the extraction you are doing. Make it brief and something that you will recognize.

```
grep -A93 'Mass Balance' snp.opt | grep -A10 'Branch 1' | grep -A1 'Phosphate' | grep CMBRS | awk '{print $6}' > PhoB1.dat
```

```
grep -A93 'Mass Balance' snp.opt | grep -A10 'Branch 2' | grep -A1 'Phosphate' | grep CMBRS | awk '{print $6}' > PhoB2.dat
```

```
grep -A93 'Mass Balance' snp.opt | grep -A30 'Branch 1' | grep -A1 'Nitrate-Nitrite' | grep CMBRS | awk '{print $6}' > NitB1.dat
```

```
grep -A93 'Mass Balance' snp.opt | grep -A30 'Branch 2' | grep -A1 'Nitrate-Nitrite' | grep CMBRS | awk '{print $6}' > NitB2.dat
```

```
paste Time.dat Elev.dat AlgB1.dat AlgB2.dat OxB1.dat OxB2.dat PhoB1.dat PhoB2.dat NitB1.dat NitB2.dat> tmp.dat
```

#This section takes all of the files that you just created and puts them into one file, called tmp.dat. Be sure to include every file. The file names will be columns in the tmp.dat file. This will run in a loop so that the extractions will get all of the data out of the snp.opt file and create multiple rows. The tmp.dat file will be a completely filled out file with multiple rows and columns of data.

```
awk '{print $1, $2, $3+$4, $5+$6, $7+$8, $9+$10}' tmp.dat > MassOut.dat  #Add algae, dissolved oxygen, phosphate, and nitrate-nitrite from Branch1 and Branch2 together
```

#This command is to allow you to add your branches together to get total mass. Columns 1 and 2 are simply time and elevation so they do not need to be modified. For example, the $3+$4, means that the 3rd and 4th column of the tmp.dat file will be added together to get one value and will be one column. Column 3 is AlgB1.dat and column 4 is AlgB2.dat. Now the total amount of algae will be the 3rd column in the MassOut.dat file. $5+$6 is adding OxB1.dat and OxB2.dat together and will be in the 4th column of the MassOut.dat file, and so on. If you have more than 2 branches then you need to add more files together to get the total mass. It is good practice to manually add all of the branches together for each mass and check them with you MassOut.dat file to make sure it worked correctly.

```
octave /cygdrive/c/cygwin/home/DC_OORC_0010/bin/OctProg.m
```

#Opens up Octave within the script so you don’t have to do it as an additional step. The Octave script is called OctProg.m and the rest of the name is the pathway to get to the script.

```
paste T.dat E.dat V.dat A.dat C.dat Ox.dat C2.dat P.dat C3.dat N.dat C4.dat> Conc.dat
```

#This creates the Conc.dat file and puts the columns in order. T.dat is the 1st column, followed by E.dat in the 2nd column, V.dat in the 3rd column, etc.

```
rm -rf tmp.dat AlgB1.dat AlgB2.dat Time.dat Elev.dat OxB1.dat OxB2.dat PhoB1.dat PhoB2.dat NitB1.dat NitB2.dat
```

#“rm” means “remove”. This is removing all of the individual files that are no longer needed. These files were created in intermediate steps and were then put into other files so now the main file with all of those intermediate files is all that is needed. This is a housekeeping step to keep things clean and get rid of excess files.

```
rm -rf T.dat E.dat V.dat A.dat C.dat Ox.dat C2.dat P.dat C3.dat N.dat C4.dat
```

#“rm” means “remove”. This is removing all of the individual files that are no longer needed. These files were created in intermediate steps and were then put into other files so now the main file with all of those intermediate files is all that is needed. This is a housekeeping step to keep things clean and get rid of excess files.

A.2 Calculations and Table Set-up

```
% program to interpolate water volume from elevation and capacity curve

% uses the capacity curve for Deer Creek
```

```
% the data for the curve are in the file DrCrkVol.dat

% this file has 5 columns, the

% 1) line number

% 2) Elevation

% 3) Storage in Branch 1

% 4) Storage in Branch 2

% 5) Total storage


% first load in the capacity curve

Crv = load('/cygdrive/c/cygwin/home/DC_OORC_0010/bin/DrCrkVol.dat');
```

%This is looking up the file, DrCrkVol.dat which contains the storage capacity curve for Deer Creek. The file has 5 columns: The line number, Elevation, Storage in Branch 1, Storage in Branch 2, and the Total Storage. If your reservoir has more than 2 branches there will be more columns but the final column will still be the Total Storage, or sum of the branches.. The main part that can get messed up here is the file path. Be sure you are referencing the correct file from the correct model. Crv is now the storage capacity curve for Deer Creek.

```
% next put the Elevation and total volume in variables Elv and Str

Elv = Crv(:,2);

Stor = Crv(:,5);
```

%The variable Elv is now the 2nd column of DrCrkVol.dat, or the Elevation, and Stor is the 5th column of the file, or the Total Storage. Remember to change the 5 if you have more than 2 branches to make sure that you are extracting the Total Storage for the reservoir.

```
% next load the data point you want to interpolate from a file

% the file is ElevIn.dat

Data = load('./MassOut.dat');

Time = Data(:,1);

WtrElv = Data(:,2);

Alg = Data(:,3);

Oxy = Data(:,4);
```

```
Pho = Data(:,5);

Nit = Data(:,6);
```

%This is the same process as was done with the DrCrkVol.dat file, except now with the MassOut.dat file which was created in the ExtMass script. In this case it will load the MassOut.dat file and name it Data. Each variable will correspond with a column in MassOut.dat. For example, Time will be column 1 and Alg will be column 3.

%Now the script will open Octave automatically to interpolate Storage Capacities from the Storage Capacity Curve to give Total Volume of the reservoir and then calculate total concentrations for each specified constituent.

%Octave Script

% next interpolate the value using the function (this is a 'one' not an 'L')

```
Vol = interp1(Elv,Stor,WtrElv);
```

%This will interpolate the total water volume for the reservoir at given water surface elevations from the storage capacity curve. It will look up the elevation for the each JDAY and interpolate from the graph the corresponding water storage, or volume. Still have some questions about how this one works…..

```
ConcAlg = Alg./Vol./1000000;

ConcOxy = Oxy./Vol./1000000;

ConcPho = Pho./Vol./1000000;

ConcNit = Nit./Vol./1000000;
```

%These commands give the total concentrations for Algae, Dissolved Oxygen, Phosphate, and Nitrate, respectively, for the reservoir. For example, ConcAlg will be the total algae mass (g) from MassOut.dat, divided by the total volume, Vol (L), of the reservoir for the same day. Then it will be converted from g/L to mg/L by dividing by 1000000. Not multiply??

%open a file to send the answer to, the 'w' means for writing

```
Tfile=fopen('T.dat','w');

Efile=fopen('E.dat','w');

Vfile=fopen('V.dat','w');

Afile=fopen('A.dat','w');

Cfile=fopen('C.dat','w');
```

```
Oxfile=fopen('Ox.dat','w');
C2file=fopen('C2.dat','w');
Pfile=fopen('P.dat','w');
C3file=fopen('C3.dat','w');
Nfile=fopen('N.dat','w');
C4file=fopen('C4.dat','w');


%write the Vol to the output file uses 8 places, 6 before the decimal, 1 for the decimal, and 1 after
fprintf(Tfile,'%8.4f\n',Time);
fprintf(Efile,'%8.4f\n',WtrElv);
fprintf(Vfile,'%8.4f\n',Vol);
fprintf(Afile,'%8.4f\n',Alg);
fprintf(Cfile,'%8.4f\n',ConcAlg);
fprintf(Oxfile,'%8.4f\n',Oxy);
fprintf(C2file,'%8.4f\n',ConcOxy);
fprintf(Pfile,'%8.4f\n',Pho);
fprintf(C3file,'%8.4f\n',ConcPho);
fprintf(Nfile,'%8.4f\n',Nit);
fprintf(C4file,'%8.4f\n',ConcNit);
fclose(Tfile);
fclose(Efile);
fclose(Vfile);
fclose(Afile);
fclose(Cfile);
fclose(Oxfile);
fclose(C2file);
```

```
fclose(Pfile);
fclose(C3file);
fclose(Nfile);
fclose(C4file);
#File Clean-up
```