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Evaluating Climate Change Effects in Two Contrasting Reservoirs Using Two-Dimensional Water Quality and Hydrodynamic Models

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Evaluating Climate Change Effects in Two Contrasting
Reservoirs Using Two-Dimensional Water Quality
and Hydrodynamic Models

Oliver Obregon

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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ABSTRACT

Evaluating Climate Change Effects in Two Contrasting Reservoirs Using Two-Dimensional Water Quality and Hydrodynamic Models

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Doctor of Philosophy

I analyzed and compared impacts from global climate change (GCC) and land use change to Deer Creek (United States) a temperate reservoir and Aguamilpa (Mexico), a tropical reservoir by using calibrated CE-QUAL-W2 (W2) water quality and hydrodynamic models based on field data over an extended time period. I evaluated and compared the sensitivity to predicted GCC and land use changes. I individually evaluated changes to air temperature (T_{AIR}), inflow rates (Q), and nutrient loads (PO_4-P and NO_3-NO_2-N) followed by analysis of worst case scenarios. I developed analysis methods using indexes to represent the total reservoir change calculated using the total parameter mass (i.e., algae, dissolved oxygen, total dissolved solids) normalized by the reservoir volume to eliminate apparent mass changes due to volume changes. These indexes have units of average concentrations, but are better thought of as a global reservoir index or normalized concentration. These indexes allow analysis of the total reservoir and not just specific zones.

Total normalized algal concentrations were impacted more by changes in nutrient inflows (land use) in both reservoirs than to changes in T_{AIR} and Q . For Deer Creek, PO_4-P changes significantly increased normalized algal concentrations in the reservoir and in dam releases when PO_4-P inflow was increased by 50%. Aguamilpa was more sensitive to NO_3-NO_2-N changes, exhibiting significant increases in normalized algal concentration for the +50% NO_3-NO_2-N simulation. Both reservoirs showed small changes to normalized algal concentration for the +3°C T_{AIR} simulation with the largest changes occurring during warm seasons. However, Deer Creek exhibited decreased total algal levels when T_{AIR} was increased by 3°C while Aguamilpa showed increased total algal levels with the 3°C increase in T_{AIR} . These contrasting trends, a decrease in Deer Creek and an increase in Aguamilpa, were produced by algae succession processes. Changes in Q affected normalized algal concentration in both reservoirs in different ways. In Aguamilpa, total algal levels increased under dry conditions while Deer Creek showed little general change associated with flow changes. Worst case scenario simulations, which included changing more than one parameter, showed that GCC changes can cause large impacts if they occur simultaneously with high nutrient loadings. These results begin to show how GCC could impact reservoirs and how these impacts compare to potential impacts from land use change. The results show that both temperate and tropical reservoirs are impacted by GCC but are more sensitive to nutrients. The methods, plots, and tools developed in this study can assist water managers in evaluating and studying GCC and land use changes effects in reservoirs worldwide.

Keywords: climate change, water quality modeling, tropical reservoir, temperate reservoir

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“the 10,000hr rule is a definite key in success” –Malcolm Gladwell

TABLE OF CONTENTS

LIST OF TABLES	ix
LIST OF FIGURES	xi
1 Introduction.....	1
1.1 Research Objectives	4
1.2 Project Hypothesis.....	4
1.3 Research Scope and Limitations	5
1.4 Dissertation Outline.....	6
2 Literature Review	9
2.1 Climate Change and Water Resources.....	9
2.2 Application of Water Quality Models.....	11
2.3 Temperate and Tropical Reservoirs	14
2.4 Regional Climate Change Projections.....	15
2.4.1 North America	15
2.4.2 Latin America	18
3 Temperate Deer Creek Reservoir.....	23
3.1 Deer Creek Study Area and Description	23
3.2 Methods.....	24
3.2.1 Water Quality Model First Approach	24
3.2.2 Model Input.....	25
3.2.3 Model Calibration	26
3.3 Assessment Methods and Scenarios.....	31
3.3.1 Assessment Methods and Tools.....	31
3.3.2 Scenarios and Parameters	32

3.4	Deer Creek-Results and Discussion	34
3.4.1	Changing Air Temperature (T_{AIR})	34
3.4.2	Changing Inflow Volumes (Q_{IN}).....	42
3.4.3	Changing Nutrients (NC).....	48
3.5	Deer Creek-Conclusions	53
4	Tropical Aguamilpa Reservoir	57
4.1	Aguamilpa Study Area and Description.....	57
4.2	Methods-Tropical.....	59
4.2.1	Tropical Water Quality Model Approach.....	60
4.2.2	Tropical Model Inputs.....	60
4.2.3	Tropical Model Calibration.....	62
4.3	Methods-Tropical Aguamilpa	69
4.3.1	Assessment Methods and Tools.....	69
4.3.2	Scenarios and Parameters	69
4.4	Results-Tropical Reservoir.....	70
4.4.1	Changing Air Temperature in Aguamilpa (T_{AIR})	70
4.4.2	Changing Inflow Volumes (Q)	82
4.4.3	Changing Nutrients in Aguamilpa (NC)	91
4.4.4	Aguamilpa-Conclusions.....	108
5	GCC Effects in Temperate vs Tropical Reservoir	111
5.1	Methods Long-Term Deer Creek Model.....	112
5.1.1	Update and Extend Inputs Model	113
5.1.2	Long-Term Deer Creek Model Calibration/Validation	113
5.1.3	Evaluation of GCC Effects (Long-Term Deer Creek Model)	114
5.1.4	GCC Outputs Analysis (Long-Term Deer Creek Model).....	115

5.2	Results (Long-Term Deer Creek Model)	115
5.2.1	Long-Term Deer Creek Model: T_{AIR} Changes	116
5.2.2	Long-Term Deer Creek Model: Inflow Volumes (Q) Changes	122
5.2.3	Worst Case Scenario: Long-Term Deer Creek	128
5.3	Downstream GCC Effects Analysis and Worst Case: Tropical-Aguamilpa	133
5.3.1	Downstream Aguamilpa: T_{AIR} Changes	134
5.3.2	Downstream Aguamilpa: Q Changes	136
5.3.3	Aguamilpa: Worst Case Scenario (WCS)	139
5.4	GCC Effects in Tropical Aguamilpa and Temperate Deer Creek	145
6	Conclusions	149
6.1	New Paths for Research	152
	REFERENCES	155
	Appendix A. Deer Creek	161
A.1	CE-QUAL-W2 Deer Creek Animations	161
A.2	Scripts-Deer Creek	163
A.2.1	GCC Simulation Scripts	163
A.2.2	Extraction and Concentration Outputs Calculation Scripts	168
	Appendix B. Aguamilpa	171
B.1	CE-QUAL-W2 Aguamilpa Animations	171
B.2	Scripts-Aguamilpa	173
B.2.1	GCC Simulation Scripts-Tropical	173
	Appendix C. Research Outcomes	177
C.1	Journal Articles	177
C.2	Book Sections	178

C.3	Conference Papers/Proceedings/Presentations.....	178
C.4	Master's Theses.....	181

LIST OF TABLES

Table 3-1: Volumetric Characteristics of Deer Creek Dam and Reservoir	24
Table 4-1: Volumetric Characteristics of Aguamilpa Dam and Reservoir.....	59
Table 4-2: Calibration Coefficients and Values Used for the Aguamilpa Reservoir	63
Table 5-1: Calibration Coefficients and Values Used for Long-Term Deer Creek Model	114
Table 5-2: Maximum Delta Total Algal and Dissolved Oxygen Concentrations for Deer Creek and Aguamilpa Reservoirs	147

LIST OF FIGURES

Figure 2-1: Projected Mean Annual Air Temperature Change (3.61 °C) for the 2070-2099 Period for the Upper Colorado Region by Using 1950-1979 Projections as Base Case (USBOR 2011).....	17
Figure 2-2: Projected Mean Annual Percentage Precipitation Change (5%) for the 2070-2099 Period for the Upper Colorado Region by Using 1950-1979 Projections as Base Case (USBOR 2011).....	18
Figure 2-3: Example of the Projected Air Temperature Change (°C) for July 2050 in Mexico From the ECHAM General Circulation Model (GCM) and A2 Special Report on Emissions Scenario (Conde <i>et al.</i> 2008)	20
Figure 2-4: Example of the Projected Precipitation Change (%) for July 2050 in Mexico From the ECHAM General Circulation Model (GCM) and A2 Special Report on Emissions Scenario (Conde <i>et al.</i> , 2008)	21
Figure 3-1: A) Deer Creek Reservoir Location; B) Inflows, Outflows, and Sampling Sites; C) W2 Segmentation; D) W2 Model Cross Section (at the Deepest Site); and E) W2 Model Grid.....	23
Figure 3-2: Example Water Temperature Calibration From the Near Dam Sampling Site for: A) Spring Turnover (April 2007), and B) Summer Stratification in July 2007 (Normal Reservoir) and C) Summer Stratification in 2008 (Low Reservoir). Note That the Low Reservoir Levels in June of 2008 are Similar to Those of July 2007.....	28
Figure 3-3: Example TDS Calibration From the Near Dam Sampling Site Showing Data: A) Near Spring Turnover in April 2007, B) After Stratification in June 2007, and Mid-Summer in August 2008.....	29
Figure 3-4: Example DO Calibration From the Near Dam Sampling Site Showing Data: A) Near Spring Turnover in April 2007, B) Very Low Reservoir Levels in June 2008, and C) A Relatively Full Reservoir Late in the Summer for August 2009	30
Figure 3-5: Chl-A Profiles at the Near Dam Sampling Point by Adjusting T_{AIR} for: A) Summer 2007; B) Summer 2008; and C) Summer 2009	35
Figure 3-6: Total Algal Concentration in Deer Creek by Changing T_{AIR}	37
Figure 3-7: Total Dissolved Oxygen Concentration by Adjusting T_{AIR}	38
Figure 3-8: A) Total Average Phosphate Concentrations; and B) Total Average Nitrate-Nitrite Concentrations by Adjusting T_{AIR}	40

Figure 3-9: The Difference between Top Water Temperature and Bottom Water Temperature in the Water Column from the Near Dam Sampling Point by Adjusting T_{AIR}	42
Figure 3-10: Chl-A Profiles at the Near Dam Sampling Point by Adjusting Q_{IN} for: A) Summer 2007; B) Summer 2008; and C) Summer 2009.....	43
Figure 3-11: Total Algal Concentration by Changing Q_{IN}	45
Figure 3-12: Total Dissolved Oxygen Concentration by Adjusting Q_{IN}	46
Figure 3-13: A) Total Phosphate Concentration; and B) Total Nitrate-Nitrite Concentration by Adjusting Q_{IN}	47
Figure 3-14: Total Algal Concentration by Adjusting $NC-NO_3-NO_2-N$	49
Figure 3-15: Chlorophyll a Profiles at the Near Dam Sampling Point by Adjusting $NC-PO_4$ for: A) Summer 2007; B) Summer 2008; and C) Summer 2009.....	50
Figure 3-16: Total Algal Concentration by Adjusting $NC-PO_4-P$	51
Figure 3-17: Total Dissolved Oxygen Concentration by Adjusting $NC-PO_4-P$	53
Figure 3-18: A) Total Phosphates as P Concentration; and B) Total Nitrate-Nitrite as N Concentration by Adjusting Inflow $NC-PO_4-P$ 50%.....	55
Figure 4-1: Location of the Aguamilpa Reservoir and Dam, Nayarit, Mexico	58
Figure 4-2: A) Aguamilpa W2 Model Segmentation; B) Cross-Section at Near Dam Sampling Site (Santiago River); and C) Example Model Grid for Branch 1 (Santiago River).....	60
Figure 4-3: Location of the Climatological and Gauging Stations Used as Inputs for the Aguamilpa W2 Model.....	62
Figure 4-4: Sampling Sites Used to Calibrate the Aguamilpa W2 Model.....	64
Figure 4-5: Example Water Temperature Calibration From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Initial Mixing Period (December 2008) and C) Summer Stratification in 2009 (Low Reservoir).....	65
Figure 4-6: TDS Calibration From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Mixing Period (February 2009) and C) Summer Stratification (June 2009).....	66

Figure 4-7: DO Calibration Plots From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Spring Stratification (March 2009) and C) Summer Stratification (June 2009). Note: Oxycline is Observed all the Time in the Reservoir	67
Figure 4-8: Chl-A Calibration Plots From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Mixing Period (December 2008) and C) Summer Stratification (June 2009)	68
Figure 4-9: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting T_{AIR} for A) June 2007; B) June 2011; and C) June 2015	71
Figure 4-10: Total Algal Concentration in Aguamilpa Reservoir by Altering T_{AIR}	73
Figure 4-11: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation	74
Figure 4-12: Total Dissolved Oxygen Concentration in Aguamilpa by Altering T_{AIR}	75
Figure 4-13: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation.....	76
Figure 4-14: Total Phosphate as P Concentration in Aguamilpa by Changing T_{AIR}	77
Figure 4-15: Total Nitrate-Nitrite as N Concentration in Aguamilpa by Changing T_{AIR}	78
Figure 4-16: Difference of Total Phosphate as P Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation	78
Figure 4-17: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation.....	79
Figure 4-18: Total Dissolved Solids Concentration in Aguamilpa by Changing T_{AIR}	80
Figure 4-19: Water Temperature Difference between Epilimnion and Hypolimnion (Top Water Temperature and Bottom Water Temperature) in the Water Column from the Near Dam Sampling Point in Aguamilpa by Adjusting T_{AIR}	81
Figure 4-20: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting Q for A) June 2007; B) June 2011; and C) June 2015.....	83
Figure 4-21: Total Algal Concentration in Aguamilpa Reservoir by Altering Q	85
Figure 4-22: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation.....	86
Figure 4-23: Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering Q	87

Figure 4-24: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation	87
Figure 4-25: Total Phosphates as P Concentration in Aguamilpa Reservoir by Altering Q	88
Figure 4-26: Difference of Total Phosphates as P Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation.....	89
Figure 4-27: Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering Q	89
Figure 4-28: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation	90
Figure 4-29: Total Dissolved Solids Concentration in Aguamilpa Reservoir by Altering Q	91
Figure 4-30: Difference of Total Dissolved Solids Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation.....	92
Figure 4-31: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting $NC-PO_4-P$ for A) June 2007; B) June 2011; and C) June 2015.....	94
Figure 4-32: Total Algal Concentration in Aguamilpa by Altering $NC-PO_4-P$	95
Figure 4-33: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering $NC-PO_4-P$ Compared to the No-Change Simulation	96
Figure 4-34: Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-PO_4-P$	97
Figure 4-35: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering $NC-PO_4-P$ Compared to the No-Change Simulation.....	97
Figure 4-36: Total Nitrate-Nitrite as N Concentration in Aguamilpa by Altering $NC-PO_4-P$	98
Figure 4-37: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering $NC-PO_4-P$ Compared to the No-Change Simulation.....	99
Figure 4-38: Total Dissolved Solids Concentration in Aguamilpa by Altering $NC-PO_4-P$	100
Figure 4-39: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting $NC-NO_3-NO_2-N$ for A) June 2007; B) June 2011; and C) June 2015	102
Figure 4-40: Total Algal Concentration in Aguamilpa by Adjusting $NC-NO_3-NO_2-N$	103
Figure 4-41: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering $NC-NO_3-NO_2-N$ Compared to the No-Change Simulation.....	104

Figure 4-42: Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-NO_3-NO_2-N$	105
Figure 4-43: Difference of Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-NO_3-NO_2-N$	106
Figure 4-44: Total Phosphate as P Concentration in Aguamilpa by Changing $NC-NO_3-NO_2-N$	107
Figure 4-45: Difference of Total Phosphates as P Concentration in Aguamilpa by Altering $NC-NO_3-NO_2-N$	107
Figure 4-46: Total Dissolved Solids Concentration in Aguamilpa by Changing $NC-NO_3-NO_2-N$	108
Figure 4-47: Difference of Total Dissolved Solids Concentration in Aguamilpa by Changing $NC-NO_3-NO_2-N$	109
Figure 5-1: Difference of Total Algal Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model	117
Figure 5-2: Difference of Total Algal Concentration Downstream from Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model	118
Figure 5-3: Difference of Total Dissolved Oxygen Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model	119
Figure 5-4: Difference of Total Dissolved Oxygen Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model	120
Figure 5-5: Difference of Total Dissolved Solids Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model.....	121
Figure 5-6: Difference of Total Dissolved Solids Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C T_{AIR}$ Simulations and the Base Model	122
Figure 5-7: Difference of Total Algal Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\% Q$ Simulations and the Base Model	123
Figure 5-8: Difference of Total Algal Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\% Q$ Simulations and the Base Model	124

Figure 5-9: Total Phosphates as P Concentration in Deer Creek (Long-Term) by Adjusting 10% Q	124
Figure 5-10: Difference of Total Dissolved Oxygen Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model.....	126
Figure 5-11: Difference of Total Dissolved Oxygen Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model.....	126
Figure 5-12: Difference of Total Dissolved Solids Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model.....	127
Figure 5-13: Difference of Total Dissolved Solids Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model.....	128
Figure 5-14: Difference of Total Algal Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	129
Figure 5-15: Difference of Total Algal Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	130
Figure 5-16: Difference of Total Dissolved Oxygen Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	131
Figure 5-17: Difference of Total Dissolved Oxygen Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	131
Figure 5-18: Difference of Total Dissolved Solids Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	132
Figure 5-19: Difference of Total Dissolved Solids Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C).....	133

Figure 5-20: Difference of Total Algal Concentration Downstream From Aguamilpa Reservoir between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model.....	134
Figure 5-21: Difference of Total Dissolved Oxygen Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model.....	135
Figure 5-22: Difference of Total Dissolved Solids Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model.....	136
Figure 5-23: Difference of Total Algal Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model.....	137
Figure 5-24: Difference of Total Dissolved Oxygen Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model.....	138
Figure 5-25: Difference of Total Dissolved Solids Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model.....	139
Figure 5-26: Difference of Total Algal Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR}=+3^{\circ}\text{C}$ (HHTair= $+3\text{C}$); and Case 2: Low Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR} = +3^{\circ}\text{C}$ (LHTair= $+3\text{C}$).....	140
Figure 5-27: Difference of Total Algal Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR}=+3^{\circ}\text{C}$ (HHTair= $+3\text{C}$); and Case 2: Low Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR} = +3^{\circ}\text{C}$ (LHTair= $+3\text{C}$).....	141
Figure 5-28: Difference of Total Dissolved Oxygen Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR}=+3^{\circ}\text{C}$ (HHTair= $+3\text{C}$); and Case 2: Low Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR} = +3^{\circ}\text{C}$ (LHTair= $+3\text{C}$).....	142
Figure 5-29: Difference of Total Dissolved Oxygen Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR}=+3^{\circ}\text{C}$ (HHTair= $+3\text{C}$); and Case 2: Low Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR} = +3^{\circ}\text{C}$ (LHTair= $+3\text{C}$).....	143
Figure 5-30: Difference of Total Dissolved Solids Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR}=+3^{\circ}\text{C}$ (LHTair= $+3\text{C}$); and Case 2: Low Q , High $NO_3\text{-}NO_2\text{-}N$, and $T_{AIR} = +3^{\circ}\text{C}$ (HHTair= $+3\text{C}$).....	144

Figure 5-31: Difference of Total Dissolved Solids Concentration Hourly Discharged
Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa
(Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$
(HHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$
(LHTair=+3C).....144

1 INTRODUCTION

Projected impacts of Global Climate Change (GCC) are of concern to drinking water experts, limnologists and engineers. GCC can potentially affect worldwide water resources in various ways. Impacts such as more intense storms and droughts produced by large-scale meteorological phenomenon, such as *El Niño* and *La Niña*, have been predicted by climatological models. This could affect water quality and quantity as the environment in water supply reservoirs is changed. Water shortages and flooding are examples of potential GCC effects to water supply. In this study, I evaluate how changes in air temperature and inflow could affect water quality of water storage reservoirs and impact drinking water resources. It is well known that phytoplankton density is directly correlated with changes in nutrient loading, but GCC effects can alter these correlations because of shifting seasonal timing and other changes such as temperature and reservoir volume. If these changes favor cyanobacteria and green algal blooms, the resulting toxins can degrade the quality of the water, making it dangerous for other living organisms, while if the changes favor diatoms or do not favor increased algae growth water quality could increase. Most water supply reservoirs have a variety of uses including drinking water, irrigation, recreation, and wildlife habitat. A decrease in water quality would impact all of these areas.

Water quality models have been used worldwide to better manage water supply reservoirs and have supported the design and implementation of best management practices (BMP's) on the

watersheds that surround the reservoirs. Total phosphorous (TP), total nitrogen (TN), chlorophyll *a* (Chl-A), total dissolved solids (TDS), and inorganic suspended solids (ISS) are some of the parameters that have been simulated in these water quality models to provide insight into the reservoirs being studied. Physicochemical and biological processes that affect these water quality parameters and their interaction with anthropogenic and natural contamination have been studied to better understand how water bodies respond to various changes in the environment. Also, this interaction has been evaluated to know how water quality can be improved by implementing BMP's.

Water quality models need to play another important role, helping researchers and water managers predict potential future water quality scenarios. In this mode, managers can evaluate a number of possible future conditions and determine management strategies for each one. Water quality models can also help fill data gaps due to a lack of frequent temporal and spatial water quality monitoring programs. This is especially required in developing countries.

To address a lack of data and associated predictions, water quality models can be used to simulate future water quality scenarios in reservoirs that supply, or are planned to supply, drinking water. These simulations help managers understand how GCC might affect water resources located in temperate, tropical, developed, and developing areas. Many temperate reservoirs are situated in developed countries where more data are available and this has allowed scientists to develop good approaches to future predictions. Tropical reservoirs are often located in developing countries and the supporting data for predictions and management is limited in the literature. Yet tropical reservoirs are important for the communities where they are located. In many cases, especially in developing countries, reservoirs that were originally designed for flow control and irrigation are now being tasked with providing the main drinking water supply source

for growing areas. These new water uses require managers to better understand water quality processes and the impact that environmental change could have on a reservoir. Water quality in reservoirs used for flood control and irrigation is not as important as it is in reservoirs used for drinking water supply.

In this project, I selected two reservoirs to represent temperate and tropical reservoirs in developed and developing areas. These reservoirs were Deer Creek, a temperate reservoir, located in Utah, United States; and Aguamilpa, a tropical reservoir, located in Nayarit, Mexico.

My research evaluates the magnitude of water quality impacts that predicted GCC changes could have on these two reservoirs located in two different geographic zones. This study is quantitative, rather than just qualitative. Reservoir changes are compared using indices that represent the entire reservoir and show changes over time. The study identifies similarities and/or differences in the impacts to temperate and tropical reservoirs and how these reservoirs respond in similar and different manners to GCC changes. Air temperatures from global and regional zones can change terrestrial biological systems and hydrologic systems as well and could potentially change inflows. In addition, regions around reservoirs could change or develop resulting in different nutrient loadings. I evaluated these potential changes to determine their impact on the reservoirs.

I built and calibrated 2-dimensional water quality and hydrodynamic models to assess GCC effects on in-reservoir water quality for Deer Creek and for Aguamilpa. Building these models included data collection and the estimation and generation of missing values in the time series. I used the measured and generated data to build and calibrate both models. Once the models were developed and calibrated, I changed the air temperatures (T_{AIR}), inflows (Q) and

nutrient loadings individually and also evaluated worst case scenarios by changing all the variables simultaneous used to represent GCC and development effects.

1.1 Research Objectives

The main goal of this project is to use water quality and hydrodynamic models to evaluate potential changes in reservoir processes produced by Global Climate Change (GCC) in temperate and tropical reservoirs.

- Use Deer Creek and Aguamilpa to represent tropical and temperate reservoirs respectively and to build water quality and hydrodynamic models.
- Develop tools to evaluate GCC and development effects on in-reservoir water quality.
- Identify chemical, physical and/or biological parameters to be used as indicators of GCC and development effects, and determine how to use these indicators in reservoir evaluations.
- Assess the effects of potential GCC and development changes in Deer Creek and Aguamilpa.

1.2 Project Hypothesis

In this project I tested the hypothesis that GCC and development effects in tropical reservoirs are more severe than in temperate reservoirs. The null hypothesis is that no significant differences in GCC effects occur in either system.

H1: GCC and development effects will increase the variety of algal groups (relative abundance) in water bodies, particularly reservoirs.

H2: Tropical reservoirs will be more sensitive to GCC effects than temperate reservoirs.

1.3 Research Scope and Limitations

I assessed climate change and development effects with two-dimensional models in two different reservoirs. These reservoirs represent two contrasting scenarios, temperate and tropical. The results from this project can be generalized and can assist water managers from developed and developing countries make decisions to mitigate climate change effects in these regions. The tools and methods I developed through this project can be used by these managers to support site-specific studies of reservoirs and expected environmental changes.

I expected a number of limitations as I was developing this project. The main limitation I found was related to data gathering in which not enough field data were available to robustly develop a W2 model for the Aguamilpa reservoir. This is a situation not uncommon in developing countries. However, I was able to generate and estimate synthetic data for this model using empirical formulations and values from literature.

I calibrated the models used in this research with the available data. I had abundant hydrologic, meteorological and water quality data for Deer Creek and its calibration was defensible. I had more limited data for Aguamilpa and this calibration is less accurate. However, since the GCC evaluation changes input conditions from any observed historic values, the models just need to accurately reflect the general reservoir processes as I am interested in the change, or delta, from the base line, not the absolute value of a given parameter. In my analysis and results I report and study changes from the base case – not absolute predictions. Because of this, the limited data available to calibrate the Aguamilpa model was not an obstacle to complete this study and I feel the results are defensible. They indicate which changes are most likely to have the largest impact and in general how significant the change in the reservoir conditions will be.

1.4 Dissertation Outline

This study is divided in five main chapters starting with Chapter 1 which provides an introduction of the need to do this work, objectives, project hypothesis, and research scopes and limitations. The following four chapters are organized as follows:

- Chapter 2 describes previous and current work similar to this research study and other work on which this study was based. It includes a literature review of studies related to climate change in water resources, application of water quality models, background of tropical and temperate lakes/reservoirs, and regional global climate change (GCC) projections for North America and Latin America zones where the study areas are located.
- Chapter 3 presents preliminary evaluations of GCC effects in Deer Creek Reservoir (Utah) from a CE-QUAL-W2 (W2) model over a three-year period. This analysis includes stress conditions in the reservoir due to construction work performed during the studied period.
- Chapter 4 presents the study performed in Aguamilpa Reservoir in which I evaluated the projected GCC effects in a tropical reservoir by using a two-dimensional water quality and hydrodynamic model (W2), this model runs over an eleven-year period.
- Chapter 5 includes the results obtained from my evaluation of GCC in Deer Creek by using a long-term two-dimensional W2 model for Deer Creek; this is an extended version of the three-year model described in Chapter 3. I also present the results obtained from the simulations of two worst case scenarios for Deer

Creek. I conclude this chapter by comparing the results of evaluating GCC effects in both reservoirs.

- Chapter 6 presents the conclusions and recommendations I generated from this study and suggests additional research paths related to GCC effects in temperate and tropical reservoirs.

2 LITERATURE REVIEW

2.1 Climate Change and Water Resources

According to the Environmental Protection Agency (EPA) assessment on climate change (EPA 2011), climate change is any substantial variation in measures of climate (e.g. temperature, precipitation, or wind) for long periods of time. Climate change can be produced from natural factors and processes or from anthropogenic activities (Rosenzweig *et al.* 2008). Studies related to climate change have suggested that pollution is altering the normal trends of the climate, producing effects in terrestrial biological systems, the cryosphere, and hydrologic systems (Bates *et al.* 2008; Rosenzweig *et al.* 2008). GCC effects are already observable. For instance, glaciers have shrunk, winter ice on arctic and temperate water bodies is breaking up earlier, droughts last for longer periods in some regions, and tropical storms are more intense and frequent. These changes can affect regional and local water resources (NASA 2011). Likens (2010) stated that changes in T_{AIR} and precipitation have effects on the physical, chemical, and biological characteristics of lakes, and these variables can also operate on lakes indirectly by altering their surrounding watersheds (e.g., changing hydrological flow pathways, landscape weathering, catchment erosion, soil properties, and vegetation). All these observable effects could impact water resources and scientists are interested in studying the changes produced by GCC and other factors in lakes (natural or manmade) and rivers.

Most climate change projections are generated from climatological model outputs (USGCRP 2009). The leading group that consolidates and describes these results is the Intergovernmental Panel on Climate Change (IPCC). They publish predictions on the expected environmental changes and the potential impacts to existing systems. However, the effects of GCC in water resources, especially reservoir water quality, have not been deeply studied (Bates et al. 2008).

Even without GCC effects, a major concern is that the regional water demand will increase and reservoir inflows of both water and nutrients could change in the coming decades because of population growth and development. This increased water demand or change in inflow conditions could exacerbate GCC effects, significantly increasing impacts. Developing countries may be more vulnerable than developed countries to GCC problems due to the lack of infrastructure or resources to mitigate GCC effects. However, issues related to water demand and water quality could affect countries regardless of their development status.

I suggest that it is necessary to better understand GCC effects on reservoir processes to assist scientists and water managers in making decisions to reduce its potential impacts. Continuous observational data would be useful to assess and prevent possible damages to our water resources. Yet, the lack of data to support studies on the impacts of climate change on water quality, groundwater, and aquatic ecosystems, is a constant problem in some countries (Bates *et al.* 2008; USGCRP 2009; Obregon *et al.* 2011).

In reservoir processes, the impact of GCC on algal groups is considered one of the most important and potentially damaging effects. These changes and impacts are caused by influencing normal nutrient-phytoplankton correlations (Rosenzweig *et al.* 2008; Paerl and Huisman 2009). Relatively small changes in nutrient loads or temperatures can cause algal

blooms which significant impact water quality and in some cases can release toxins into the reservoir in sufficient concentrations to be immediately harmful. Paerl (2010) suggested that the direct associations between nutrients and algal growths can be altered by climate change. Other authors (e.g., Likens 2010) state that highly toxic algae species, usually found in tropical and subtropical regions (*Cylindrospermopsis raciborskii*), have been observed in temperate reservoirs. This invasion is attributed to climate change due to warmer temperatures that can favor the growth of these tropical algae species. Understanding how these processes interact and how they will change a reservoir ecosystem is critical. Monitoring data and simulations can both enhance this understanding. These two approaches support each other: additional data helps produce more accurate and validated models and model results can help design a monitoring plan that accurately reflects the state of a reservoir (Afshar and Saadatpour 2009; Obregon *et al.* 2011).

2.2 Application of Water Quality Models

Scientists and water managers need tools that allow them to evaluate and predict future water quality scenarios produced by GCC and other issues. Computational water quality and hydrodynamic models can be these supporting tools. Models (one-dimensional, two-dimensional or three-dimensional) have been used on worldwide water bodies to design and implement Best Management Practices (BMP's) helping improve the quality of the water by reducing points and non-points nutrients loads.

Afshar and Saadatpour (2009) applied a water quality model and summarized how models have been incorporated into monitoring programs. These programs usually support analyses such as the total maximum daily load (TMDL) to evaluate eutrophication processes in lakes and reservoirs. Changes in water temperatures and nutrients loads are the most common

parameters that have been simulated with modeling tools (Kim and Kim 2006; Kuo *et al.* 2006; Williams 2007; Miller 2008). Selective withdrawal or other temperature regulatory devices in reservoirs have also been evaluated with models to observe how thermal stratification can alter water quality and reservoir ecosystem evolution (Bartholow *et al.* 2001; Ma *et al.* 2008). Water quality models have also been combined with hydrologic models to estimate water quality parameters that can be input into coupled models (Debele *et al.* 2008; White *et al.* 2010a; White *et al.* 2010b).

Other important concerns related to climate change and its effects on water resources are changes in water quantity in both river and overland flow. These changes could result in reservoir low stages, reservoir overflows, and other issues. These impacts could be compounded by the limited storage capacity of some reservoirs if flows are increased during wet seasons, and could also result in lower reservoir levels and potentially changed ecosystems for lower-flow regimes. Related to evaluating these types of issues, water quality and hydrodynamic models have assisted water managers investigating the effects of expanding storage capacity of existing reservoirs (Choi *et al.* 2007). These expansions have occurred in places where space restricts the construction of additional reservoirs or in climate regions where large dams are located (Risley *et al.* 2010).

Despite all of these water quality modeling studies, I have only found a few studies that have used water quality and hydrodynamic models to evaluate climate change effects on in-reservoir water quality. One such study was conducted by Fang *et al.*, (2007) in which different future inflow and climatic scenarios for the Amistad Reservoir (El Paso, Texas) were simulated. These simulations showed an effect on the reservoir stratification processes. Another work, probably the most similar to this study, was prepared by Elshemy and Meon (2011) for Lake

Nubia, in Sudan. In this study a two-dimensional hydrodynamic and water quality model was used to evaluate the effects of global climate change on the reservoir's water quality. They used two water quality indices (the National Sanitation Foundation Water Quality Index and the Canadian Council of Ministers of the Environment Water Quality Index) to evaluate the simulated scenarios (A2 and B1 from eleven global climate models outputs). They concluded that the changes in the water quality indices they used were caused by climate change. They also found that these changes were more controlled by inflow changes than air temperature changes. In another study results from three calibrated one-dimensional models from three different lakes in New Zealand, suggested that nutrients, represented by total phosphorous (TP) and total nitrogen (TN), will increase through the year 2100 as results of GCC (Trolle *et al.* 2010). The study reported that these incremental concentrations in nutrient loads would raise chlorophyll *a* concentrations, surrogate for the algal population density in the reservoirs.

Lake Tana, located in Ethiopia, is another water body that was evaluated for climate change effects with a three-dimensional hydrodynamic model but it was only assessed for hydrodynamic effects without including water quality simulations (Dargahi and Setegn 2010). Most of these studies of climate change effects in reservoirs have been done in temperate lakes or reservoirs located in developed countries. There are few studies for tropical lakes or reservoirs located in developing countries (e.g., Lake Tana). Hence, there is a need to understand the potential effects of climate change in tropical reservoirs and how these changes compare to those predicted for temperate reservoirs. Both types of reservoirs, temperate and tropical, behave in unusual ways and can respond differently to climate change.

A report prepared by Vose *et al.* (1999) evaluated the effects of climatic changes produced by incremental increases of air temperature and CO₂. In this study, they compared

watersheds from two contrasting ecosystem regions using hydrologic models. The first watershed is located in dry tropical western Mexico and the second located in the mesic temperate southeastern United States. Their study suggested that the major GCC effects in these contrasting watersheds were changes in evapotranspiration and streamflow.

All the studies described above evaluated GCC impacts to watersheds or reservoirs but the assessments and comparisons of GCC effects on water quality in two contrasting reservoirs have not been reported in the literature. In addition, the limited studies that have been reported have focused on water supply, not on water quality. This is why this project is valuable because two reservoirs with different characteristics and locations were evaluated to learn what the future GCC impacts can be by adjusting climatic conditions.

2.3 Temperate and Tropical Reservoirs

The degree to which reservoirs are affected by loading changes from either pollutants or nutrients depends on whether they are deep or shallow, large or small, and tropical or temperate (Wetzel 2001; Kalff 2002; Likens 2010). Temperate reservoirs are usually constantly monitored because they are used as sources of drinking water supply in developed countries. On the other hand, tropical reservoirs are fewer when compared with temperate reservoirs and are rarely reported in the literature. They are generally located in developing countries and most were designed for hydropower generation and flow control. Yet, the economic development and the fast population growth in tropical regions have made authorities from these countries build more reservoirs that can supply drinking water as well as repurpose existing reservoirs to meet growing demand and potentially mitigate future GCC effects (Obregon 2008).

Lewis Jr (2000) described the similitudes and contrasts related to climate interaction between temperate and tropical reservoirs systems. For example, the minimum solar irradiance

in tropical reservoirs is greater than in temperate reservoirs. This minimum solar irradiance affects the duration and time of the seasonal mixing periods in the reservoir's water column. Also, reservoirs in the tropics often receive water from larger drainage areas relative to their storage capacity than do temperate reservoirs. In terms of nutrient-cycling efficiency, tropical reservoirs are considered more sensitive to eutrophication (water quality depletion) than temperate reservoirs. The limiting nutrient in temperate reservoirs is generally phosphorous while in tropical reservoirs it can be either phosphorus or nitrogen. However, both types of reservoirs exhibit similar phytoplankton and zooplankton species composition (Lewis Jr 1996; Lewis Jr 2000).

2.4 Regional Climate Change Projections

The accuracy of regional climate change projections has been improved by advances in modeling and a greater understanding of the physical dynamics of the climate system. Atmosphere-Ocean General Circulation Models (AOGCM) have been the main modeling approach used to make regional climate change projections combining physical understanding of the processes that govern regional responses and historical events of climate change. Published sources state that the global trend will be warming in the 21st century (IPCC 2007). Regional climate change projections for two regions (Rocky Mountain-North America and Latin America) that contain the two reservoirs addressed as part of this study are described as follows:

2.4.1 North America

Generally, the climate changes in North America are expected to exceed the global mean warming. Warming is predicted to be larger in winter in northern regions and in summer in the southwest United States. Precipitation is predicted to increase in Canada and the northeast USA

and decrease in the southwest USA. However, predictions indicate that precipitation will tend to increase in winter and spring in southern Canada and decrease in summer. These studies predict that snow seasons will tend to decrease in most of North America but increase in the northernmost part of Canada (IPCC 2007; Bates *et al.* 2008). Air temperatures in the Rocky Mountain region have been projected to increase from 1 °C to 3 °C by 2050 and from 2 °C to 6 °C by 2100 by IPCC (IPCC 2007; Gray and McCabe 2010). Increments on average annual air temperatures, decrements on average annual precipitation and runoff were predicted for the Colorado River. Air temperatures are expected to be warmer by 1.0 °C, 1.7 °C and 2.4 °C for the 2010-2039, 2040-2069, and 2070-2098 periods, respectively. Annual precipitation will decrease by 3%, 6%, and 3% for the same periods of time; and runoff will decrease 14%, 18%, and 17% producing degradation of the water resources systems which may reduce the storage volume of reservoirs in the region (Christensen *et al.* 2004). In order to understand the potential hydrologic effects produced by climate changes, Gray and McCabe (2010) combined water balance and tree approach modeling. Their results suggested that increasing air temperatures from 1 °C to 3 °C could negatively affect water availability in the upper Yellowstone region representing the central Rocky Mountains (Colorado, Idaho, Montana, Utah and Wyoming), thus decreasing streamflow and reservoir storage. In 2011 the U.S. Department of the Interior Bureau of Reclamation published a report that summarizes and includes a well-documented literature review related to past and projected climate change effects on hydrology and water resources in Western United States (Pacific Northwest Region, Mid-Pacific Region, Lower Colorado Region, Upper Colorado Region and Great Plains Region). The projections reported by USBOR (2011) for the northern portion of Upper Colorado Region (northwestern Colorado, northern Utah, and

southwestern Wyoming) show warmer (Figure 2-1) and wetter (Figure 2-2) conditions for the 2070-2099 by using 1950-1979 projections as base scenario.

For this study I assumed change of plus and minus 3 °C based on these predictions and to evaluate sensitivity of the system to temperature changes. I also increased and decreased flow by 10% based on these predictions.

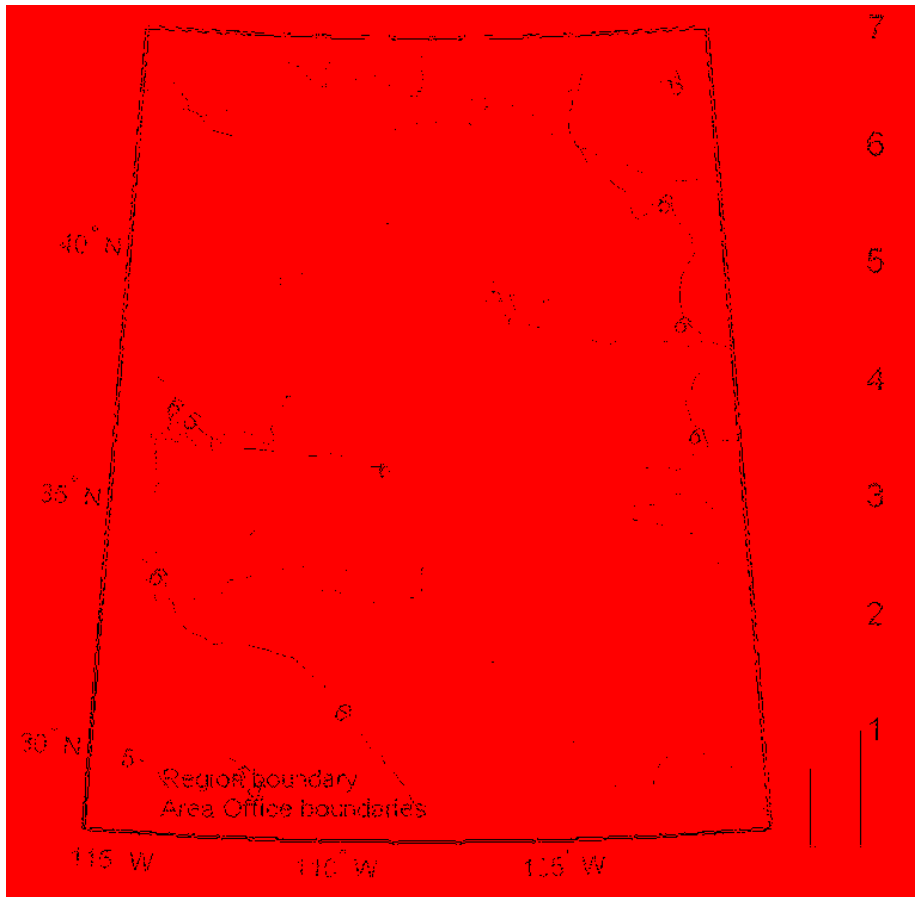


Figure 2-1: Projected Mean Annual Air Temperature Change (3.61 °C) for the 2070-2099 Period for the Upper Colorado Region by Using 1950-1979 Projections as Base Case (USBOR 2011)

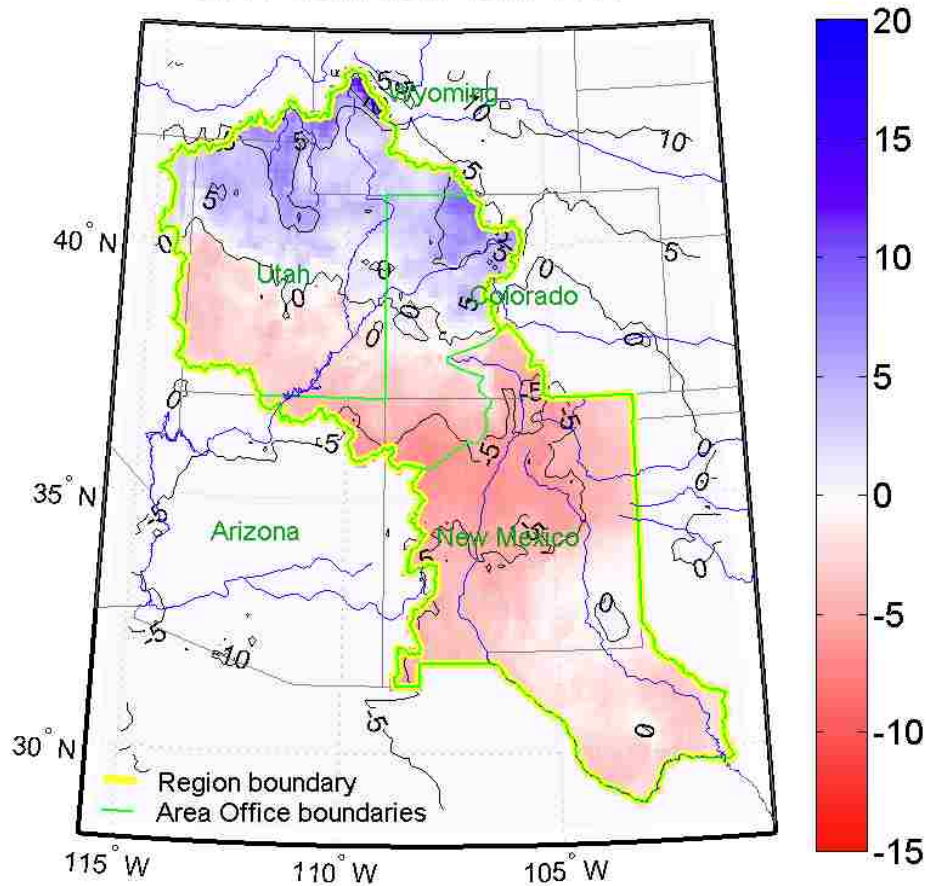


Figure 2-2: Projected Mean Annual Percentage Precipitation Change (5%) for the 2070-2099 Period for the Upper Colorado Region by Using 1950-1979 Projections as Base Case (USBOR 2011)

2.4.2 Latin America

As a result of its geographical location, Latin America is characterized by a large variety of climates. This climatic spectrum includes cold, icy high elevations, as well as temperate and tropical climates. Estimates for air temperature increases ranging from 1 °C to 4 °C for the B2 emissions scenario (e.g., following environmentally, economically and socially sustainable locally oriented pathways) and from 2 °C to 6 °C for the A2 scenario (e.g., self-reliance and preservation of local identities) have been projected by different climate models for Latin America for 2100 time period (Bates *et al.* 2008). These projections, together with fast

population growth, will create water-stressed periods which will require large investments in water supply systems. General Circulation Model (GCM) projections suggest larger rainfall anomalies for tropical regions and smaller ones for the extra-tropical parts of South America. GCM projections have also predicted more frequent extreme dry seasons in Central America (Arnell 2004; Bates *et al.* 2008).

Climate change projections for Mexico were used by Peterson *et al.* (2002) to evaluate how the fauna in Mexico may respond under the projected GCC scenarios. These estimated projections indicated warmer and drier annual mean conditions for Mexico for the mid-21st century. Annual mean air temperature may increase between 1.6 °C and 2.5 °C and precipitation may decrease between 70 mm and 130 mm.

In a study prepared by Mendoza *et al.* (1997) regional-scale thermal-hydrological models were used to assess the vulnerability of twelve hydrologic regions in Mexico to future climate change scenarios. The climate change projections for 2050 were generated by GCM approaches and energy balance models. The results reported from the vulnerability study for the Lerma-Chapala-Santiago watershed (zone VI), suggested annual changes in precipitation (-16.8% to 24.9%), air temperature (2.2 °C to 3.0 °C), and runoff (-41.6% to 123.2%).

Other climate change scenarios projected for Mexico (years 2030 and 2050) are reported by the Climate Change and Solar Radiation Group at the National Autonomous University of Mexico, UNAM. This group chose three GCMs (ECHAM5/MPI, UKHADGEM1 and GFDL CM 2.0) and Special Report on Emissions Scenarios (A1B, A2, B1, and B2) to generate monthly climate change projections. These GCMs were chosen because they represented well the climatic conditions observed in Mexico (Conde *et al.* 2008). Results from the GCMs reported that approximately 48% of the Mexican territory may be affected with more severe droughts and

warmer temperatures ($\sim +2$ °C) for 2050, especially at central zones of the country (Lerma-Chapala-Santiago). Figure 2-3 and Figure 2-4 illustrates examples of air temperature and precipitation projections for Mexico generated from the ECHAM5 for July 2050. Also, the Mexican National Institute of Ecology (INE) has reported total annual precipitation and average annual air temperatures projections for the state of Nayarit, Mexico for three future scenarios (years 2020, 2050, and 2080). These projections indicated total annual precipitation changes of -5% to +5%, -20% to +10%, and -20% to +10% and average annual air temperature changes of 0.6 °C to 1.2 °C, 1.0 °C to 2.0 °C, and 2.0 °C to 4.0 °C for 2020, 2050, and 2080 scenarios, respectively (INE 2011).

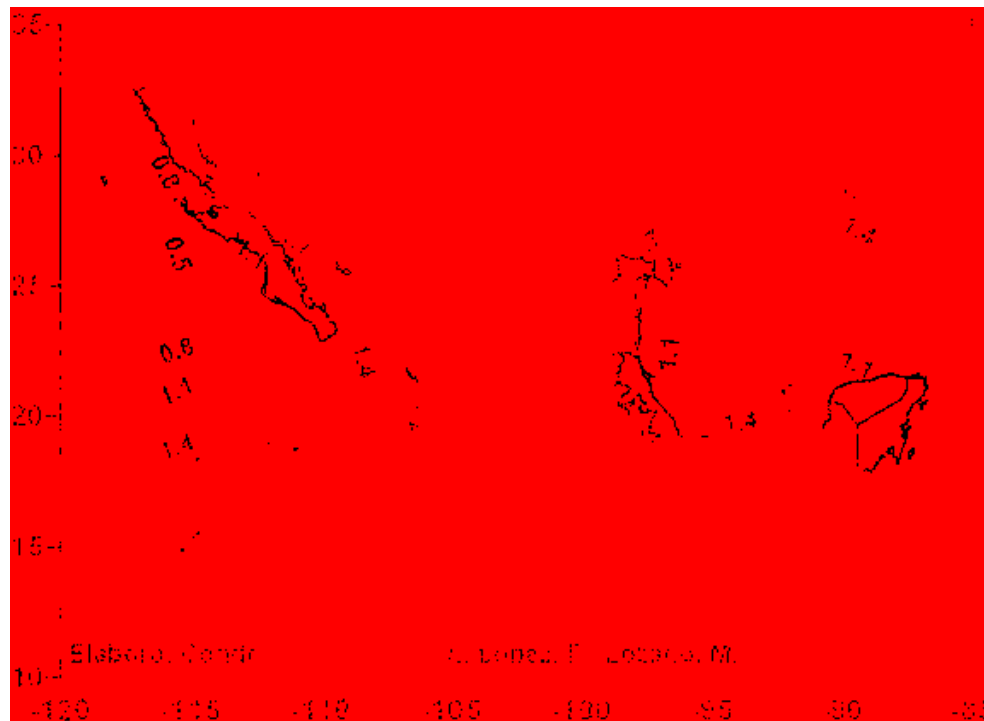


Figure 2-3: Example of the Projected Air Temperature Change (°C) for July 2050 in Mexico From the ECHAM General Circulation Model (GCM) and A2 Special Report on Emissions Scenario (Conde *et al.* 2008)

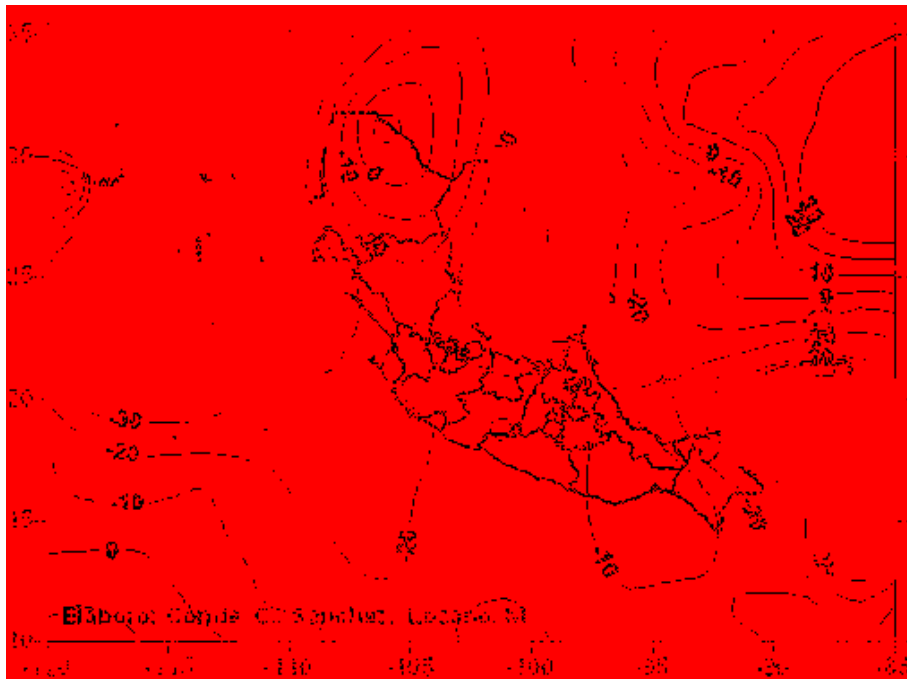


Figure 2-4: Example of the Projected Precipitation Change (%) for July 2050 in Mexico From the ECHAM General Circulation Model (GCM) and A2 Special Report on Emissions Scenario (Conde et al., 2008)

3 TEMPERATE DEER CREEK RESERVOIR

3.1 Deer Creek Study Area and Description

Deer Creek Reservoir, a major water supply reservoir in Utah, was used for this study. Deer Creek is located approximately 56 kilometers (km) southeast of Salt Lake City and 30 km east of Utah Lake (Figure 3-1A). It is an important source of drinking water supply for nearly one million people along the Wasatch Front, providing 90.6 million cubic meters (Mm³) of potable water to seven water districts. Other uses of Deer Creek include flood control, power generation, and recreation (BOR 2009; Casbeer 2009).

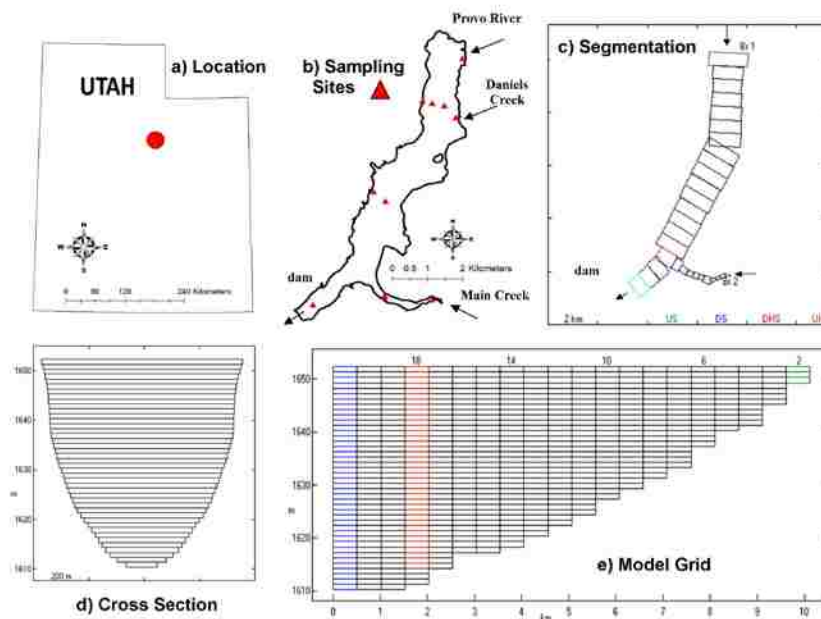


Figure 3-1: A) Deer Creek Reservoir Location; B) Inflows, Outflows, and Sampling Sites; C) W2 Segmentation; D) W2 Model Cross Section (at the Deepest Site); and E) W2 Model Grid

The reservoir covers 12 km² when it is full and receives inflows from Provo River, Main Creek, Snake Creek, and Daniel’s Creek (Figure 3-1B). It has a capacity of 185 Mm³ and its surrounding watershed covers an area of 694.7 km². This watershed area includes lands located below Jordanelle Reservoir, and does not include any watershed draining into Jordanelle Reservoir, an upstream impoundment (PSOMAS 2002). Annual precipitation in the region ranges from 410 to 1,020 mm and the frost-free season ranges from 80 to 100 days (Casbeer 2009). Deer Creek is considered a dimictic-temperate reservoir because it experiences two complete mixing periods each year, one in spring and another one in fall (Gaufin and McDonald 1965; Wetzel 2001).

Table 3-1: Volumetric Characteristics of Deer Creek Dam and Reservoir

<i>Characteristic</i>	<i>Value</i>
Long term mean flow	28.3 m ³ /s
Normal maximum water level	1651 m
Normal minimum water level	1617 m
Gross head	40.2 m
Reservoir volume (at 1651 m)	185 Mm ³
Reservoir area	12 km ²
Mean depth (volume/area)	15.4 m

3.2 Methods

3.2.1 Water Quality Model First Approach

I used CE-QUAL-W2 (W2) version 3.5 to develop a model of Deer Creek Reservoir. W2 is a finite-difference, laterally averaged, two-dimensional hydrodynamic and water-quality model supported by the U.S. Army Corps of Engineers (Cole and Wells 2006). I chose this model because it is used world-wide and is specifically used by the U.S. Bureau of Reclamation

(USBOR) in the Upper Colorado Basin. I obtained the data required to create the W2 model from local, state and federal agencies and used the Watershed Modeling System (WMS) and W2i-AGPM modeling system for W2 version 3.5 (Loginetics 2003; Chilton 2011) for model development and result analysis.

I developed the calibrated Deer Creek Reservoir water quality model using field data from 2007 through 2009 for the first approach. This chosen period presented uncharacteristic change in the reservoir conditions due to construction work at the spillway (PRWUA 2009). During this period the reservoir went from spill conditions (full) in 2007 to less than 60% of capacity in 2008 to spill conditions again in 2009. This period represents the lowest level that the reservoir has been since dam construction in the 1930s in addition to full conditions at the beginning and end of the study period. The Deer Creek model that I developed was able to replicate the extreme observed reservoir conditions during the 2007-2009 period, giving me confidence in the ability of the model to evaluate environmental changes and stresses on the reservoir.

I used this period as the base case for evaluating the impacts of GCC on Deer Creek. This allowed me to evaluate the impacts of GCC on both high and low reservoir periods representing the potential range of future conditions.

3.2.2 Model Input

I gathered meteorological, gauging, and water quality data from the Environmental Protection Agency (EPA), Central Utah Water Conservancy District (CUWCD), United States Geological Survey (USGS), the Brigham Young University (BYU) Deer Creek Research Group and from the EPA STORET and USGS databases.

The Deer Creek geometric computational grid (Figure 3-1C, 3.1D, and 3.1E) was created using the original bathymetric survey (Nicholas T. Williams, Upper Colorado BOR, 2009, personal communication). The geometry was verified by comparing the computed storage-elevation curve with the BOR storage-elevation curve which matched closely. I obtained meteorological data from the CUWCD climatological station located northeast of Deer Creek (Heber City) for the period from 2007-2009 (Dr. Reed Y. Oberndorfer, CUWCD, 2009, unpublished data). Using these data I created hourly input data files for T_{AIR} , dew point temperature, wind direction and speed, cloud cover and solar radiation data. The model initial conditions were based on the reservoir characteristics as described in PSOMAS (2002) and observed values (BYU Research group, 2009, unpublished data). Boundary conditions included inflow water temperature, hydrologic inputs and inflow water quality, and associated distributed flows (ungauged inflows). The distributed files represent the ungauged data along the reservoir and were estimated following the criteria described by Miller (2008) and Cole and Wells (2006).

3.2.3 Model Calibration

I calibrated the model against measured data collected from sampling sites shown in Figure 3-1B. These measured data included water balance, water temperature, total dissolved solids (TDS), dissolved oxygen (DO) and chlorophyll-a (Chl-A). The accuracy of the calibration was measured by a statistical parameter called global absolute mean error (AME) of four parameters: water temperature, TDS, DO and Chl-A. The AME is individually calculated for each parameter by using the absolute total sum of the predicted minus the observed values, divided by the number of observations (Hanna *et al.* 1999) and is represented by Equation 3-1:

$$AME = \frac{1}{n} \sum_{i=1}^n |f_i - y_i| \quad (3-1)$$

where n is the number of measurements, f_i is the predicted value, and y_i is the true or measured value.

I first calibrated the water balance followed by hydrothermal calibration (Figure 3-2) using the procedures of Cole and Wells (2006). Next TDS (Figure 3-3), DO (Figure 3-4), and Chl-A were calibrated in order. Hourly data were not available for each parameter, and even daily data were unavailable for some time periods. Even though TDS is not as conservative as salinity to calibrate a W2 model, I used TDS because it was the only available data with characteristics similar to salinity, the recommended parameter (Cole and Wells 2006). According to Cole and Wells (2006) previous W2 models have shown that DO and phytoplankton (represented by Chl-A) are much better indicators of proper hydrodynamic calibration than either salinity or temperature because DO and phytoplankton gradients are more spatially diverse in the water column than salinity or temperature gradients, so being able to replicate these data show a good calibration. However, Cole and Wells (2006) recommend that TDS and/or temperature should always be used first for hydrodynamic calibration which is then refined using DO and Chl-A calibrations. This is the approach I following in calibration of this model.

Following these procedures resulted in a model thermal calibration with an AME value of 0.96 which means the average model value is within 0.96 °C of the observed value. Example thermal calibration profiles near the dam for three separate dates are shown in Figure 3-2. DO calibration gave an AME value of 1.2 (with examples shown in Figure 3-4) which represents an average of 12% error between the observed data and the model produced data which according to Cole and Wells (2006) is a good fit for DO data. The AME for TDS was 9.6 mg/L. TDS

values ranged from 0 to 500 mg/L, so the AME represents about 5% error (Figure 3-3). The AME for Chl-A was 3.24 $\mu\text{g/L}$ which is a about a 32% error. The larger error in the chlorophyll calibration is present for a variety of reasons and was expected. Algae are spatially diverse and measurements change quickly with reservoir conditions (Miller 2008). Further, algae data were only available for limited time periods (spring and summer seasons) at the chosen sampling locations, rather than complete profiles as were available for the other water quality parameter, providing fewer data locations and times for comparison.

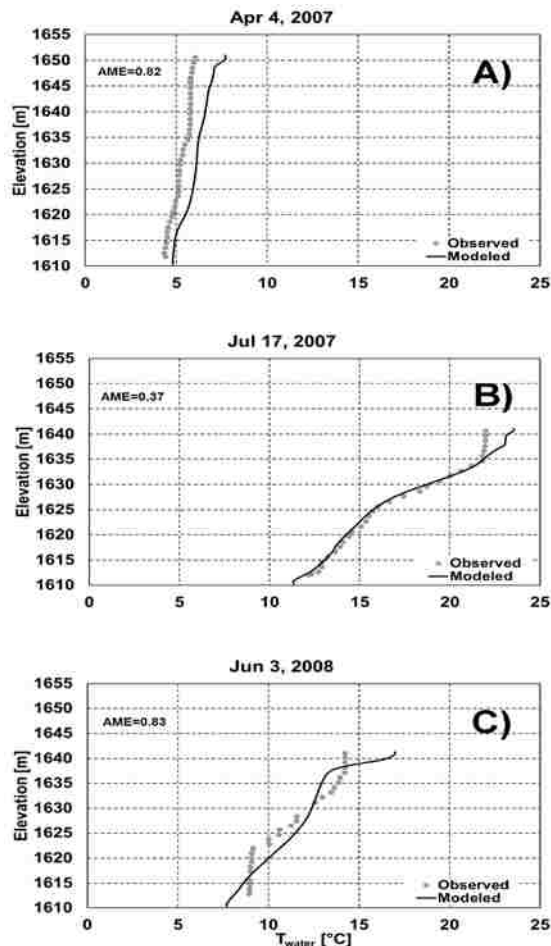


Figure 3-2: Example Water Temperature Calibration From the Near Dam Sampling Site for: A) Spring Turnover (April 2007), and B) Summer Stratification in July 2007 (Normal Reservoir) and C) Summer Stratification in 2008 (Low Reservoir). Note That the Low Reservoir Levels in June of 2008 are Similar to Those of July 2007

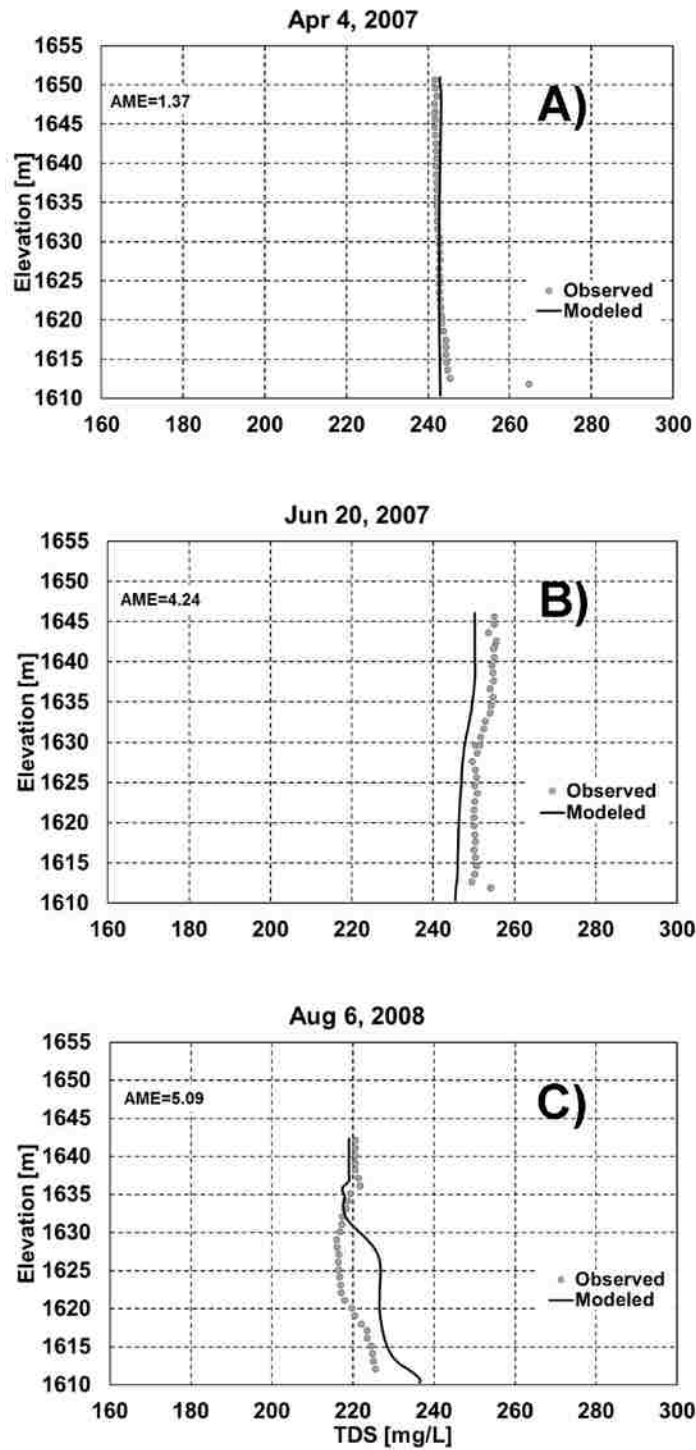


Figure 3-3: Example TDS Calibration From the Near Dam Sampling Site Showing Data: A) Near Spring Turnover in April 2007, B) After Stratification in June 2007, and Mid-Summer in August 2008

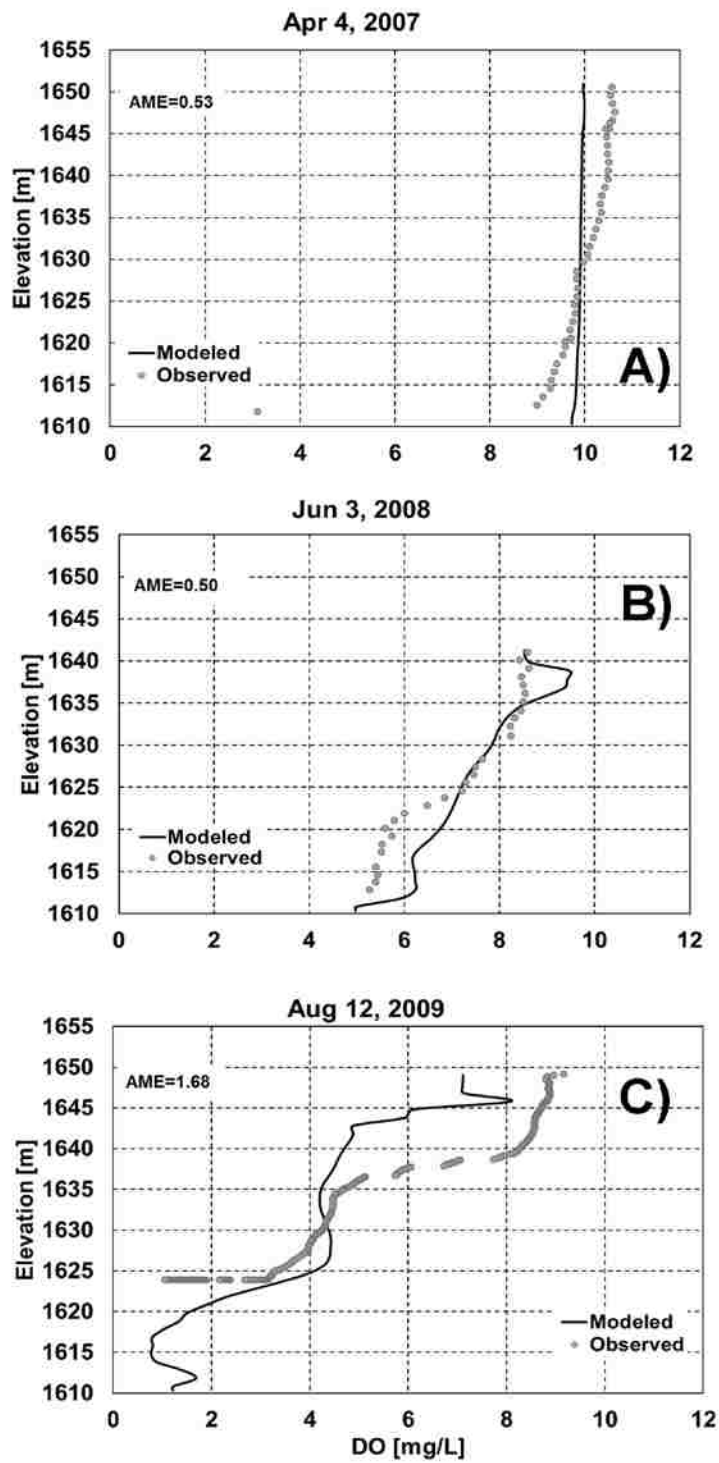


Figure 3-4: Example DO Calibration From the Near Dam Sampling Site Showing Data: A) Near Spring Turnover in April 2007, B) Very Low Reservoir Levels in June 2008, and C) A Relatively Full Reservoir Late in the Summer for August 2009

3.3 Assessment Methods and Scenarios

3.3.1 Assessment Methods and Tools

Traditionally, reservoir changes have been analyzed at a few points located at critical locations in the reservoir which can be subject to local variations. Following this approach I evaluated impacts using Chl-A concentration profiles from the deepest part of the reservoir near the dam. I found that this approach, while useful, was lacking because these profiles did not represent the entire reservoir and it was difficult to quantitatively compare numerous scenarios over the complete three-year time period. I wanted to look at global reservoir changes over the simulation time period and minimize the influence of any local variations. To overcome this limitation I developed two different types of indices and plots that analyze the total reservoir over time: total normalized parameter indicators (i.e., algae, DO, TDS) and delta temperature plots which show the stratification strength and direction.

Total normalized parameter concentration and delta temperature/stratification plots quantify aggregate water quality changes to the entire water body over time, which allows both a quantitative comparison for different simulations and analysis and comparison of temporal changes in reservoir processes (see A.2 Scripts-Deer Creek).

Total normalized parameter concentration plots present the total parameter mass (or volume) normalized by the total reservoir water volume over time (Equation 3-2).

$$y_t = \frac{\sum_i v_{i,t}}{\sum_i w_{i,t}} \quad (3-2)$$

where y is the parameter of interest (e.g., algal groups, DO, phosphates, or nitrate-nitrite), v is the mass or volume per grid cell, w is the water volume per grid cell, i is an index of all the

grid cells, and t is a given time step. I initially did not normalize these plots by reservoir volume, but because of the large change in the reservoir volume over the period of study, I found it was difficult to separate mass changes due to changes in the reservoir volume from changes in the parameter under study caused by perturbed boundary conditions. Normalization removed most of the influence of reservoir volume changes allowing the normalized indicators to present changes from the changed boundary conditions.

I developed delta stratification plots to evaluate the onset of thermal stratification, reservoir turnover, and the stratification strength. These plots graph the difference between the top temperature and the bottom temperature over time (Equation 3-3).

$$\Delta S_t = T_t^{top} - T_t^{bot} \quad (3-3)$$

where ΔS_t is the delta stratification value at time t , T_t^{top} is the temperature at the top of the reservoir at time t , and T_t^{bot} is the bottom temperature at time t . Large positive delta values indicate a strong thermal stratification while values close to zero indicate turnover conditions and negative values indicate stable winter conditions (inverse thermal stratification). These plots allowed me to compare different scenarios at an aggregate level, determining if the time of turnover was changed and if thermal stratification patterns or strength were changed. These plots have the added benefit of presenting the entire period of study in one graph. Thermal stratification plays a large role in reservoir processes and can have major impacts in other areas (Cole and Wells 2006; Likens 2010).

3.3.2 Scenarios and Parameters

For Deer Creek Reservoir I quantified the change in various reservoir water quality indicators due to potential GCC and population changes by separately modifying meteorological,

hydrological, and water-quality conditions in ranges based on GCC or population change estimates described in Section 2. I decreased and increased air temperature (T_{AIR}) by 3 °C, I increased and decreased reservoir gauged inflow (Q) by 10% to represent low (-10%) and high Q (+10%) produced by more severe droughts and storms, and I separately increased and decreased two nutrients, phosphate as phosphorous (PO_4-P) and nitrate-nitrite as nitrogen (NO_3-NO_2-N), by 50% to evaluate potential expansion of urban areas into the watershed surrounding the reservoirs (increase) and building upstream dams or implementing strict controls (decrease). These changes were made individually and not in combination to quantify the sensitivity of reservoir processes to specific potential changes. These results do not represent predictions of future reservoir conditions, which would require combinations of these parameters, but rather a study to better understand and characterize relationships between the complex reservoir processes and these potential changes.

I used three analysis tools: Chl-A profiles, total normalized concentration plots, and delta stratification plots. For the total normalized parameter concentration plots I chose algal biomass, DO, PO_4-P , and NO_3-NO_2-N as parameters to quantify impacts. The total normalized algal concentration values included three main categories of algae that I included in the W2 model: diatoms, green, and cyanobacteria. Algae growth is quite sensitive to changing reservoir conditions and perturbations and can cause problems with water treatment. Algae can impact water quality. I used total normalized concentrations of DO, PO_4-P , and NO_3-NO_2-N to understand GCC effects on the water chemistry of the reservoir. DO concentrations provide some insight into the health of a reservoir as low DO conditions can drastically change water chemistry and reservoir's ecology (Metcalf *et al.* 1991; Likens 2010). The phosphorous and nitrogen values track changes in available nutrients which are major drivers of water quality.

3.4 Deer Creek-Results and Discussion

As noted above, I evaluated the sensitivity of reservoir responses to three potential GCC-induced changes that could affect Deer Creek: air temperature (T_{AIR}), inflow volume (Q_{IN}), and inflow nutrient concentration of both PO_4 -P, and NO_3 - NO_2 -N (NC). I developed analytical methods to quantify and communicate the results. I used six different plots to analyze each scenario: Chl-A profiles plotted at the near-dam field sampling point, total normalized algal concentrations over time, total normalized DO over time, total normalized PO_4 -P over time, total normalized NO_3 - NO_2 -N over time, and a delta thermal stratification indicator plot at the near-dam field sampling point.

In this section I present each perturbation in turn (T_{AIR} , Q_{IN} , NC - PO_4 -P, and NC - NO_3 - NO_2 -N). For each perturbation I present and discuss the results using each of the six plots. In each case, the no-change scenario is used as a base case for discussion.

3.4.1 Changing Air Temperature (T_{AIR})

3.4.1.1 Chlorophyll-a Profiles (T_{AIR})

Figure 3-5 shows the Chl-A mid-summer profiles for July 30, 2007 (Figure 3-5A), July 28, 2008 (Figure 3-5B), and August 3, 2009 (Figure 3-5C) at the Near Dam field sampling point (a location in the lentic zone). Each plot includes three profiles representing changing the T_{AIR} by -3, 0, and +3 °C. During the first summer (2007) there was minimal change in the epilimnion (approximately the first 5 m depth) when T_{AIR} was decreased 3°C but the Chl-A profile in the epilimnion showed an increase when T_{AIR} was increased 3°C (Figure 3-5A). In 2008, the Chl-A profile showed a decrease in the epilimnion when T_{AIR} was decreased 3 °C compared with the +3°C and base line simulations, with no increase observed for the increased temperature

simulation. The 2008 summer is the period when the reservoir was very low and warmer inflow temperatures had minimal effect on the reservoir as the reservoir surface was already warmer in the summer due to the shallow depth. In 2008 below the thermocline, Figure 3-5B shows that Chl-A concentrations slightly increased with increasing T_{AIR} 3 °C (elevations of 1630 m to 1638 m) compared with the base case and -3 °C simulations. In 2009 Chl-A concentrations decreased when T_{AIR} values were colder (-3 °C) and increased when T_{AIR} values were warmer (+3 °C) in the region from 1642 m to 1645 m near the thermocline. However, in the epilimnion there was no difference in either perturbed scenario compared with the base model (Figure 3-5C). These plots showed that the vertical distributions of Chl-A concentrations are only slightly affected by predicted changes in T_{AIR} .

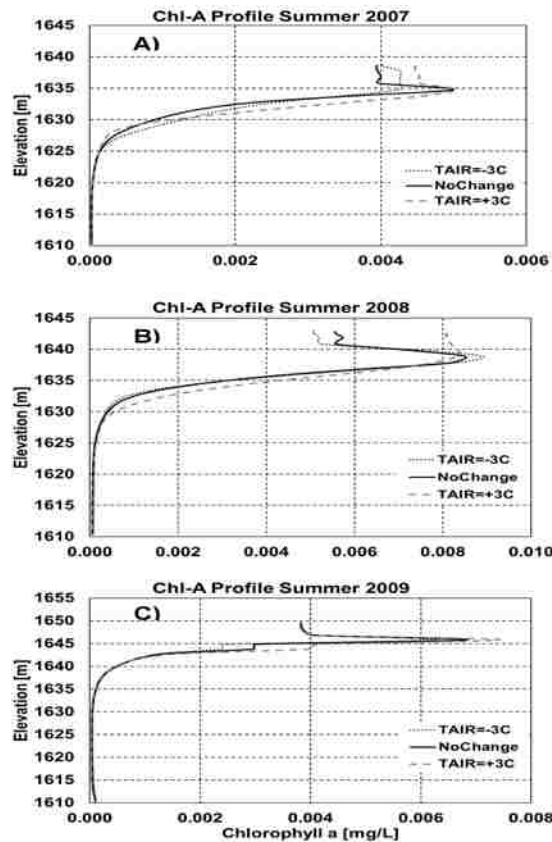


Figure 3-5: Chl-A Profiles at the Near Dam Sampling Point by Adjusting T_{AIR} for: A) Summer 2007; B) Summer 2008; and C) Summer 2009

3.4.1.2 Total Algal Concentration (T_{AIR})

Total average algal concentrations allow analysis of the entire reservoir, rather than the single point shown in the profiles. These results are presented in Figure 3-6. In general total algal average concentration peak values increased and the peak concentrations occurred earlier when T_{AIR} was increased 3 °C. I observed that immediately prior to reservoir turn-over (at the beginning May and at the end September 2007) the total average algal concentration was noticeably increased for the 3 °C increased T_{AIR} simulation. However, there were some days during spring-summer 2007 (May) where this trend changed and total algal concentration decreased when T_{AIR} was increased 3 °C. This effect could be produced by the seasonal succession in algae groups and the dominance of algae groups at different points in time due to temperature changes. As noted above, I modeled three algae categories. According to Stephens (2011) diatoms comprise the dominant algae group in Deer Creek. Also, Gaufin and McDonald (1965) suggested that as summer stratification progresses and water temperatures approach 21 °C, diatoms decrease and other species such as green algae appear in Deer Creek. For spring-summer seasons of 2008 and 2009, I observed that the total algal concentration kept varying, but summer total algal concentration peaks (July 2008 and July 2009) increased when T_{AIR} was increased 3 °C and decreased when T_{AIR} was decreased 3 °C. The slight variations from this trend early in the season could be due to different algal groups achieving dominance at different times when the changing T_{AIR} created different reservoir conditions.

Changing T_{AIR} influenced the timing of the peaks in total average algal concentrations. Increases in T_{AIR} , caused the peak to occur earlier in the season. This is of concern to water managers and treatment plant operations because the stratification of the reservoir will last longer if T_{AIR} increases (discussed below) and will produce longer periods of anoxic conditions

in the hypolimnion of the reservoir that can release nutrients from the sediments. This creates a feedback loop forming higher concentrations of algae when water column mixes because of the higher nutrient values caused by releases from the sediments. T_{AIR} simulations did not show any significant changes during the fall and winter seasons (January-April 2007, October 2007-April 2008, and September 2008-April 2009) in any of the three-years included in the simulations.

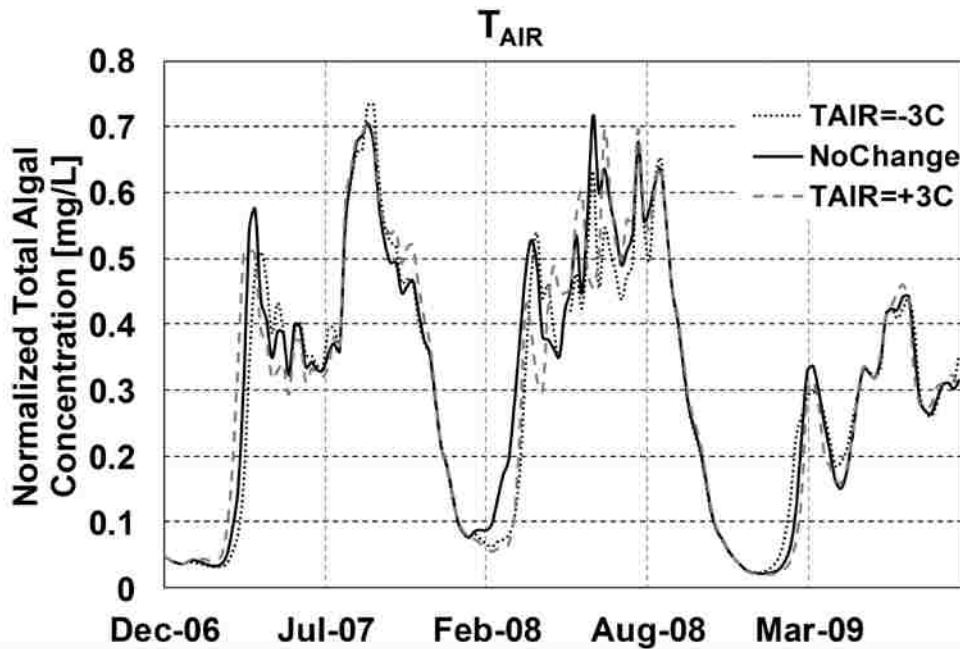


Figure 3-6: Total Algal Concentration in Deer Creek by Changing T_{AIR}

3.4.1.3 Total DO Concentration (T_{AIR})

Increased T_{AIR} decreased the total average DO concentration in the reservoir from May 2007 through the September 2007, from October 2007 to March 2008, and from the mid May 2008 through October 2009 (Figure 3-7). According to Vesilind *et al.*(2009), this is the expected trend for water temperature and DO concentrations. Total average DO concentrations declined earlier in the season when T_{AIR} was increased 3 °C indicating that DO concentrations in Deer

Creek are sensitive to changes in T_{AIR} . As noted above, this can create feedback loops to other parts of the reservoir, not all of these physical processes are adequately modeled using W2. For example, the increased solubility of various sediment compounds under anoxic conditions is not well modeled. These plots show that DO concentrations in Deer Creek are sensitive to T_{AIR} changes and are more or less linear in response. The one noted exception is the very low fall values in 2008 for the higher T_{AIR} . This year had extremely low reservoir levels and the simulations show that the reservoir is more sensitive to air temperatures when the reservoir is at low levels. This is to be expected, because there is not as much volume in the hypolimnion to support decay of organic materials and the higher temperatures support additional biomass growth and potential decay (Figure 3-6).

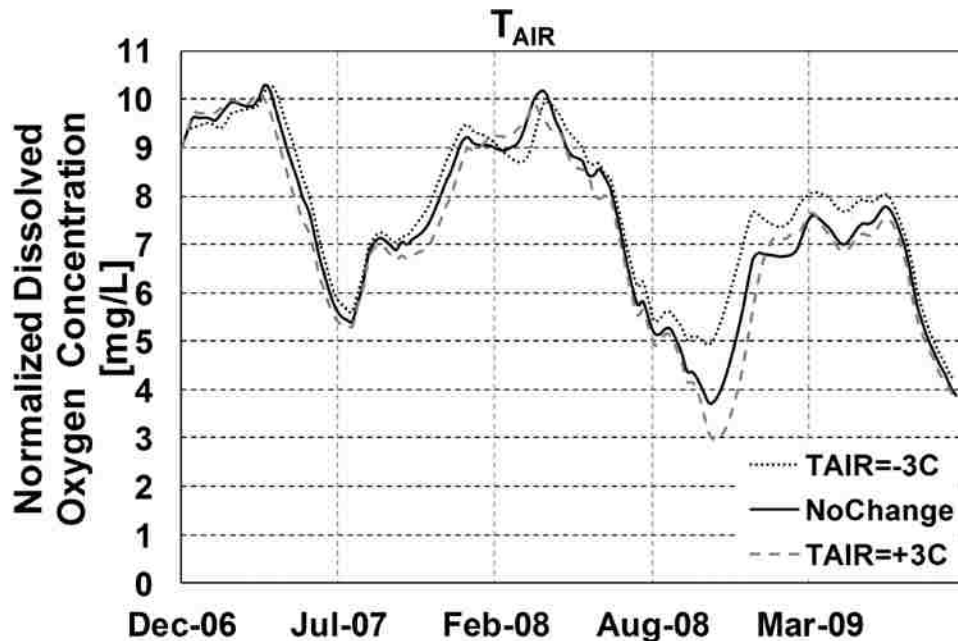


Figure 3-7: Total Dissolved Oxygen Concentration by Adjusting T_{AIR}

3.4.1.4 Total Nutrients Concentration (T_{AIR})

After evaluating the effect produced in total algal concentration and total normalized DO concentration, I evaluated total average PO_4 -P concentrations (Figure 3-8A) and total average NO_3 - NO_2 -N concentrations (Figure 3-8B) changes due to changes in T_{AIR} . Generally, there was no significant change in total average PO_4 -P concentrations when T_{AIR} was adjusted during the first two years of simulation. The only significant observable change occurred during the second summer (July 2008) when the total average PO_4 -P concentration decreased as T_{AIR} was increased 3 °C, and increased when T_{AIR} decreased 3 °C. However, for the last year when T_{AIR} increased 3 °C, the total average PO_4 -P levels increased and decreased when T_{AIR} was decreased 3 °C (Figure 3-8A). These contradictory changes are probably caused by different hydraulic retention times that Deer Creek experienced when the reservoir reached its lowest level due to construction work in 2008 and early 2009 (PRWUA 2009). However, I do not have detailed data to support this hypothesis.

Figure 3-8B shows how T_{AIR} affected total average NO_3 - NO_2 -N concentration in Deer Creek. I observed that when T_{AIR} increased 3 °C total average NO_3 - NO_2 -N concentrations increased during the fall and winter seasons. This trend was more noticeable from October 2008 to May 2009 when total average NO_3 - NO_2 -N concentration also decreased when T_{AIR} decreased 3 °C compared with the base line and +3 °C T_{AIR} simulations.

While total average PO_4 -P concentrations were slightly sensitive to changes in T_{AIR} their changes were not linear and are generally more influenced by other processes such as residence time. Changes in total average NO_3 - NO_2 -N concentrations demonstrated a more linear response, though it appears that reservoir levels may also contribute to the observed changes.

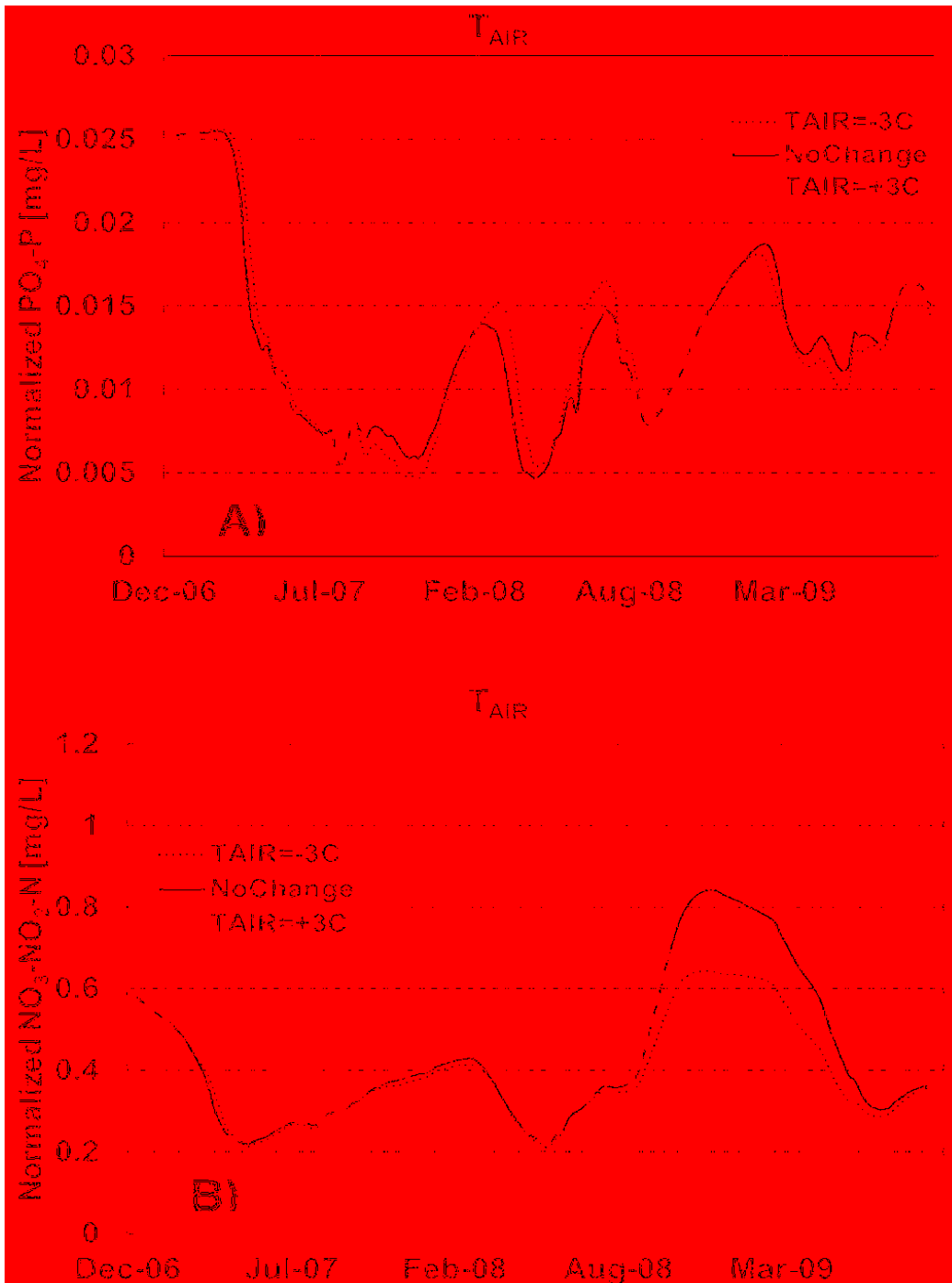


Figure 3-8: A) Total Average Phosphate Concentrations; and B) Total Average Nitrate-Nitrite Concentrations by Adjusting T_{AIR}

3.4.1.5 Stratification Effects (T_{AIR})

Impacts to reservoir stratification caused by changing T_{AIR} were analyzed by plotting the difference between the surface water temperature and the bottom water temperature for the near-dam sampling point (Figure 3-9). This plot shows the strength of stratification and indicates turnover periods (when the value approaches zero). In April 2007, the +3°C simulation shows stratification increases earlier than the base line and -3°C simulations. This indicates that stratification started earlier with increased T_{AIR} . This trend is also present in the following years, but it is less evident. The result is similar for the end of the stratification period with higher T_{AIR} resulting in a later decrease compared to the base case. The +3°C line returns to zero, indicating turnover, later in the year in the second and third years. This shows that increased T_{AIR} causes the stratification to start earlier and end later in the year. In addition to longer stratification periods, the difference in temperature between the water surface and the deeper reservoir is stronger in the third year, with this change not as noticeable in the first and second years. This could be due to changing reservoir volumes or because the hydraulic retention time of the reservoir is on the order of one year and the thermal impacts are not as noticeable early in the simulation.

As expected with increased temperatures, the period when the reservoir is frozen decreases. This is shown in the plot by the times where the lines drop below zero (i.e., the top is colder than the bottom). This trend is most evident in January 2008. The +3°C scenario line drops below zero later and comes back up to zero earlier than for the other scenarios.

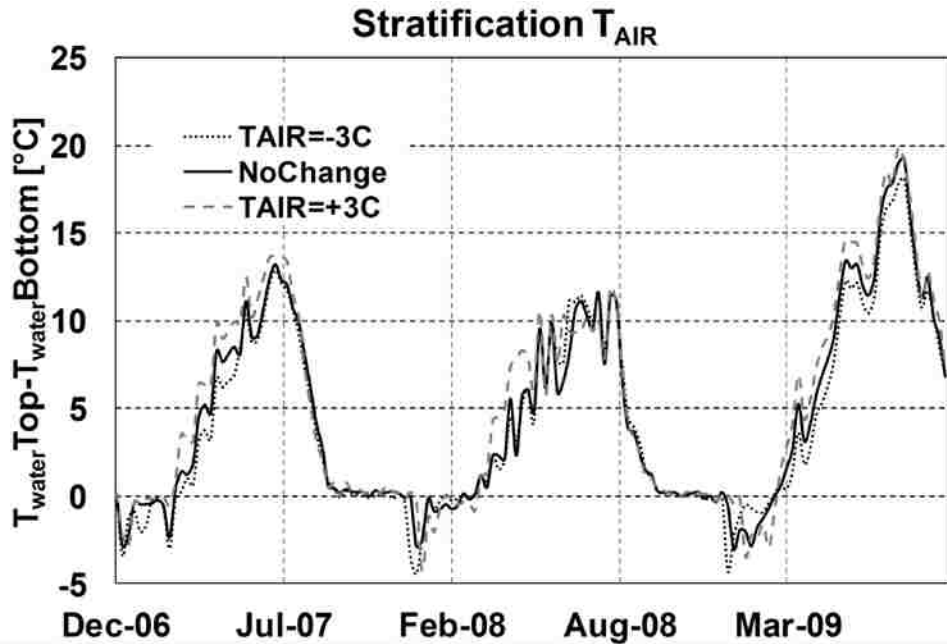


Figure 3-9: The Difference between Top Water Temperature and Bottom Water Temperature in the Water Column from the Near Dam Sampling Point by Adjusting T_{AIR}

3.4.2 Changing Inflow Volumes (Q_{IN})

3.4.2.1 Chlorophyll-a Profiles Concentration (Q_{IN})

Figure 3-10 shows Chl-A profiles for decreased, base case, and increased inflows at the Near-Dam sampling point. Inflow changes significantly affect reservoir levels because I did not change reservoir outflows correspondingly. This is consistent with expected reservoir operations that are required to meet various irrigation, ecological, and other downstream flow requirements during the summer. In these plots, Chl-A levels are plotted against elevation, thus higher reservoir conditions result in the profile being higher on the graph. Significant Chl-A only occurs in the top 5 to 7 meters regardless of the inflow value and, as noted, changing inflows affected the elevation of this range due to changing reservoir levels, however the depths are relatively consistent, though this is not evident from these plots. High Chl-A concentration

peaks were observed when Q_{IN} was reduced by 10% reaching a peak concentration of 0.010 of 0.010 mg/L (10 $\mu\text{g/L}$) during the summer 2009. This higher relative peak value is evident in all three years. The third year shows a relatively linear response of the peak value to inflow changes, while in the first two years there is little different between the peaks for the base case and the increased flow case.

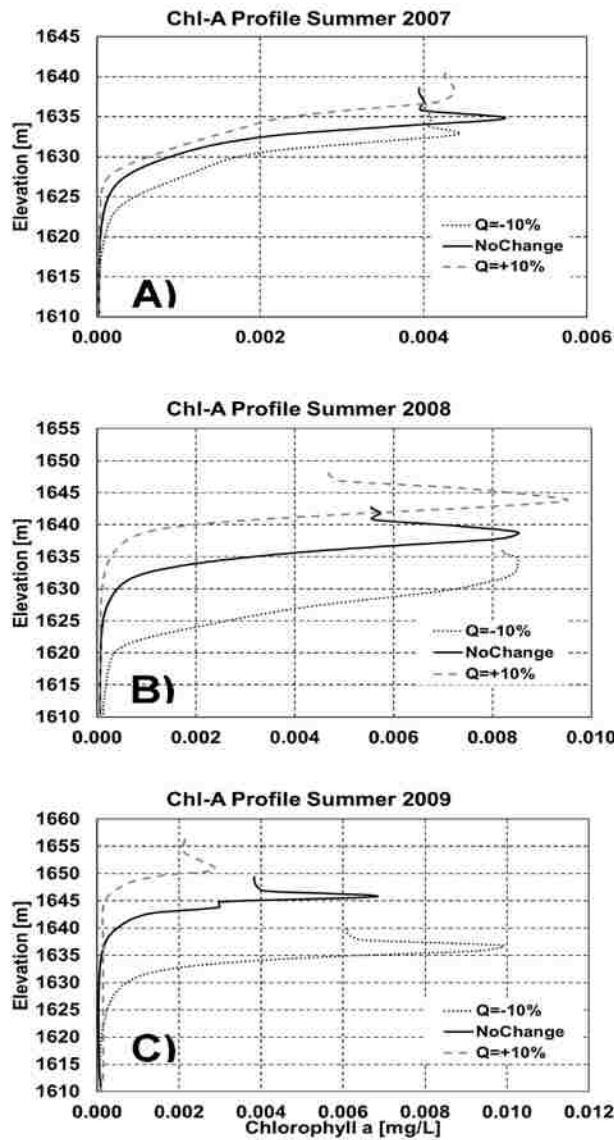


Figure 3-10: Chl-A Profiles at the Near Dam Sampling Point by Adjusting Q_{IN} for: A) Summer 2007; B) Summer 2008; and C) Summer 2009

3.4.2.2 Total Algal Concentration (Q_{IN})

Figure 3-11 shows the predicted total average algal concentrations for decreasing and increasing Q_{IN} by 10%, and the base case scenario for Deer Creek. These plots use the total average concentration to remove the large apparent impacts of changing reservoir levels that made the profile plots difficult to analyze. Figure 3-11 shows minimal changes in the first spring-summer season (April-August 2007) due to changing flows. However, from July 2007 on, the three simulations show consistent trends with the lower inflows resulting in higher total average algal concentration values. These values reached their maximums of 1.01 mg/L and 0.59 mg/L for the -10% Q_{IN} simulation during the second and third spring-summer seasons (April-August 2008 and 2009), respectively.

These simulations show that total average algal concentrations have a relatively linear response to changing Q_{IN} with lower flows resulting in higher total average concentrations. However, remember that these data are normalized by the entire reservoir volume, which includes the water below 15 m in depth which has little to no algae. This low-algal zone is a larger percentage of the total reservoir volume for high water levels and the dilution effect is noticeable over larger volume changes in the model period.

3.4.2.3 Total Average DO Concentration (Q_{IN})

The changes in Q_{IN} into Deer Creek had no effect on the total average DO concentration for the reservoir during the first winter and spring this is mostly due to the residence time of the reservoir which is on the order of one year. Starting in the first September, the decreased Q_{IN} resulted in a lower total average concentration of DO compared to the +10% Q_{IN} and the base model simulations. This indicates that lower Q_{IN} produced higher total algal concentrations and that these algal concentrations demand more DO as they die and decay (Figure 3-12). However,

at the end of the second September through November, the trend was opposite. The -10% Q_{IN} resulted in lower DO concentrations. After November the trend reversed to lower Q_{IN} resulting in higher DO concentrations. This can be partially explained by changing reservoir hydraulics with underflows providing higher oxygen content water to the hypolimnion and by the increased volume of water (and thus available oxygen reservoir) in the portion of the reservoir below 15 meters when the reservoir is full in 2009.

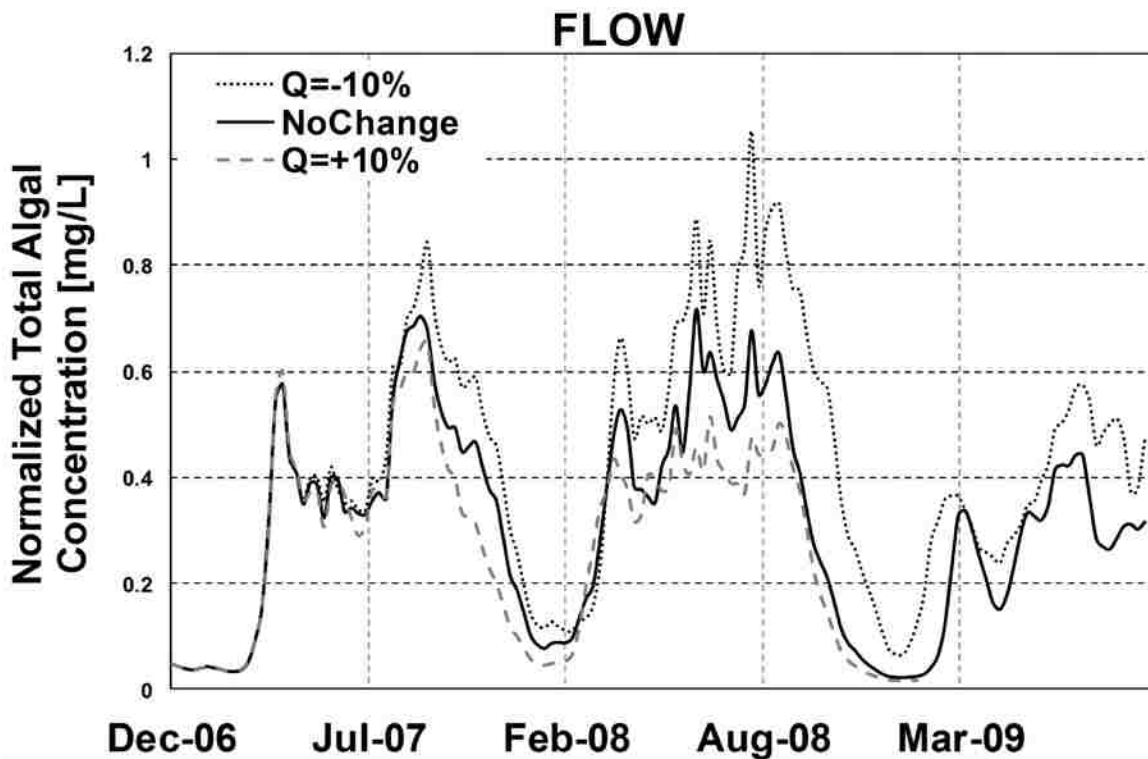


Figure 3-11: Total Algal Concentration by Changing Q_{IN}

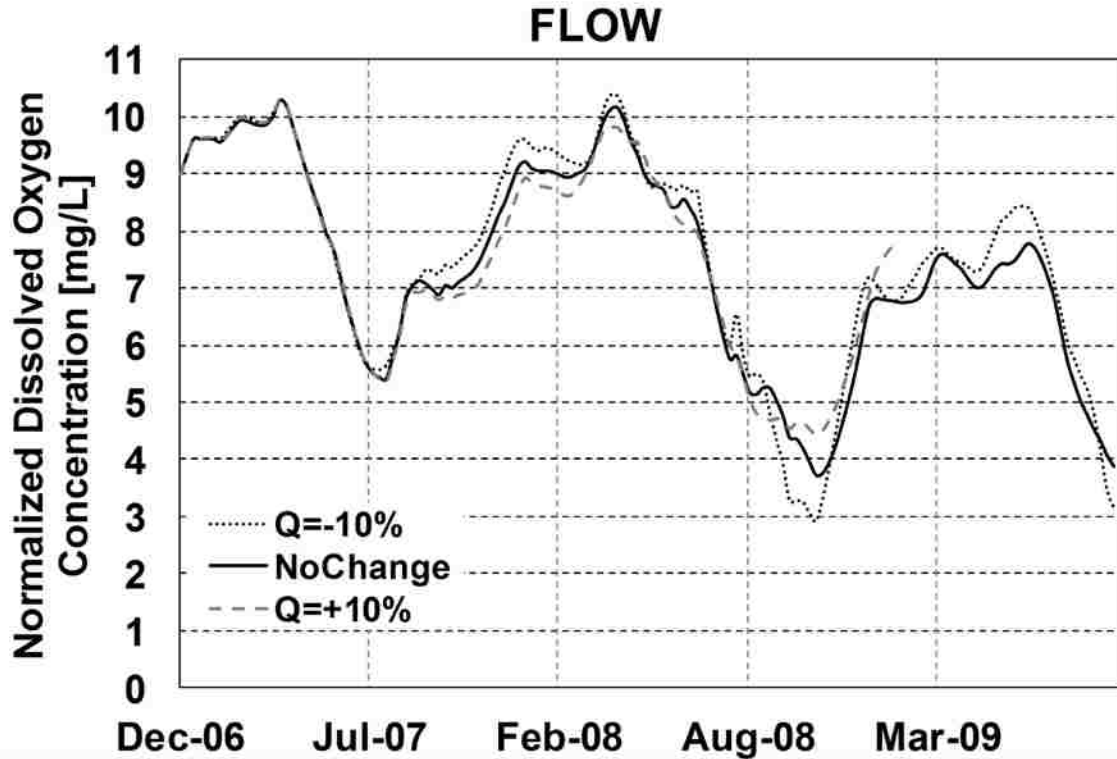


Figure 3-12: Total Dissolved Oxygen Concentration by Adjusting Q_{IN}

3.4.2.4 Total Average Nutrient Concentration (Q_{IN})

Decreasing and increasing the Q_{IN} by 10% influenced the total average PO_4 -P (Figure 3-13A) and NO_3 - NO_2 -N concentrations (Figure 3-13B) in Deer Creek. During the first winter (January-April) total average PO_4 -P concentrations did not change in the reservoir when Q_{IN} was altered 10% compared to the base model. However, after April 2007, this trend changed and total average PO_4 -P concentration increased in the +10% Q_{IN} simulation and decreased in the -10% Q_{IN} simulation compared to the base model. An interesting change occurred during the last summer of our simulations, total average PO_4 -P concentrations were higher for the -10% Q_{IN} simulation than the base model (Figure 3-13A).

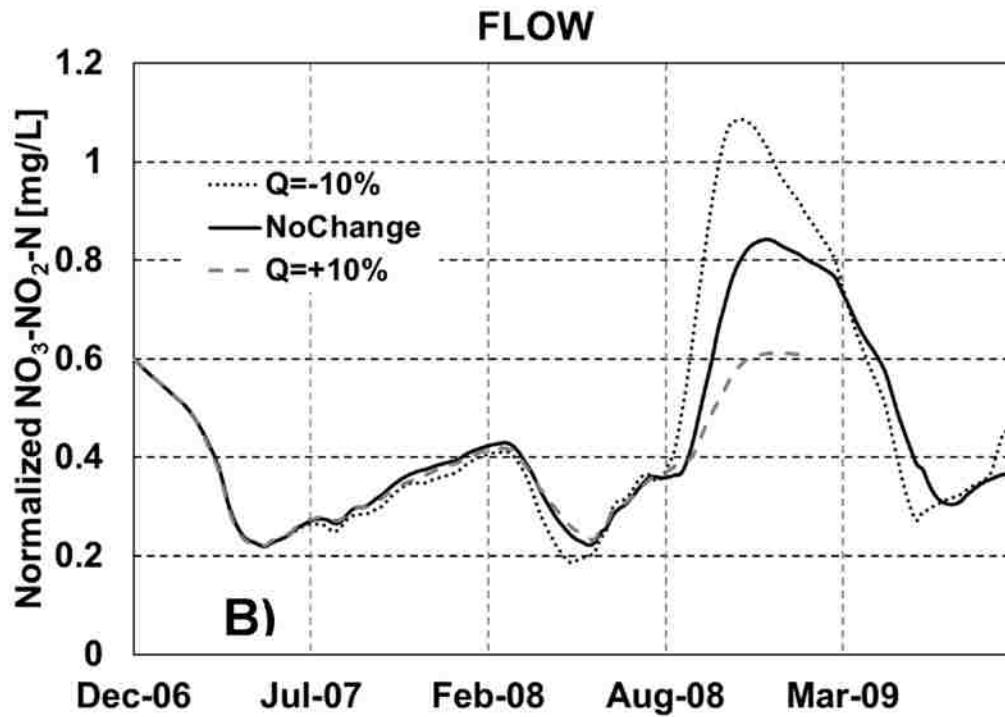
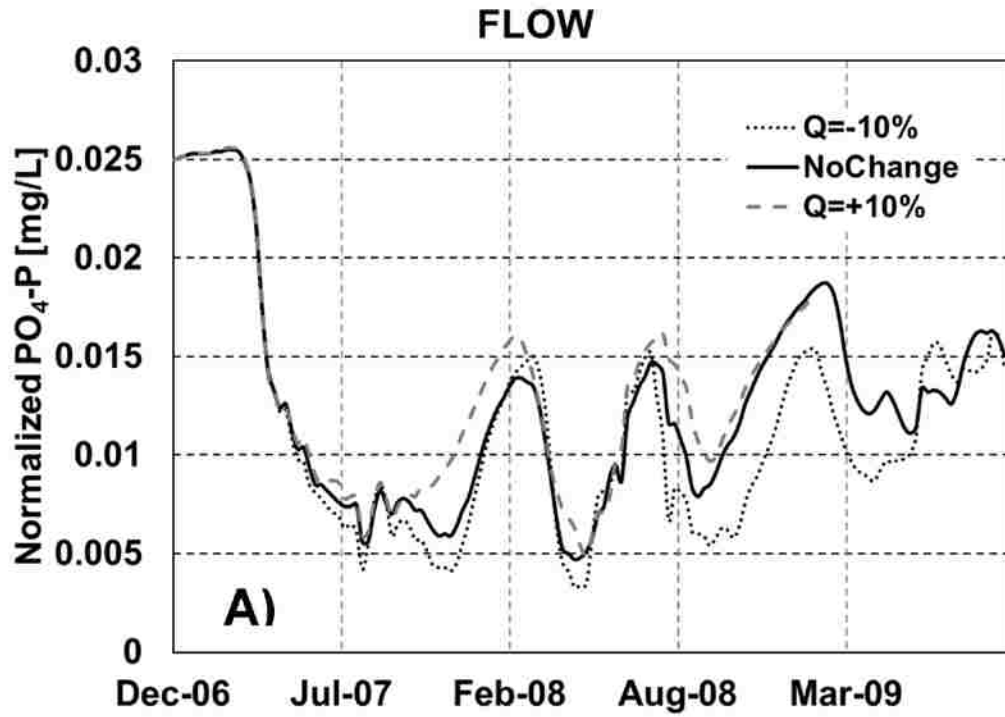


Figure 3-13: A) Total Phosphate Concentration; and B) Total Nitrate-Nitrite Concentration by Adjusting Q_{IN}

The changes in Q_{IN} had a strong impact on total NO_3 - NO_2 -N concentrations (Figure 3-13B). However, this impact was not noticeable until October 2008 when the +10% Q_{IN} simulation produced slightly increased total average NO_3 - NO_2 -N concentrations. This trend continued until the July 2008 when there was no change observed among the three simulations. The largest difference was observed from October 2008 through March 2009 when total average NO_3 - NO_2 -N concentrations were higher and lower for the -10% Q_{IN} and +10% Q_{IN} simulations, respectively, compared to the base model (Figure 3-13B).

The fact that the simulations show little change among the scenarios in the first year might indicate that my initial conditions for the model were incorrect. Since I did not have field data to calibrate the model for in-reservoir nutrient concentrations (though I did have data for inflow concentrations), based on this, the initial concentrations are suspect. As the model proceeds, the in-reservoir nutrient concentrations for the second and third years may be more representative of the system. In these latter two years, total average nutrient concentrations generally respond linearly to changing inflows, with lower flows resulting in higher concentrations.

3.4.3 Changing Nutrients (NC)

3.4.3.1 NC (NO_3 - NO_2)

I simulated increasing and decreasing nitrate-nitrite (NO_3 - NO_2 -N) concentrations by 50%. However, I did not observe significant changes in any of the analysis parameters as a result of these changes (e.g., Figure 3-14). Since Deer Creek is not nitrogen limited, increased inflow concentrations of NO_3 - NO_2 -N have little impact. The simulations with increased and decreased NO_3 - NO_2 -N concentrations did not significantly change the total average algal concentration, the

indicator that would be most sensitive to nutrient levels. This was expected as the limiting nutrient in most of the temperate reservoirs like Deer Creek is phosphorous (Lewis Jr 1996; Wetzel 2001). As there was little observed change, I will not discuss each parameter for the *NC-NO₃-NO₂* scenarios and focus my discussion only on *NC-PO₄-P*.

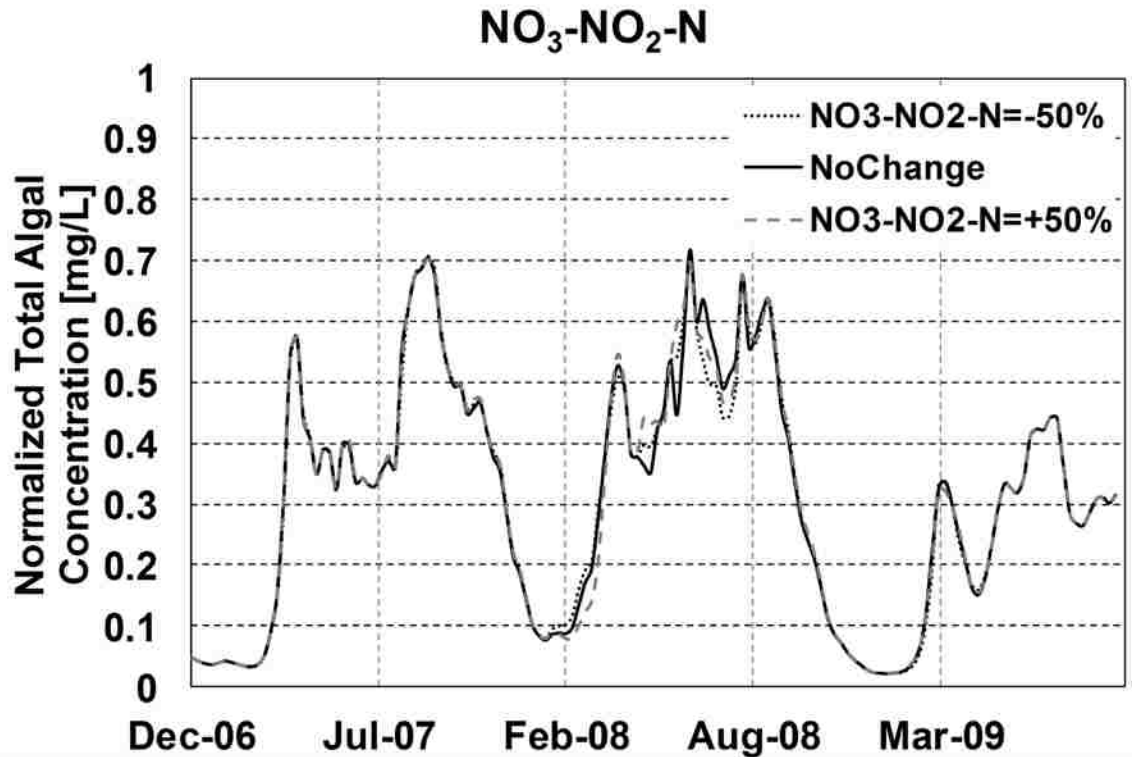


Figure 3-14: Total Algal Concentration by Adjusting *NC-NO₃-NO₂-N*

3.4.3.2 Chlorophyll-a Profiles (*NC-PO₄-P*)

Decreasing and increasing inflow *NC-PO₄-P* concentrations had large impacts on Chl-A vertical profiles. The +50% *NC-PO₄-P* simulation shows the highest concentration of Chl-A in the reservoir for all three summers (Figure 3-15). The concentrations near the thermocline are much higher than the base case and the -50% *NC-PO₄-P* simulations. Increasing amounts of *NC-PO₄-P* into Deer Creek also increase the Chl-A concentration in the reservoir, as Deer Creek

being a temperate reservoir is generally considered phosphorous limited (Lewis Jr 1996; Wetzel 2001). Figure 3-15 shows the predicted Chl-A profiles at the Near Dam sampling point (lentic zone). These predicted Chl-A profiles indicate that there are strong correlations between inflow $NC-PO_4-P$ concentrations and Chl-A concentrations. This correlation is approximately linear, with increased $NC-PO_4-P$ inflow resulting in increased Chl-A concentrations.

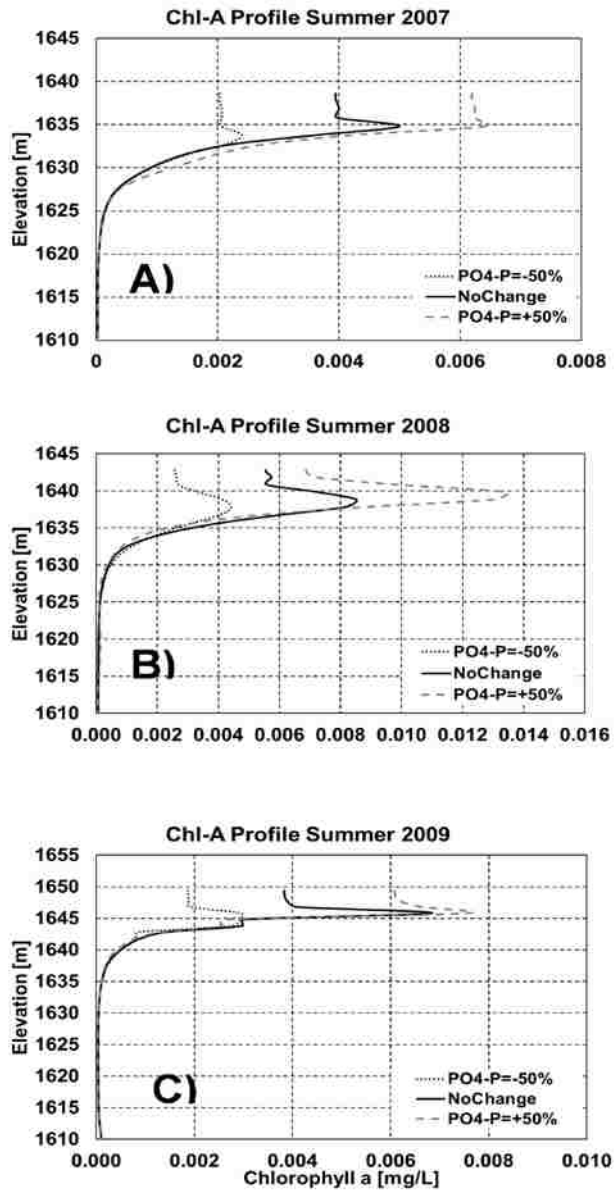


Figure 3-15: Chlorophyll a Profiles at the Near Dam Sampling Point by Adjusting $NC-PO_4$ for: A) Summer 2007; B) Summer 2008; and C) Summer 2009

3.4.3.3 Total Average Algal Concentration ($NC-PO_4-P$)

Increasing and decreasing $NC-PO_4-P$ inflow concentrations demonstrated the most significant changes in total average algal concentrations I observed in the Deer Creek simulations. This was especially evident in the total average algal concentration plots. The computed temporal total average algal concentrations increased during the spring-summer and fall seasons (April-December) when inflow $NC-PO_4-P$ concentrations were increased 50% (Figure 3-16) while there was little to no change during the winter months (January-April). Again these changes are approximately linear with increased $NC-PO_4-P$. I would expect this to continue until $NC-PO_4-P$ is no longer the limiting nutrient, a condition I would not expect to happen in Deer Creek.

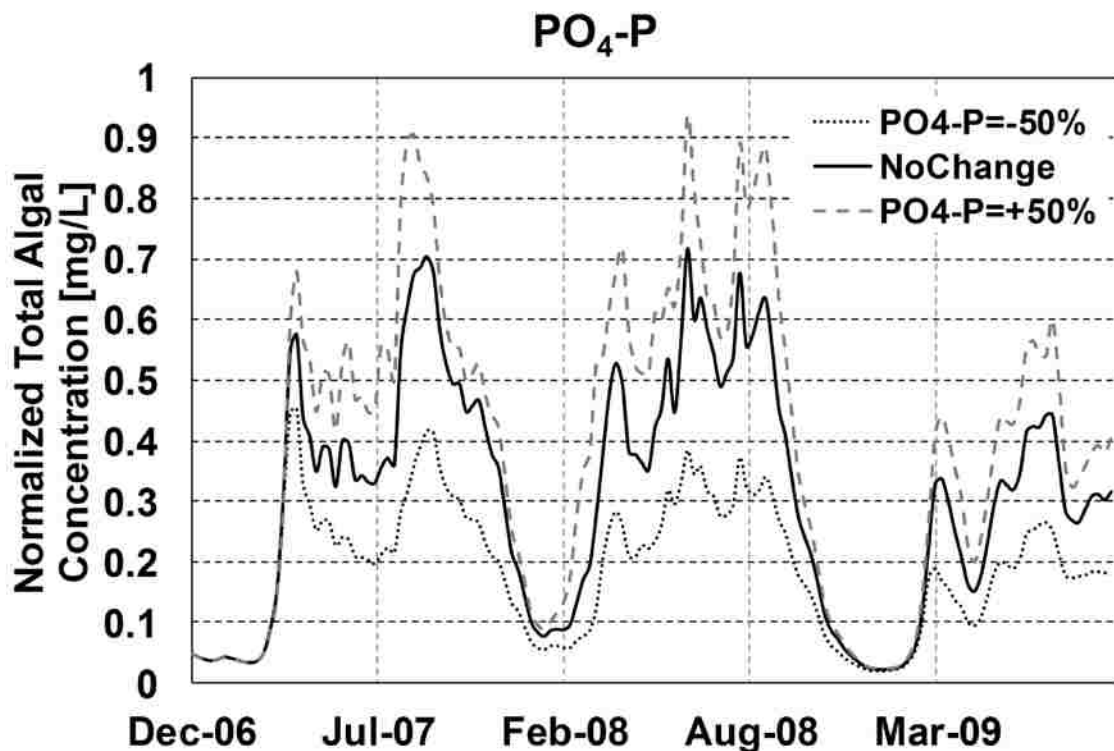


Figure 3-16: Total Algal Concentration by Adjusting $NC-PO_4-P$

3.4.3.4 Total Average DO Concentration (NC- PO_4 -P)

Figure 3-17 shows that changes in PO_4 -P had major impacts on total average DO concentrations during the last two winter and spring seasons (January-May). These impacts are interesting because during the second winter-spring, total average DO concentrations increased when PO_4 -P increased 50% and decreased when PO_4 -P decreased 50% compared to the base simulation. This trend completely switched for the last year of my simulation when the +50% PO_4 -P simulation depleted total DO concentrations and the -50% phosphate simulation increased the total DO concentration in Deer Creek. This was probably due to the very low reservoir levels and resulting short residence times for the water during the middle period. With shorter residence times, inflow of oxygen and outflows from the lower reservoir levels (those with low DO) could have larger impacts on total average DO concentrations. I am attributing this apparent anomaly to these low reservoir conditions with significantly different hydraulic processes.

3.4.3.5 Total Nutrients Concentration (NC- PO_4 -P)

As expected my changes in phosphate inflow concentrations influenced the total average phosphate concentration in Deer Creek (Figure 3-18A). Total average NO_3 - NO_2 -N concentrations also changed with inflow PO_4 -P concentrations. I observed that total average NO_3 - NO_2 -N concentrations decreased for the +50% NC- PO_4 -P simulation and increased for the -50% NC- PO_4 -P simulation for the first twenty two months of my simulation. Like the total DO concentration (NC- PO_4) assessment, the initial trend completely changed and total NO_3 - NO_2 -N concentrations decreased for the +50% NC- PO_4 -P simulation and increased for the -50% NC-

$PO_4\text{-P}$ simulation compared to the base model (Figure 3-18B). Again, I attribute the apparent anomaly to shorter residence times and changed hydraulics in the reservoir.

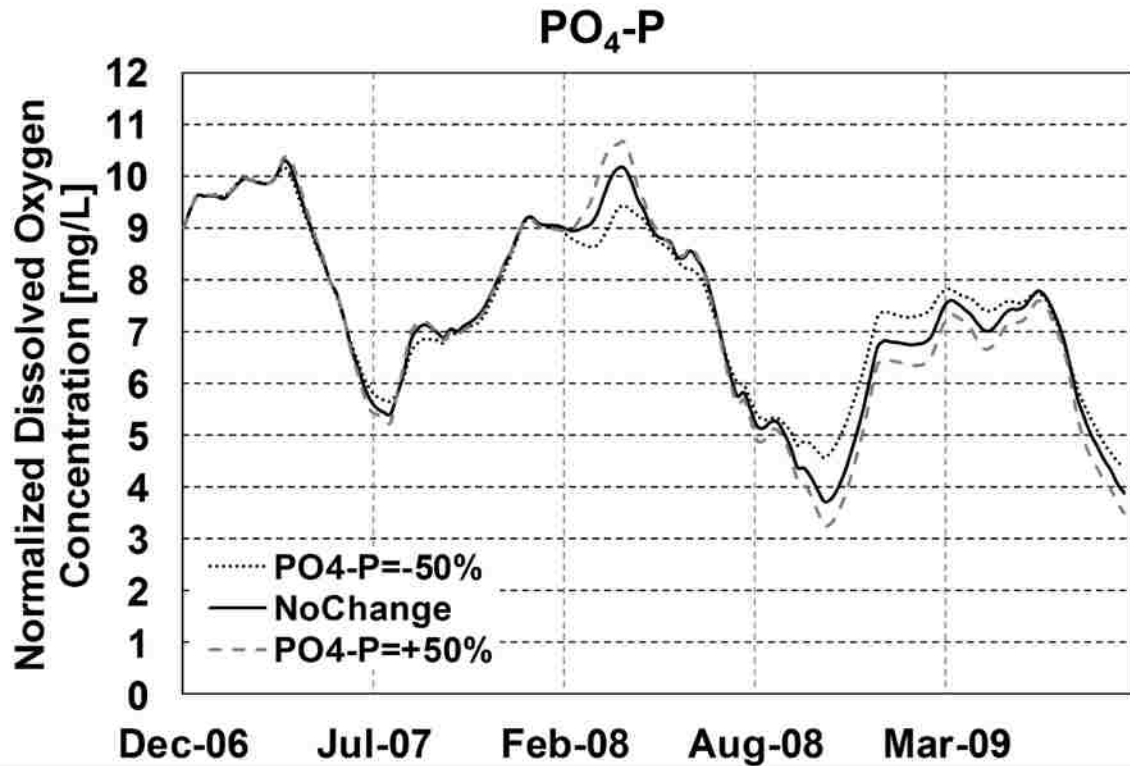


Figure 3-17: Total Dissolved Oxygen Concentration by Adjusting $NC\text{-}PO_4\text{-P}$

3.5 Deer Creek-Conclusions

I systematically assessed the sensitivity of various indicators of reservoir water quality to potential GCC change effects from three environmental variables using a calibrated W2 water-quality and hydrodynamic model. My findings indicate that Deer Creek Reservoir is sensitive to the magnitude of climate changes predicted by IPCC (2007) and Bates *et al.* (2008). Changes in T_{AIR} showed significant effects on Deer Creek during the spring and summer months. Increasing T_{AIR} caused higher water temperatures which influenced the stratification of the reservoir.

Similar to Stefan *et al.*, (1998) and Livingstone (2003), my simulations indicated that increases in T_{AIR} will cause longer stratification periods, shorter ice-cover periods, and stronger stratification in the reservoir. The increased T_{AIR} also resulted in increased total algal concentration, decreased DO concentrations, decreased flows, and earlier peak nutrient concentrations. This could cause larger and more severe anoxic zones in the reservoir which will deplete the health of the water and could impact water treatment facilities.

Inflow volume changes also influenced the reservoir. In particular, decreased inflow caused increased total algal concentrations. These changes can cause the proliferation of harmful algal groups such as blue-green (cyanobacteria) blooms that may affect human health as Miller (2008), Paerl and Huisman (2009), and Erturk (2012) suggested in their studies.

Phosphate produced the most significant effects in time-varying total average algal concentrations in the reservoir. The simulations support that phosphate is the limiting nutrient for algal growth in Deer Creek as reported for other temperate reservoirs (Lewis Jr 1996; Wetzel 2001). Increased inflow phosphorus concentrations could result from changes in land use of the watershed surrounding the reservoirs or the building of upstream dams. Simulated changes of NO_3 - NO_2 - N concentrations had little or no impact on the reservoir's total algal concentrations.

Further study of this topic may include extending the model to time period greater than five years (see Chapter 5) to analyze these trends over a longer period of time because my simulation period included extreme conditions in Deer Creek that appeared to affect some of my results (PRWUA 2009; Chilton 2011). My simulation results could be altered by the fluctuation of hydraulic retention times that the reservoir experimented and could influence my predictions.

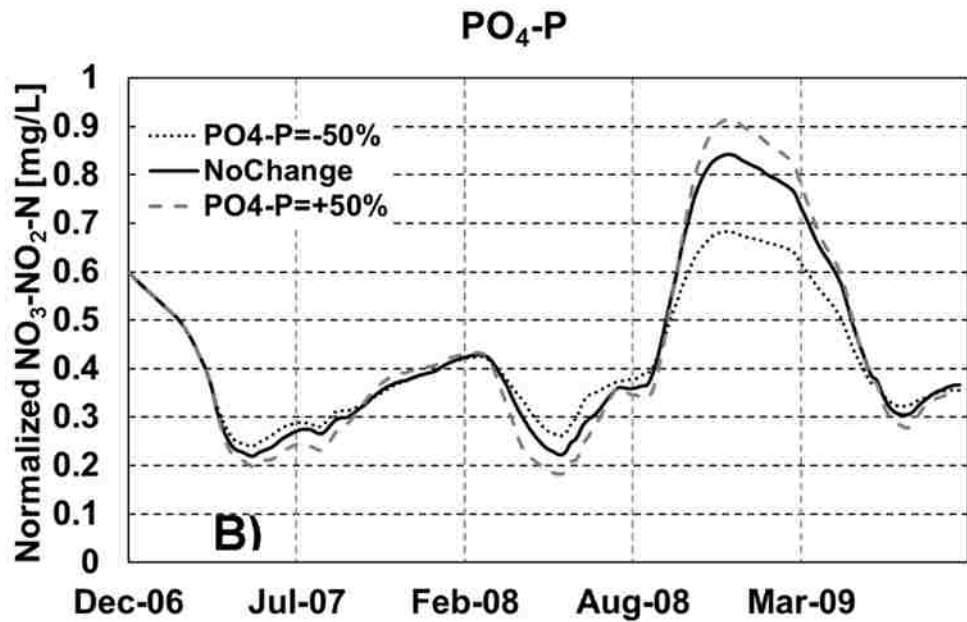
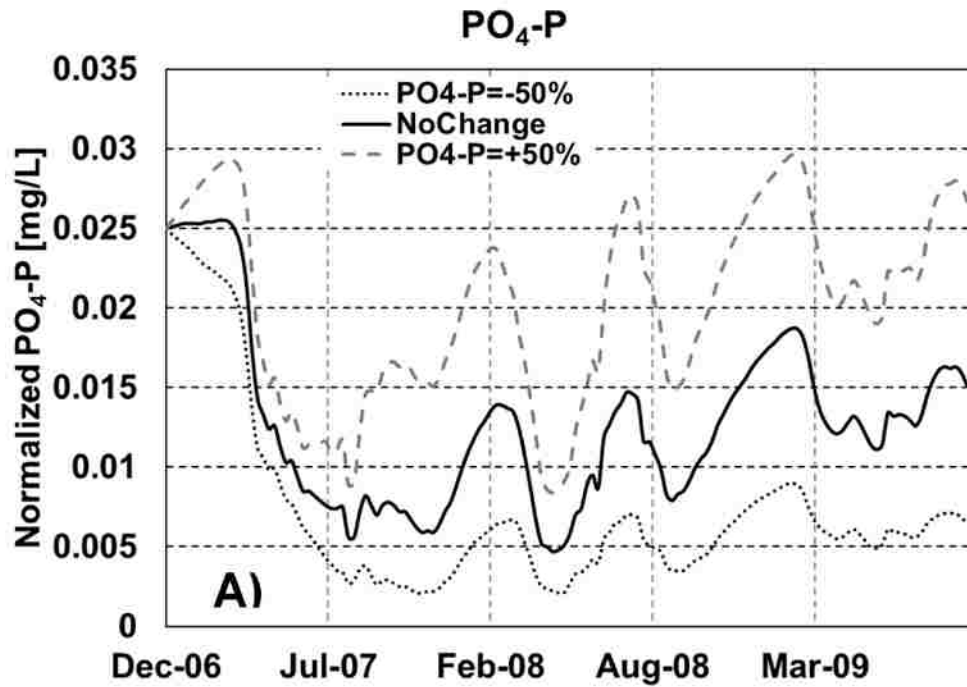


Figure 3-18: A) Total Phosphates as P Concentration; and B) Total Nitrate-Nitrite as N Concentration by Adjusting Inflow $NC-PO_4-P$ 50%

4 TROPICAL AGUAMILPA RESERVOIR

In this section, I described the study area, methods, and results for the Aguamilpa Reservoir. I used this reservoir to evaluate GCC effects in a tropical reservoir. This reservoir is located in an area where the obtaining of field data and technology sources are limited compared to reservoirs located in temperate regions such as Deer Creek.

4.1 Aguamilpa Study Area and Description

The Santiago River is one of the most important rivers in Mexico and it is part of the hydrologic region known as Lerma-Chapala-Santiago. This region receives urban and industrial wastewater effluents from the states of Jalisco and Nayarit (Figuroa *et al.* 2007). The Aguamilpa Reservoir is located in the state of Nayarit, Mexico along Huaynamota River and Santiago River which has fifteen dams along its length, making it one of the most developed rivers in Mexico (Figure 4-1). The upstream dams, La Yesca, El Cajon and Santa Rosa, create a natural depuration of the contaminated waters in Santiago River due to depression and sedimentation. Aguamilpa has a complete mixing period once per year in the water column which makes it a warm-monomictic-tropical reservoir (Wetzel 2001; Kalff 2002). The construction of the Aguamilpa dam was concluded in 1994. Construction was primarily for power generation and represented one of the most important hydroelectric projects constructed by the Mexican Federal Government in the 90's and was funded by the World Bank. Aguamilpa

has had a positive impact in the region by improving the community's productivity, mainly in the indigenous area (Figueroa *et al.* 2007). The reservoir is also used for flood control, irrigation, and fishing. The rock filled dam is 187 m high and 642 m long with a maximum storage capacity of 6,950 Mm³ at 232 m above sea level (CFE 1991; Marengo 2006; Obregon 2008).

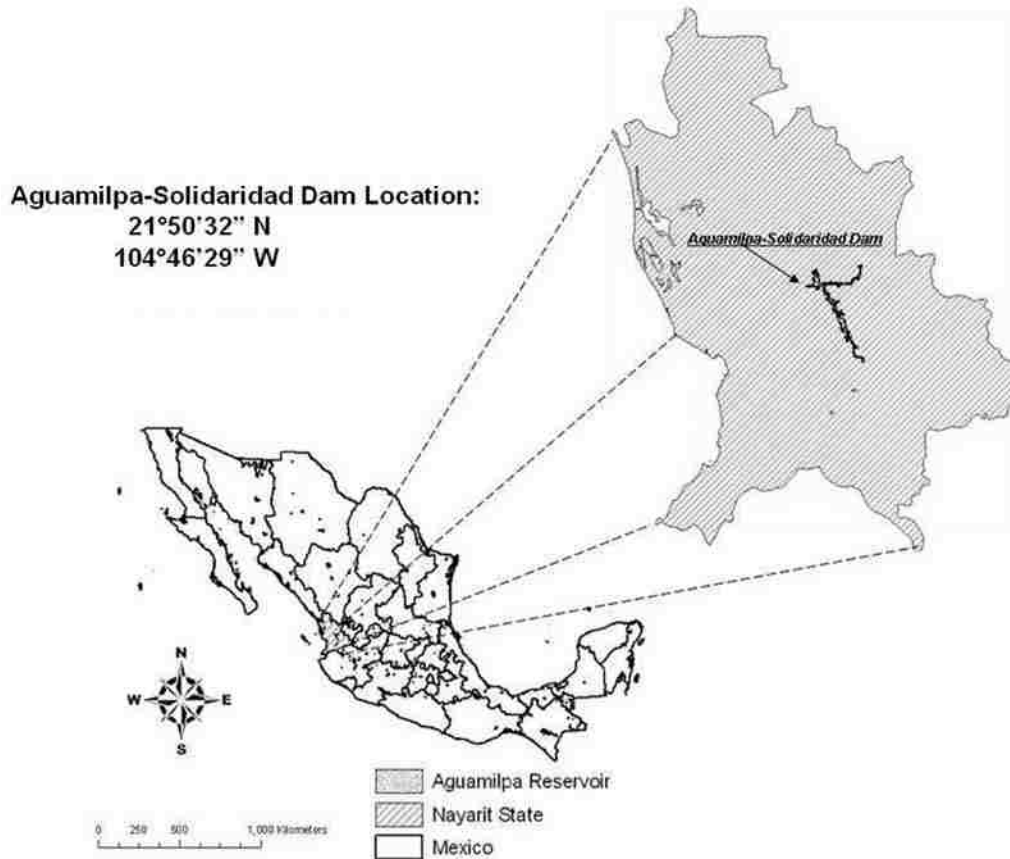


Figure 4-1: Location of the Aguamilpa Reservoir and Dam, Nayarit, Mexico

Table 4-1 summarizes the volumetric characteristics of Aguamilpa. There are three seasons that describe the climatological and hydrological characteristics in the region where Aguamilpa is located. These seasons are: a warm dry season that goes from March through June, a rainy season from July through October and a relatively cool dry season from November

through February (Navarro-Rodríguez *et al.* 2004; García-Cabrera 2007; Rangel-Peraza *et al.* 2009).

Table 4-1: Volumetric Characteristics of Aguamilpa Dam and Reservoir

<i>Characteristic</i>	<i>Value</i>
Long term mean flow	220 m ³ /s
Normal maximum water level	232 m
Normal minimum water level	190 m
Gross head	147.5 m
Reservoir volume (at 232 m)	6,950 Mm ³
Reservoir area (at 232 m)	128 Km ²
Mean depth (volume/area)	54.3 m

4.2 Methods-Tropical

Similar to the Deer Creek assessment, I used a CE-QUAL-W2 (W2) model to evaluate the effects of climate change on Aguamilpa. The geometry of this reservoir is deep and the long-narrow waterbody makes it suitable to be modeled with W2 (Cole and Wells 2006). I developed the W2 model for Aguamilpa for the 2007-2009 period where I have data available as a result of a directed research project and based on a previous model built for the reservoir (Obregon 2008; Obregon *et al.* 2011). Data to support this model were obtained and collected from Mexican government agencies and field work. To avoid effects produced by initial conditions during the beginning of the simulation and to focus on impacts caused by changed boundary condition, I extended the model nine more years, resulting in a simulation of twelve years. I developed the W2 model and performed the evaluation of GCC effects in Aguamilpa in four main steps: 1) Model inputs, 2) Calibration, 3) Climate change assessments, and 4) Analysis of results.

4.2.1 Tropical Water Quality Model Approach

4.2.2 Tropical Model Inputs

The main components for the Aguamilpa W2 model included: a geometric computational grid, meteorological boundary conditions, initial conditions, boundary conditions and distributed input files. The Aguamilpa geometric computational grid (Figure 4-2 A, B and C) was based on reservoir bathymetry simplified for two-dimensions and the methodology described by Obregon (2008). The bathymetry included three main branches, 103 segments (with ~1000 m length and ~1500 m width), and 170 layers of 1 meter height.

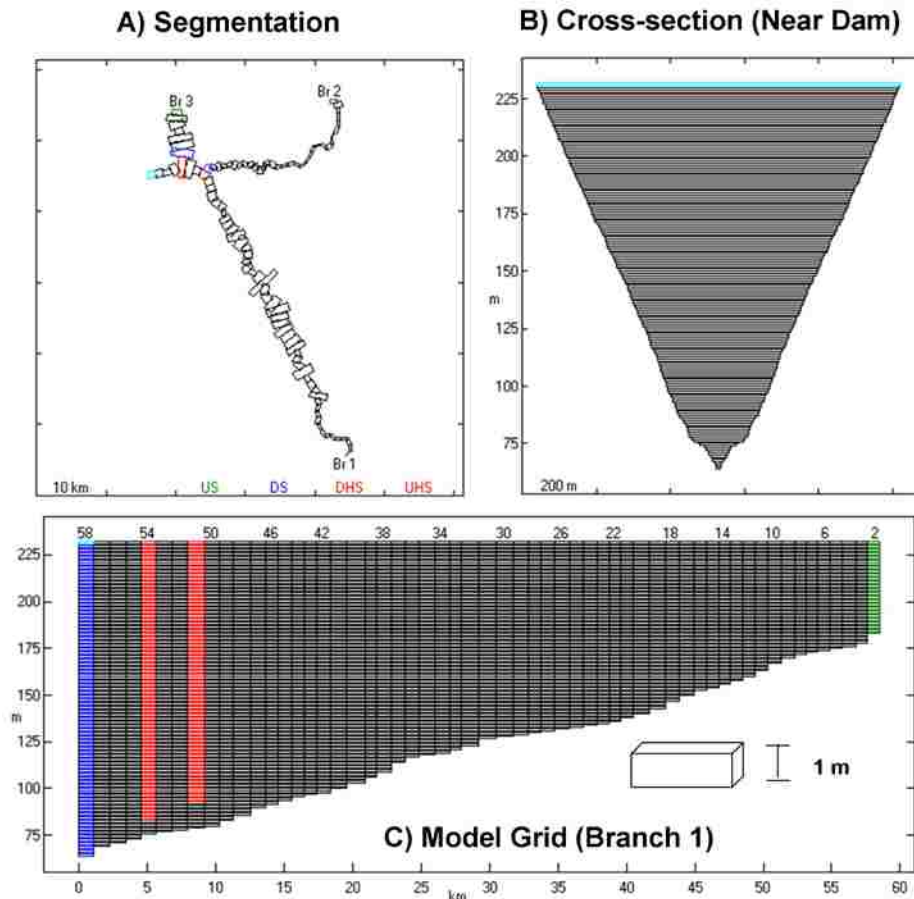


Figure 4-2: A) Aguamilpa W2 Model Segmentation; B) Cross-Section at Near Dam Sampling Site (Santiago River); and C) Example Model Grid for Branch 1 (Santiago River)

Meteorological boundary conditions included hourly T_{AIR} , dew point temperature, wind direction and speed, cloud cover and solar radiation data from local climatological stations shown in Figure 4-3 (Fabricio Galindo-Copado, Departamento de Hidrometria, CFE Nayarit, personal communication, November 5, 2009). I obtained this 2007-2009 data from the Mexican Federal Electricity Commission (CFE). The model initial conditions were based on reported characteristics in CFE (1991), Obregon (2008), and observed values. Boundary conditions included water temperature, hydrologic inputs, and inflow water quality both as known point sources (streams and rivers) from upstream and/or downstream points of Aguamilpa. The distributed input files were established using measured data and computed values, and they represent ungauged data along the reservoir such as direct precipitation, groundwater, unmeasured nutrient loads, and unmeasured inflows from surrounding tributaries or overland flow (Cole and Wells 2006; Cole and Wells 2008; Debele *et al.* 2008). The entire simulation period was twelve years. I built the model using three years of data but since the reservoir's residence time is 432 days, essentially a spin up period, any changes to the reservoir boundary conditions will not be significant until after this period. This spin up period allows the model to no longer be under the influence of initial conditions as it responds to the specified inflow and meteorological forcing for each selected scenario. Based on this spin up period and reservoir's residence time, I quadrupled the three-year model making it a twelve-year simulation to avoid having wrong interpretation of model's results. This assumed that each three year period has the same temperature, precipitation, etc. patterns as the first three years. This allows the changed boundary conditions (e.g., inflow/ outflow, nutrients) to become evident in the reservoir in the latter years.

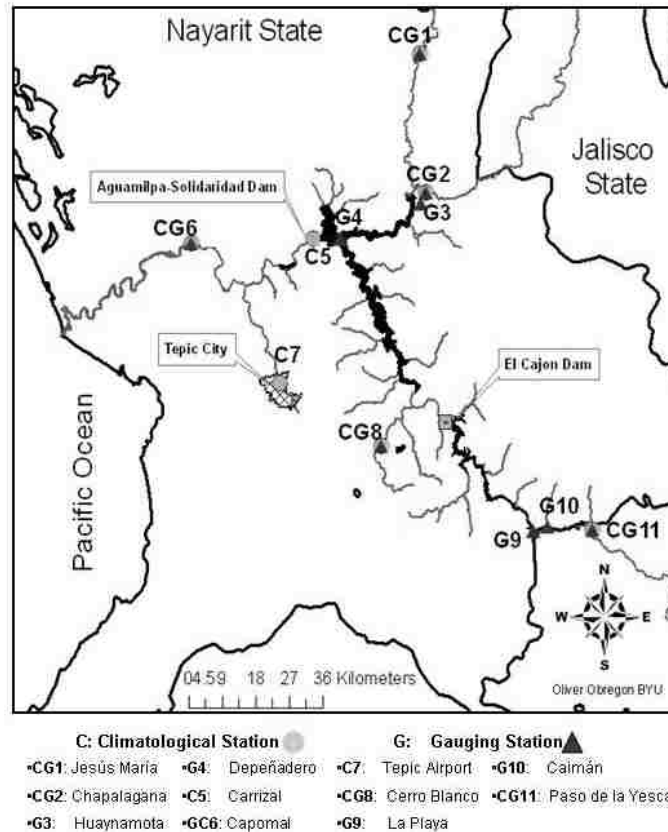


Figure 4-3: Location of the Climatological and Gauging Stations Used as Inputs for the Aguamilpa W2 Model

4.2.3 Tropical Model Calibration

I used water balance, temperature, total dissolved solids (TDS), dissolved oxygen (DO), and chlorophyll a (Chl-A) data to calibrate the Aguamilpa model. First, I calibrated the model to measured hydrothermal conditions by adjusting the coefficients recommended by Zison (1978) and Cole and Wells (2006). Table 4-2 shows the calibration coefficients used for Aguamilpa. Next, I used observed water temperature and water quality data collected by CFE, the National Water Commission (CONAGUA), the Center for Research and Applied Technology in Jalisco (CIATEJ) and the BYU Research Group for further calibration (Figure 4-4). TDS data were used to confirm hydrothermal calibration because TDS were the only available data with

characteristics similar to salinity, which is often used as an indicator. Then, I used observed DO and Chl-A data for final calibration. According to Cole and Wells (2006) previous W2 models have shown that DO and phytoplankton are much better indicators of proper hydrodynamic calibration than either salinity or temperature. This is because DO and phytoplankton gradients are more spatially diverse in the water column. This spatial diversity also makes DO and phytoplankton problematic for initial calibration but good for final calibration steps.

Table 4-2: Calibration Coefficients and Values Used for the Aguamilpa Reservoir

<i>Kinetic Coefficients</i>	<i>Calibration Value</i>
Chezy bottom friction factor ($m^{1/2}/s$)	70
Horizontal eddy viscosity (m^2/s)	1.0
Horizontal eddy diffusivity (m^2/s)	1.0
Light extinction coefficient for background value (m^{-1})	0.42
Algal growth rate (day^{-1})	0.73 ^a , 1.34 ^b , 0.50 ^c
Algal respiration rate (day^{-1})	0.04
Algal excretion rate (day^{-1})	0.04
Algal mortality rate (day^{-1})	0.073 ^a , 0.134 ^b , 0.050 ^c
Algal settling rate (day^{-1})	0.20 ^a , 0.10 ^b , 0.050 ^c
Light saturation intensity at maximum photosynthetic rate (W/m^2)	86 ^a , 24 ^b , 36 ^c
Algal half-saturation for phosphorous limited growth (mg/L)	0.047 ^a , 0.050 ^b , 0.030 ^c
Algal half-saturation for nitrogen limited growth (mg/L)	0.014 ^a , 0.014 ^b , 0.000 ^c
Ammonium nitrification rate (day^{-1})	0.12
Nitrate denitrification rate (day^{-1})	0.03
Sediment oxygen demand ($g\ m^{-2}\ day^{-1}$)	0.2-0.7

^a Diatoms, ^b Greens, ^c Cyanophyta

Field algae data from in Aguamilpa were not available making this deficiency the main limitation of the tropical model. However, I estimated inflow algae data based on a previous studies prepared by Garcia-Cabrera (2007) and Ibarra-Montoya *et al.*,(2010) for Aguamilpa and from other studies developed in Mexico (López and Dávalos-Lind 1998) or for other tropical

lakes or reservoirs (Lind *et al.* 1992; Calijuri *et al.* 2002; Reddy and ebrary 2005) and using empirical formulations.

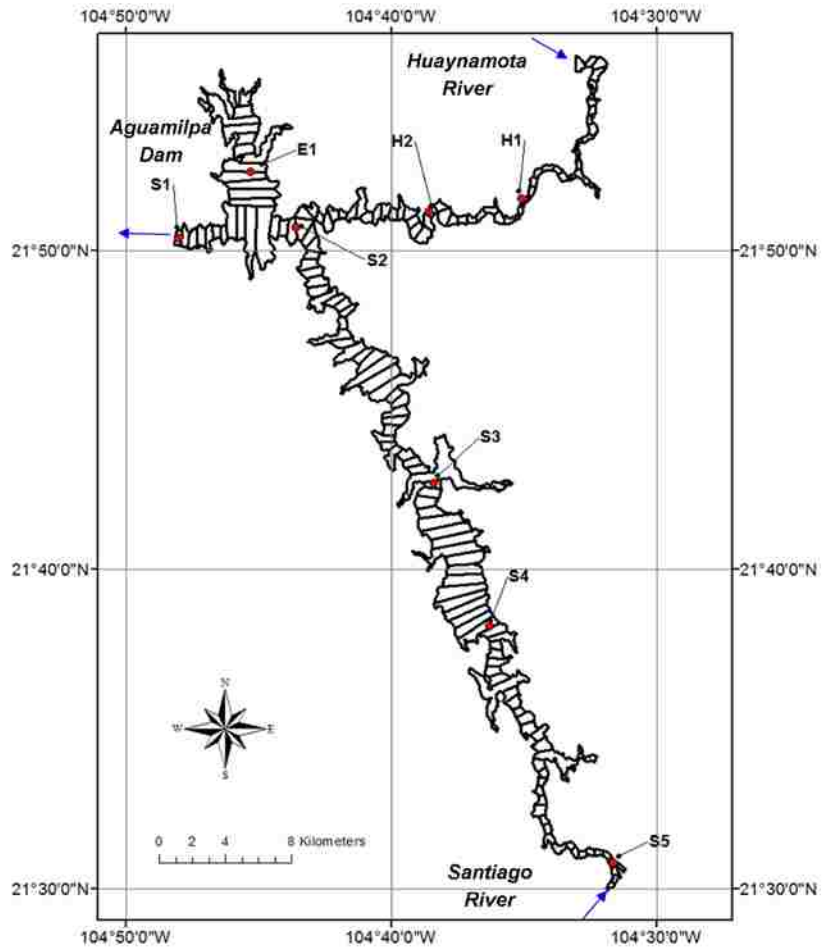


Figure 4-4: Sampling Sites Used to Calibrate the Aguamilpa W2 Model

I used the same statistical global absolute mean error (AME) measure implemented for the Deer Creek model (Hanna *et al.* 1999) to evaluate Agumilpa's model calibration of four parameters. These parameters were: water temperature, TDS, DO and Chl-A. The global AME values for water temperature were 0.71°C which considered the comparison between modeled and observed values from all the sampling sites. Figure 4-5 shows examples of water temperature calibration from the near dam sampling site (lentic zone) including two stratification

periods (Figure 4-5A and C) and the beginning of the mixing period (Figure 4-5B). The global AME for TDS (Figure 4-6), DO (Figure 4-7) and Chl-A (Figure 4-8) were 24.0 mg/L, 1.2 mg/L and 4.5 $\mu\text{g/L}$, respectively. Global AME values for Chl-A are high due to the lack of algae data. Nevertheless the Chl-A calibration is adequate to perform the evaluation and analysis of GCC changes in Aguamilpa.

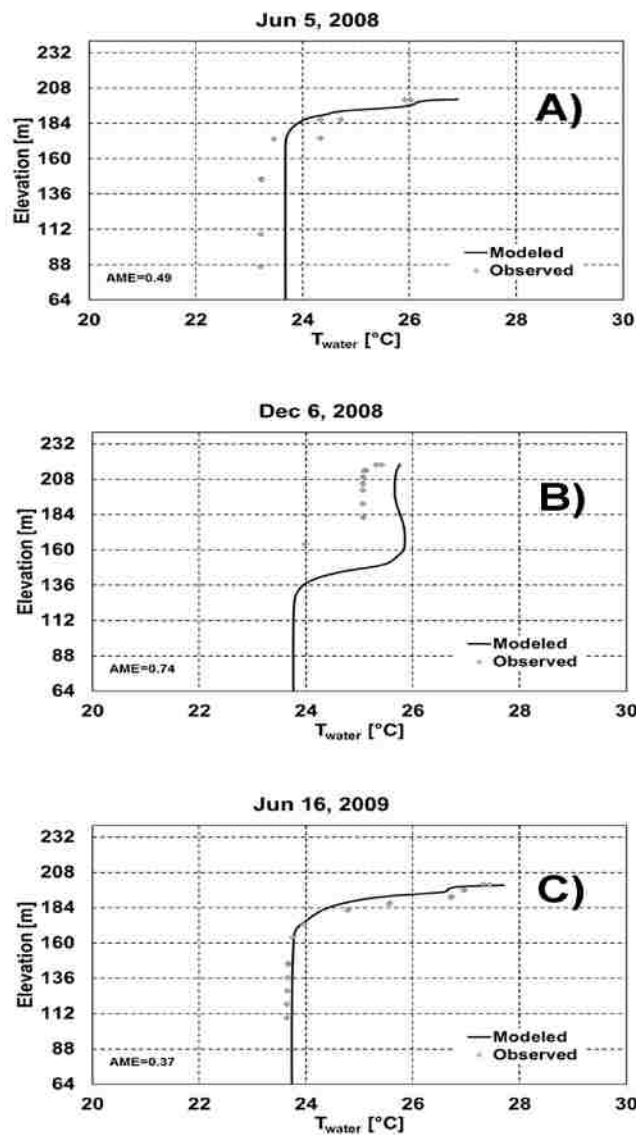


Figure 4-5: Example Water Temperature Calibration From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Initial Mixing Period (December 2008) and C) Summer Stratification in 2009 (Low Reservoir)

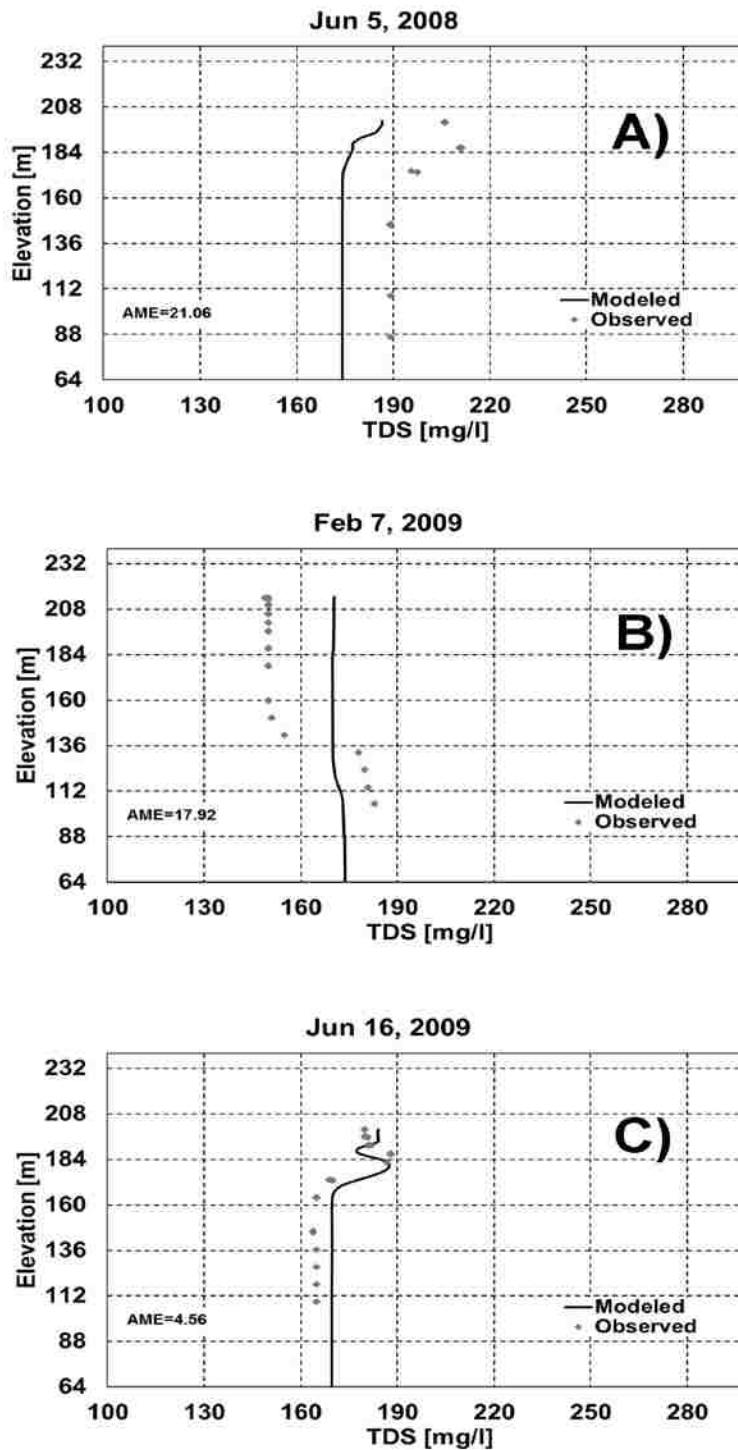


Figure 4-6: TDS Calibration From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Mixing Period (February 2009) and C) Summer Stratification (June 2009)

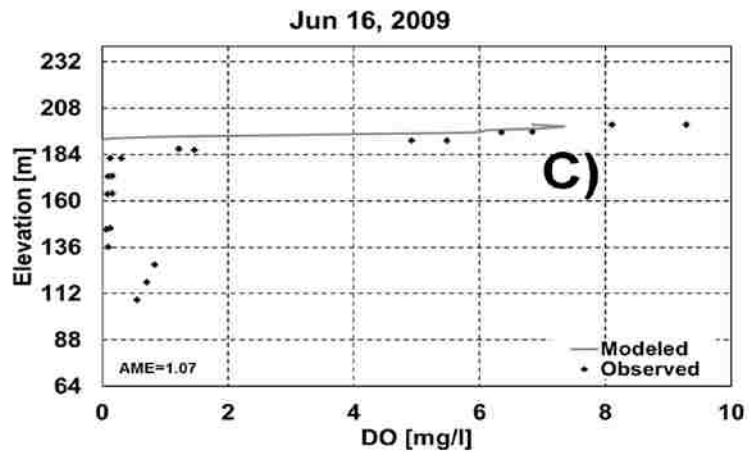
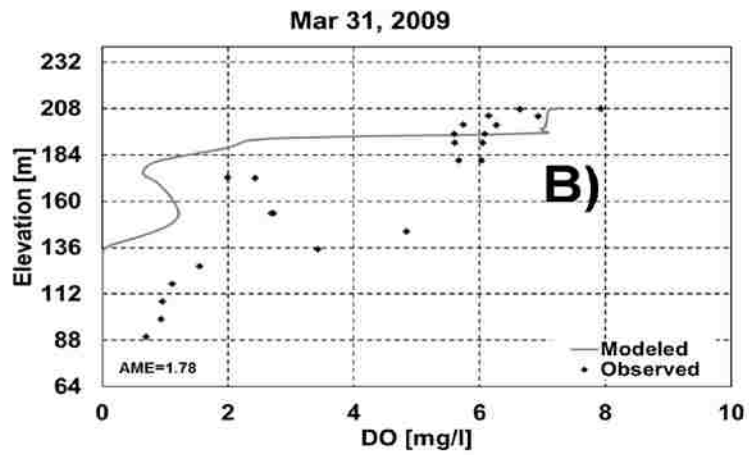
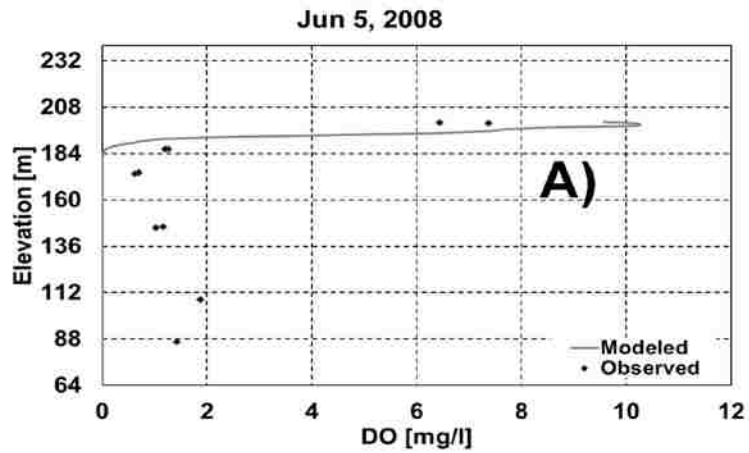


Figure 4-7: DO Calibration Plots From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Spring Stratification (March 2009) and C) Summer Stratification (June 2009). Note: Oxycline is Observed all the Time in the Reservoir

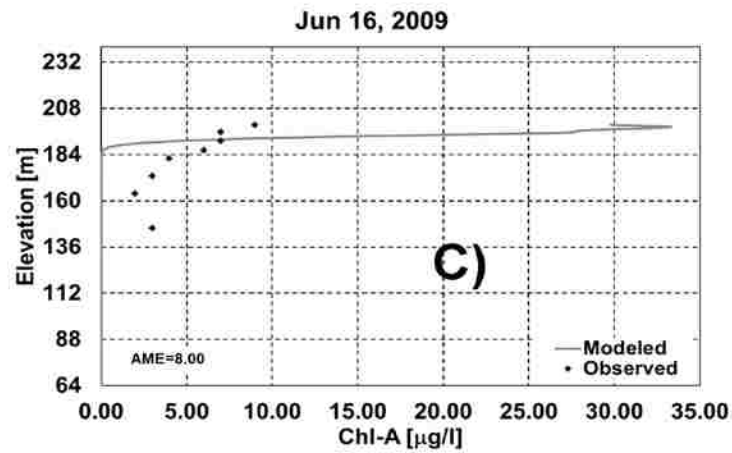
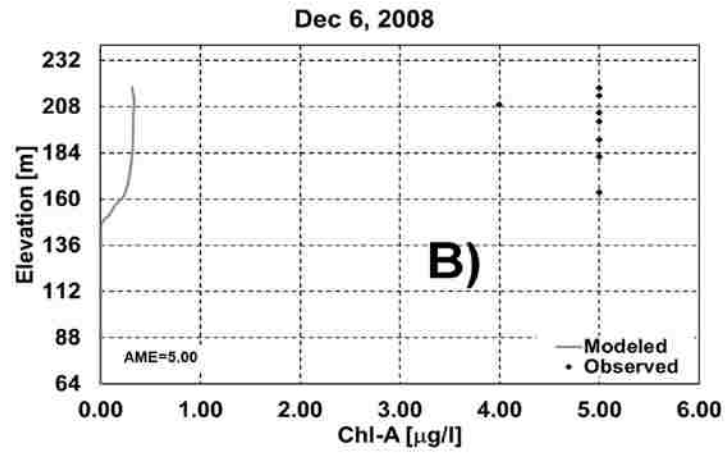
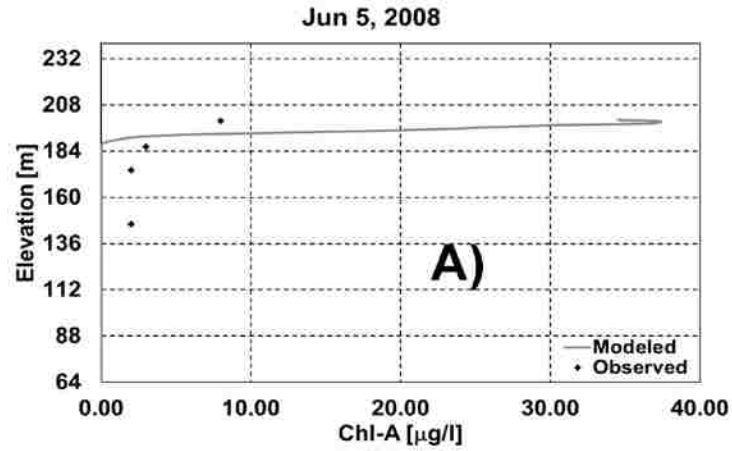


Figure 4-8: Chl-A Calibration Plots From the Near Aguamilpa Dam Sampling Site for: A) Summer Stratification (June 2008), and B) Winter Mixing Period (December 2008) and C) Summer Stratification (June 2009)

4.3 Methods-Tropical Aguamilpa

4.3.1 Assessment Methods and Tools

Similar to Deer Creek, I looked at global or total reservoir changes over the simulation time period to minimize the influence of any local variations. To overcome the limitations induced by local variations in the analysis, I used the same two plot types used for Deer Creek to analyze the entire Aguamilpa Reservoir over time: total normalized concentration (Equation 3-2 in Section 3.3) and delta temperature/stratification plots (Equation 3-3, Section 3.3). These plots show how in-reservoir water quality is affected by the projected boundary or forcing function changes due to GCC.

Unlike the preliminary analysis for Deer Creek reservoir, I also used five water quality parameters modeled in the hourly discharges downstream from the Aguamilpa dam as endpoints. These were total algal concentration, DO, and TDS concentrations. These plots allow evaluation of GCC impacts that might occur downstream from the dam.

4.3.2 Scenarios and Parameters

Once the W2 model was calibrated, I assessed the climate change effects in Aguamilpa by modifying meteorological, hydrological, and water quality conditions based on GCC estimates projected for Latin America (IPCC 2007) and Mexico (Conde *et al.* 2008). This included decreasing and increasing the T_{AIR} by 3 °C, changing inflows to represent low (-10%) and high (+10%) flow conditions and decreasing and increasing the nutrients, phosphate (PO_4 -P) and nitrate-nitrite (NO_3 - NO_2 -N), by 50%. The nutrient changes could be caused by building upstream dams (El Cajon and La Yesca) or expansion of urban areas in the surrounding

watersheds. Each of these changes was made individually and compared to my calibrated base model.

4.4 Results-Tropical Reservoir

First, I compared the impacts from GCC induced changes using Chl-A profiles. Next I present analyses using the total normalized algal concentrations and other total normalized parameters: DO, TDS, total PO₄-P and total NO₃-NO₂-N. As presented in Section 2, the total normalized parameter concentration is the total parameter mass in the reservoir divided by the total water volume (Equation 3-2). This normalization was done to reduce potential impacts resulting from seasonal drawdown in Aguamilpa. Total parameter concentration also allowed me to compare changes in the entire reservoir, and not just on focused zones where the reservoir presents higher algae growth than others.

4.4.1 Changing Air Temperature in Aguamilpa (T_{AIR})

4.4.1.1 Chl-A Profiles (T_{AIR})

The Chl-A profiles based on the air temperature simulations are shown in Figure 4-9. These profiles are from the deepest part of the Aguamilpa reservoir near the dam. By adjusting T_{AIR} -3 °C and +3 °C, the Chl-A concentration decreased for both simulations during June 2009 compared with the No-Change simulation (Figure 4-9A). However, for the June 2011 profile (Figure 4-9B), I observed that Chl-A concentration increased, reaching a peak value of approximately 31 µg/L when T_{AIR} was increased +3 °C and decreased to 25 µg/L for T_{AIR} -3 °C relative to the highest observed Chl-A concentration peaks in the base model (29 µg/L). Also, the Chl-A concentration peaks, for the June 2015 profile (Figure 4-9C), increased when T_{AIR} was

increased/decreased 3°C compared to the No-Change simulation. It is important to note that the three Chl-A peaks were observed at three different reservoir elevations. This indicates that T_{AIR} changes have a more direct effect on the reservoir's volume, influencing the location of algae in the water column rather than just impacting total algae concentration in the reservoir. Based on these results, I compared average Chl-A concentration for each simulation and I noticed a general Chl-A increase when T_{AIR} was decreased -3°C and decrease for the +3°C T_{AIR} simulation compared to the base model.

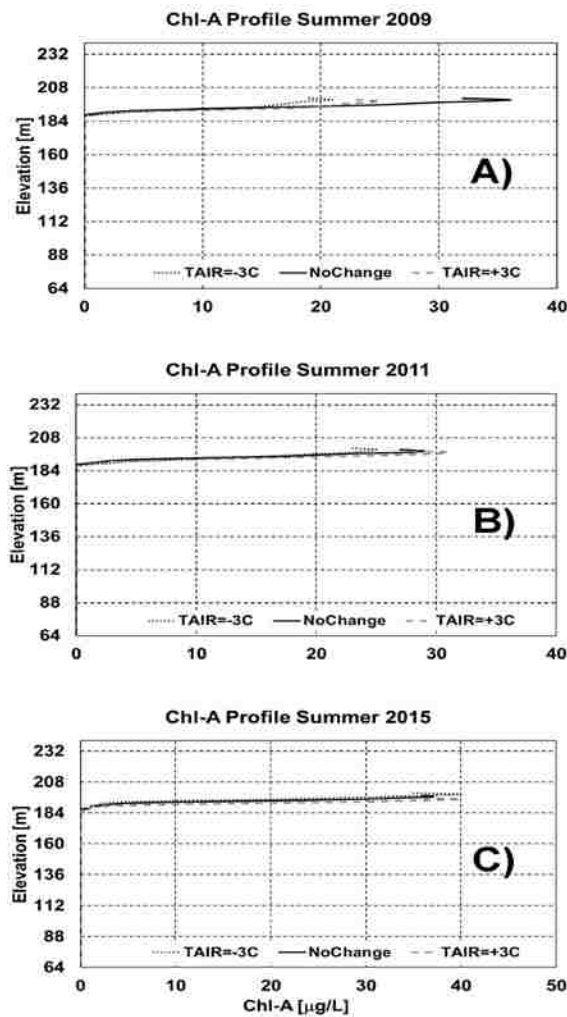


Figure 4-9: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting T_{AIR} for A) June 2007; B) June 2011; and C) June 2015

These Chl-A profiles did not conclusively assess T_{AIR} effects in Aguamilpa, and indicated that the use of other descriptive indicators were required (e.g., normalized algal concentration). Using total normalized algal concentrations plots let me analyze GCC effects in all zones of the reservoir (lotic, transitional and lentic) throughout the simulation period and rather than a single site at a specific time.

4.4.1.2 Total Algal Concentration (T_{AIR})

The total algal concentrations from the first two simulated years (2007-2008) were not considered for evaluating GCC effects in Aguamilpa because the reservoir has an average hydraulic residence time of 432 days which means that the results of the first two years of the simulations are significantly influenced by initial conditions and do not reflect the changed forcing functions or boundary conditions. For the next ten simulated years, I did not observed changes in the total algal concentration during the winter/cold dry season (December-March) when T_{AIR} was changed ± 3 °C (Figure 4-10). The main observed change in total algal concentration by adjusting T_{AIR} occurred in the time of appearance of peak concentration. I observed that the first total algal concentration peak appeared earlier in each spring season when T_{AIR} was increased 3 °C and emerged later in the spring for the -3 °C T_{AIR} simulation compared with the base model. During the beginning of the warm dry season (March-April) of each year, total algal concentration increased for the +3 °C T_{AIR} simulation and decreased when T_{AIR} was decreased -3 °C. This same trend was observed when the rainy season ends and the cold dry season starts (July-November), right before the reservoir starts turning over (November-December). An opposite trend occurred before the rainy season starts (May-June) because total algal concentration increased for the -3 °C T_{AIR} simulation and decreased for the +3 °C T_{AIR} simulation. Figure 4-11 shows the observed trends occurring in Aguamilpa. In this plot I

present the difference of the total algal concentration among the $-3\text{ }^{\circ}\text{C}$ T_{AIR} simulation and $+3\text{ }^{\circ}\text{C}$ T_{AIR} simulation and the base model. By plotting the changes or deltas from the base case, deviations are more clearly seen and evaluated. Generally, the trend observed in Figure 4-11 indicates that total algal concentration increased when T_{AIR} was increased $3\text{ }^{\circ}\text{C}$ and decreased when T_{AIR} was decreased $3\text{ }^{\circ}\text{C}$ with some exceptions occurring early in the rainy season (before June) when the opposite trend was observed. These findings suggest that total algal concentration in Aguamilpa changes due to T_{AIR} changes but are small.

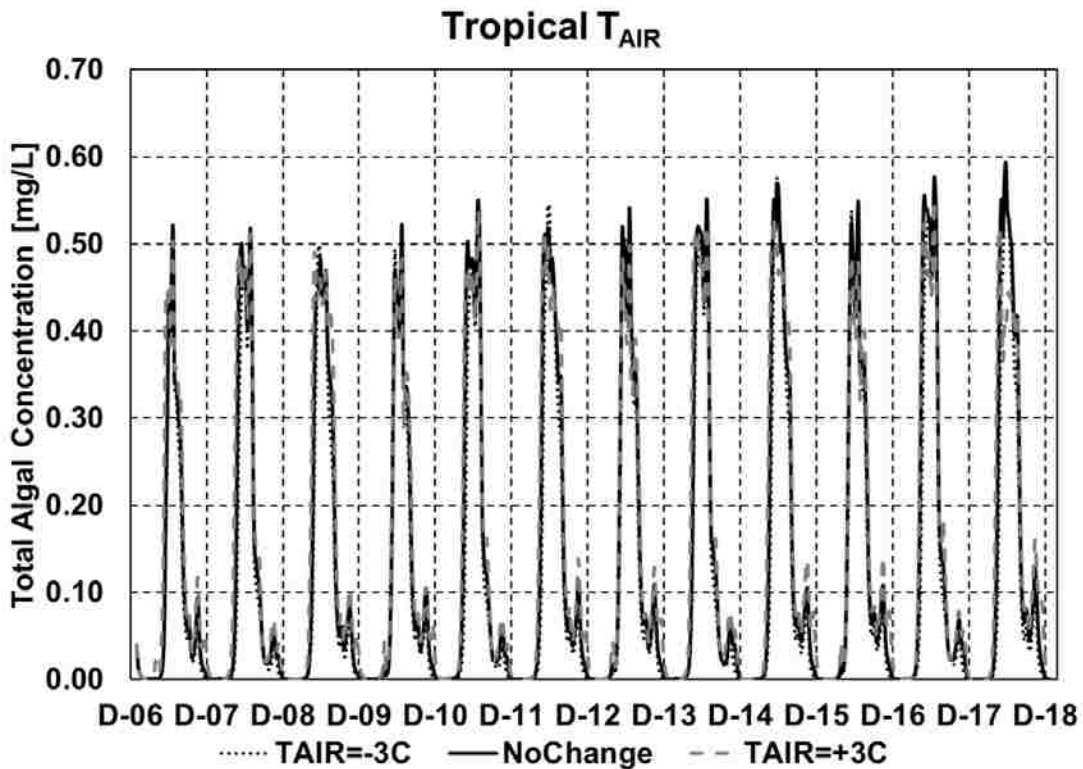


Figure 4-10: Total Algal Concentration in Aguamilpa Reservoir by Altering T_{AIR}

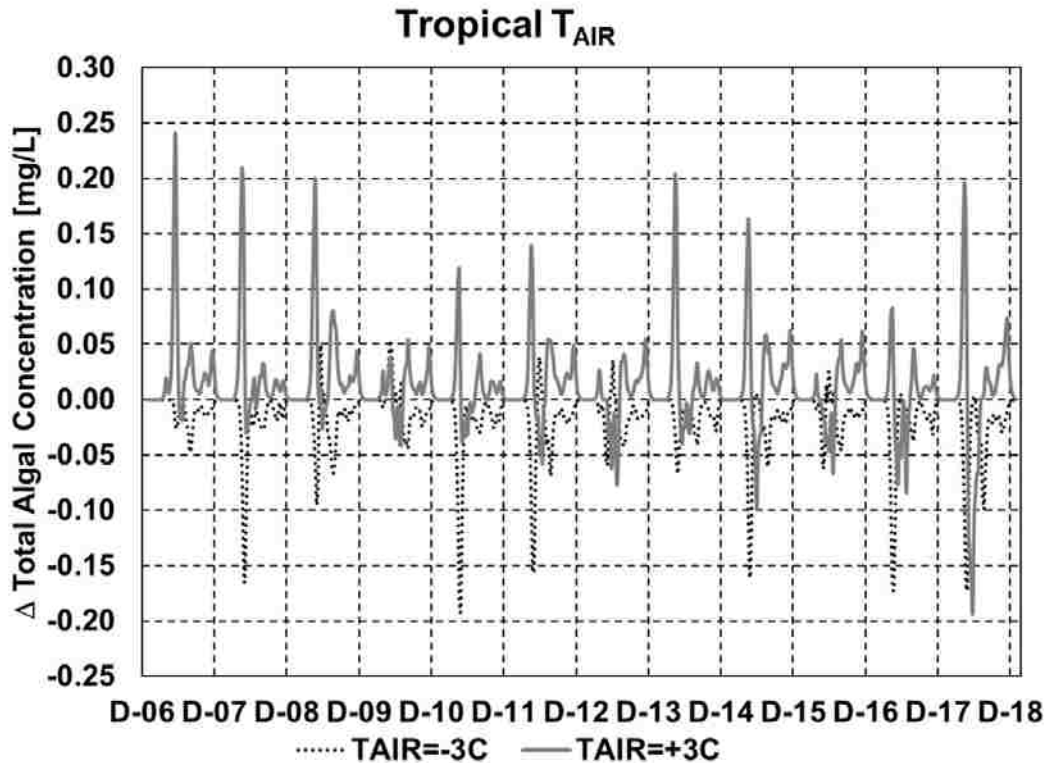


Figure 4-11: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation

4.4.1.3 Total DO Concentration (T_{AIR})

Figure 4-12 shows the effects of changing $\pm 3^\circ\text{C}$ T_{AIR} on the total normalized dissolved oxygen concentration in Aguamilpa. I observed that DO concentration increased when T_{AIR} was decreased 3°C and oxygen was depleted for the $+3^\circ\text{C}$ T_{AIR} simulation compared with the base model. The reservoir reached its highest total normalized DO value of approximately 3.1-3.5 mg/L at the end of each summer (September-October). Other high DO peaks were observed at the end of winter and beginning of spring (March) of each modeled year. Peak oxygen values coincided with the lowest total algal concentrations observed in Figure 4-10. High algal concentrations deplete oxygen in Aguamilpa during the warm dry season (March-June). I also

observed that the lowest oxygen concentrations for Aguamilpa occurred during the beginning of summer (Jun) of each year with concentrations lower than 1.0 mg/L.

Figure 4-13 shows the difference of the total DO concentration between the -3°C T_{AIR} and the $+3^{\circ}\text{C}$ T_{AIR} simulations and the base model. These differences confirmed the observed trends in Figure 4-12 indicating that the total DO concentration in Aguamilpa is affected by T_{AIR} changes and shows that total DO concentration increased when T_{AIR} was decreased 3°C and decreased for the -3°C T_{AIR} simulation with maximum changes of approximately $\pm 30\%$.

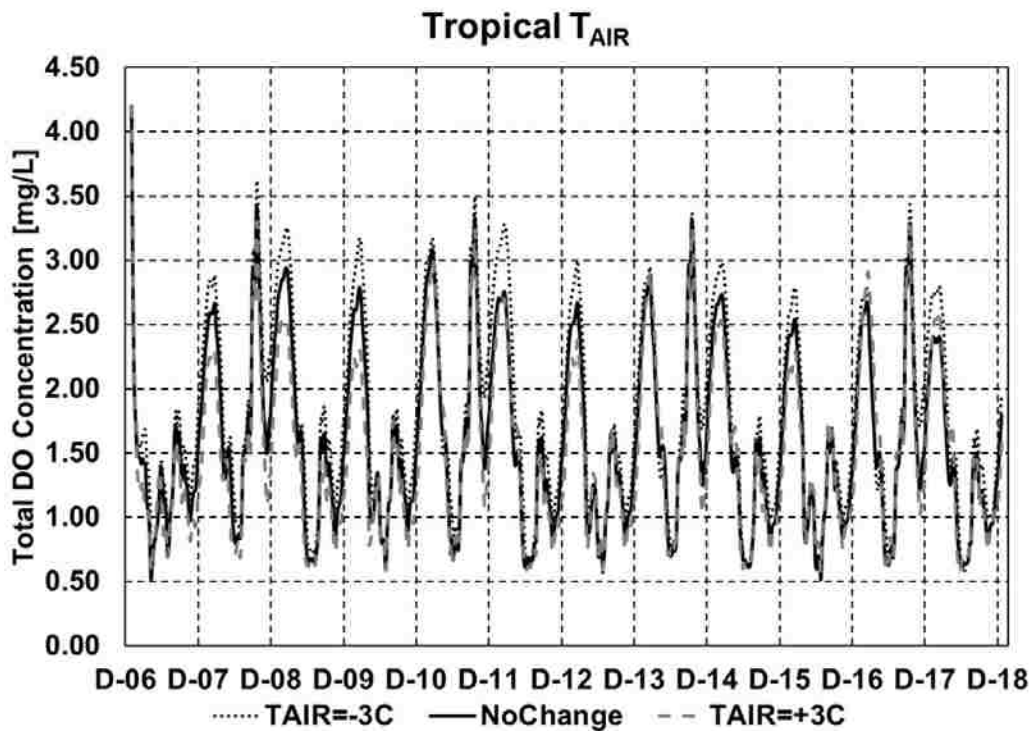


Figure 4-12: Total Dissolved Oxygen Concentration in Aguamilpa by Altering T_{AIR}

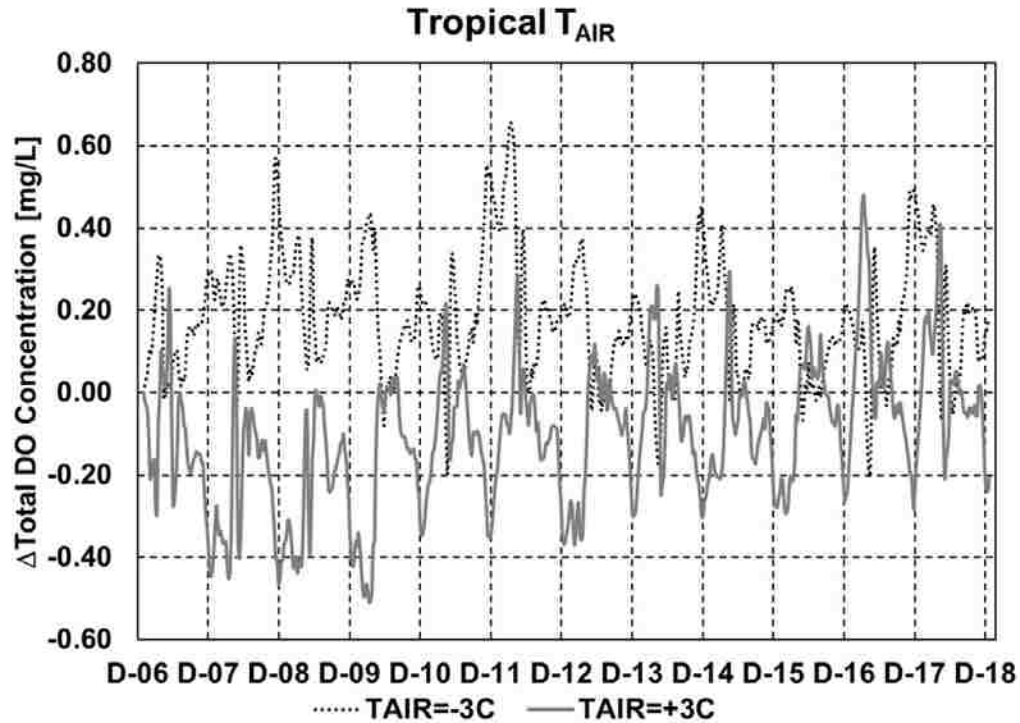


Figure 4-13: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation

4.4.1.4 Total Nutrients Concentration (T_{AIR})

The effects of T_{AIR} changes on the reservoir nutrients concentrations, represented by total phosphate as P (PO_4 -P) and total nitrate-nitrite as N (NO_3 - NO_2 -N) concentrations, are presented in Figure 4-14 and Figure 4-15, respectively. Total PO_4 -P concentration did not show significant changes when T_{AIR} was changed by plus or minus $3^\circ C$ (Figure 4-14). Generally, total PO_4 -P concentration slightly increased when T_{AIR} decreased by $3^\circ C$ showing an opposite effect for the $-3^\circ C$ T_{AIR} simulation. This small change, which represents approximately $\pm 0.20\%$, was more noticeable during spring and summer seasons (March-September) when total PO_4 -P concentration showed maximum and minimum difference of -0.009 mg/L and $+0.0057$ mg/L respectively compared to the base model (Figure 4-16).

I observed that total $\text{NO}_3\text{-NO}_2\text{-N}$ concentration changes due to changes in air temperature in Aguamilpa showed a similar tendency to the total $\text{PO}_4\text{-P}$ concentration (Figure 4-15). However, the total $\text{NO}_3\text{-NO}_2\text{-N}$ concentration plots were more affected by T_{AIR} changes than the total $\text{PO}_4\text{-P}$ concentration. The difference of total $\text{NO}_3\text{-NO}_2\text{-N}$ concentration for the -3°C T_{AIR} and $+3^\circ\text{C}$ T_{AIR} simulations compared to the base model are shown in Figure 4-17. I noticed that the biggest difference in total $\text{NO}_3\text{-NO}_2\text{-N}$ concentration occurred during the warm dry season (March-June) and coincided with the total algal peaks observed in Figure 4-10. This match suggests that total algal concentrations in Aguamilpa are more affected by changes in $\text{NO}_3\text{-NO}_2\text{-N}$ concentrations than changes in $\text{PO}_4\text{-P}$ concentrations produced by warmer temperature, which is one of the critical conditions for efficient denitrification (Lewis Jr 2000). However, more evidence backing up this hypothesis is presented by simulating nutrients changes in Aguamilpa as described in the next sections.

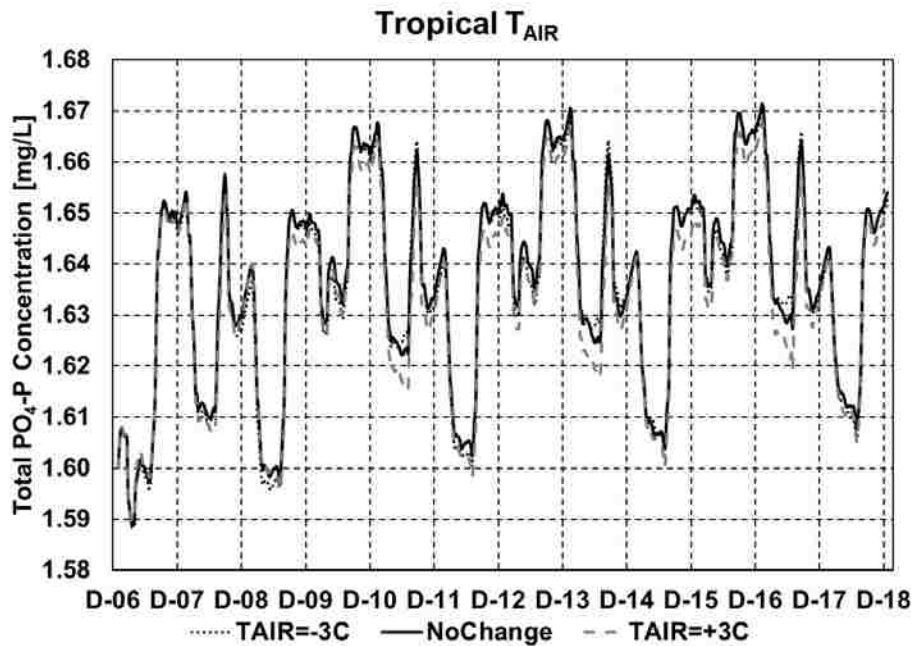


Figure 4-14: Total Phosphate as P Concentration in Aguamilpa by Changing T_{AIR}

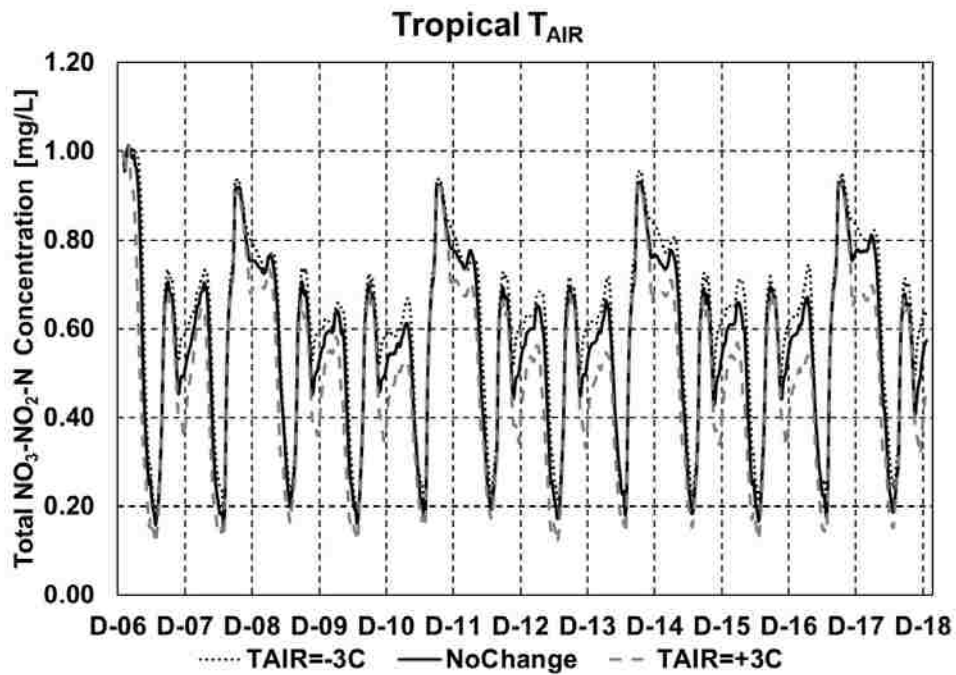


Figure 4-15: Total Nitrate-Nitrite as N Concentration in Aguamilpa by Changing T_{AIR}

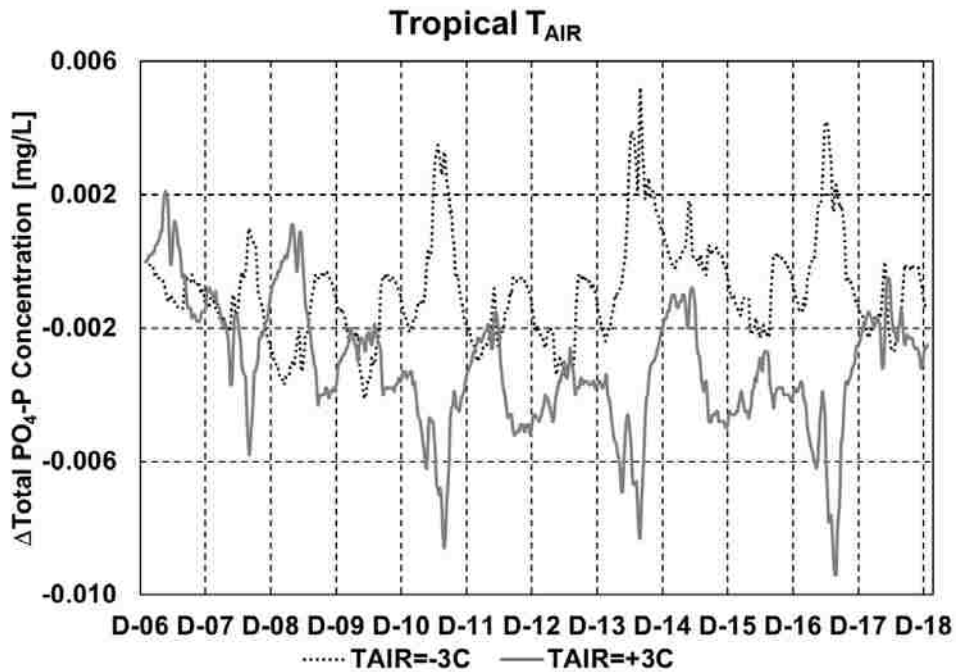


Figure 4-16: Difference of Total Phosphate as P Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation

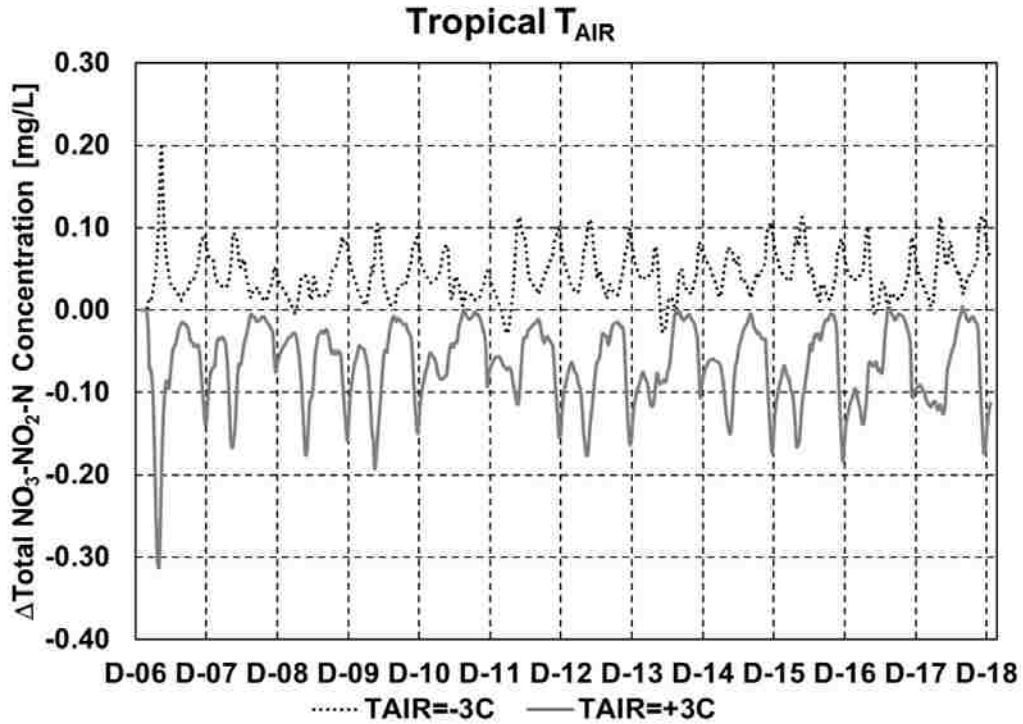


Figure 4-17: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering T_{AIR} Compared to the No-Change Simulation

4.4.1.5 Total TDS Concentration (T_{AIR})

Conductivity, which is sensitive to variations in dissolved solids (TDS) is a measurement of mostly mineral salts (Chapman 1996). I used TDS as another indicator to evaluate GCC effects in Aguamilpa from changing T_{AIR} . One of the projected effects of GCC in water bodies is a greater variation in TDS (Means III *et al.* 2010). Figure 4-18 shows TDS changes produced by T_{AIR} variations. As this plot shows, the TDS changes were insignificant when T_{AIR} was increased/decreased 3°C reaching a maximum percent TDS change of approximately 0.8%.

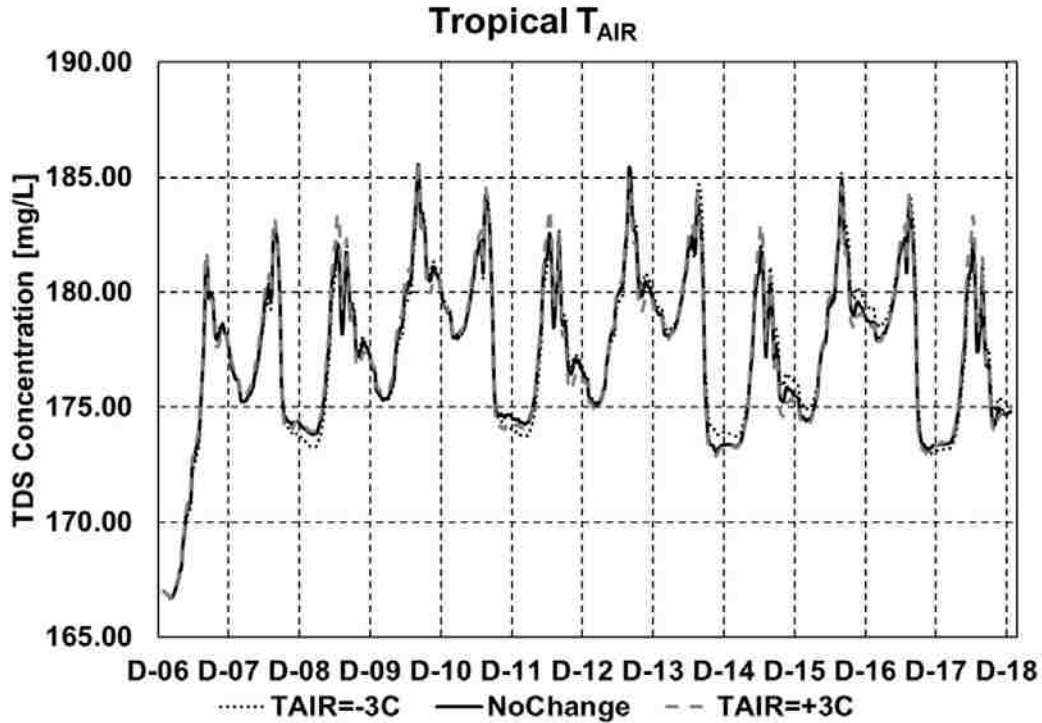


Figure 4-18: Total Dissolved Solids Concentration in Aguamilpa by Changing T_{AIR}

4.4.1.6 Tropical-Aguamilpa Stratification Effects (T_{AIR})

In order to understand how T_{AIR} affected the temperature stratification of Aguamilpa, I used the difference between top water and bottom water from the deepest part of the reservoir (Near Dam) at midday. I used these values to identify the times when the reservoir turns over (value approaching zero) and the intensity of the stratification (Figure 4-19). It is important to recall that the stratification plots (delta temperatures) use data corresponding to the times of the highest solar radiation. This is the time of day when surface water gets warmest due to deeper penetration of solar radiation into the water column (Victorica-Almeida 1996). Changes in T_{AIR} did not affect the reservoir's mixing period (December-March). Stratification was stronger for spring-summer seasons (April-September) when T_{AIR} was increased 3°C. During the months when the reservoir was stratified (April-December) I observed that water temperature slightly

fluctuated for the -3°C and $+3^{\circ}\text{C}$ T_{AIR} simulations compared to the base model. For instance, a stronger stratification occurred when T_{AIR} was increased 3°C and -3°C T_{AIR} produced a weaker stratification (2010 and 2016 simulations). However, during September, I observed the opposite effect when the T_{AIR} of -3°C showed a slightly stronger stratification than the $+3^{\circ}\text{C}$ T_{AIR} and the base model simulations. This fluctuation in stratification may be produced by other climatic and hydrologic factors such as changes in wind speed/direction, storms and in/outflows that occur during the rainy season (Wetzel 2001).

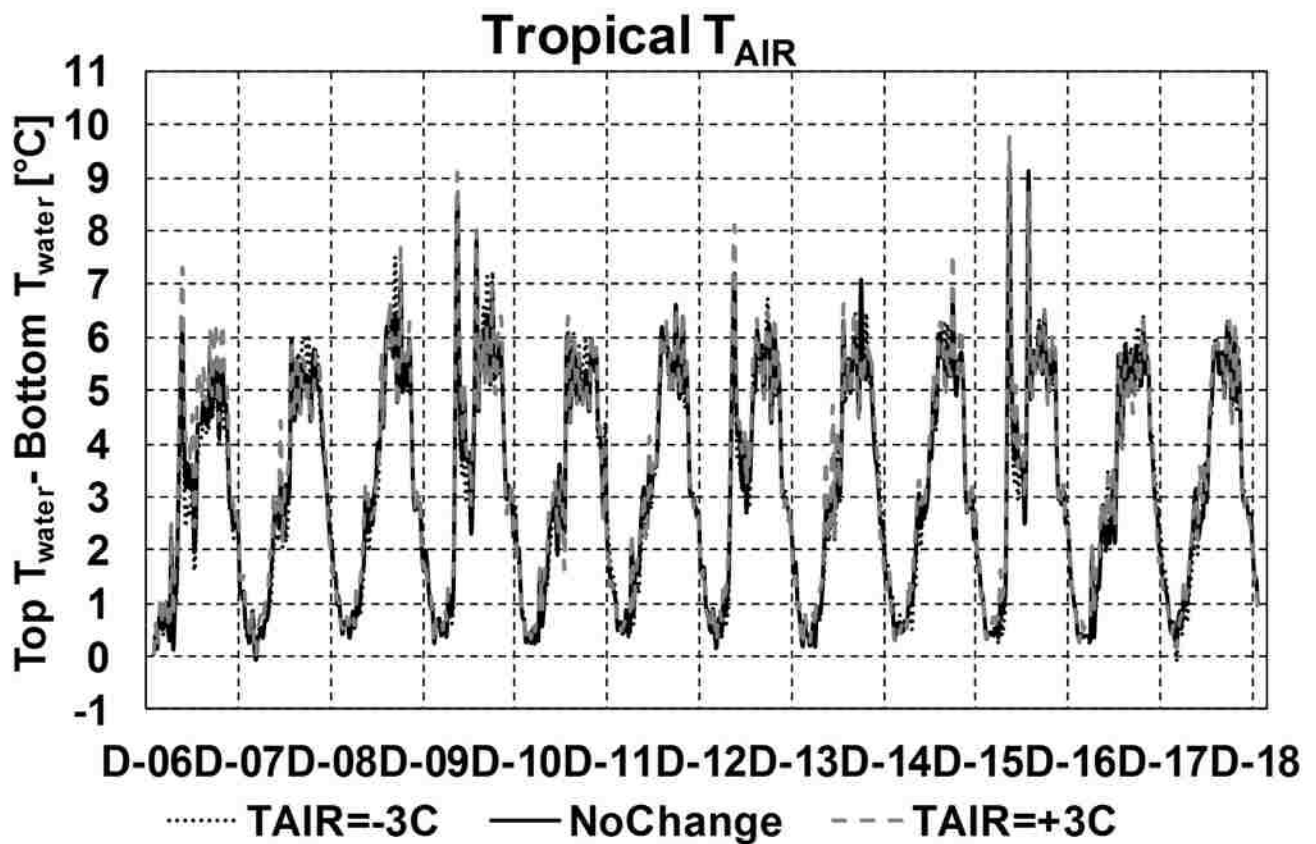


Figure 4-19: Water Temperature Difference between Epilimnion and Hypolimnion (Top Water Temperature and Bottom Water Temperature) in the Water Column from the Near Dam Sampling Point in Aguamilpa by Adjusting T_{AIR}

4.4.2 Changing Inflow Volumes (Q)

4.4.2.1 Chl-A Profiles Concentration (Q)

Figure 4-20 shows Chl-A concentration profiles generated by changing Q (inflow and outflow) by $\pm 10\%$ relative to the base model. I extracted these Chl-A profiles from three different days at the deepest part of Aguamilpa, S1-Near Dam sampling site (Figure 4-4). The first profile (Figure 4-20A) indicated that the Chl-A peak concentration slightly decreased (by $0.12 \mu\text{g/L}$) for the $+10\%$ Q simulation and increased for the -10% Q simulation by $0.04 \mu\text{g/L}$ compared to the base model. This small variation could be caused by two reasons: First, the -10% Q simulation creates longer residence time causing the water to receive sunlight for longer periods without too much movement. These steady conditions could increase water temperature in the epilimnion which contributes to algae growth. Second, high Q produce shorter residence time that decrease the contact time required for algae to grow by consuming nutrients and sunlight. On the other hand, the Chl-A concentration profiles for 2011 (Figure 4-20B) trended to increase for both simulations. However, I compared peak Chl-A concentration and their location in the water column. These comparisons showed that the different scenarios had peak values at different reservoir elevations. The -10% Q simulation presented its Chl-A peak value of $19 \mu\text{g/L}$ at 199.5 m while the $+10\%$ Q was $23 \mu\text{g/L}$ at 198.5 m . Similar trends were observed for the 2015 profile (Figure 4-20C) where peak Chl-A concentration were located at higher elevations when Q was increased by 10% .

Average Chl-A concentrations from each profile were also calculated and compared indicating that Chl-A levels from the $\pm 10\%$ Q simulations were higher than the base model for the summer 2011 and 2015 profiles (Figure 4-20B and C). On the other hand, average Chl-A concentration decreased for the $+10\%$ Q simulation and increased for the -10% Q plot compared

to my base model (Figure 4-20A). This contradictory observation illustrates the difficulty of using profiles from single locations at a few time steps. The results obtained by using the total normalized parameter concentration are presented in the following sections and show impacts to the total reservoir over the entire simulation.

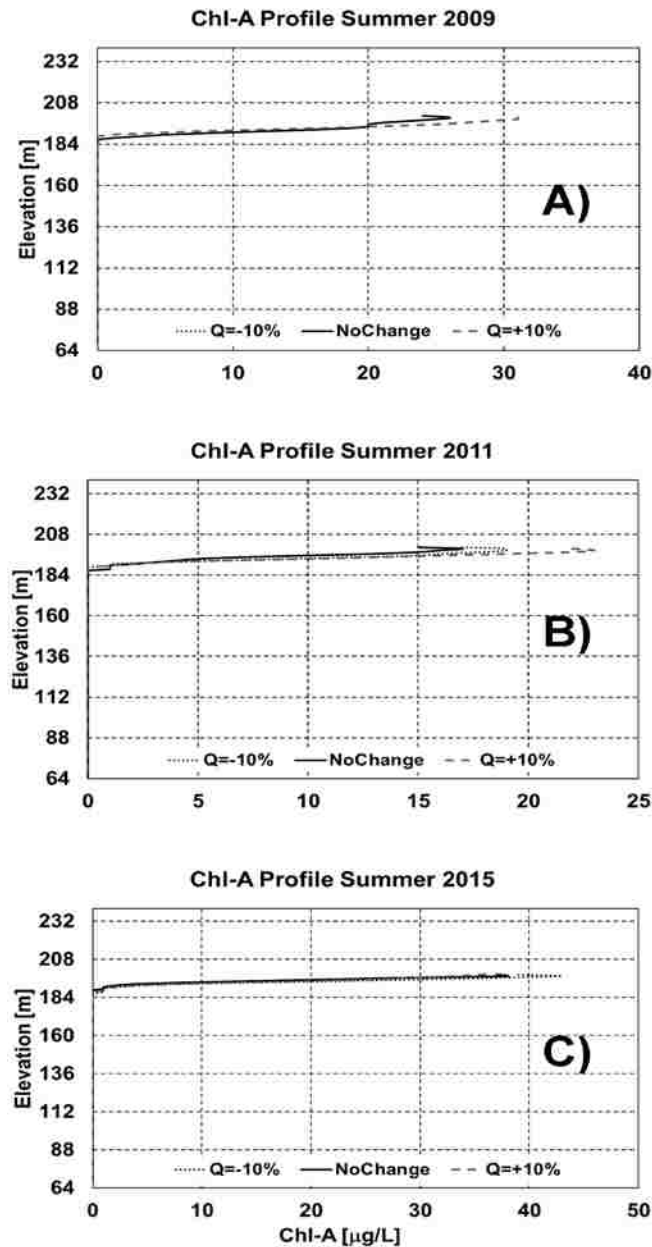


Figure 4-20: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting Q for A) June 2007; B) June 2011; and C) June 2015

4.4.2.2 Total Algal Concentration (Q)

I used total normalized algal concentration as an evaluator of GCC impacts caused by adjusting Q by $\pm 10\%$ (Figure 4-21). I observed that algal levels did not vary when Q was changed 10% during winter season (November-March). Contrary to what occurred in winter, total algal concentration tended to decrease when Q was increased 10% and increase for the -10% Q simulation compared to the No-Change plot during the end of the warm dry season (May-June) and the beginning of the rainy season (July), when the trend was stronger. Also, this same trend is observed, with less intensity, immediately before the reservoir's mixing period starts (middle of October).

To analyze these trends, I calculated and plotted the difference of total normalized algal concentration for the $\pm 10\%$ Q simulations and the base model (Figure 4-22). These change or delta plots confirmed the trend observed in Figure 4-21 where total normalized algal levels increased during dry conditions (-10% Q) and decreased for wet conditions (+10% Q). Moreover, the difference of total algal concentration graphs shows that algae levels decreased when Q decreased 10% during the last part of the cold dry season (January-February) and first two weeks of the warm dry season (March) of each simulated year.

4.4.2.3 Total DO Concentration (Q)

Figure 4-23 shows total normalized DO concentration for the base case and by varying Q by $\pm 10\%$. The highest total normalized DO concentration observed for any of the three simulations was 3.7 mg/L. This DO concentration occurred at the end of the rainy season (September) and corresponded to the +10% Q simulation. According to the total normalized DO concentrations plots, DO was increased for the +10% Q and decreased for -10% Q simulations compared to my base model with values reaching up to 3.7 mg/L. These trends were stronger

during the end of the cold dry season (February) and rainy season (September). Also, I calculated and compared the average total normalized DO concentration from the three simulated scenarios and my calculations indicated that there was not difference between the -10% Q simulation and the base model with average DO which resulted on 1.60 mg/L for both cases. However, the +10% Q simulation showed a higher average DO concentration than the -10% Q and No-Change simulations with an average DO value of 1.71 mg/L.

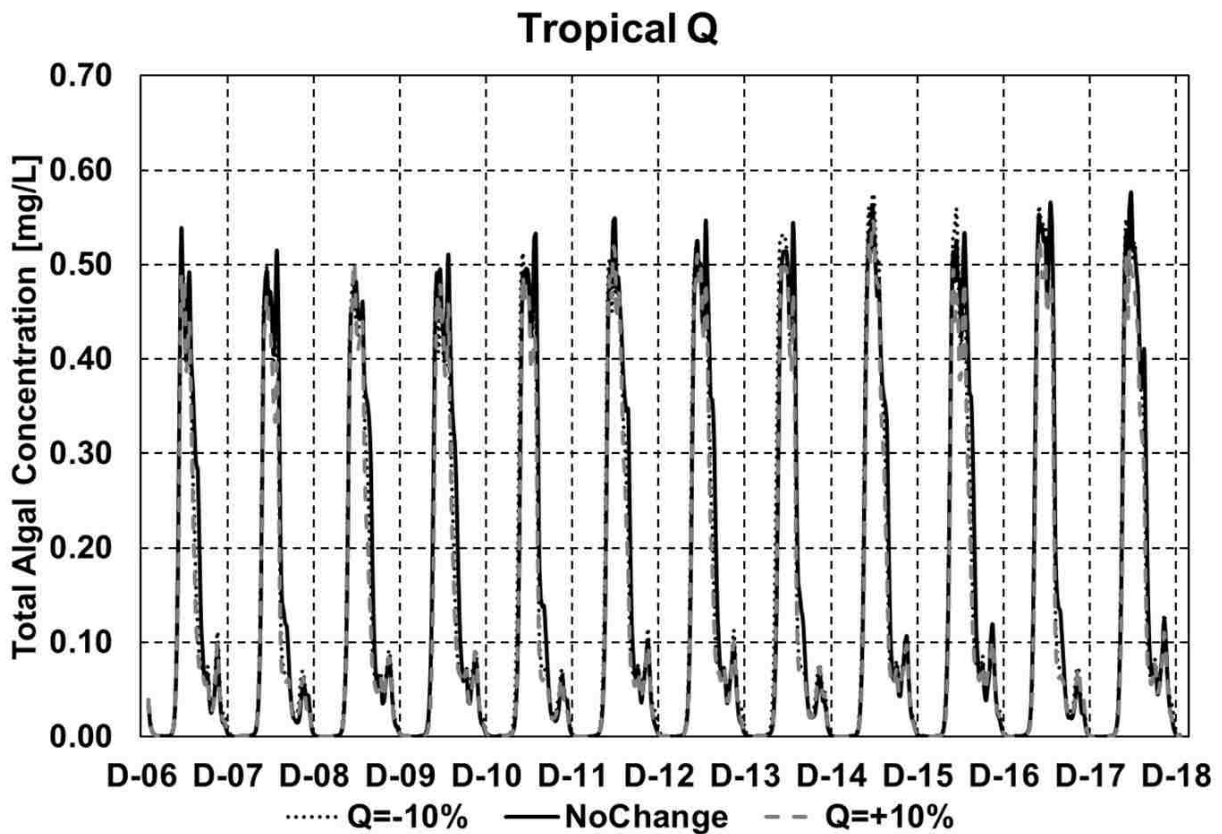


Figure 4-21: Total Algal Concentration in Aguamilpa Reservoir by Altering Q

In Figure 4-24 I present the difference of total normalized DO concentration for the $\pm 10\%$ Q simulations compared with the base model. This plot better shows where variations of the normalized DO levels occurred for the dry and wet scenarios modeled in Aguamilpa. It

confirmed that total normalized DO levels decreased with low Q values and increased with higher Q due to shorter water residence time produced by the +10% Q simulation. Longer hydraulic residence times generate stagnant water in the hypolimnion, depleting DO concentration in that zone of the reservoir.

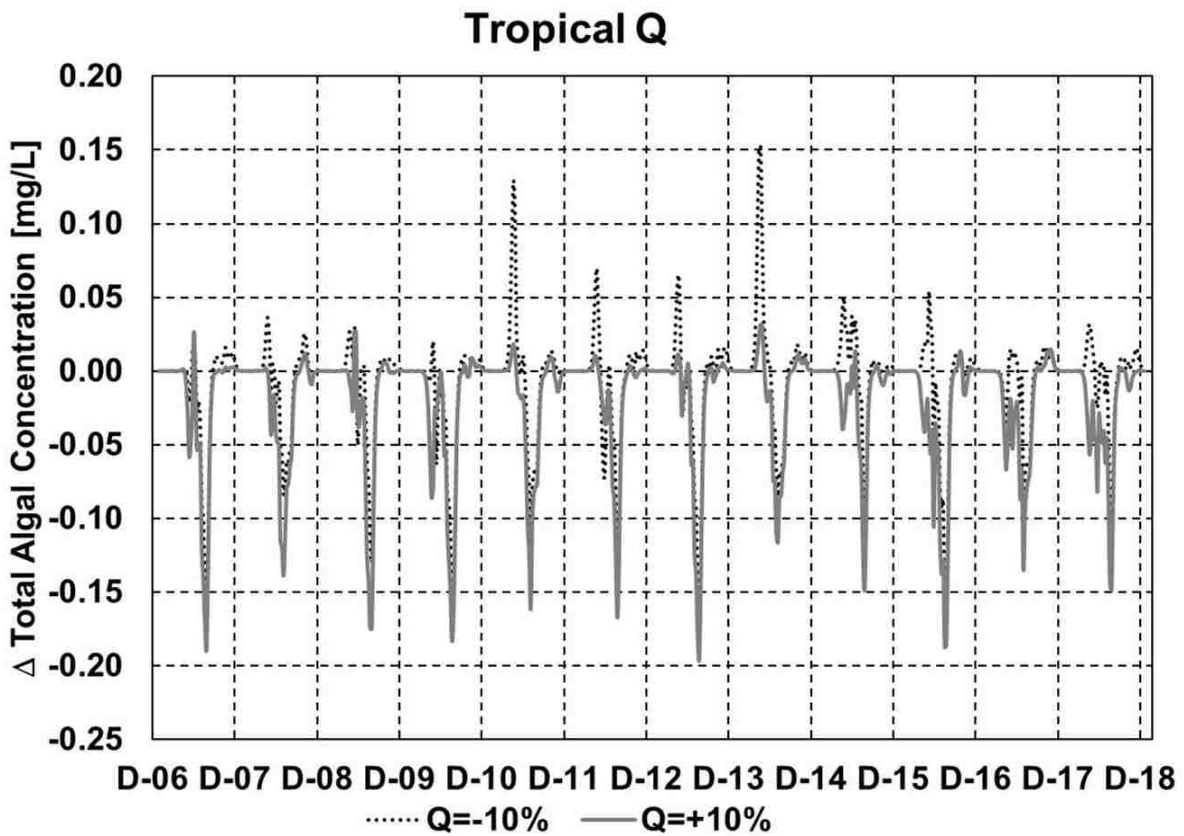


Figure 4-22: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation

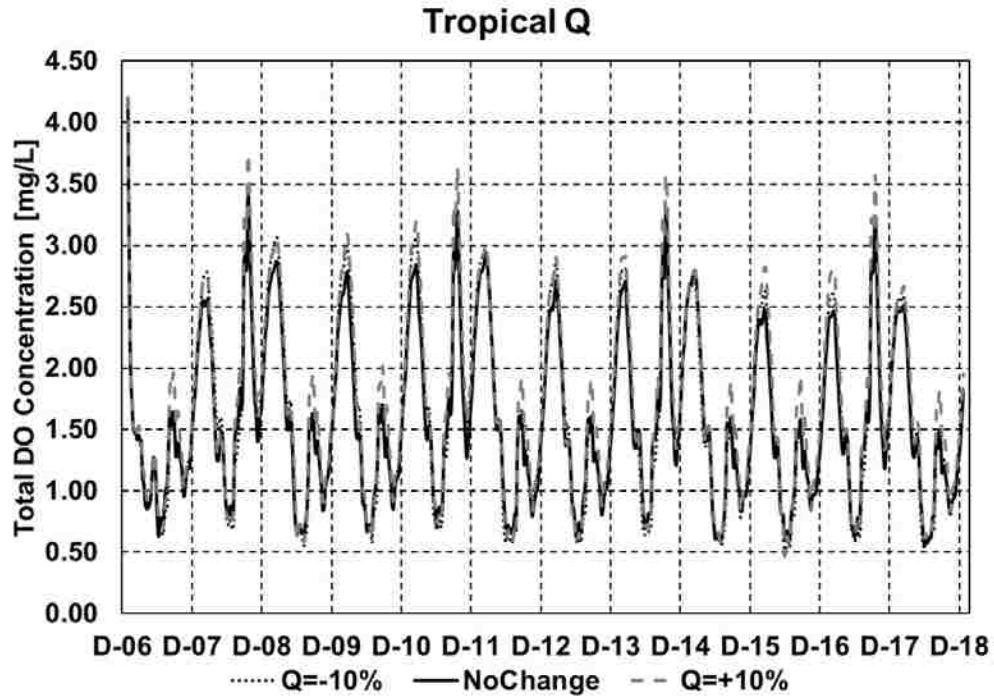


Figure 4-23: Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering Q

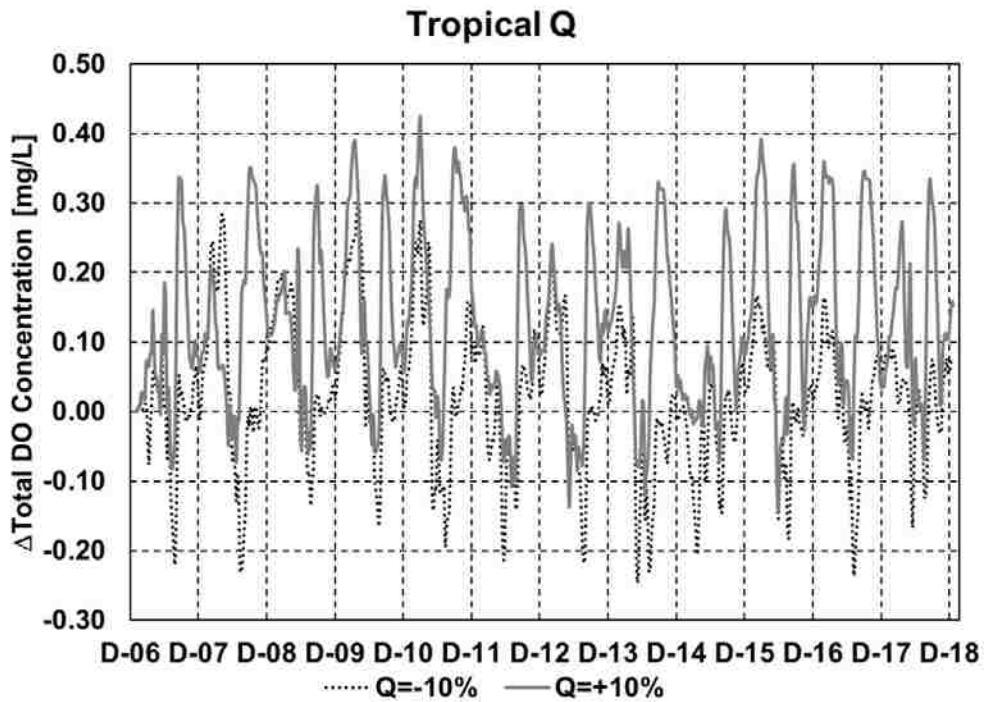


Figure 4-24: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation

4.4.2.4 Total Nutrients Concentration (Q)

I evaluated impacts of Q changes due to climate on nutrients by altering Q by $\pm 10\%$. I used total normalized $\text{PO}_4\text{-P}$ concentration and total normalized $\text{NO}_3\text{-NO}_2\text{-N}$ concentration to evaluate these impacts. First, I present the total normalized $\text{PO}_4\text{-P}$ concentration plots (Figure 4-25) which generally did not vary when Q was increased or decreased. I observed a small rise in total normalized $\text{PO}_4\text{-P}$ concentration when Q was decreased 10% and small decline for the +10% Q simulation compared to my base model. These variations occurred during the warm dry season (March-June) and can be considered insignificant because they do not represent a percent of change greater than 0.5%. Figure 4-26 shows the difference of total normalized $\text{PO}_4\text{-P}$ concentration from each one of the two simulations (-10% Q and +10% Q) with the No-Change model. Also, I observed that the difference of total normalized $\text{PO}_4\text{-P}$ concentration was stronger when the reservoir presented anoxic conditions (Figure 4-23) showing that phosphates are released from sediment (Chapman 1996).

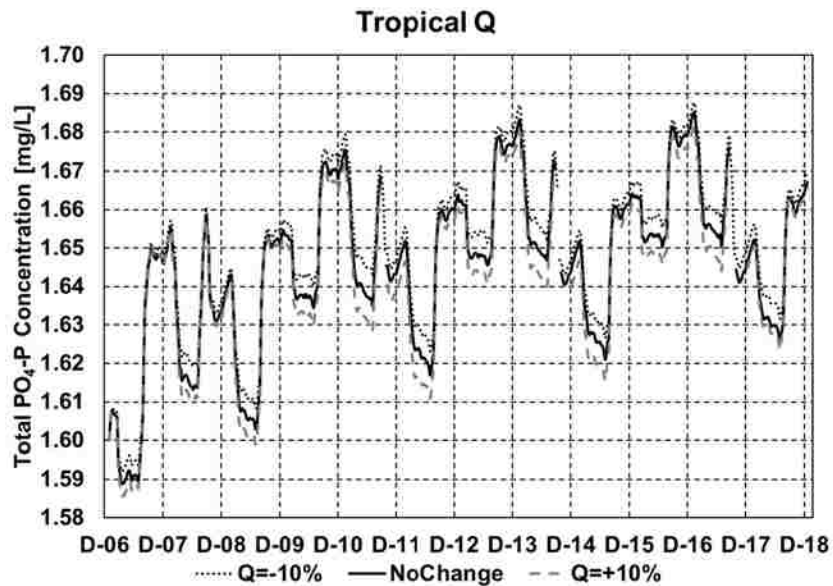


Figure 4-25: Total Phosphates as P Concentration in Aguamilpa Reservoir by Altering Q

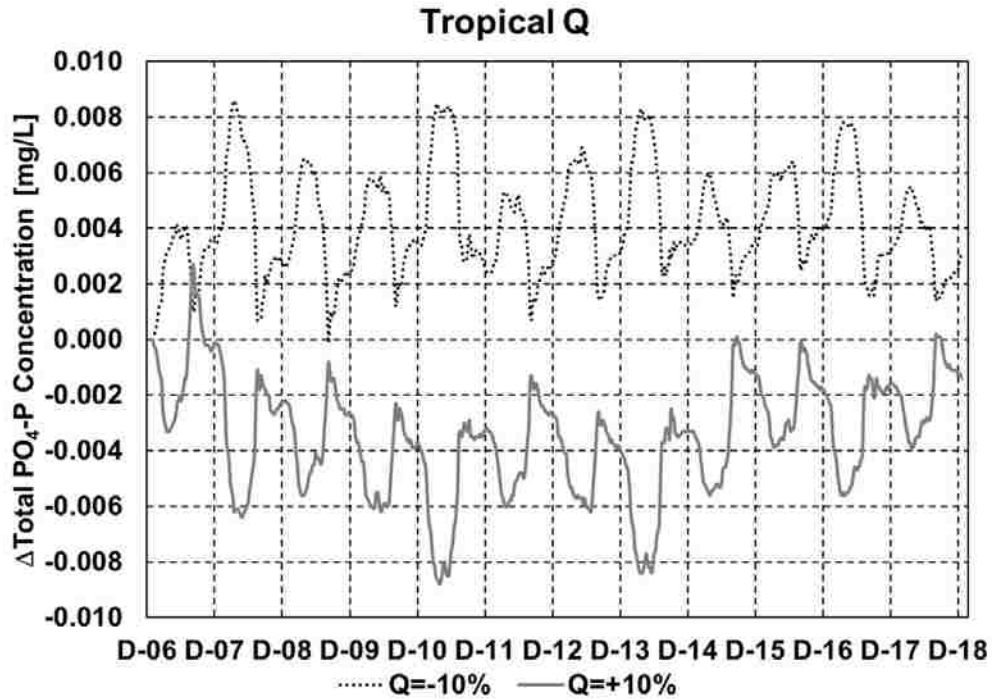


Figure 4-26: Difference of Total Phosphates as P Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation

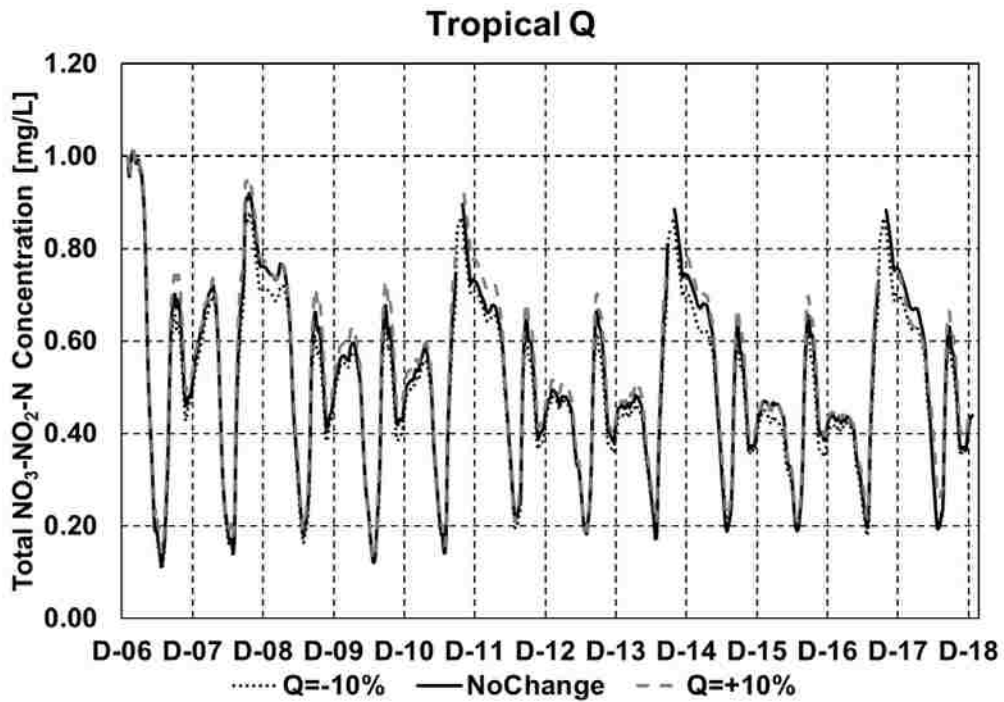


Figure 4-27: Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering Q

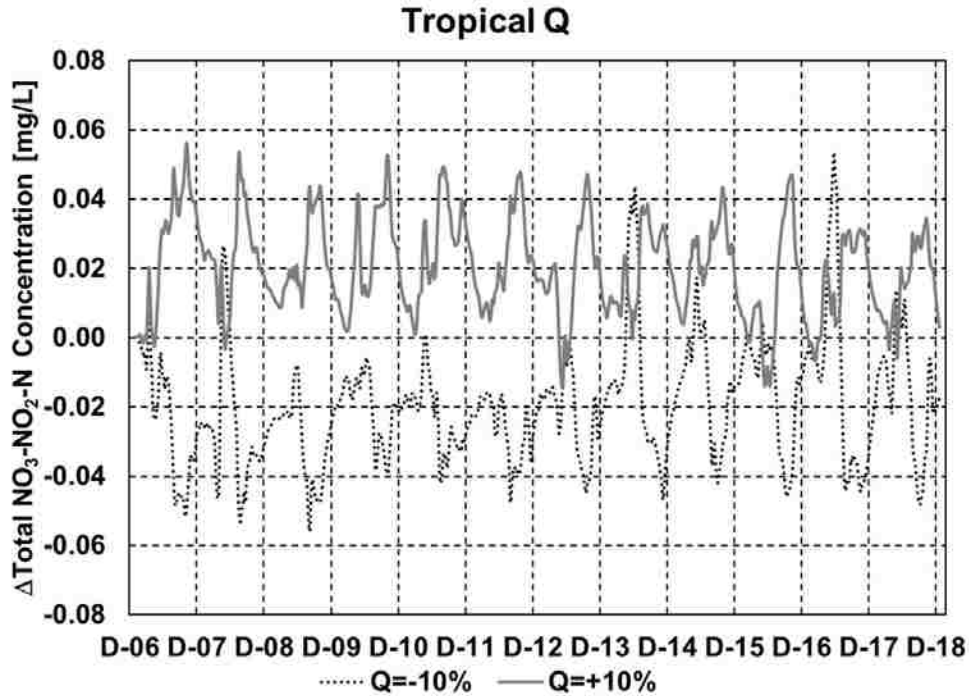


Figure 4-28: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation

4.4.2.5 Total Dissolved Solids Concentration (Q)

I evaluated the impacts of altering 10% Q in Aguamilpa because of GCC on the TDS concentration. Chapman (1996) notes that TDS consists of minerals, organic matter, and nutrients that have dissolved in water and that TDS levels are highest in waterbodies during low flow conditions, when groundwater becomes the main source of water. Alternatively, TDS levels are low during high flow conditions because storm runoff is the main source of water transporting more material that contributes to the increase of dissolved solids in a waterbody (Chapman 1996; Kalff 2002). These same correlations were observed for Aguamilpa when I altered 10% Q (Figure 4-29). TDS concentrations increased when Q was decreased 10% and dropped for the +10% Q simulation compared to the base model line.

I also compared the difference of TDS concentration resulting from the $\pm 10\%$ Q simulations with the base model (Figure 4-30). Although, these differences were not significant because they did not exceed a change of 0.9%, they were more pronounced during the cold dry season (November-February) when Aguamilpa exhibited its lowest concentration of TDS. These seasonal trends concurred with the results from a water quality assessment prepared by Rangel-Peraza *et al.*, (2009) for Aguamilpa and for other tropical reservoirs (Rahman *et al.* 2005; Mustapha 2009).

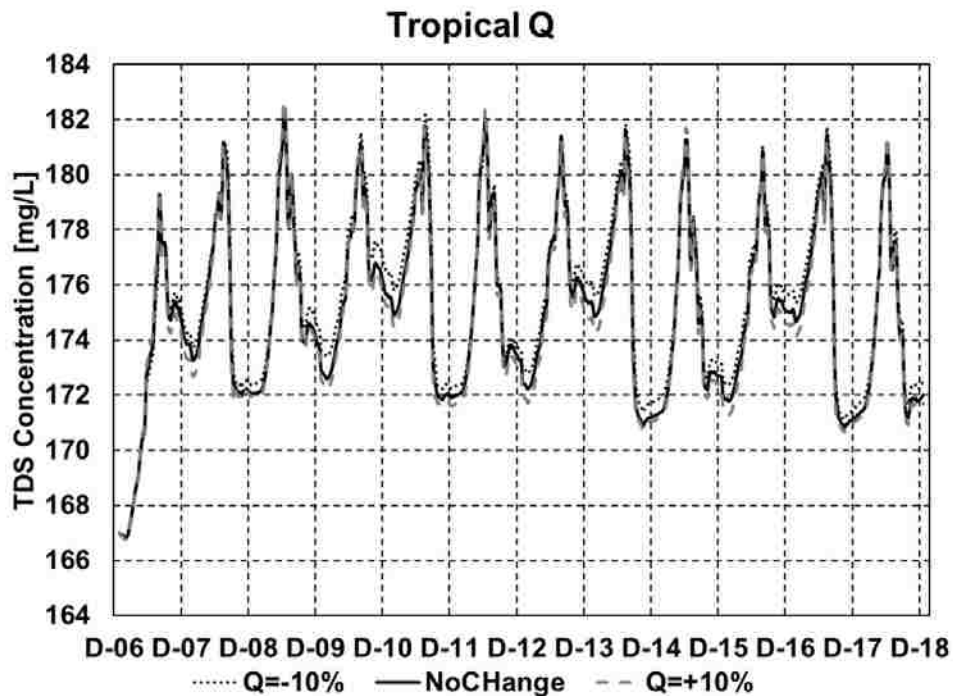


Figure 4-29: Total Dissolved Solids Concentration in Aguamilpa Reservoir by Altering Q

4.4.3 Changing Nutrients in Aguamilpa (NC)

According to Lewis Jr (1996; 2000), the limiting factor for algae growth in a tropical lake or reservoir could be phosphorous or nitrogen or both. Based on this statement, I separately

modified inflow phosphates ($NC-PO_4-P$), and nitrate-nitrite ($NC-NO_3-NO_2-N$) concentration to evaluate the potential response of in-reservoir's water quality by altering these nutrients. These modifications in nutrients concentrations can be caused by climatic changes, land use changes, or construction of upstream reservoirs (i.e., El Cajon and La Yesca).

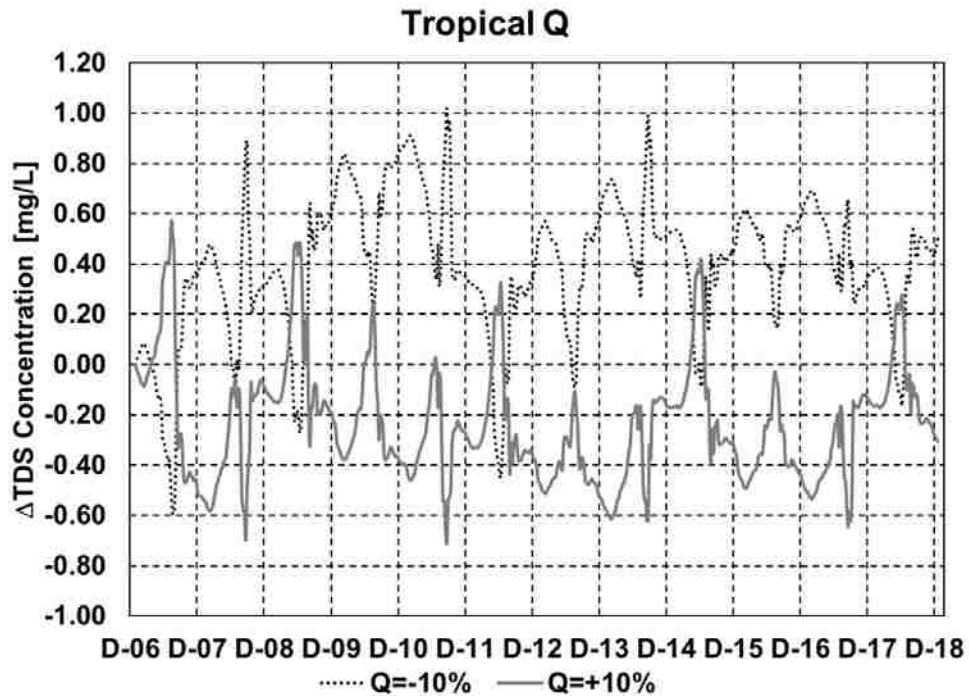


Figure 4-30: Difference of Total Dissolved Solids Concentration in Aguamilpa Reservoir by Altering Q Compared to the No-Change Simulation

4.4.3.1 Chl-A Profiles ($NC-PO_4-P$)

Phosphorous in lakes and reservoirs represents one of the two main nutrients (nitrogen is the other one) which typically control primary productivity as both dissolved and particulate species (Metcalf *et al.* 1991; Wetzel 2001). Natural sources of phosphorous in waterbodies come from the weathering of phosphorous bearing rocks and the decomposition of organic matter (Chapman 1996; Kalff 2002). Also, anthropogenic sources, such as domestic and industrial

wastewaters and runoff transporting water with fertilizers, contribute to increase phosphorous concentration in lakes and reservoirs affecting their trophic status (Wetzel 2001). High concentrations of phosphorous in a reservoir can increase phytoplankton biomass and affect water quality, producing low transparency, green color, undesirable odor and depletion of oxygen in deep waters (Likens 2010). Dissolved orthophosphates and polyphosphates, and organically bound phosphates are the forms in which phosphorous is found in natural waters. Phosphate concentrations are usually expressed as $PO_4\text{-P}$ which is heavily consumed in the epilimnion of the reservoir when high productivity of phytoplankton occurs. Based on these principles, I began my evaluation of nutrients changes by altering $NC\text{-}PO_4\text{-P}$ 50% and using Chl-A profiles to assess the effect of $NC\text{-}PO_4\text{-P}$ changes. Figure 4-31 shows Chl-A concentration profiles from three different modeled years. Chl-A concentrations did not change for any of the three profiles when $NC\text{-}PO_4$ concentration was adjusted up or down 50% compared to the base model (Figure 4-31A, Figure 4-31B, and Figure 4-31C). The only change that I observed occurred in the summer 2011 plot when Chl-A concentration peaks were slightly higher for the $\pm 50\%$ $NC\text{-}PO_4\text{-P}$ simulations than the base model. I also compared the average Chl-A concentration of the profiles shown in Figure 4-31 and there were no difference between both simulations and the base model suggesting Chl-A concentrations are not affected by altering $NC\text{-}PO_4\text{-P}$ 50%. However, these Chl-A concentration profiles were not conclusive. In order to evaluate if there was any effect in the whole reservoir, I used total normalized algal concentration as indicator of quantifying $NC\text{-}PO_4\text{-P}$ concentration changes and these results are described in the next section.

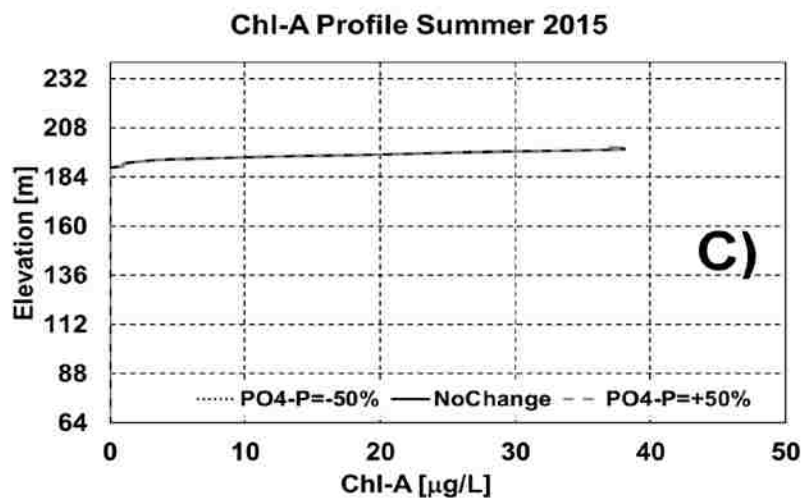
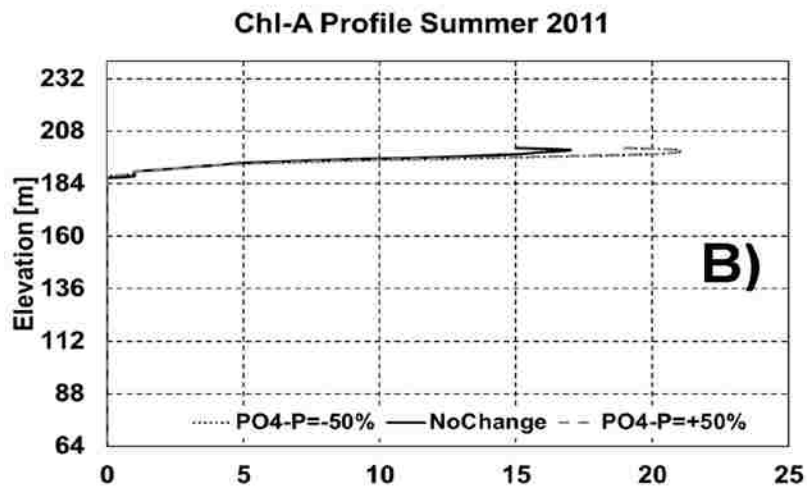
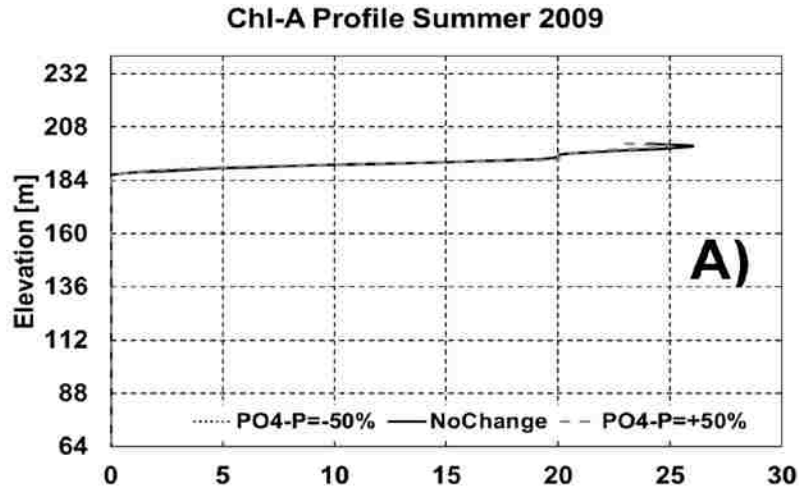


Figure 4-31: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting $NC-PO_4-P$ for A) June 2007; B) June 2011; and C) June 2015

4.4.3.2 Total Algal Concentration ($NC-PO_4-P$)

Figure 4-32 shows that the total algal concentration in Aguamilpa was not affected by changing $NC-PO_4-P$ 50%. I also used Figure 4-33 to evaluate the difference between the $\pm 50\%$ $NC-PO_4-P$ simulations and the base model. I observed that there were small differences in total normalized algal concentration, particularly at the beginning of the warm dry season (April). Comparing the average total algal concentration of the three simulations (-50% $NC-PO_4-P$, No-Change, and $+50\%$ $NC-PO_4-P$), I did not observe any difference when $NC-PO_4-P$ was decreased/increased 50% (0.14 mg/L). This indicates that algae growth in the reservoir was not limited by phosphorous.

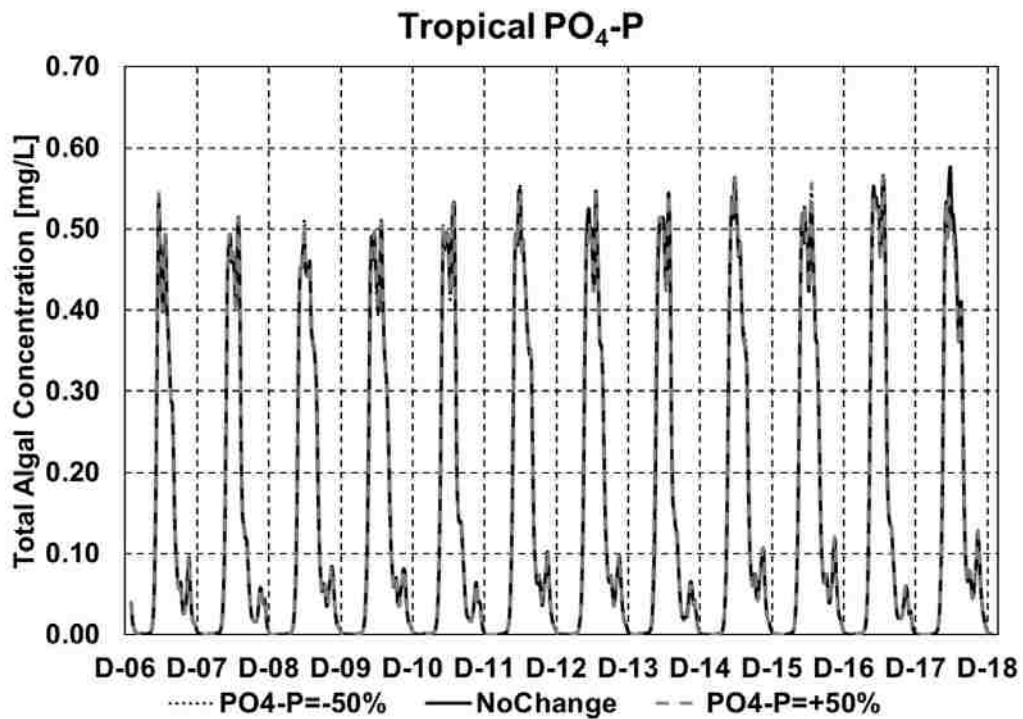


Figure 4-32: Total Algal Concentration in Aguamilpa by Altering $NC-PO_4-P$

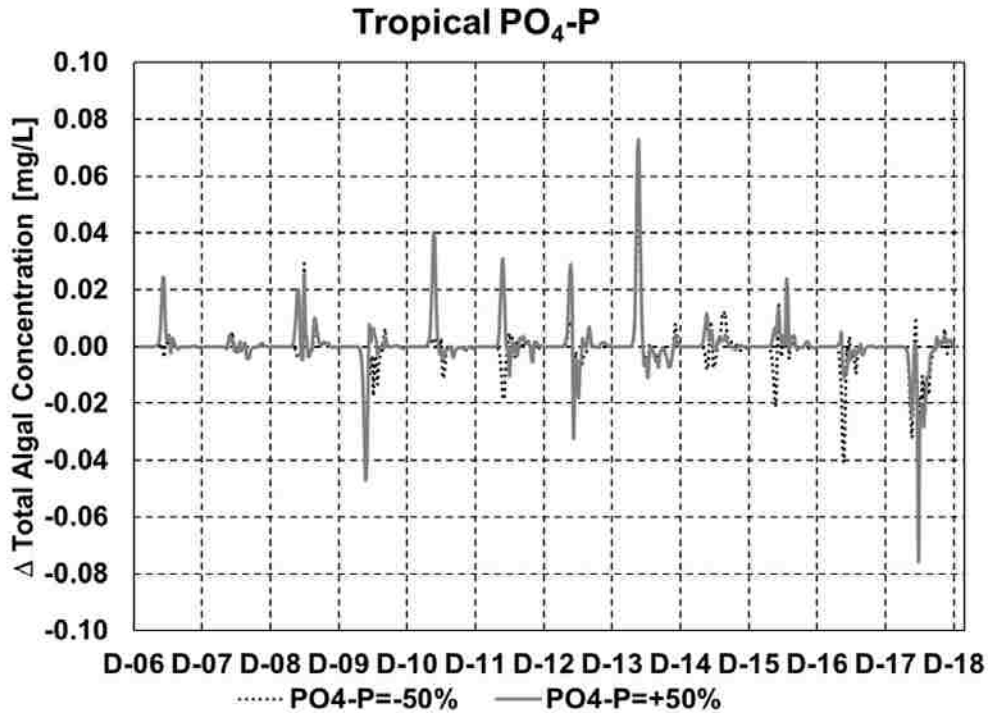


Figure 4-33: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering $NC-PO_4-P$ Compared to the No-Change Simulation

4.4.3.3 Total DO Concentration ($NC-PO_4-P$)

Figure 4-34 shows the total DO concentration in Aguamilpa which results from changing $NC-PO_4-P$ up and down by 50%. I did not observe any high change in total normalized DO concentration with either of the $\pm 50\%$ $NC-PO_4-P$ simulations indicating that oxygen in whole reservoir is not affected by $NC-PO_4-P$ variations. However, analyzing Figure 4-35 I noticed a slightly decrease in total DO concentration when $NC-PO_4-P$ inflow concentration was increased 50% and a decrease in total DO when $NC-PO_4-P$ was decreased 50%, particularly during the beginning of the warm dry season (Apr). Generally, total normalized DO concentration was not affected by $NC-PO_4-P$ variations and this was confirmed by comparing average total DO concentrations from the three simulations. Total DO concentration for the -50% $NC-PO_4-P$, No-

Change, and +50% $NC-PO_4-P$ simulations were 1.59 mg/L, 1.58 mg/L and 1.58 mg/L, respectively.

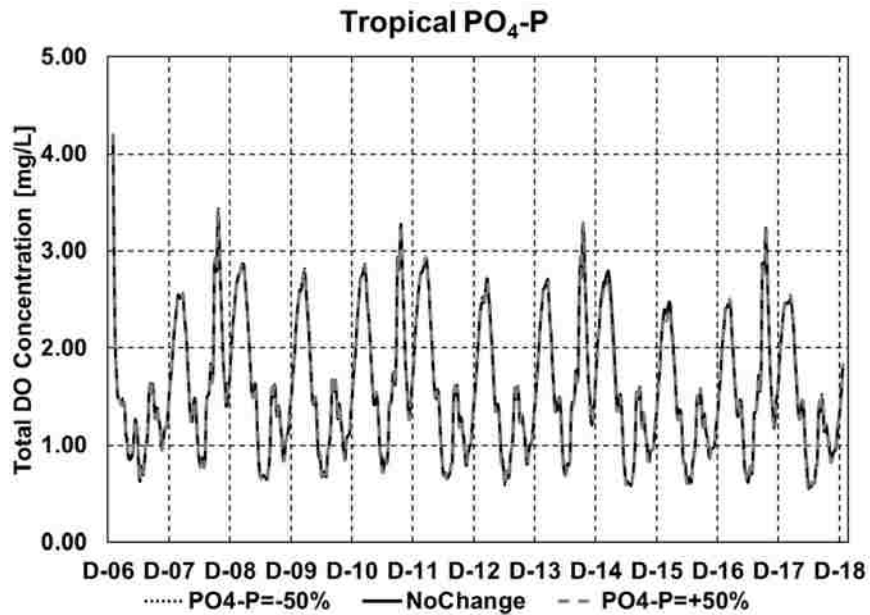


Figure 4-34: Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-PO_4-P$

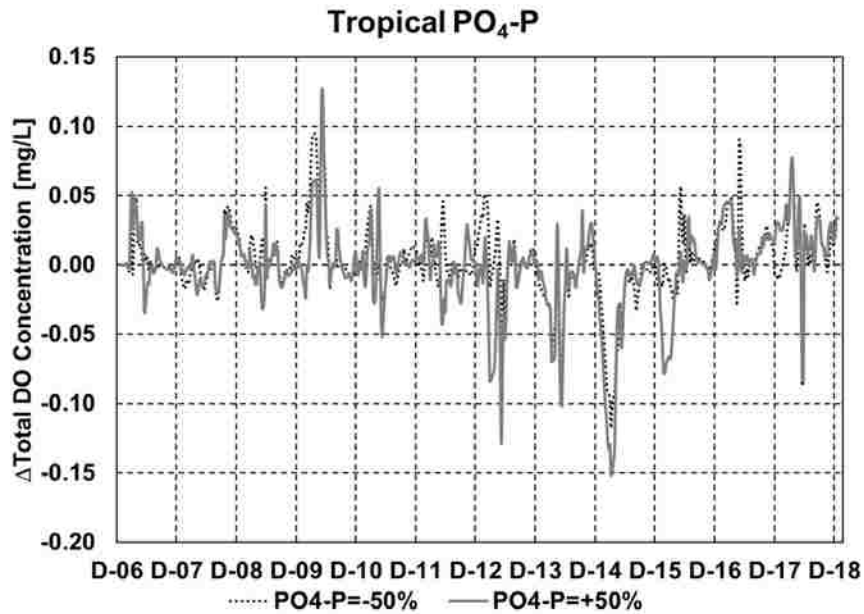


Figure 4-35: Difference of Total Dissolved Oxygen Concentration in Aguamilpa Reservoir by Altering $NC-PO_4-P$ Compared to the No-Change Simulation

4.4.3.4 Total NO_3-NO_2-N Concentration ($NC-PO_4-P$)

I did not include the analysis of total PO_4-P concentration resulting from changing the inflow $NC-PO_4-P$ levels by 50%. I only show the effects on total normalized NO_3-NO_2-N concentration by altering the inflow $NC-PO_4-P$ levels up and down by 50% (Figure 4-36). I did not observe significant changes in Figure 4-36 or when I compared the average total NO_3-NO_2-N concentration values of the three simulations ($NO_3-NO_2-N= 0.56$ mg/L). Nevertheless, small differences of total NO_3-NO_2-N concentration did exist when comparing $\pm 50\%$ inflow $NC-PO_4-P$ simulations with the base model. These changes, which are most obvious in the delta plots, are shown in Figure 4-37. The big peaks match with those observed in Figure 4-35 for the delta of total normalized DO concentration with the base case. This indicates that the $NC-PO_4-P$ changes did not directly affect the total NO_3-NO_2-N concentration but it did have an influence on the DO levels which, in turn can vary NO_3-NO_2-N levels by the nitrification process.

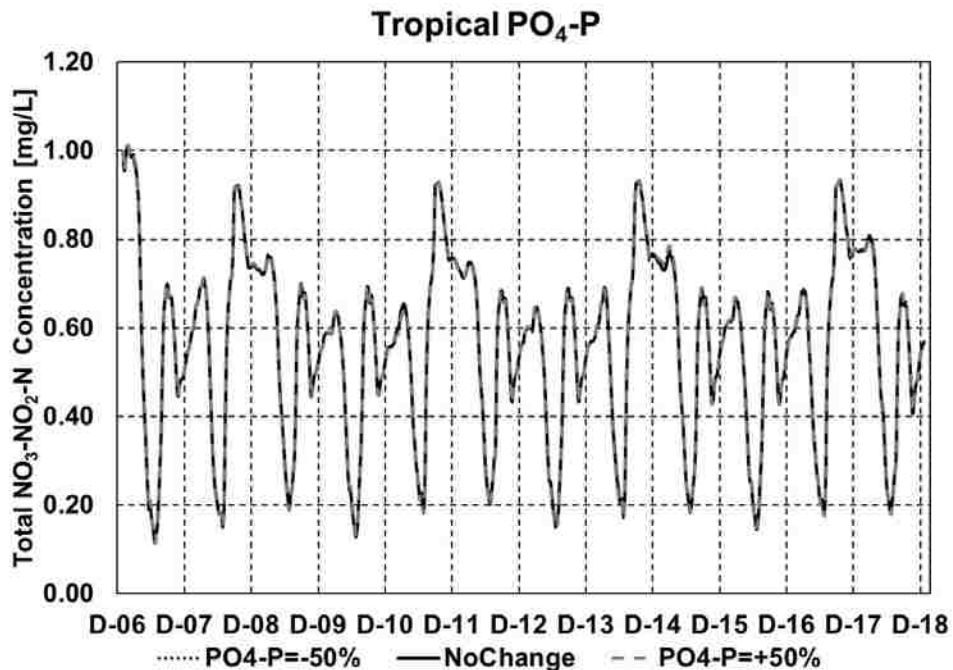


Figure 4-36: Total Nitrate-Nitrite as N Concentration in Aguamilpa by Altering $NC-PO_4-P$

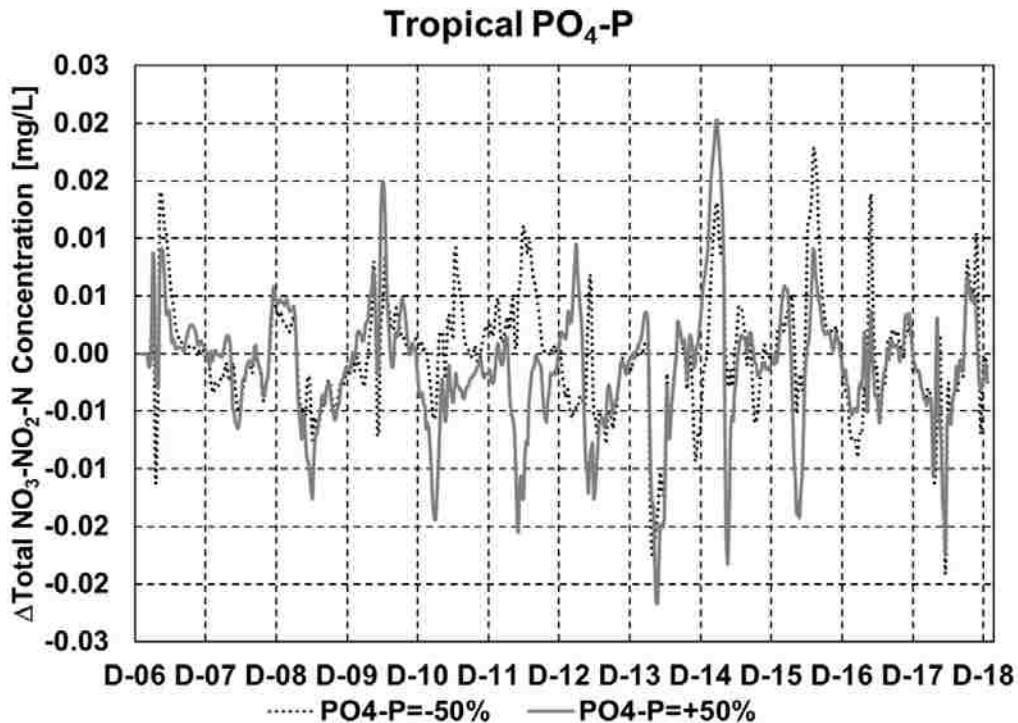


Figure 4-37: Difference of Total Nitrate-Nitrite as N Concentration in Aguamilpa Reservoir by Altering *NC-PO₄-P* Compared to the No-Change Simulation

4.4.3.5 Total TDS Concentration (*NC-PO₄-P*)

Figure 4-38 shows that TDS levels in Aguamilpa were not affected by *NC-PO₄-P* changes. Average TDS concentrations from the three simulations were almost equal (177.6 mg/L). The biggest observed variation occurred during the middle of the rainy season (August) when TDS slightly increased when the inflow *NC-PO₄-P* levels were increased 50% but this change was not significant because it represents less than a 0.1% change. Also, this TDS change can be more attributed to streamflow variations than inflow *NC-PO₄-P* concentration changes.

After analyzing Chl-A profiles, total algal concentration, and other water quality plots by increasing/decreasing *NC-PO₄-P* as a nutrient, I decided to focus my analysis on changes in nitrogen concentration based on my findings and other studies of tropical reservoirs (Lind *et al.*

1992; Lewis Jr 2000; Rahman *et al.* 2005). I studied potential nitrogen changes by modifying inflow nitrate-nitrite ($NC-NO_3-NO_2$) concentrations as the main sources of nitrogen in Aguamilpa.

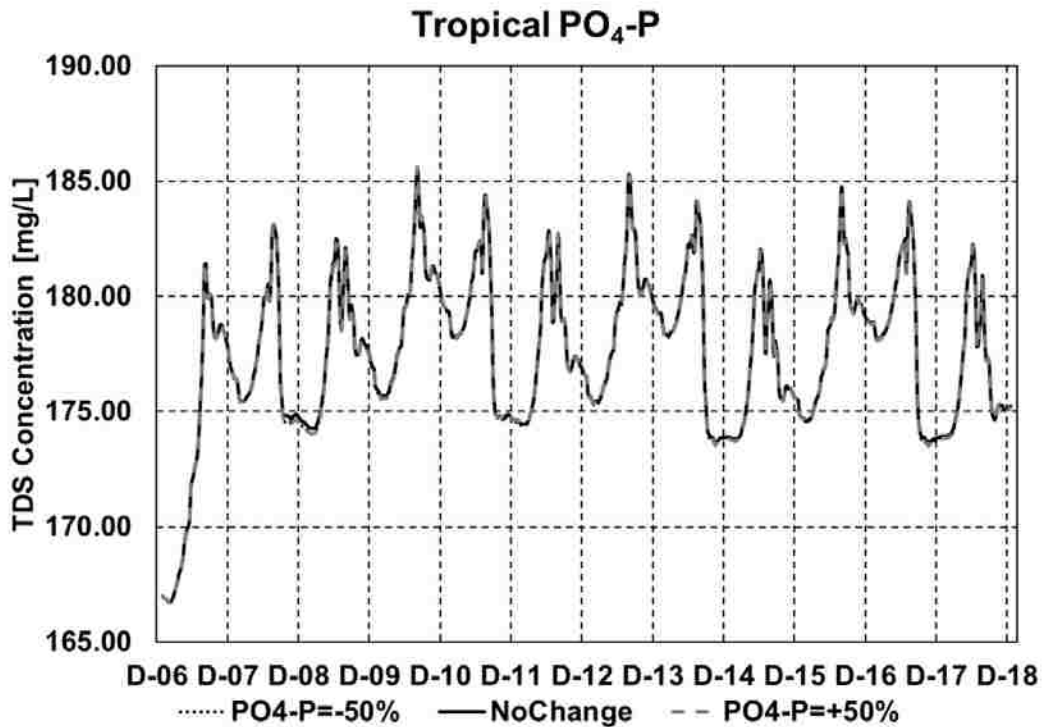


Figure 4-38: Total Dissolved Solids Concentration in Aguamilpa by Altering $NC-PO_4-P$

4.4.3.6 Chl-A Profiles ($NC-NO_3-NO_2-N$)

According to Chapman (1996) nitrogen is a basic nutrient (together with phosphorous) for living organisms, both are a constitute source for building proteins. Nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) are the usable forms in which nitrogen is found in natural waters. NO_3-N and NO_2-N (biochemically reduced from NO_3-N) are used to determine the level of nitrogen available as a nutrient in surface water and are also used as indicator of organic pollution, generally produced by urban untreated wastewater discharges or runoff containing

high concentration of inorganic nitrate fertilizers (Wetzel 2001). $\text{NO}_3\text{-N}$ enhances nutrient eutrophication and algal blooms and is mostly consumed in the upper layers of the water column when there is a high productivity of phytoplankton (Reddy and ebrary 2005). Based on this, I modified inflow $\text{NO}_3\text{-NO}_2\text{-N}$ concentrations to evaluate impacts from $\text{NO}_3\text{-NO}_2\text{-N}$ in Aguamilpa. Similar to the $\text{NC-PO}_4\text{-P}$ evaluations, I used Chl-A concentration profiles to assess the effects produced by $\text{NC-NO}_3\text{-NO}_2\text{-N}$ changes in the deepest zone of Aguamilpa (near the dam sampling site). I did not observe significant impacts from $\text{NC-NO}_3\text{-NO}_2\text{-N}$ changes on Chl-A concentration profiles (Figure 4-39A, B, and C). Figure 4-39A shows that there was a slight decrease of Chl-A concentration when $\text{NC-NO}_3\text{-NO}_2\text{-N}$ was decreased 50%. A contrary effect is observed in Figure 4-39B, when peak Chl-A concentrations were both higher for $\pm 50\%$ $\text{NC-NO}_3\text{-NO}_2\text{-N}$ simulation compared to the base model. I observed that Chl-A peak concentrations increased when $\text{NC-NO}_3\text{-NO}_2\text{-N}$ was increased 50%, reaching a peak Chl-A concentration of 38 $\mu\text{g/L}$ compared with the peak concentration of 26 $\mu\text{g/L}$ and 37 $\mu\text{g/L}$ for the -50% $\text{NC-NO}_3\text{-NO}_2\text{-N}$ simulation and base model, respectively. These Chl-A profiles are confusing and not conclusive because they can be affected by other environmental variables such as wind forces. I used global reservoir indicators similar to previous evaluations. These included: normalized total algal concentration, normalized total DO concentration, normalized total $\text{PO}_4\text{-P}$ concentration, and normalized total TDS concentration. These quantifications are described in the following sections.

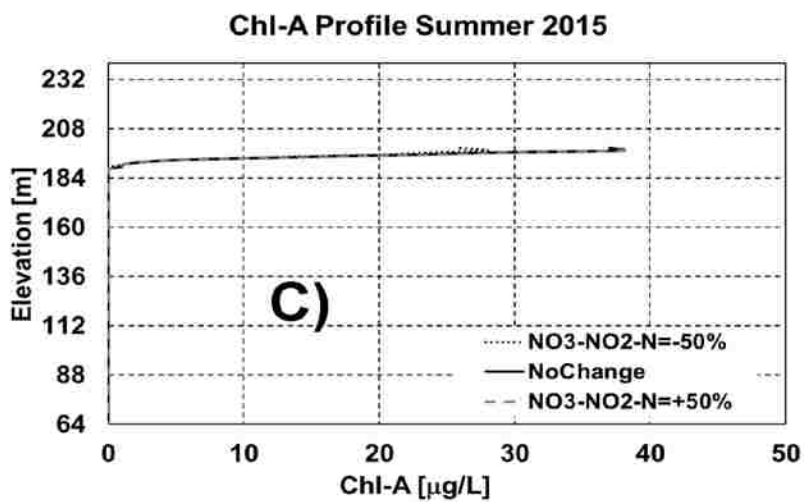
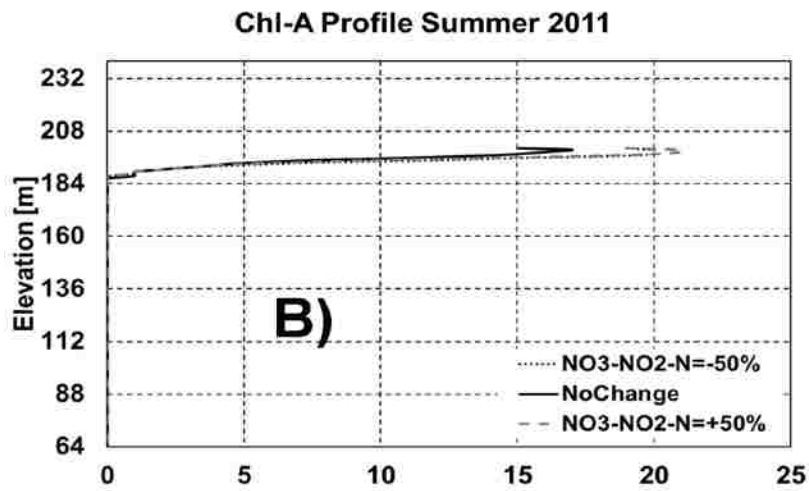
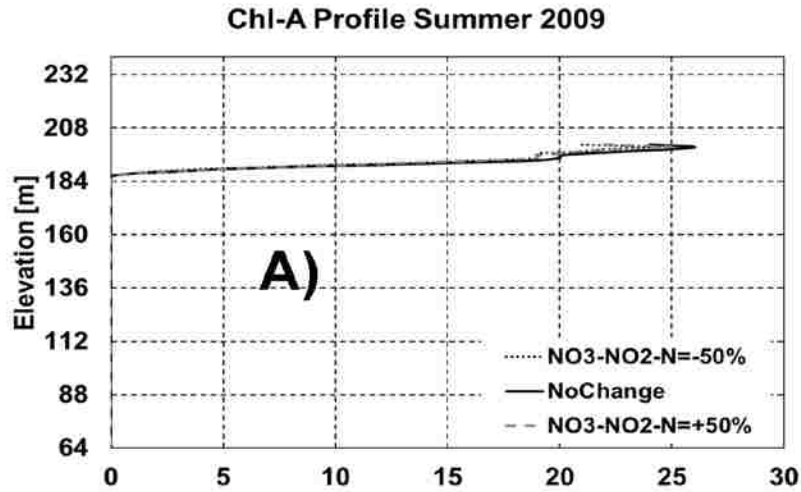


Figure 4-39: Chl-A Profiles at the Near Dam Sampling Point in Aguamilpa by Adjusting $NC-NO_3-NO_2-N$ for A) June 2007; B) June 2011; and C) June 2015

4.4.3.7 Total Algal Concentration ($NC-NO_3-NO_2-N$)

During the time that Aguamilpa turns over (December-March) of each year, total normalized algal concentration did not vary when $NC-NO_3-NO_2-N$ concentration were increased/decreased 50%. Immediately after this mixing period ended while the reservoir stratified (Figure 4-19), I observed that total algal concentration started increasing, compared to the base case, reaching the peak concentration of approximately 0.59 mg/L for the +50% $NC-NO_3-NO_2$ simulation during the end of the warm dry season (May-June). It is noticeable (Figure 4-40) that total algal concentration considerably increased when inflow $NC-NO_3-NO_2$ was increased 50% and decreased when $NC-NO_3-NO_2$ was decreased 50%. This trend particularly occurred during spring and summer of each simulated year. Figure 4-40 indicates that Aguamilpa, a tropical reservoir, was more sensitive to changes in $NC-NO_3-NO_2-N$ than in $NC-PO_4-P$, suggesting that algae growth is limited by nitrogen.

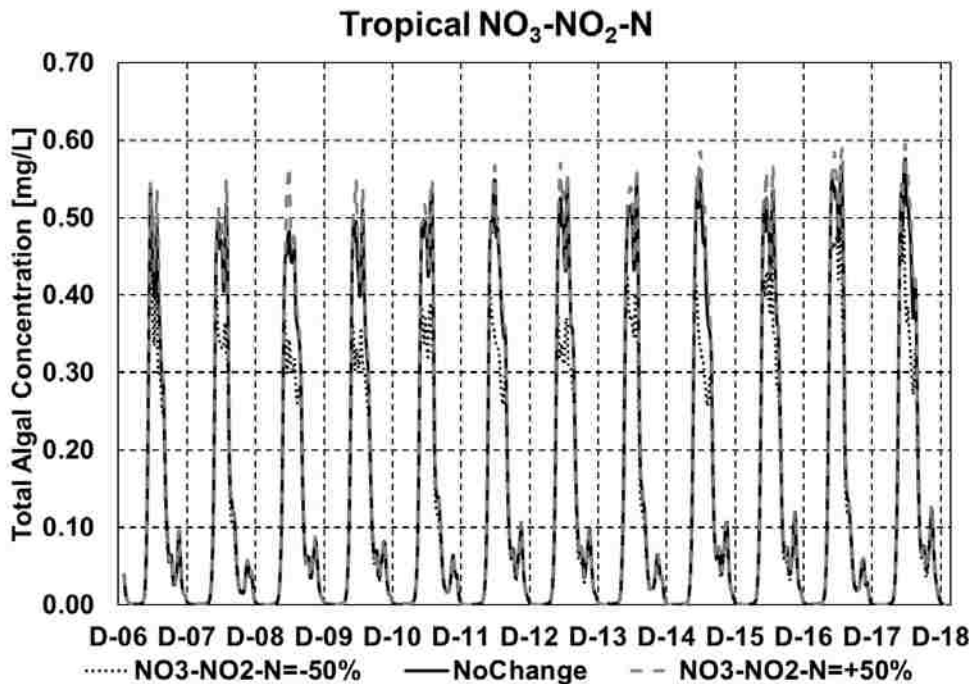


Figure 4-40: Total Algal Concentration in Aguamilpa by Adjusting $NC-NO_3-NO_2-N$

I also used Figure 4-41 to evaluate the difference of total algal concentration between $\pm 50\%$ $NC-NO_3-NO_2-N$ simulations and the base model. This delta plot confirmed that total algal concentration in Aguamilpa is highly affected by $NC-NO_3-NO_2-N$ changes, mostly during dry conditions in the area. The largest observed difference of total algal concentration represents an approximately -40% change caused by decreasing 50% $NC-NO_3-NO_2-N$ concentrations and +19% change caused by the +50% $NC-NO_3-NO_2-N$ simulation.

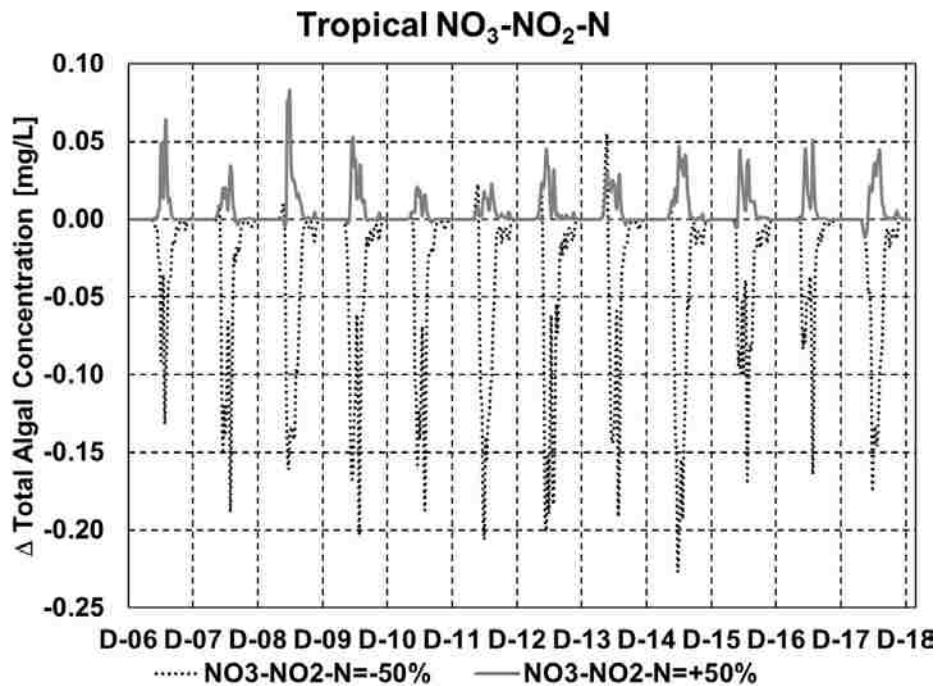


Figure 4-41: Difference of Total Algal Concentration in Aguamilpa Reservoir by Altering $NC-NO_3-NO_2-N$ Compared to the No-Change Simulation

4.4.3.8 Total Average DO Concentration ($NC-NO_3-NO_2-N$)

Figure 4-42 shows how total normalized DO concentration changed when $NC-NO_3-NO_2-N$ concentration was altered 50%. I observed that total normalized DO concentration trended to increase when $NC-NO_3-NO_2-N$ was decreased 50% and decrease for the -50% $NC-NO_3-NO_2-N$

simulation compared to my base model (No-Change). This trend was more pronounced during the mixing period of each modeled year (December-April) when the reservoir was re-oxygenated.

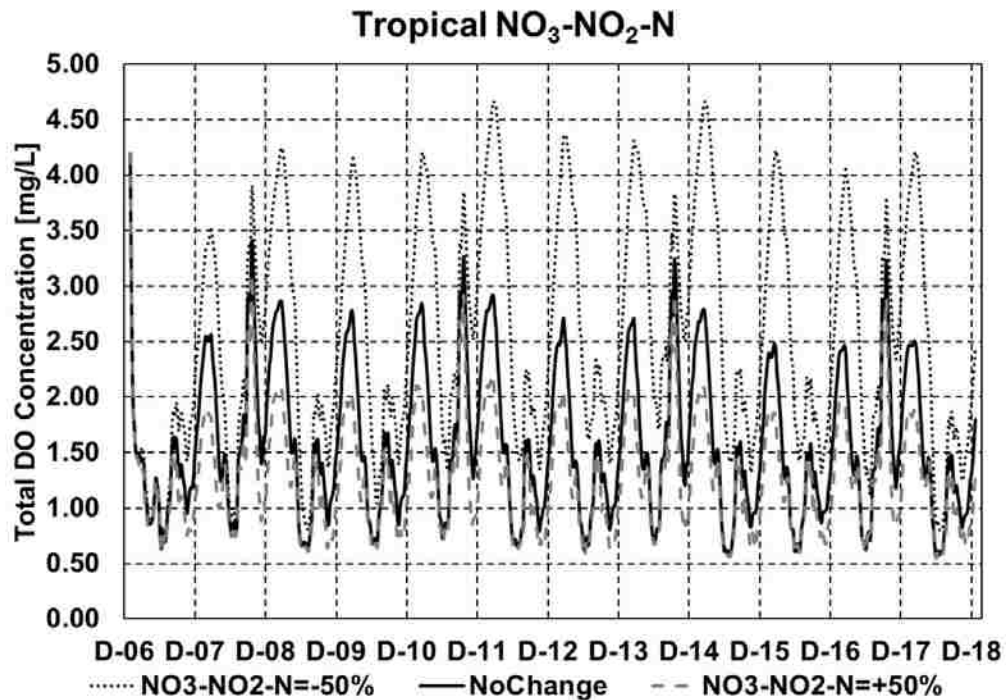


Figure 4-42: Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-NO_3-NO_2-N$

Also, the total DO concentration showed the same inclination during anoxic conditions ($DO < 1.0 \text{ mg/L}$), normally occurring on mid-summer (July) of each modeled year. It is important to note that the total normalized DO concentration plot (Figure 4-42) is correlated to the total normalized algal concentration (Figure 4-40). Total DO concentration decreased when total algal concentration showed higher values (June-July). This correlation occurred when the reservoir was stratified (Figure 4-19) suggesting that ammonium (NH_4) concentrations could become the main source of nitrogen for algae growth due to denitrification processes. Figure 4-43 shows the difference of total DO concentration among the $\pm 50\%$ $NC-NO_3-NO_2$ simulations

and the base model following the same trends observed in Figure 4-43. Both plots serve to explain how DO concentrations are related to $NC-NO_3-NO_2$ concentrations produced by nitrification processes in the reservoir.

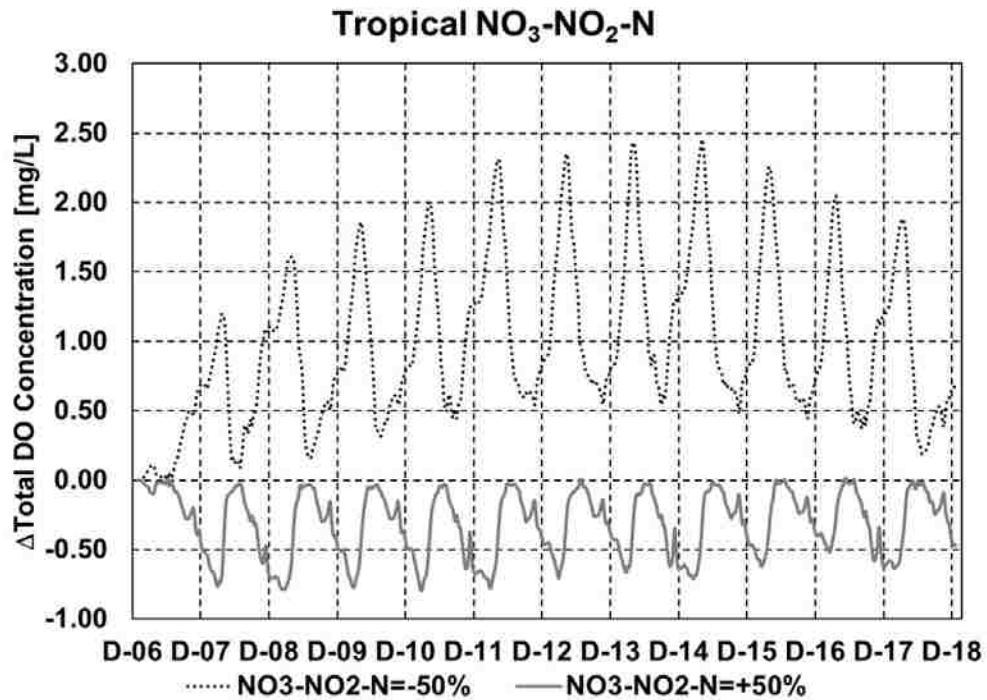


Figure 4-43: Difference of Total Dissolved Oxygen Concentration in Aguamilpa by Altering $NC-NO_3-NO_2-N$

4.4.3.9 Total Nutrients Concentration ($NC-NO_3-NO_2-N$)

In order to evaluate the effects of changing $NC-NO_3-NO_2-N$ concentration on Aguamilpa reservoir nutrients, I used total normalized PO_4-P concentration and total normalized NO_3-NO_2-N concentration plots. Because the total NO_3-NO_2-N concentration plots show the same trend as the inflow 50% $NC-NO_3-NO_2-N$ concentration change, I do not present these plots. Figure 4-44 displays total PO_4-P concentration results from changing inflow $NC-NO_3-NO_2$ by 50%. This change did not affect total PO_4-P concentration. Even though Figure 4-45 shows a change in the

difference of total $\text{PO}_4\text{-P}$ concentration of the 50% $\text{NC-NO}_3\text{-NO}_2$ simulations and base model, this change does not represent more than 0.25%.

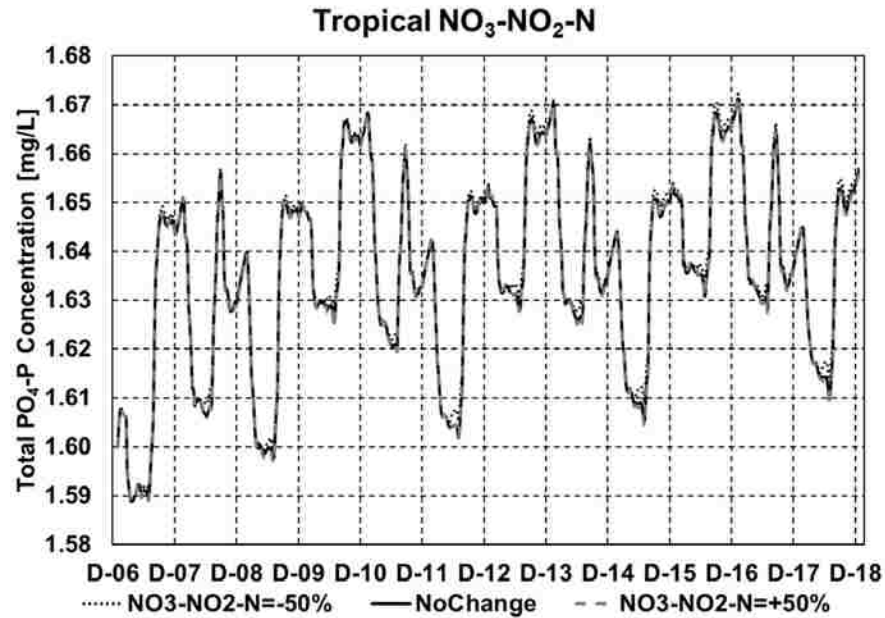


Figure 4-44: Total Phosphate as P Concentration in Aguamilpa by Changing $\text{NC-NO}_3\text{-NO}_2\text{-N}$

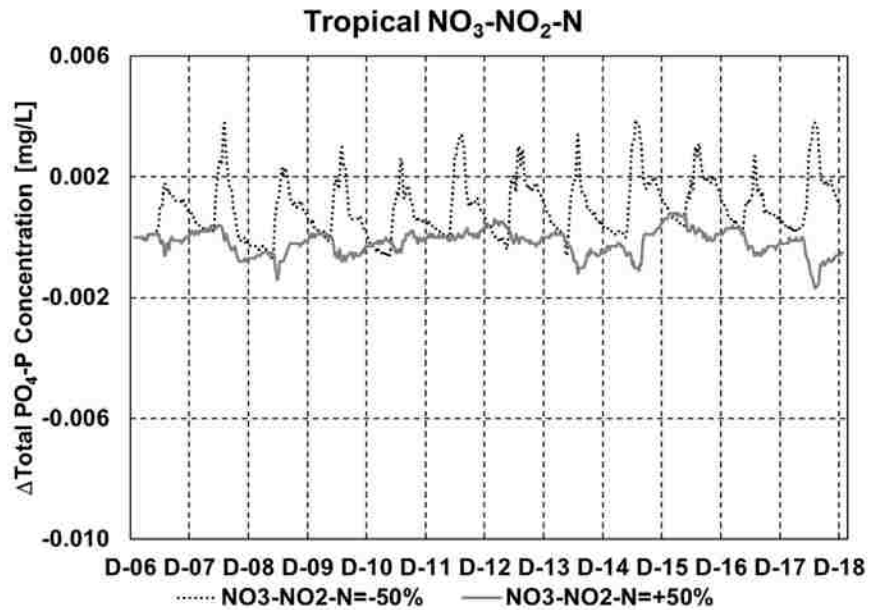


Figure 4-45: Difference of Total Phosphates as P Concentration in Aguamilpa by Altering $\text{NC-NO}_3\text{-NO}_2\text{-N}$

4.4.3.10 Total TDS Concentration ($NC-NO_3-NO_2-N$)

Like in $NC-PO_4-P$ concentration changes (Figure 4-38), $NC-NO_3-NO_2$ variations did not produce effects in TDS levels in Aguamilpa (Figure 4-46). This evaluation was confirmed by comparing the difference of TDS from the $\pm 50\%$ $NC-NO_3-NO_2$ simulations to the base model (No-Change). There were some small fluctuations that do not exceed 0.15% of the difference, indicating that total $NC-NO_3-NO_2$ concentrations changes do not affect the total TDS concentrations in Aguamilpa.

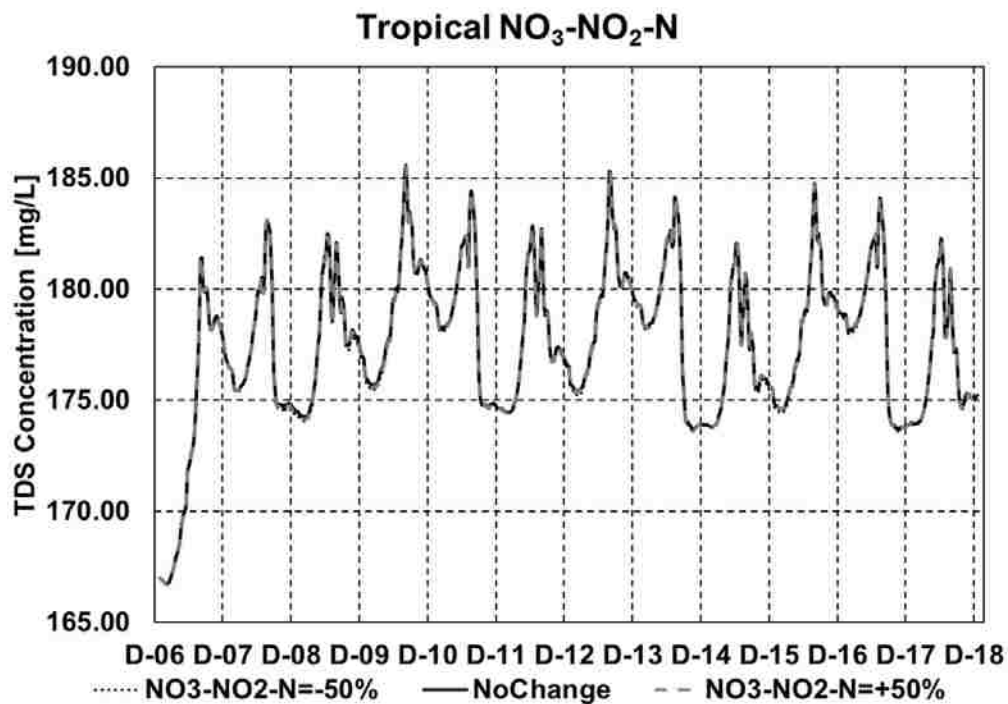


Figure 4-46: Total Dissolved Solids Concentration in Aguamilpa by Changing $NC-NO_3-NO_2-N$

4.4.4 Aguamilpa-Conclusions

The most significant change that I observed in Aguamilpa occurred when I increased and decreased the inflow nitrate-nitrite as nitrogen (NO_3-NO_2-N) concentrations by 50% (Figure

4-41). Total algal concentration decreased when NO_3-NO_2-N was decreased, and increased when NO_3-NO_2-N was increased during the spring-summer seasons (March- July). I also increased and decreased phosphates as phosphorous (PO_4-P) but the total algal concentration did not vary (Figure 4-32). This indicates that the algal growth is not limited by increased inflow of PO_4-P into Aguamilpa but is limited by and sensitive to NO_3-NO_2-N inflows.

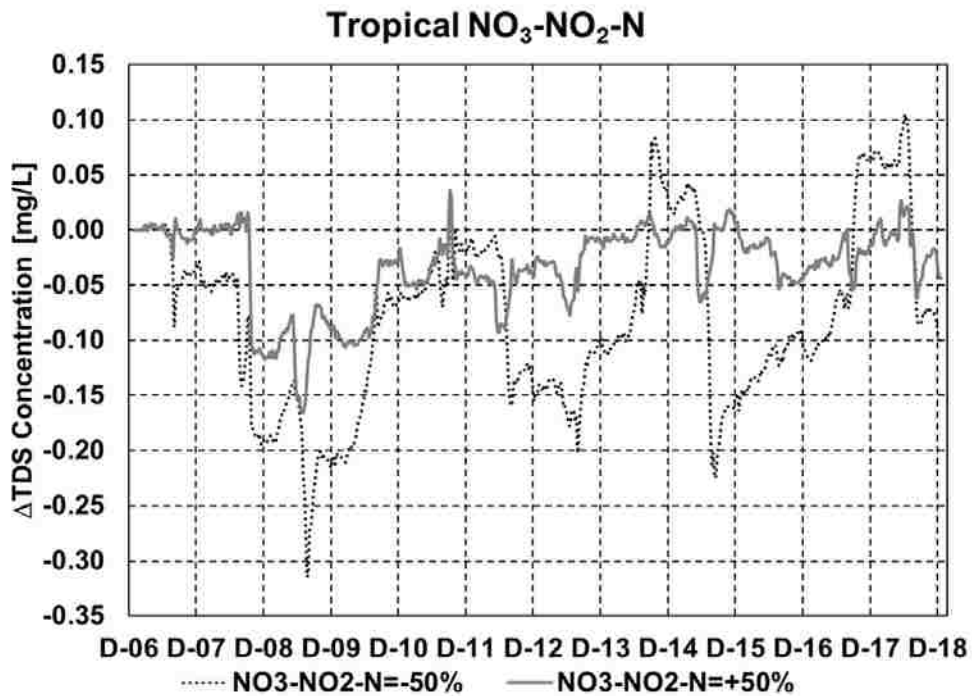


Figure 4-47: Difference of Total Dissolved Solids Concentration in Aguamilpa by Changing $NC-NO_3-NO_2-N$

I assessed potential climate change effects in Aguamilpa, a large tropical reservoir, by using a W2 water quality and hydrodynamic model. My findings suggested that climate changes predicted by IPCC (2007) and Conde *et al.*, (2008) could mainly impact the Aguamilpa system during the warm dry season (March-June) and the beginning of the cold dry season (November). Through these two periods, the $+3^{\circ}C$ T_{AIR} change showed significant effects in Aguamilpa using indicators such as increased total normalized algal concentration peaks. However, at the

beginning of the rainy season (June), the total normalized algal concentration trends were reversed showing increases for the -3°C T_{AIR} simulation. These findings show that total algal normalized concentration in Aguamilpa is more affected by flow and nutrient changes than T_{AIR} alterations. Yet, the T_{AIR} increase produced earlier, longer and stronger stratification periods. This longer and stronger stratification will likely deplete oxygen concentration (anoxic conditions) in the deep water of Aguamilpa affecting its water quality, such as has occurred in other tropical deep reservoirs (Chapman 1996; Lewis Jr 2000; Rahman *et al.* 2005).

The simulated $\text{NO}_3\text{-NO}_2\text{-N}$ changes produced the most significant effects in time-varying total normalized algal concentrations in the reservoir. I found that $\text{NO}_3\text{-NO}_2\text{-N}$ is the limiting nutrient for algal growth in Aguamilpa. Total algal concentrations may increase with more intense droughts during the warm dry season. These changes can cause the proliferation of harmful algal groups such as blue-green or cyanobacteria blooms that may affect human health as Paerl and Huisman (2009) reported in their studies. However, these GCC effects can be mitigated by implementing good reservoir operations and BMP's in the surrounding watersheds. These operations and practices should include withdrawal control from upstream reservoirs (i.e., El Cajon and La Yesca) and Aguamilpa itself. Also, it is necessary to design and implement plans to control nonpoint source pollution. These sources, coming from surface runoff, precipitation or hydrologic modification, can contribute to $\text{NO}_3\text{-NO}_2\text{-N}$ input and, when combined with extreme drought and higher temperatures, will make Aguamilpa a likely candidate for more dangerous algae groups to deplete its water quality. I compared the results I obtained for Aguamilpa to results from long-term model for Deer Creek Reservoir, a temperate reservoir located in Utah, United States to evaluate how two contrasting reservoirs are affected by GCC (Chapter 5).

5 GCC EFFECTS IN TEMPERATE VS TROPICAL RESERVOIR

In this chapter I explain similar and different impacts to both reservoirs (Temperate vs. Tropical) produced by GCC. For this comparison, I evaluated worst case scenarios of climate change in Deer Creek and Aguamilpa reservoirs by modeling extreme hydrological, water quality and climatic conditions. I based my analysis on GCC projections for Utah (USA) and Nayarit (Mexico) together with my results obtained from the 2007-2009 simulation for Deer Creek (Chapter 3) and the 12-year Aguamilpa model (Chapter 4), respectively. I extended the existing two-dimensional water quality and hydrodynamic model for Deer Creek to 11 years (2000-2011) for my evaluation. Data collection, estimation and generation of missing values were processed to extend, calibrate and validate the long-term Deer Creek model. The extended Deer Creek model was not a replicate of the first three years, but uses base data from the entire 11-year period. Air temperatures (T_{AIR}), inflows (Q), phosphorous (PO_4 -P) loadings, and worst case scenarios were the changes that I made to represent GCC effects in Deer Creek. In this chapter I used the results obtained from worst case scenarios simulated for Aguamilpa and compared them to Deer Creek's results.

Unlike the 2007-2009 Deer Creek and the 12-year Aguamilpa model simulations where I used Chl-A profiles and total algal concentration as indicators of GCC effects, for this comparison I calculated the difference or delta of the total normalized parameter indicator concentration from each simulated scenario and the No-Change simulation. This allowed

comparison of the two dissimilar reservoirs and what I compared was the percent change from the base case. I also included the difference of the total normalized parameter indicator concentration for hourly discharge downstream from the dams of both reservoirs and evaluated their differences and similarities.

In the following sections, I present the changes made in the methods used for the long-term Deer Creek model (Section 5.1). Then, I show the results obtained from evaluating T_{AIR} , and Q changes by using the long-term Deer Creek model (Section 5.2). Results obtained by running worst case scenarios for Aguamilpa and GCC effects downstream from the dam are shown in section 5.3.3. Finally, I evaluated differences and similarities of GCC effects between these two contrasting reservoirs, temperate vs. tropical in section 5.4.

5.1 Methods Long-Term Deer Creek Model

I used W2 version 3.6 to evaluate the effects of climate change on Deer Creek's water quality (Cole and Wells 2008). Then, the same methodology used in my preliminary 3-year Deer Creek model (Section 3.2) was followed to create updated input files for this new long-term model (2000-2011) for Deer Creek. Required data to create the W2 input files were obtained from CUWCD, USBOR, Utah Division of Water Quality (UDWD), and EPA-STORET database. Empirical calculations and literature values were applied to interpolate missing observed values. This long-term Deer Creek model was developed in four main steps: 1) Update and extend inputs model, 2) Model calibration and validation, 3) Evaluation of GCC effects and 4) GCC outputs analysis.

5.1.1 Update and Extend Inputs Model

I updated and extended the following inputs for the long-term Deer Creek model: meteorological data, initial conditions and boundary conditions. The bathymetry file was the same as the one developed in Chapter 3 and shown in Figure 3-1C, D and E. I expanded the meteorological input files with hourly T_{AIR} , dew point temperature, wind direction and speed, and solar radiation data from Snake Creek climatological station (Dr. Reed Y. Oberndorfer-CUWCD, personal communication, Sep 21, 2011). Cloud cover data was not available from the Snake Creek station, thus I used cloud cover data from a climatological station located at the Salt Lake City International Airport. The initial conditions used to create the long-term Deer Creek W2 model were defined by using the characteristics of Deer Creek Reservoir reported in PSOMAS (2002), from a USBOR document (Nicholas T. Williams, Deer Creek Dam CFR Description of Dam and Operations-unpublished manuscript, 2011), and observed values. Boundary conditions included water temperature, hydrologic inputs, and inflow water quality. The distributed files were constructed by using observed-collected data and computed values. The distributed files represent the ungauged data (inflow and outflows) along the reservoir (Cole and Wells 2008).

5.1.2 Long-Term Deer Creek Model Calibration/Validation

The long-term Deer Creek W2 model (11 years) was calibrated by using the same hydrodynamic and water quality parameters that I used for my preliminary 3-year model (Chapter 3, Section 3.2.3): water balance, temperature, TDS, dissolved oxygen (DO), phosphates (PO_4 -P) and Chl-A. The field data that I used for model calibration and validation were collected by CUWCD and the BYU research group from the sampling points shown in Figure 3-1B for the 2000-2011 period. Field algae data were obtained from a study prepared by Rushforth Phycology Laboratory (Rushforth, S.R., and Rushforth, S.J., A Study of

Phytoplankton Floras from Deer Creek Reservoir Wasatch County, Utah 2005-unpublished manuscript, April 2006). I also adjusted the coefficients recommended by Cole and Wells (2008) to calibrate and validate the long-term W2 model for Deer Creek. Table 5-1 shows the final calibration coefficients and values used to get the best calibrated/validated model for Deer Creek (11 years simulated). Field data collected in 2002-2004 was used for calibration purposes and data from 2005-2007 was used for validation.

Table 5-1: Calibration Coefficients and Values Used for Long-Term Deer Creek Model

<i>Kinetic Coefficients</i>	<i>Calibration Value</i>
Chezy bottom friction factor ($m^{1/2}/s$)	70
Horizontal eddy viscosity (m^2/s)	1.0
Horizontal eddy diffusivity (m^2/s)	1.0
Light extinction coefficient for background value (m^{-1})	0.3
Algal growth rate (day^{-1})	0.73 ^a , 1.34 ^b , 0.50 ^c
Algal respiration rate (day^{-1})	0.04
Algal excretion rate (day^{-1})	0.04
Algal mortality rate (day^{-1})	0.073 ^a , 0.134 ^b , 0.050 ^c
Algal settling rate (day^{-1})	0.20 ^a , 0.10 ^b , 0.050 ^c
Light saturation intensity at maximum photosynthetic rate (W/m^2)	86 ^a , 24 ^b , 20 ^c
Algal half-saturation for phosphorous limited growth (mg/L)	0.047 ^a , 0.050 ^b , 0.030 ^c
Algal half-saturation for nitrogen limited growth (mg/L)	0.014 ^a , 0.014 ^b , 0.000 ^c
Ammonium nitrification rate (day^{-1})	0.03
Nitrate denitrification rate (day^{-1})	0.50
Sediment oxygen demand ($g\ m^{-2}\ day^{-1}$)	1.70 (segment average)

a Diatoms, *b*. Greens, *c*. Cyanophyta

5.1.3 Evaluation of GCC Effects (Long-Term Deer Creek Model)

The calibrated-validated model was used to evaluate the GCC effects in Deer Creek through first separately modifying meteorological, hydrological and water quality conditions and then evaluating combined cases by running worst case scenarios (WCS's): 1) Low flow, high

PO₄-P and high T_{AIR} ; and 2) High flow, high PO₄-P and high T_{AIR} . First, I increased/decreased T_{AIR} by 3 °C. Second, I evaluated the in-reservoir effects caused by low (-10%) and high flows (+10%) produced by more severe droughts and storms. Then, based on my preliminary 3-year model (Chapter 3) in which I observed that PO₄-P is the limiting nutrient in Deer Creek, I decided to only analyze changes in PO₄-P (±50%) as previous work showed that nitrogen had limited impacts.

5.1.4 GCC Outputs Analysis (Long-Term Deer Creek Model)

I used the difference of total normalized parameter concentration indicators (i.e., algae, DO, and TDS) among the simulated scenarios and the base model to assess GCC impacts on Deer Creek. Total normalized parameter concentration indicator values were used to evaluate the total water quality concentration in whole reservoir (lotic, transitional, and lentic locations). I analyzed the total normalized parameter concentration balance in the reservoir, its potential difference with the base model, and used it as indicator of GCC effects. I used the difference of total normalized parameter concentration discharged downstream from the dam to evaluate GCC downstream effects.

5.2 Results (Long-Term Deer Creek Model)

For this evaluation of the long-term model's performance, I used the same AME statistical evaluator used in previous models (Section 3.2.3 and Section 4.2.3) for five parameters: water temperature, TDS, DO, PO₄-P and Chl-A (Hanna *et al.* 1999). I would like to emphasize that field data collected in 2003-2004 were used for calibration and 2005-2007 data for model validation. The AME values for the long-term Deer Creek model were: 1.08 °C, 13.90

mg/L, 1.27 mg/L, 9.00 µg/L, and 4.20 µg/L, for water temperature, TDS, DO, PO₄-P and Chl-A, respectively.

In my simulations, meteorological and hydrological effects were assessed for Deer Creek. Results obtained from the PO₄-P changes simulations by using the long-term Deer Creek model showed similar trends to my preliminary 3-year model (Section 3.4.3). This indicates that PO₄-P changes have the highest impact in total normalized algal concentration in Deer Creek. Also, together with the PO₄-P changes simulations, I present T_{AIR} and flow evaluations separately first and then combined as worst scenario.

5.2.1 Long-Term Deer Creek Model: T_{AIR} Changes

5.2.1.1 Δ Total Algal Concentration-Deer Creek (T_{AIR} Changes)

I began my analysis by comparing the calibrated-validated model (base long-term model) to the $\pm 3^{\circ}\text{C}$ T_{AIR} simulations. Figure 5-1 shows the difference of total normalized algal concentration for the $\pm 3^{\circ}\text{C}$ T_{AIR} simulations with the base model. It was necessary to ignore the first modeled year (2000) to let the model have a spin up period because Deer Creek presents an average residence time of 242 days. This spin up period allows the model to get beyond the influence of initial conditions as it responds to the changed inflow and meteorological forcing functions.

I observed that the general trend in Figure 5-1 presents an increase in total normalized algal concentration when T_{AIR} was decreased 3°C and a decrease when T_{AIR} was increased 3°C . The highest changes occurred during spring-summer season reaching peak differences of +0.04 mg/L (~53% change) and -0.03 mg/L (~32% change) for -3°C and $+3^{\circ}\text{C}$ T_{AIR} simulations respectively. These results indicate that algae species succession and the dominance of algae

species can occur in Deer Creek due to the projected increase in T_{AIR} because as summer stratification progresses and water temperatures increase, diatoms groups will be lower as they are replaced by warmer-water groups such as green algae.

However, for the 2008-2009 years, the general trend was different showing higher increments in delta total algal concentration for the $+3^{\circ}\text{C}$ T_{AIR} plot than the -3°C T_{AIR} plot. These contradictory changes could be caused by the different hydraulic retention times that Deer Creek experienced when the reservoir reached its lowest level caused by the construction work in 2008 and early 2009 (PRWUA 2009).

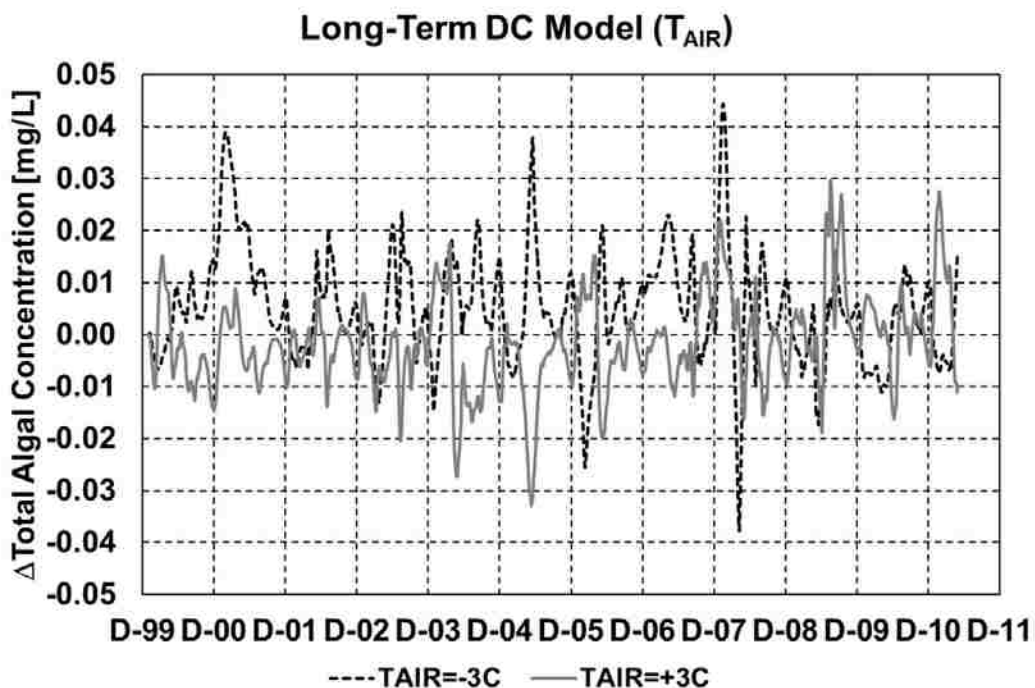


Figure 5-1: Difference of Total Algal Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model

In order to evaluate the effects of T_{AIR} changes downstream of Deer Creek, I used delta total normalized algal concentration hourly discharged from the dam (Figure 5-2). I observed similar general trends as illustrated in Figure 5-1. However, there were times when the

difference of algal concentration released downstream of the dam was higher for the $+3^{\circ}\text{C } T_{AIR}$ simulation than the $-3^{\circ}\text{C } T_{AIR}$ simulation. This reversal was most apparent right before the reservoir's fall turn over (October-November).

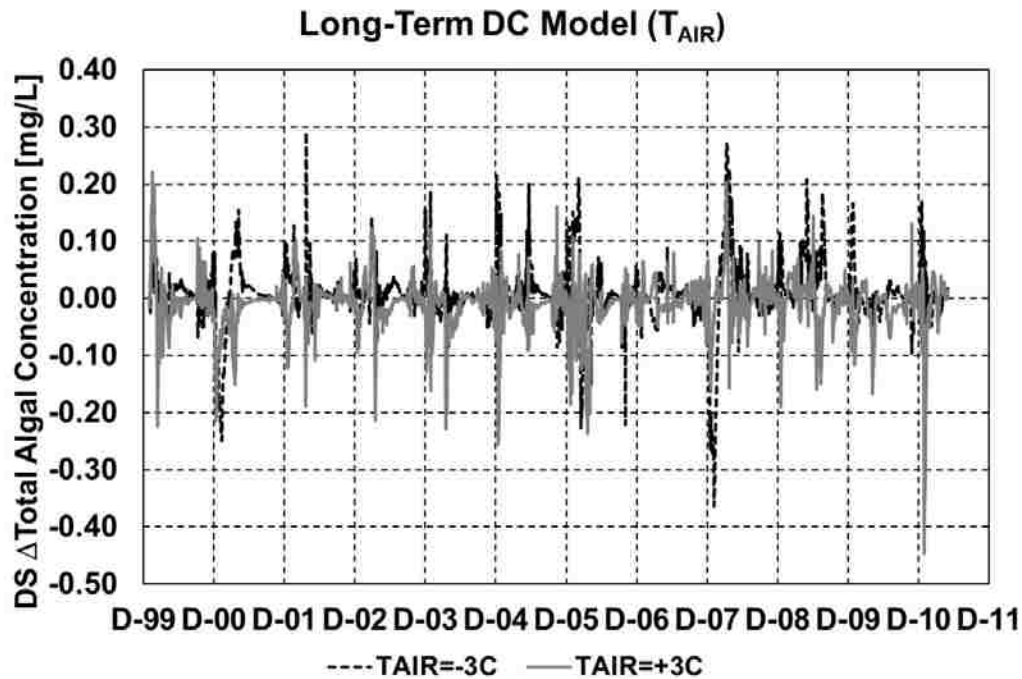


Figure 5-2: Difference of Total Algal Concentration Downstream from Deer Creek Reservoir (Long-Term) between the $\pm 3^{\circ}\text{C } T_{AIR}$ Simulations and the Base Model

5.2.1.2 Δ Total DO Concentration-Deer Creek (T_{AIR} Changes)

Another indicator used to evaluate GCC effects in Deer Creek is total normalized DO concentration. I compared both $\pm 3^{\circ}\text{C } T_{AIR}$ simulations to my base long-term model by obtaining the difference of total normalized DO concentration in-reservoir and downstream from the Deer Creek dam. Figure 5-3 shows the difference of total DO concentration in Deer Creek after changing T_{AIR} 3°C . The general trend is that total DO concentration decreased when T_{AIR} was increased 3°C and increased for the $-3^{\circ}\text{C } T_{AIR}$ simulation, reaching maximum differences of -0.54

mg/L (~9%) and +0.64 mg/L (~13%), correspondingly. There were times when the general trends were reversed and the +3°C T_{AIR} simulation showed a positive difference of total DO concentration, suggesting that T_{AIR} increase can raise total DO levels in Deer Creek, particularly in March as the reservoir begins to warm. However, this observed reversal in the difference of total DO concentration occurred during the end of winter season and beginning of spring (March-April) when snow starts melting due to the increase of seasonal T_{AIR} . This melting process generates higher flows that directly affect DO concentration in Deer Creek and can be the main cause of this temporal switch.

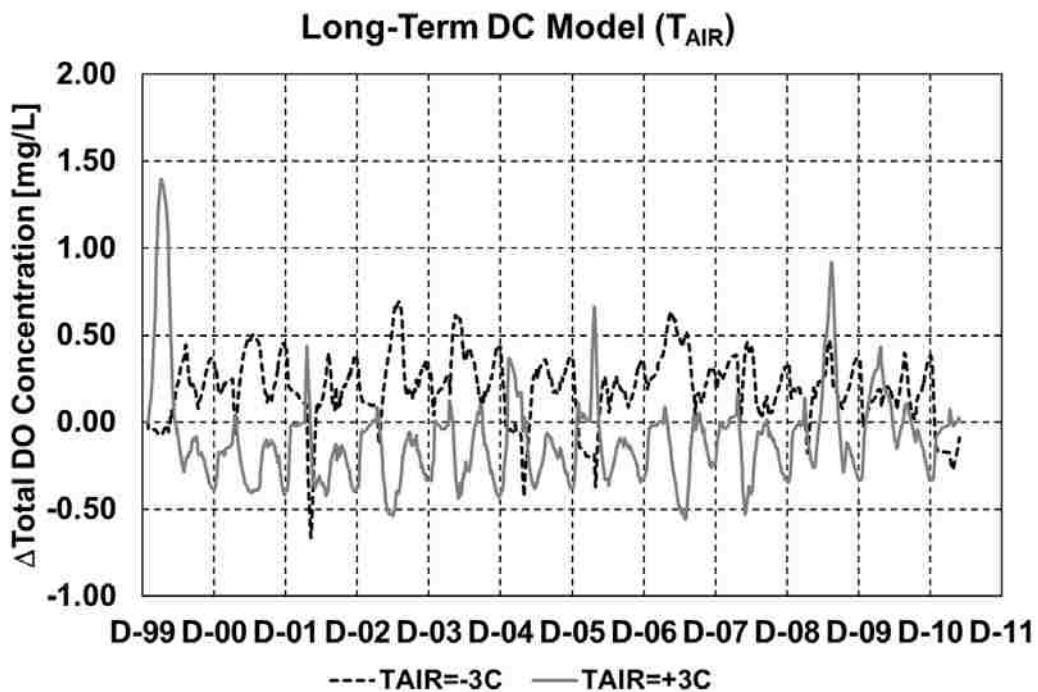


Figure 5-3: Difference of Total Dissolved Oxygen Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C$ T_{AIR} Simulations and the Base Model

Figure 5-4 presents the difference of DO concentration discharged hourly (noon and midnight) downstream from the dam between the $\pm 3^\circ C$ T_{AIR} simulation and the long-term base model. The downstream comparison showed a similar trend to that observed in Figure 5-3 where

the $+3^{\circ}\text{C } T_{AIR}$ simulation decreased the total DO concentration and the $-3^{\circ}\text{C } T_{AIR}$ simulation depleted DO levels discharged downstream of Deer Creek dam. I also observed that the difference of total DO concentration for the last three years (from the last part of 2008 to 2011), were not large. This small difference could be caused by the shorter hydraulic residence times that Deer Creek has experienced due to construction work and controlled seasonal discharges.

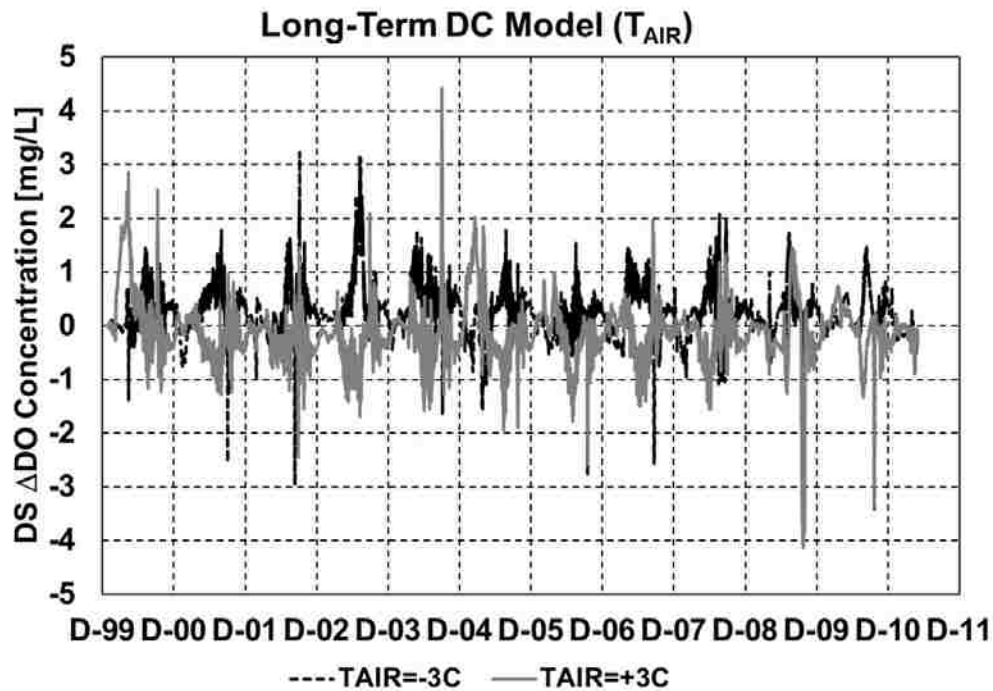


Figure 5-4: Difference of Total Dissolved Oxygen Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 3^{\circ}\text{C } T_{AIR}$ Simulations and the Base Model

5.2.1.3 Δ TDS Concentration-Deer Creek (T_{AIR} Changes)

TDS concentration, which is a physicochemical and temperature sensitive parameter, is another indicator I used to evaluate GCC effects in Deer Creek. I used it because TDS variation is one of the projected effects of GCC in water resources (Means III *et al.* 2010).. Figure 5-5 and Figure 5-6 show the difference of TDS concentration between the $\pm 3^{\circ}\text{C } T_{AIR}$ simulation and the

long-term base model in Deer Creek and concentrations downstream from the dam. Both graphs exhibit similar general trends indicating that TDS concentration increased when T_{AIR} was increased 3°C and decreased for the +3C T_{AIR} simulation. There were some cases where the general trend switched but that could be caused by high seasonal flows. Though, in the case of Figure 5-5 the observed difference of TDS concentration is insignificant because it does not represent a change greater than 2%. For Figure 5-6, I observed that the difference in TDS concentration discharged downstream from the dam is not either significant because it does not exceed the 10% of change.

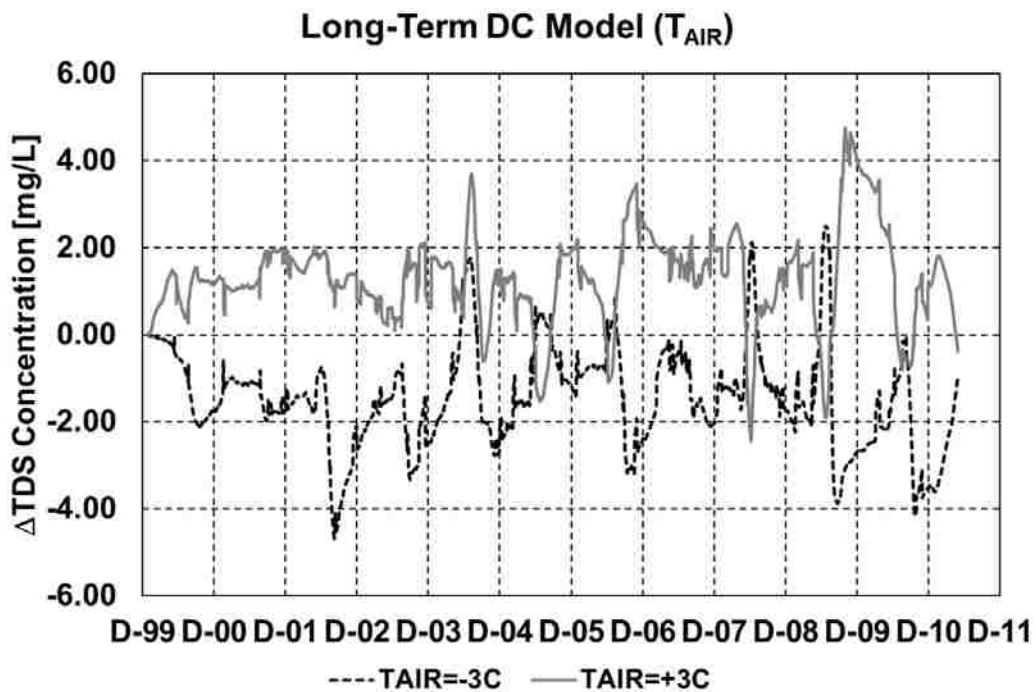


Figure 5-5: Difference of Total Dissolved Solids Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 3^\circ C$ T_{AIR} Simulations and the Base Model

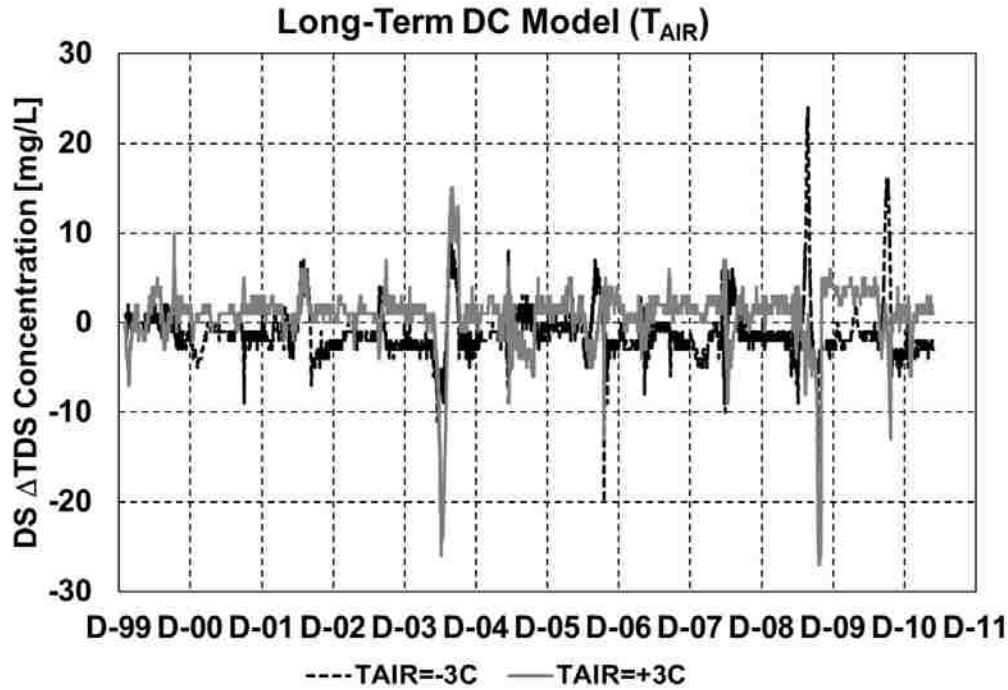


Figure 5-6: Difference of Total Dissolved Solids Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model

5.2.2 Long-Term Deer Creek Model: Inflow Volumes (Q) Changes

5.2.2.1 Δ Total Algal Concentration-Deer Creek (Q Changes)

The next GCC effect included $\pm 10\%$ Q changes representing the projected dry and wet conditions that the reservoir could experience. Figure 5-7 shows the difference in total normalized algal concentration between the $+10\%$ Q simulation, the -10% Q simulation and the long-term base model. These differences exhibited two trends, one for the 2000-2004 period where total algal concentration increased up to 23% when Q was increased 10% and decreased down to 17% for the -10% Q simulation compared to the base model. This initial trend was swapped for the 2005-2011 period where total algal concentration increased for the -10% Q

simulation and decreased for the +10% Q simulation. I observed that the switch coincided with the reduction in the amount of $\text{PO}_4\text{-P}$ flowing into Deer Creek.

Similar to the T_{AIR} simulation, I evaluated Q effects downstream of the dam (Figure 5-8). The difference of algal concentration daily released from the dam showed the same two trends that the reservoir presented in Figure 5-7. This indicates that total algal (diatoms, green and blue-green groups) concentration is still governed by the amount of $\text{PO}_4\text{-P}$ (Figure 5-9) flowing into the reservoir regardless of the flow.

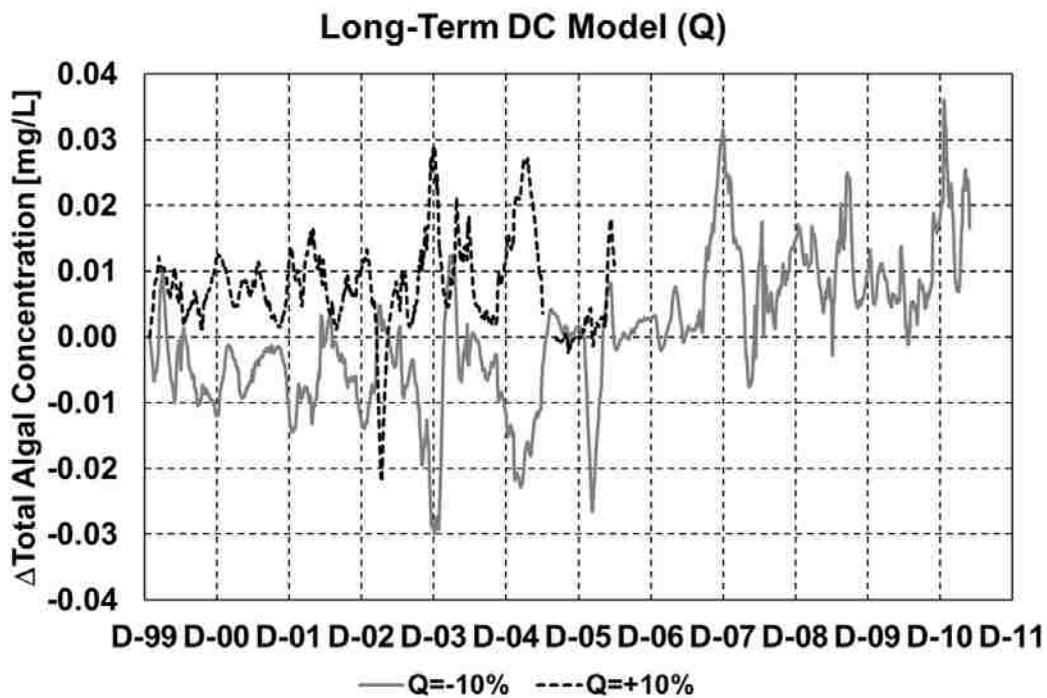


Figure 5-7: Difference of Total Algal Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

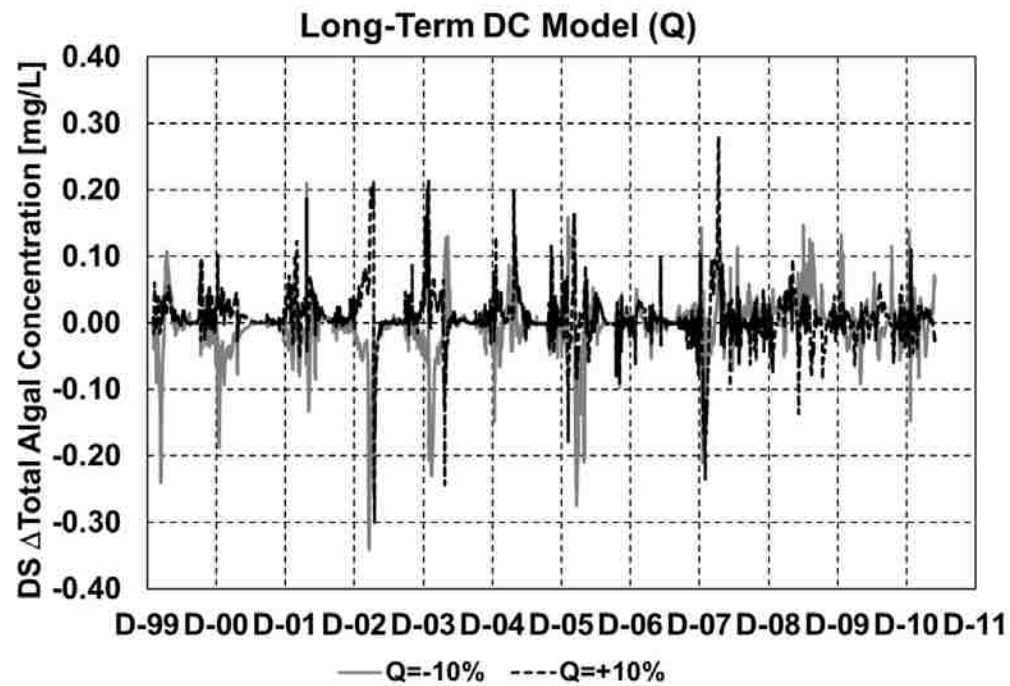


Figure 5-8: Difference of Total Algal Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

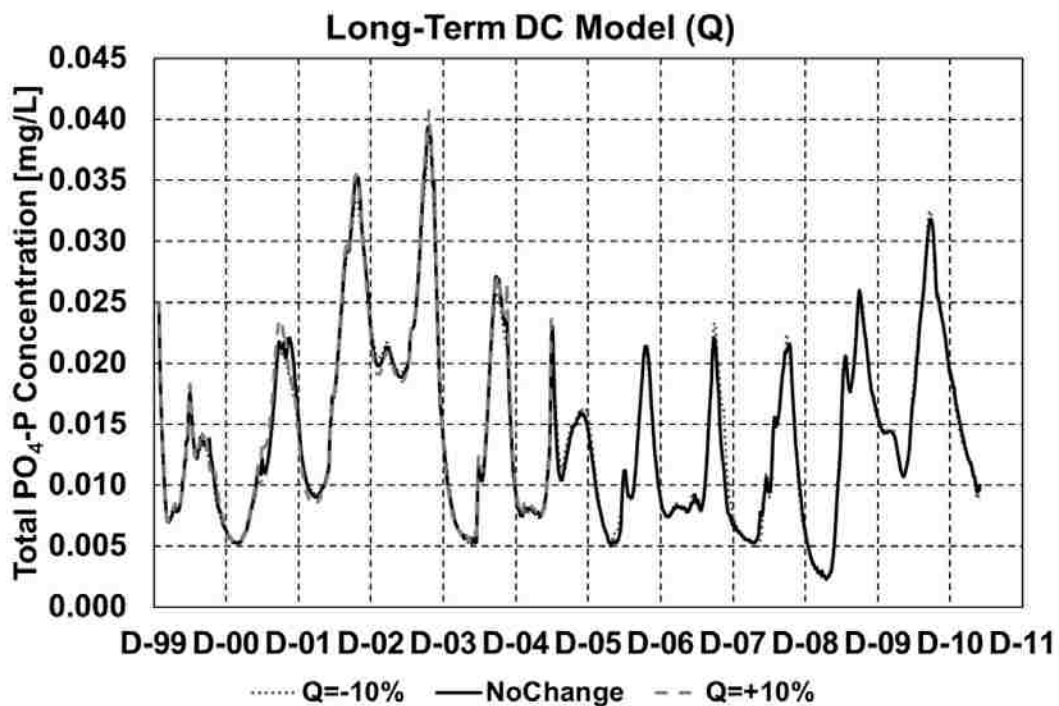


Figure 5-9: Total Phosphates as P Concentration in Deer Creek (Long-Term) by Adjusting 10% Q

5.2.2.2 Δ Total DO Concentration-Deer Creek (Q Changes)

Another indicator of GGC effects by adjusting 10% Q was total normalized DO concentration. Figure 5-10 illustrates the difference of total normalized DO concentration in Deer Creek among the $\pm 10\%$ Q simulations and the long-term base model. In these plots, I observed two main trends: the first goes from 2000 to 2005 and the second includes the 2006-2011 period. The first trend shows the effects of Q changes, indicating that total normalized DO levels are depleted by decreasing 10% Q and raised by increasing 10% Q . There were some points, particularly right before the reservoir turns over (March-April 2004), when total normalized DO concentration was increased for the -10% Q simulation and decreased for the +10% Q simulation. Yet, these variations can be produced by the amount of $\text{PO}_4\text{-P}$ flowing into Deer Creek (Figure 5-9). I did not consider the second trend (2009-2011) for my evaluation because the long-term base model was over-flooded after 2009 and concentrations were not available.

Figure 5-11 displays the difference of DO concentration hourly discharged downstream from the dam. In this plot, I observed the same trends as in Figure 5-10. However, the difference of DO concentration released from the dam was bigger than the difference observed in whole reservoir. This suggests that water with lower DO levels would be discharged from the dam when dry conditions occur potentially affecting aquatic life downstream Deer Creek. Also, I observed that the hourly discharged DO concentration was sometimes higher for the -10% Q simulation than the +10% Q simulation. This switch can be caused by algae photosynthesis that is releasing oxygen.

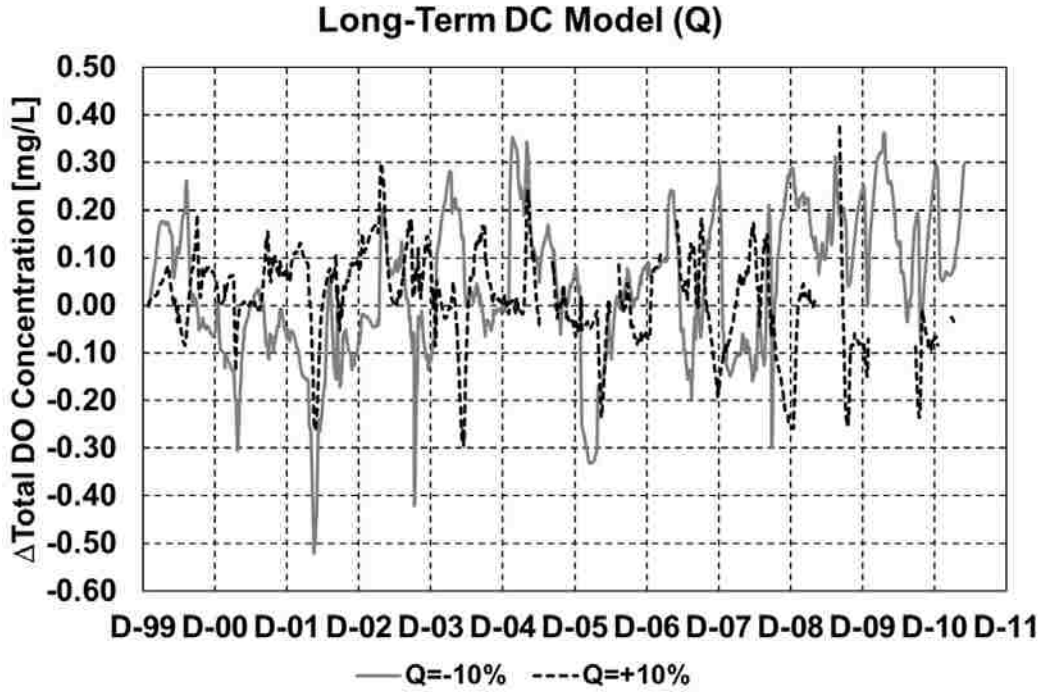


Figure 5-10: Difference of Total Dissolved Oxygen Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

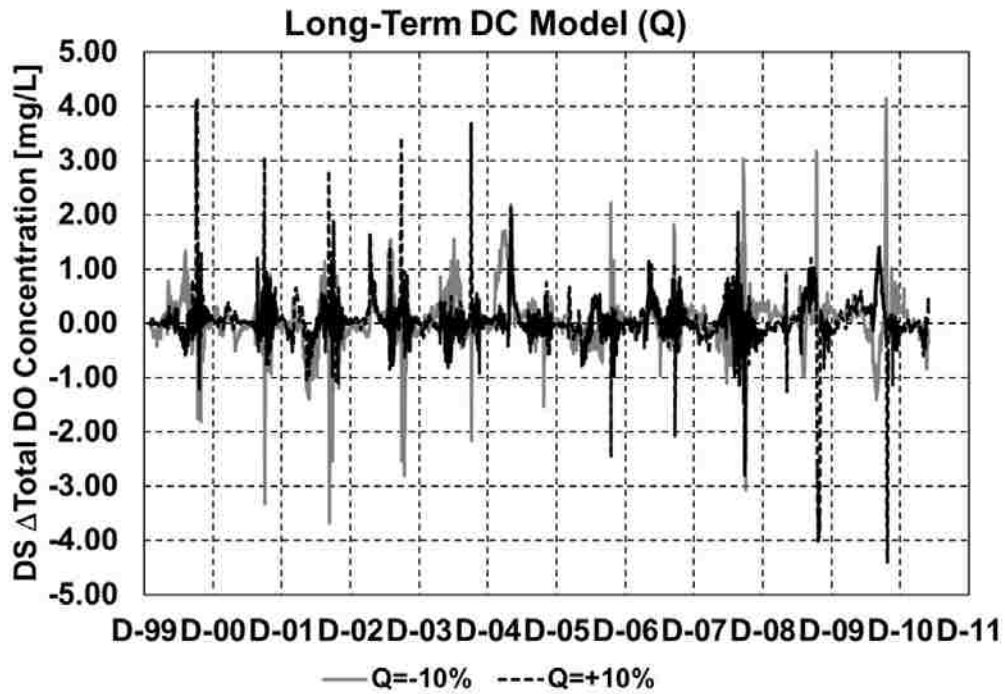


Figure 5-11: Difference of Total Dissolved Oxygen Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

5.2.2.3 Δ TDS Concentration-Deer Creek (Q Changes)

In Figure 5-12 and Figure 5-13, I show the difference of TDS concentration in the entire reservoir and downstream from the dam resulting by altering 10% Q . These two plots used the difference of TDS concentration from both simulations (-10% Q and +10% Q) with the long-term base model (No-Change). Again, I only considered the 2000-2005 period for my analysis because the model was overflowed after 2005. However, these six years point out that TDS was insignificantly affected by 10% Q changes. TDS concentration somewhat decreased when Q was decreased 10% and increased for the +10% Q . These changes approximately represent variation no greater than 2% and 10% for Figure 5-12 and Figure 5-13 respectively.

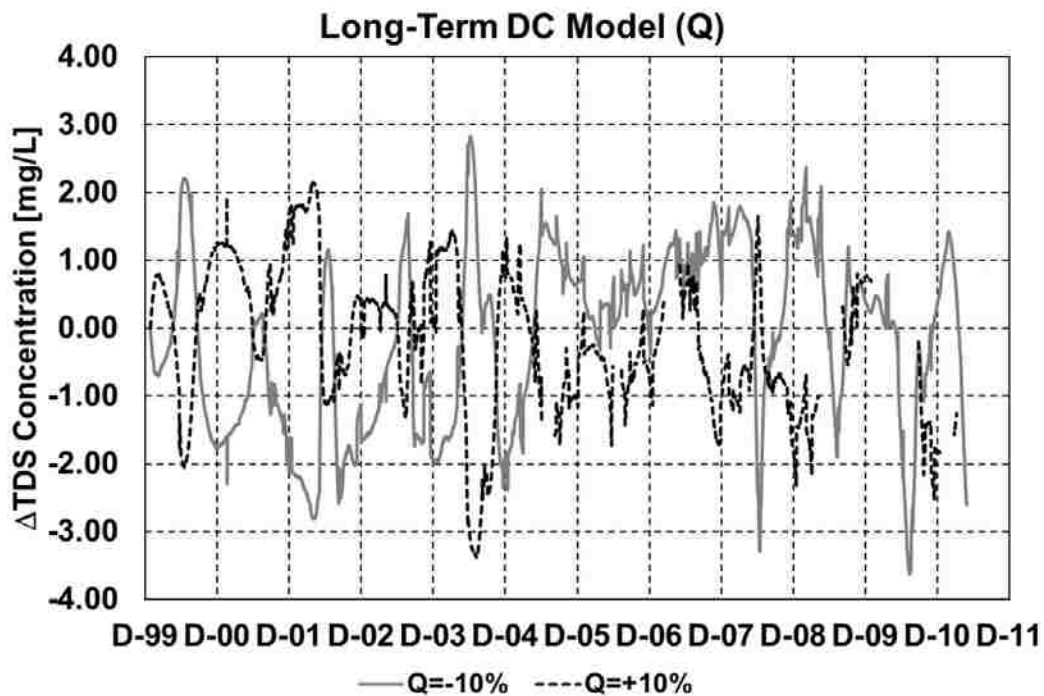


Figure 5-12: Difference of Total Dissolved Solids Concentration in Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

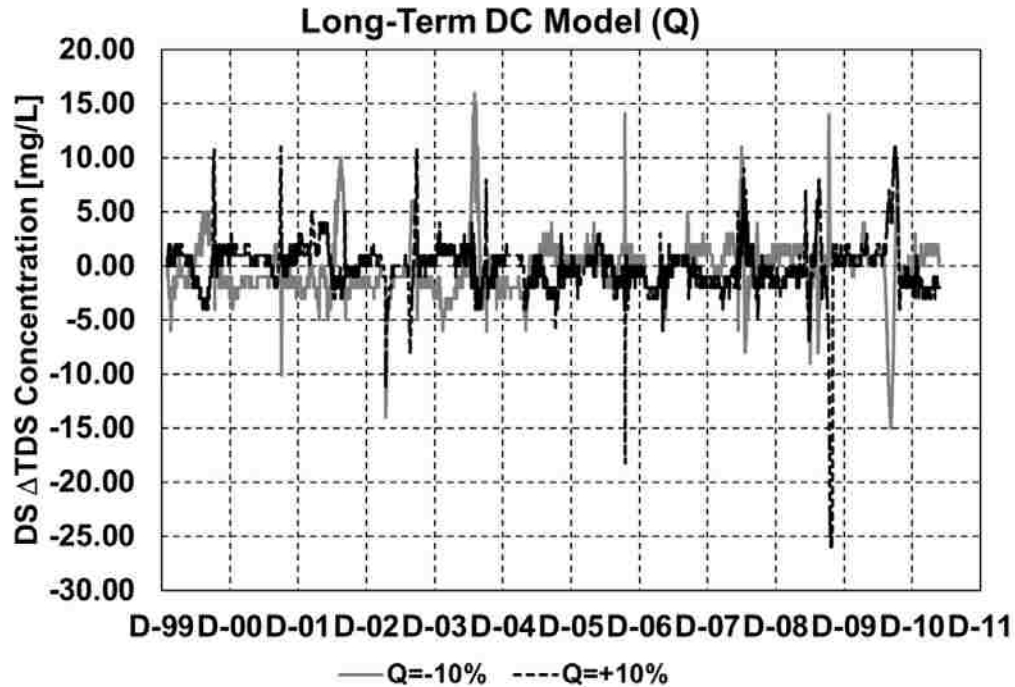


Figure 5-13: Difference of Total Dissolved Solids Concentration Downstream From Deer Creek Reservoir (Long-Term) between the $\pm 10\%$ Q Simulations and the Base Model

5.2.3 Worst Case Scenario: Long-Term Deer Creek

Once I evaluated the effects of T_{AIR} and Q changes independently and knowing that inflow PO_4-P concentration has the main impact on total normalized algal concentrations, I evaluated worst case scenarios (WCS). These scenarios consisted in two cases: 1) Low Q , High PO_4-P , and High T_{AIR} ($+3^\circ C$); and 2) High Q , High PO_4-P , and High T_{AIR} ($+3^\circ C$).

5.2.3.1 Δ Total Algal Concentration-Deer Creek (WCS)

Figure 5-14 presents these two worst cases. This plot shows that the difference of total algal concentration was lower for case 1 (LHTair= $+3C$) and higher for case 2 (HHTair= $+3C$) compared to my long-term base model. Yet, case 1 showed a higher difference of total algal concentration than case 2 right before the reservoir's fall mixing period in 2009 (October-

November). This could be caused by the low water surface elevations that Deer Creek experienced in 2009 letting sunlight penetrate deeper into the water column that proliferate more algae growth.

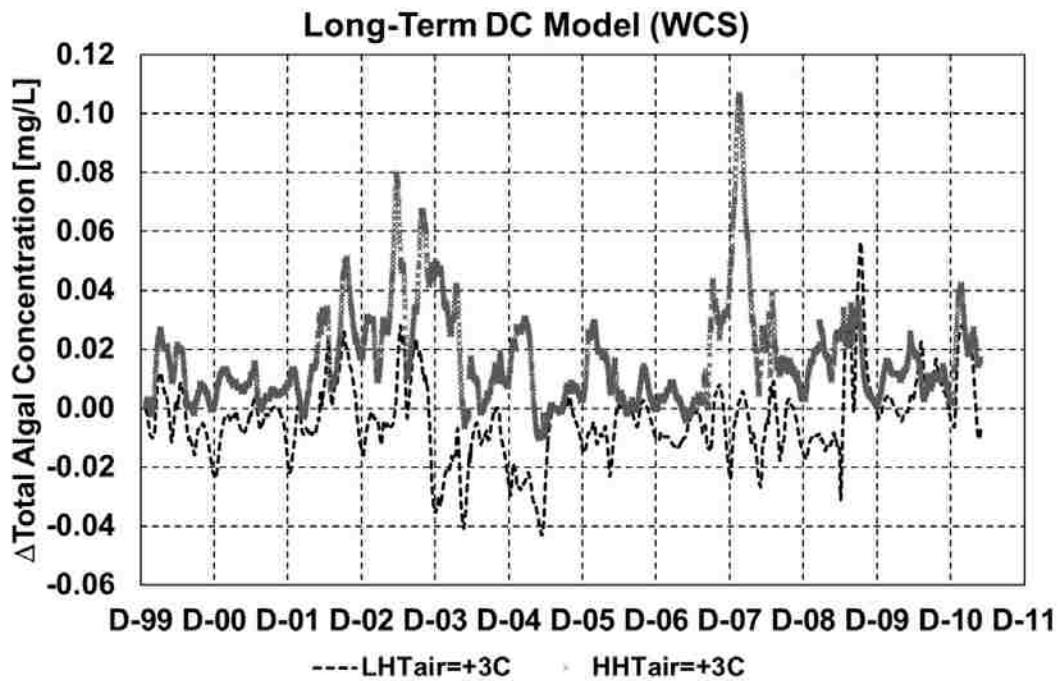


Figure 5-14: Difference of Total Algal Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

I observed the same trend shown in Figure 5-14 for both cases when I evaluated the difference in algal concentration released downstream from the dam (Figure 5-15). The higher difference for Case 1, occurred right before the reservoir's fall turnover, is more pronounced in Figure 5-15 because it includes hourly discharged data (noon and midnight). This indicates that there are times when algae growth reaches their highest concentrations produced by more intense light penetration into the water column (Wetzel 2001).

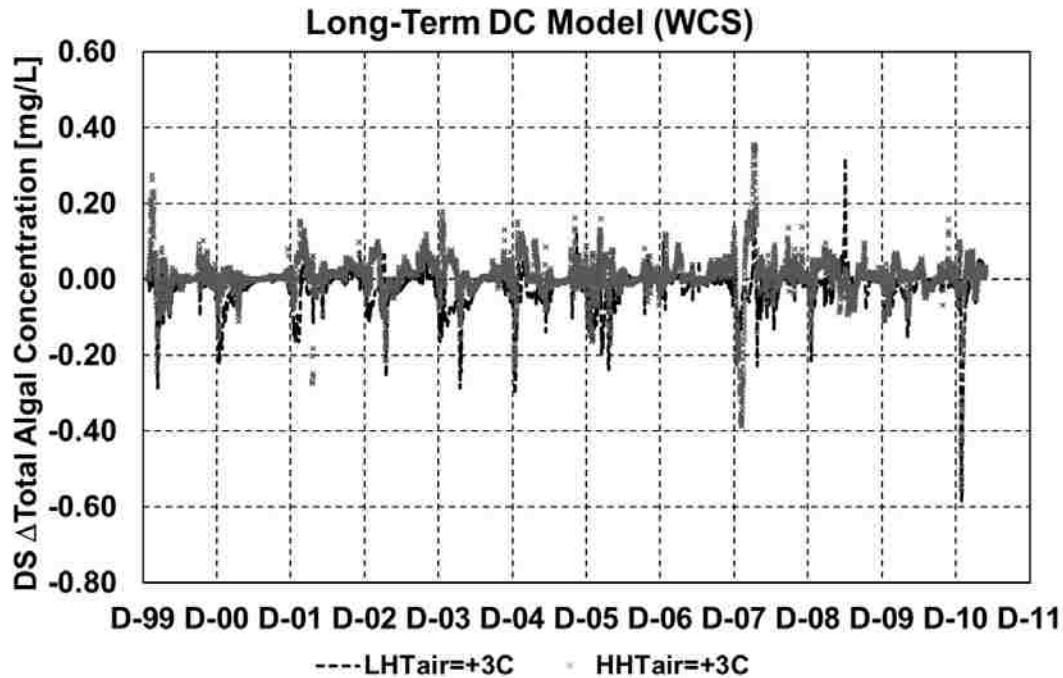


Figure 5-15: Difference of Total Algal Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

5.2.3.2 Δ Total DO Concentration-Deer Creek (WCS)

Both worst case scenarios simulations (Case 1 and Case 2) showed differences on DO compared to the long-term base model in whole reservoir (Figure 5-16) and downstream from the dam (Figure 5-17). The difference in DO between the cases was not significant but I observed that both worst case scenarios decreased total DO concentration by 5% in Deer Creek (Figure 5-16). This indicates that high PO_4-P concentration governs the decrease of DO levels. Also, evaluating the hourly discharged DO concentration plot (Figure 5-17), I noticed that there were times when DO levels showed positive differences for Case 2 (HHTair=+3C) and negative differences for Case 1 (LHTair=+3C). This suggests that higher Q will increase DO concentration downstream from the dam.

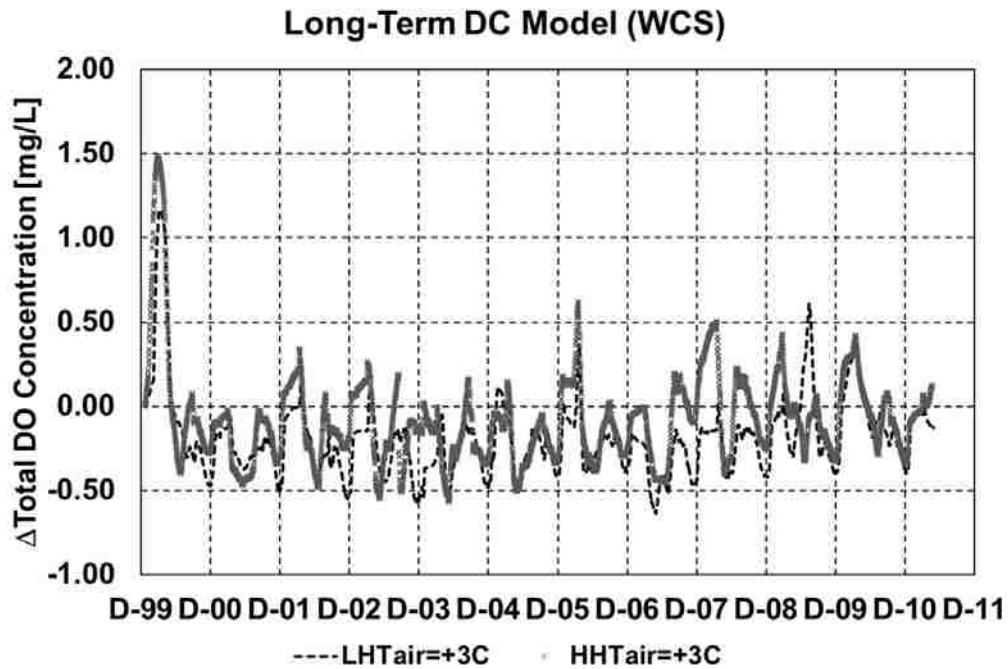


Figure 5-16: Difference of Total Dissolved Oxygen Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

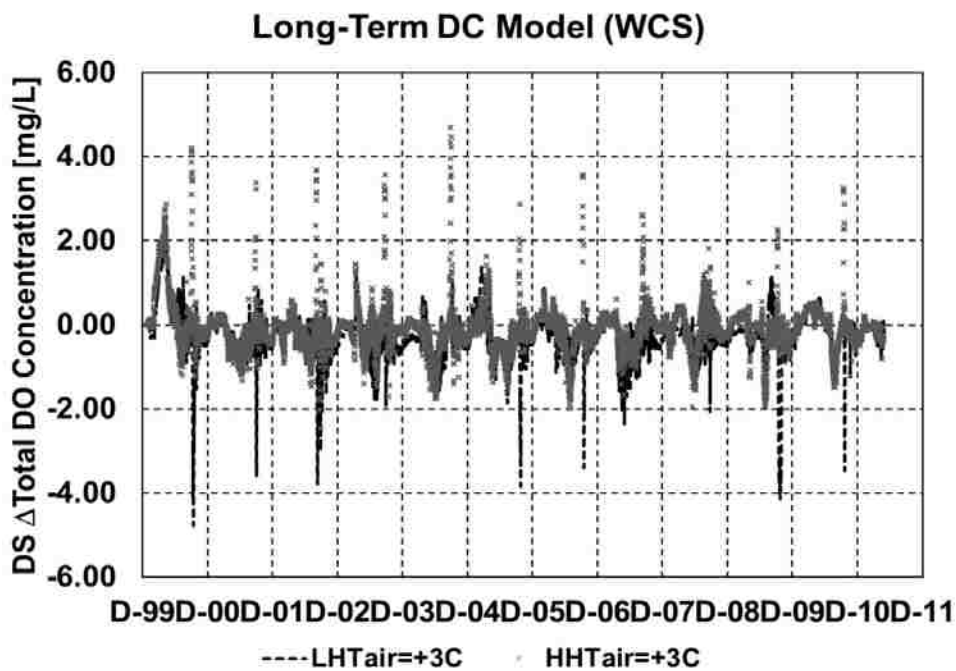


Figure 5-17: Difference of Total Dissolved Oxygen Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

5.2.3.3 Δ TDS Concentration-Deer Creek (WCS)

TDS concentration, a physicochemical indicator, was used to evaluate the effects produced by the two simulated worst case scenarios. The general trend observed in Figure 5-18 is that TDS levels were slightly higher for Case 2 (HHTair=+3C) than Case 1 (LHTair=+3C) in the entire reservoir. This difference does not exceed the 2.5% change meaning that TDS is not highly affected by worst case scenarios. I also quantified TDS levels hourly discharged from the dam for both cases (Figure 5-19). In this graph, I noticed that there is a general trend where Case 2 conditions produced a light increase and decrease for Case 1 conditions in the TDS levels discharged downstream.

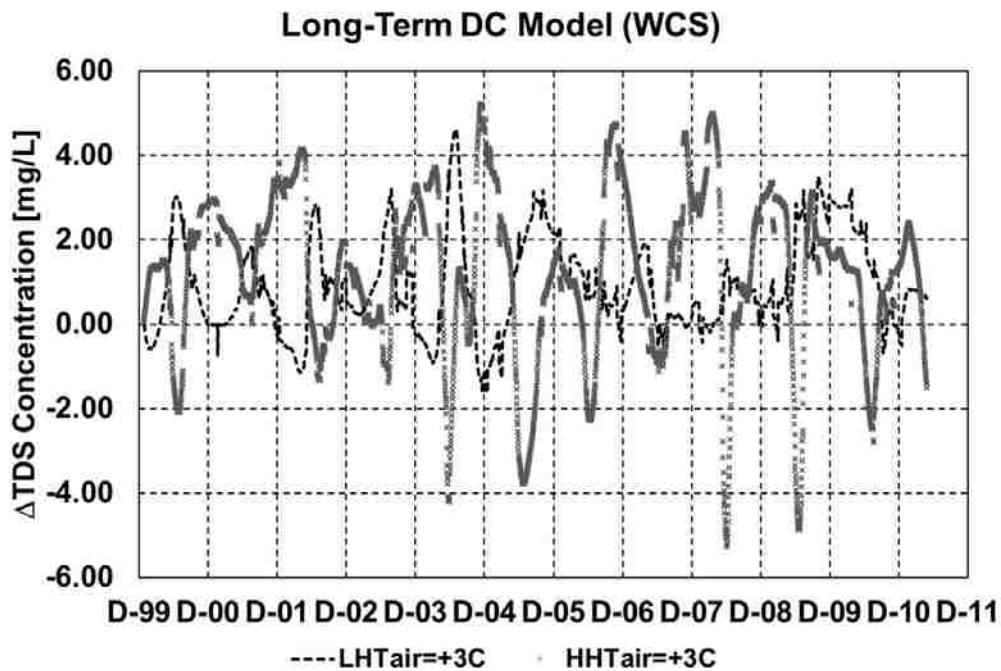


Figure 5-18: Difference of Total Dissolved Solids Concentration for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

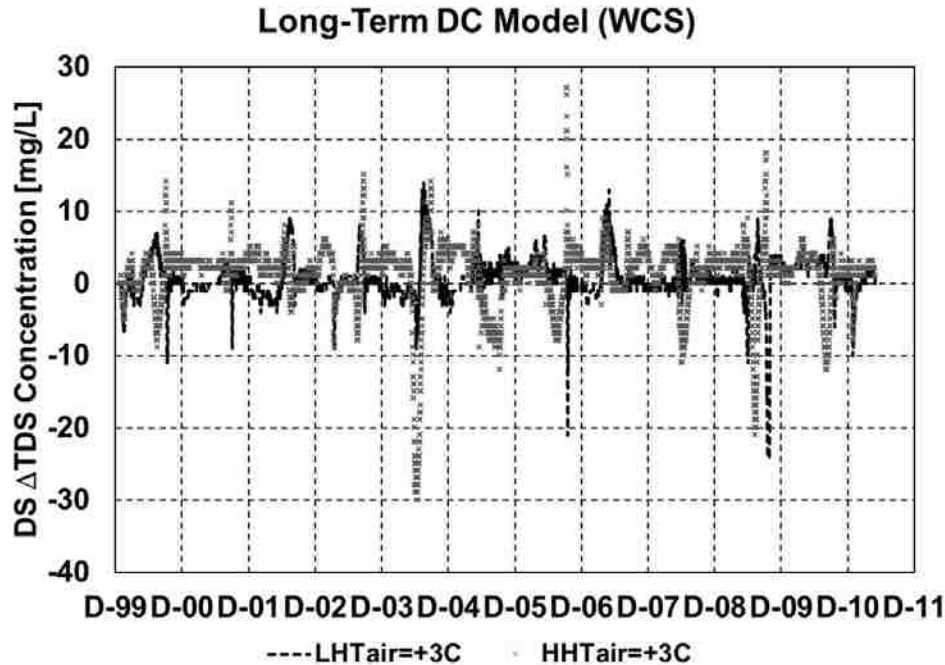


Figure 5-19: Difference of Total Dissolved Solids Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Deer Creek (Long-Term). Case 1: Low Q , High PO_4-P , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: High Q , High PO_4-P , and $T_{AIR} = +3^{\circ}C$ (HHTair=+3C)

5.3 Downstream GCC Effects Analysis and Worst Case: Tropical-Aguamilpa

In this section, I evaluated the effects of T_{AIR} and Q changes independently by using the difference of algae, DO, and TDS concentrations in hourly discharged data downstream from the Aguamilpa dam with my base model. After this evaluation, I simulated two worst case scenarios (WCS) with the following characteristics: 1) Low Q , High NO_3-NO_2-N , and High T_{AIR} ($+3^{\circ}C$); and 2) High Q , High NO_3-NO_2-N , and High T_{AIR} ($+3^{\circ}C$).

5.3.1 Downstream Aguamilpa: T_{AIR} Changes

5.3.1.1 Δ Total Algal Concentration Downstream-Aguamilpa (T_{AIR})

Figure 5-20 displays the difference of algal concentration discharged downstream from the Aguamilpa dam caused by adjusting T_{AIR} 3°C . I observed that in most of the cases, the difference of algal concentration was positive for the $+3^{\circ}\text{C}$ T_{AIR} simulation and negative for the -3°C T_{AIR} simulation. These downstream algal concentration differences matched trends observed for the entire reservoir in which warmer temperatures will increase algae in Aguamilpa.

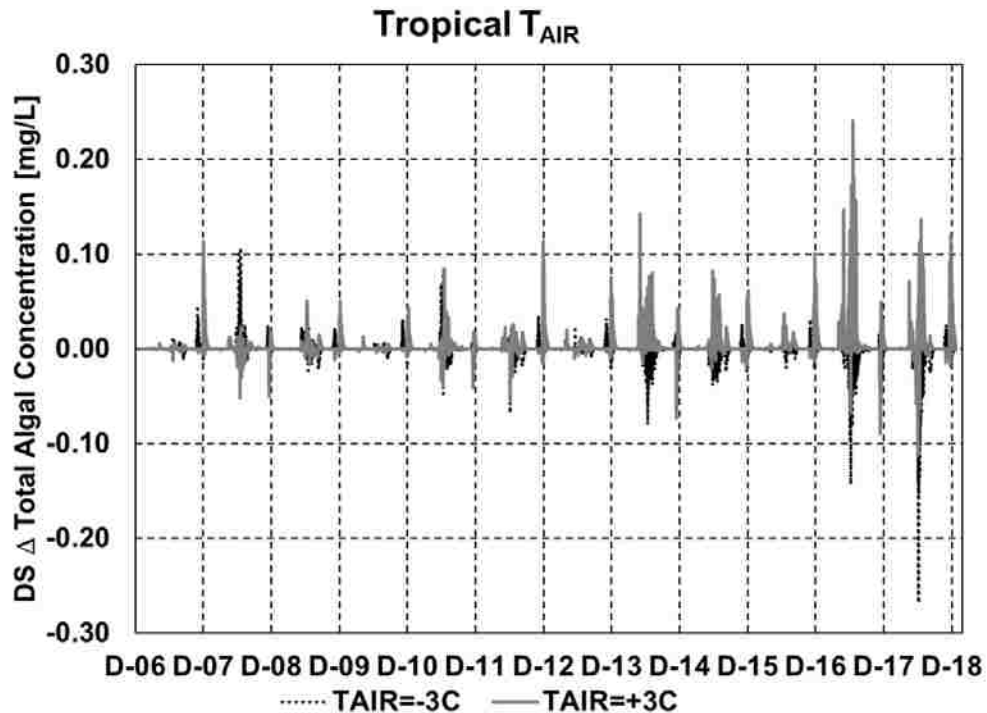


Figure 5-20: Difference of Total Algal Concentration Downstream From Aguamilpa Reservoir between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model

5.3.1.2 Δ Total DO Concentration Downstream-Aguamilpa (T_{AIR})

To evaluate the impacts produced by T_{AIR} change on DO levels discharged downstream Aguamilpa, I used the difference of total DO concentration hourly discharged, approximately every 4 hours, from the dam. I noticed that increases of 3°C T_{AIR} depleted oxygen concentrations, particularly during the dry cold season and with less intensity during the end of the rainy season (Figure 5-21). These hourly trends matched with the difference of total DO concentrations plots presented for the entire reservoir (Chapter 4).

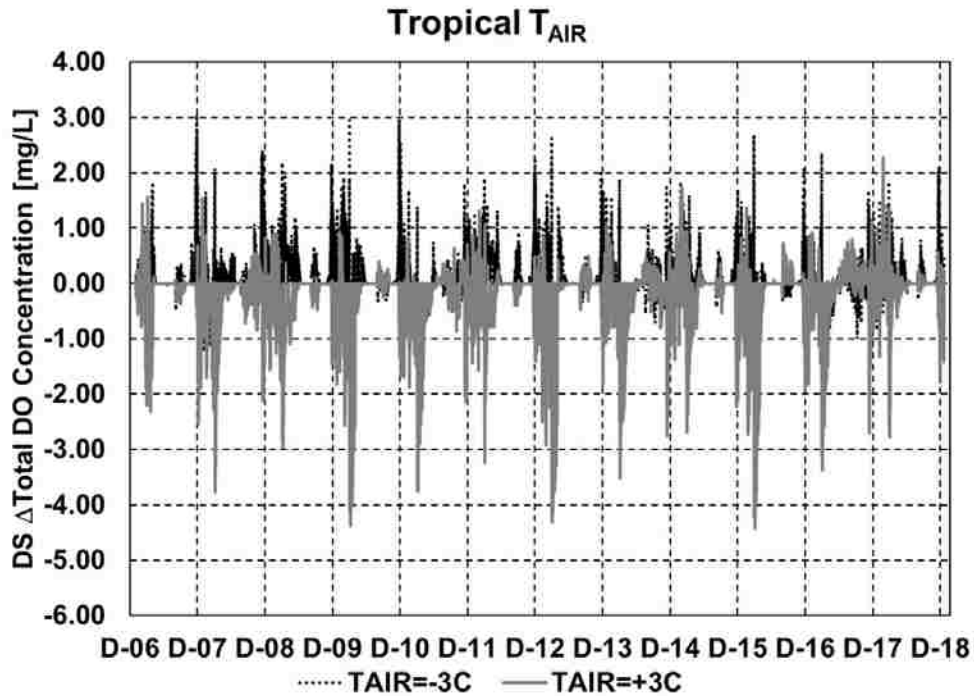


Figure 5-21: Difference of Total Dissolved Oxygen Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 3^{\circ}\text{C}$ T_{AIR} Simulations and the Base Model

5.3.1.3 Δ TDS Concentration Downstream-Aguamilpa (T_{AIR})

Figure 5-22 displays the difference in algal concentration discharged downstream from the Aguamilpa dam caused by adjusting T_{AIR} 3°C and compared with the base model. These

differences exhibited fluctuations in their trends. The general trend indicated that TDS concentration increased for warmer T_{AIR} (+3°C) and dropped for the colder T_{AIR} (-3°C) simulation. However, the observed changes did not result in significant changes because they did not represent a percent of change greater than ±8%.

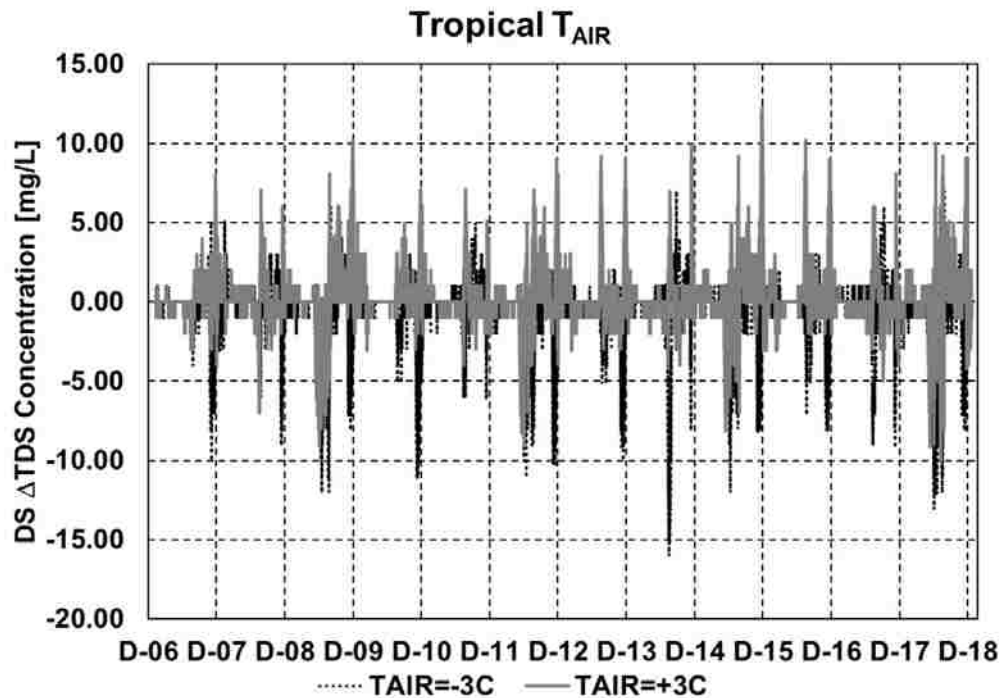


Figure 5-22: Difference of Total Dissolved Solids Concentration Discharged Downstream From Aguamilpa Reservoir between the ±3°C T_{AIR} Simulations and the Base Model

5.3.2 Downstream Aguamilpa: Q Changes

5.3.2.1 Δ Total Algal Concentration Downstream-Aguamilpa (Q)

The impacts produced by GCC downstream Aguamilpa for Q variations are shown in Figure 5-23. This plot exhibited two temporal trends, one during the warm dry season (March-June) when the difference of total normalized algal concentration was positive for the +10% Q

simulation and another one at the beginning of the cold dry season (December) when the -10% Q simulation showed a positive difference as well. Both trends are produced by two reasons, solar radiation contact and flow rates. First, these delta total algal concentrations corresponded to hourly discharged values which can be affected by longer periods of solar radiation contact due to low water levels. These low water levels can receive higher levels of solar radiation which increase algae growth together with nutrients while high Q transport higher concentration of pollutants by flow rates (gravimetric-mass).

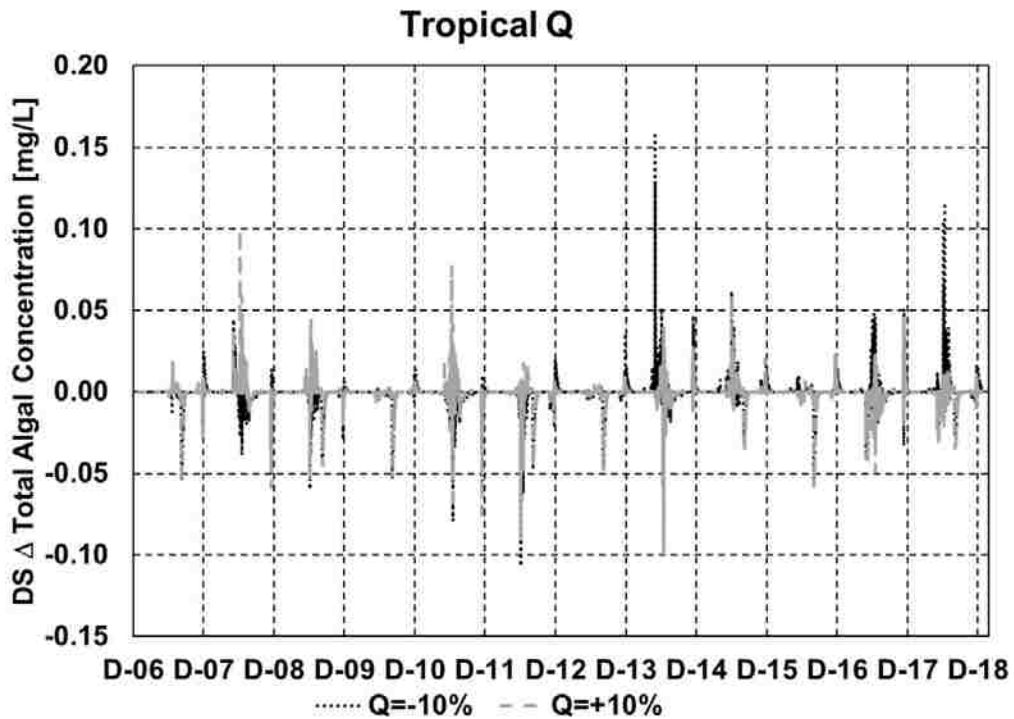


Figure 5-23: Difference of Total Algal Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model

5.3.2.2 Δ Total DO Concentration Downstream-Aguamilpa (Q)

Oxygen levels discharged downstream Aguamilpa were directly affected by Q changes. My results for calculating the difference of total DO concentration from the $\pm 10\%$ Q simulations

and the base model indicated that high Q increased DO levels (Figure 5-24). Also, DO concentrations hourly discharged downstream were reduced when Q was decreased 10%. These trends prove that higher discharges re-oxygenated water increasing DO levels discharged downstream from the Aguamilpa dam.

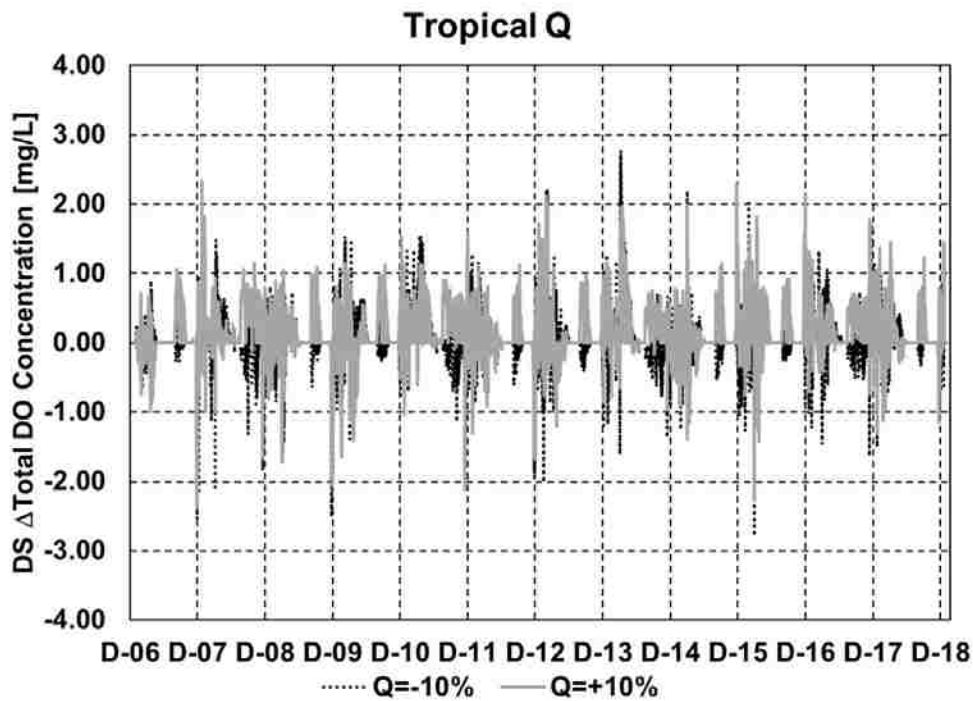


Figure 5-24: Difference of Total Dissolved Oxygen Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model

5.3.2.3 Δ TDS Concentration Downstream-Aguamilpa (T_{AIR})

I also assessed how TDS levels were affected downstream from the Aguamilpa dam when I changed Q by 10%. Discharged TDS concentrations did not vary when Q values were altered (Figure 5-25). Maximum TDS concentration differences did not represent more than 6% change meaning that the $\pm 10\%$ Q changes do not affect TDS concentrations discharged downstream.

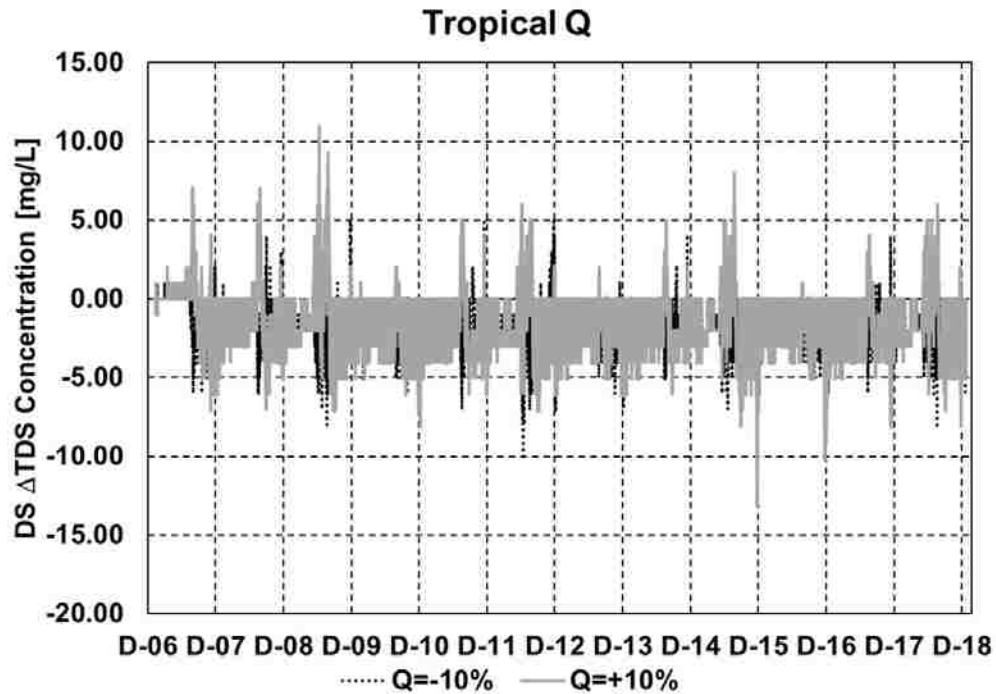


Figure 5-25: Difference of Total Dissolved Solids Concentration Discharged Downstream From Aguamilpa Reservoir between the $\pm 10\%$ Q Simulations and the Base Model

5.3.3 Aguamilpa: Worst Case Scenario (*WCS*)

Like in the long-term Deer Creek model, I simulated worst case scenarios for Aguamilpa. These scenarios included the following changes: 1) Low Q , High NO_3-NO_2-N , and High T_{AIR} ($+3^\circ C$); and 2) High Q , High NO_3-NO_2-N , and High T_{AIR} ($+3^\circ C$). I only used high NO_3-NO_2-N concentration because my previous analyses showed that these nutrients produced the highest effects in total algal concentrations in Aguamilpa. In the following section the difference in total normalized algal concentration, together with the difference in normalized DO and TDS concentrations are used to evaluate the effects produced by the worst case scenarios.

5.3.3.1 Δ Total Algal Concentration-Aguamilpa (WCS)

Figure 5-26 shows the difference of total algal concentration between the two simulated worst case scenarios and the base model. These two cases included the following characteristics: 1) High Q , high NO_3 - NO_2 - N , and $T_{AIR} = +3^\circ\text{C}$ (HHTair=+3C) and 2) High Q , high NO_3 - NO_2 - N , and $T_{AIR} = +3^\circ\text{C}$ (LHTair=+3C). The main impact produced by these two cases occurred for case 2 when Q was decreased 10%. These results indicate that total algal concentration in Aguamilpa, a large tropical reservoir, will be increased if dry and warmer conditions, combined with high concentration of nutrients, occur at the same time deteriorating the reservoir's water quality. The effects produced by the worst case scenarios are more notorious during beginning of the warm dry season (April) and right before the reservoir turns over (October-November).

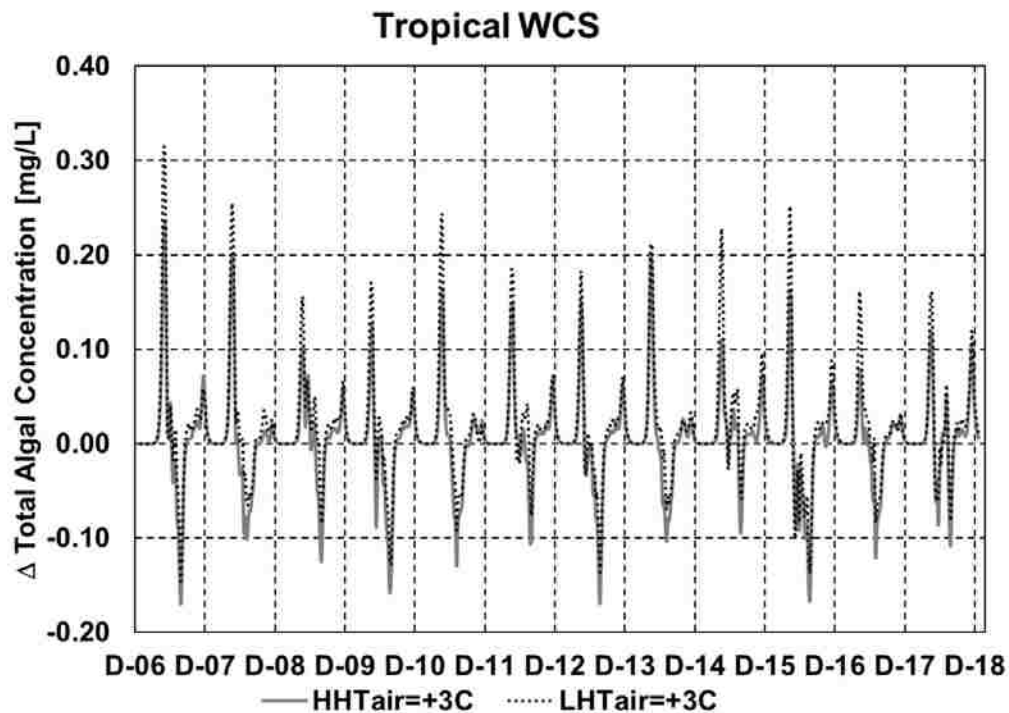


Figure 5-26: Difference of Total Algal Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3 - NO_2 - N , and $T_{AIR} = +3^\circ\text{C}$ (HHTair=+3C); and Case 2: Low Q , High NO_3 - NO_2 - N , and $T_{AIR} = +3^\circ\text{C}$ (LHTair=+3C)

I also used Figure 5-27 to evaluate the effects produced by both WCS simulations into the total algal concentration hourly discharged from the Aguamilpa dam. This plot shows contrasting trends, in some occasions case 1 (HHTair=+3C) exhibited a stronger positive difference of total algal concentrations than case 2 (LHTair=+3C), particularly during the end of the warm dry season (June). In other occasions, April, I observed a stronger positive difference of total algal concentration for case 2 than case 1 (Figure 5-27). This variability on the observed trends is due to temporal discharges changes and residence times.

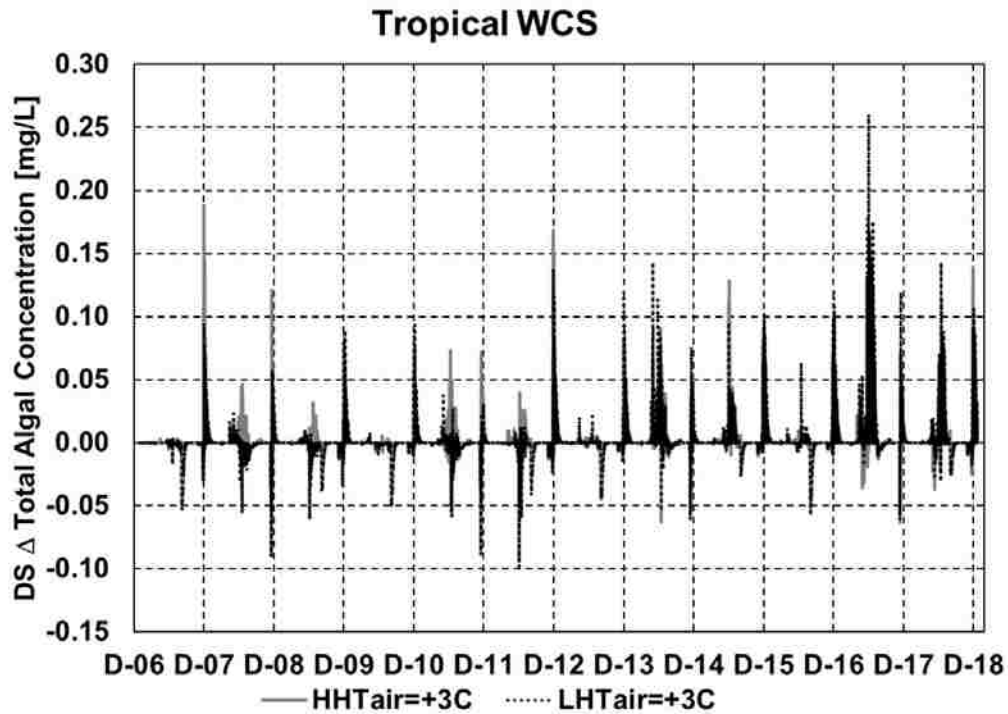


Figure 5-27: Difference of Total Algal Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (HHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR} = +3^{\circ}C$ (LHTair=+3C)

5.3.3.2 Δ Total DO Concentration-Aguamilpa (WCS)

I used the difference of total DO concentration between the two simulated WCS and the base model to quantify the effects produced in DO concentrations into the entire reservoir. The negative difference indicates DO depletions and positive designates DO increases. Figure 5-28 shows a general trend in which DO levels were depleted for both simulated WCS indicating that high concentration of NO_3-NO_2-N flowing into the reservoir will create anoxic conditions. Also, I observed that the negative difference of total DO concentration was stronger during the last part of the cold dry season and beginning of the warm dry season (February).

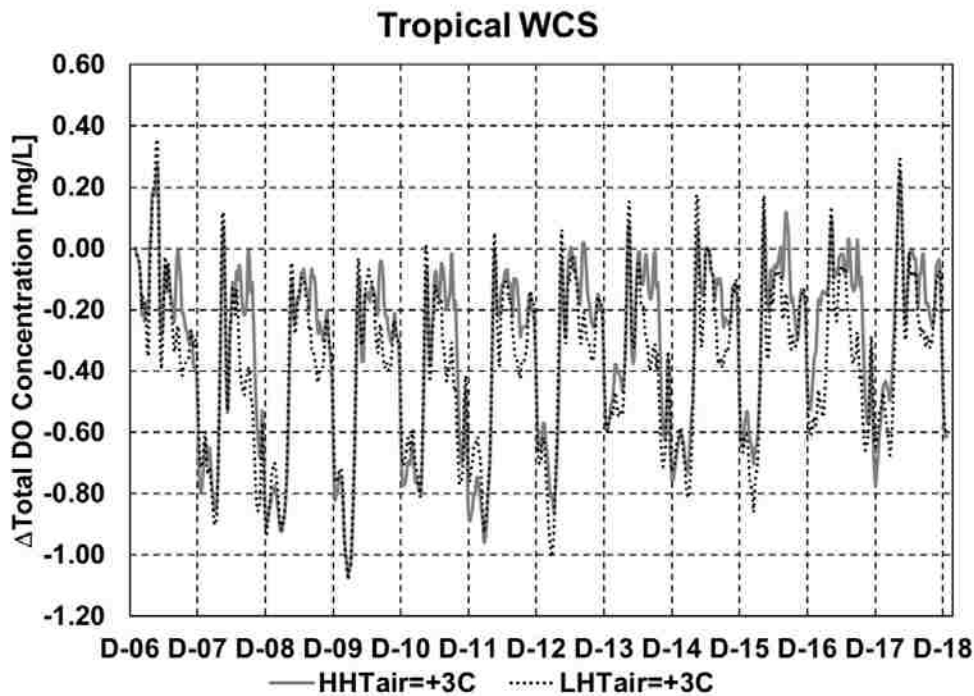


Figure 5-28: Difference of Total Dissolved Oxygen Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (HHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR} = +3^{\circ}C$ (LHTair=+3C)

Figure 5-29 illustrates the difference of total DO concentrations hourly discharged from the dam between the two WCS simulations and my base model. I observed that total DO

concentrations were decreased for case 2 and increased for case 1. These results suggested that the discharged DO concentrations are more affected by Q changes than the other changes, warm T_{AIR} and high NO_3-NO_2-N concentrations.

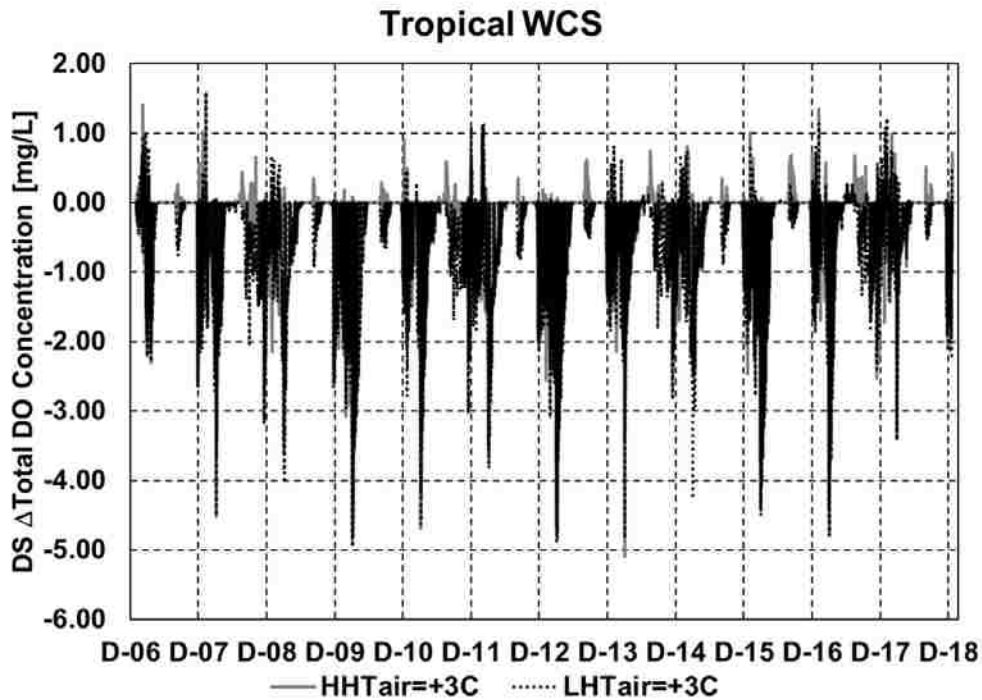


Figure 5-29: Difference of Total Dissolved Oxygen Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (HHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR} = +3^{\circ}C$ (LHTair=+3C)

5.3.3.3 Δ TDS Concentration -Aguamilpa (WCS)

TDS concentrations were not highly affected by these two WCS's simulations. The observed difference of TDS between both simulations and the base model does not represent a percent change greater than -4%. However, the small change exhibited a general trend in which the difference of TDS was stronger for case 1 than case 2 during the end of the rainy season (September) reaching a difference of -5.5 mg/L. Though, at the end of the warm dry season case

1 showed a stronger positive difference of TDS than case 2 getting values up to 1.3 mg/L. I also evaluated the effects produced by these two WCS scenarios in TDS hourly discharged from the dam (Figure 5-31) illustrating the same trends showed in Figure 5-30.

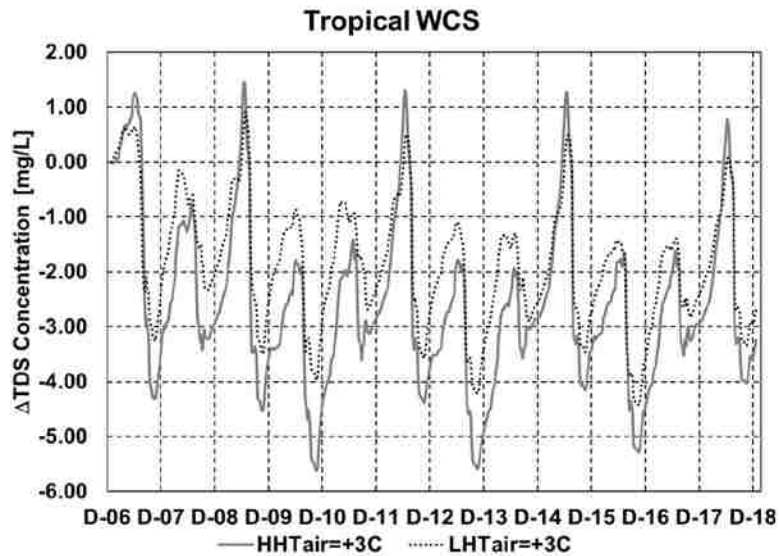


Figure 5-30: Difference of Total Dissolved Solids Concentration for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (HHTair=+3C)

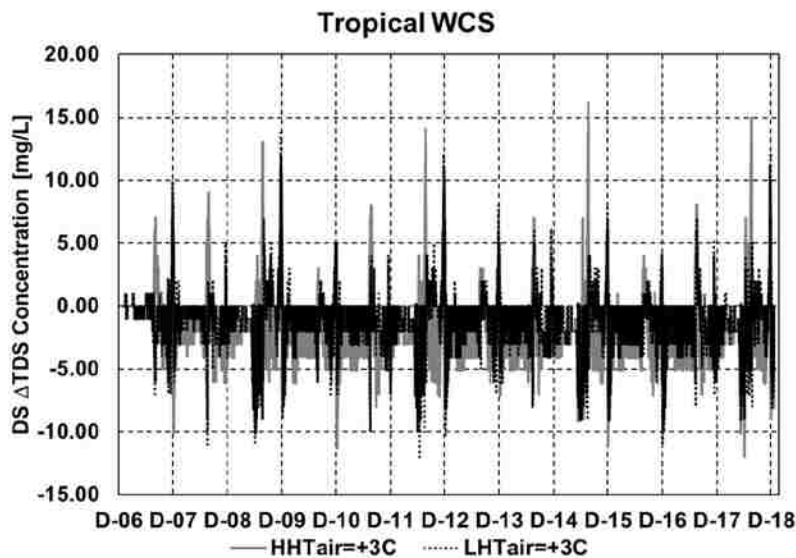


Figure 5-31: Difference of Total Dissolved Solids Concentration Hourly Discharged Downstream From the Dam for Two Worst Case Scenarios for Aguamilpa (Long-Term). Case 1: High Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (HHTair=+3C); and Case 2: Low Q , High NO_3-NO_2-N , and $T_{AIR}=+3^{\circ}C$ (LHTair=+3C).

5.4 GCC Effects in Tropical Aguamilpa and Temperate Deer Creek

Deer Creek and Aguamilpa exhibited both similar and different results when I evaluated GCC impacts on water quality. These two reservoirs have different hydrological and physicochemical characteristics that include morphology, climatology, water chemistry and water temperature. Both reservoirs were built for similar usage such as power generation and sport aquatic activities while they differ in other respects such as their use for water supply. Deer Creek is currently used as drinking water source and Aguamilpa is planned to become an important source for its neighboring towns due to the scarcity of water in that area, but is currently not used for drinking water. Despite these similarities and differences in their physical characteristics and usages, both reservoirs exhibited different impacts from projected GCC changes. For instance, variations in total normalized algal concentration values, the main indicator used in both reservoirs were different. Most of the time, low T_{AIR} temperatures resulted in increased algae population in Deer Creek while warmer T_{AIR} raised total algal concentrations in Aguamilpa. In both cases increases of T_{AIR} produced stronger and longer stratification periods that affected water quality. In the case of Deer Creek, algal succession begins earlier due to the extended stratification. Early season taxa, dominated by diatoms, are replaced by more noxious taxa such as cyanophytes. The dominant group in Aguamilpa was in the Chlorophyta, green algae, which together with Cyanophyta dominated the algal community in the whole reservoir when T_{AIR} was increased. Using normalized DO concentrations as an indicator of the effects produced by T_{AIR} changes, gave the same trends for both reservoirs, indicating that increases of T_{AIR} will deplete DO levels. This is critical for Deer Creek and Aguamilpa because low DO concentration will release nutrients from the sediments or accelerate reduction-based chemical reactions. TDS concentrations in both reservoirs were not considerably affected by T_{AIR} changes.

In evaluating wet and dry conditions represented by Q changes, the two reservoirs exhibited different results. Deer Creek presented two different trends along the entire simulation. In the first, total algal concentrations increased for wet conditions and decreased for dry conditions through the first five years (2000-2005) and this initial trend switched for the last six simulated years (2006-2011). Aguamilpa showed the same change in total normalized algal concentration during all the simulated years: Low algae for Q increases and high algae for Q decreases. It is important to point out that the amount of nutrients from the base model, particularly input PO_4 -P levels, played a significant role in the two contrasting algae trends observed in Deer Creek because, after 2005, PO_4 -P concentrations declined. This indicates that PO_4 -P levels are the main factor for algae growth in Deer Creek. Total DO concentrations were affected by Q changes in both reservoirs with DO increasing when Q was increased 10% and DO depletion for the -10% Q simulations. Neither Deer Creek nor Aguamilpa showed significant variations in TDS levels when Q was varied by 10%.

Varying input nutrients in both reservoirs had the largest impacts. Deer Creek was more sensitive to PO_4 -P concentration changes than any other factor evaluated in this study (T_{AIR} , Q , or NO_3 - NO_2 - N). In contrast, Aguamilpa was highly affected by NO_3 - NO_2 - N changes, more than any of the other variables that I modified. Deer Creek showed increases in total normalized algal concentration when I increased the input PO_4 -P concentrations and decreases when I reduced their inputs 50%. When I decreased/increased the input PO_4 -P levels for Aguamilpa by the same percentages, no significant impacts on total normalized algal concentrations occurred. Instead total normalized algal concentration in Aguamilpa was more affected by NO_3 - NO_2 - N variations. DO levels were also affected in both reservoirs. Total and discharged DO concentrations were depleted when PO_4 -P concentrations were increased 50% in Deer Creek while DO levels

decreased when NO_3 - NO_2 - N concentrations were increased 50% in Aguamilpa. The last indicator of nutrients changes was TDS but its variation was not significant for either of the two reservoirs.

I ran worst case scenarios for both reservoirs. These evaluations showed that when I ran the high Q , high *nutrients*, and $T_{AIR}=+3^{\circ}C$ (HHTair= +3C) simulation, total normalized algal concentration were higher than the case represented by low Q , high *nutrients*, and $T_{AIR}=+3^{\circ}C$ (LHTair= +3C) for Deer Creek. Aguamilpa instead showed higher total algal concentrations for the LHTair =+3C simulation than the HHTair= +3C simulation. These worst case scenarios suggested that despite the high nutrient concentration and warmer conditions, the tropical reservoir is more sensitive to dry conditions than is the temperate reservoir where wet conditions showed higher concentrations of algae. Table 5-2 shows maximum delta total algal and DO levels and their times of appearance in Deer Creek and Aguamilpa reservoirs. These maximum deltas indicate that water quality in both reservoirs can be more impacted during the warm and dry seasons for GCC and land use changes evaluated in this study.

Table 5-2: Maximum Delta Total Algal and Dissolved Oxygen Concentrations for Deer Creek and Aguamilpa Reservoirs

<i>Reservoir</i>	<i>Simulation</i>	<i>Max Δ Total Algal (mg/L)</i>	<i>Season</i>	<i>Max Δ Total DO (mg/L)</i>	<i>Season</i>
Deer Creek	T_{AIR} ($\pm 3^{\circ}C$)	+0.04 (-3 $^{\circ}C$)	Winter	-0.52 (+3 $^{\circ}C$)	Summer
	Q ($\pm 10\%$)	+0.04 (+10%)	Fall-Winter	-0.51 (-10%)	Spring
	PO_4 - P ($\pm 50\%$)	+0.05 (+50%)	Summer	No significant	
	LHTair=+3 $^{\circ}C$	+0.06	Summer	-0.58	Spring
	HHTair=+3 $^{\circ}C$	+0.10	Winter	-0.52	Spring
Aguamilpa	T_{AIR} ($\pm 3^{\circ}C$)	+0.20 (+3 $^{\circ}C$)	Warm Dry	-0.50 (+3 $^{\circ}C$)	Cold-Warm Dry
	Q ($\pm 10\%$)	+0.06 (-10%)	Warm Dry	-0.22 (-10%)	Rainy
	NO_3 - NO_2 - N ($\pm 50\%$)	+0.08 (+50%)	Warm Dry-Rainy	-0.73 (+50%)	Cold Dry
	LHTair=+3 $^{\circ}C$	+0.26	Warm Dry	-1.29	Cold Dry

The two reservoirs exhibited a significant contrast on one important fact: data availability, which is the basis for reliable models and evaluations. Even though there were gaps in the availability of temporal and spatial data for Deer Creek, it can be considered one of the most and best monitored reservoirs that would be modeled because of the long-term funding by the Central Utah Project. This allowed me to build, calibrate and validate an accurate model which generated reliable results from the GCC effects evaluations. Unlike Deer Creek, Aguamilpa is considered a new reservoir and its remoteness made it difficult to monitor. Because of this Aguamilpa is not well monitored, particularly for water quality data. However, this lack of data was mitigated by following the guidelines reported by Obregon *et al.* (2011) for minimum needed data to calibrate and validate a two-dimensional water quality and hydrodynamic model for a large tropical reservoir. Despite these limitations to my analysis in Aguamilpa, I was able to build and achieve an adequate calibration for the W2 model so that I could use the model to evaluate GCC effects in the reservoir. This was reasonable because I evaluated changes or deltas from a base case, rather than trying to be predictive of future conditions. This approach is more tolerant of minor calibration errors. The lack of data for Aguamilpa was addressed with empirical calculations and literature-based data related to previous studies in Aguamilpa (Victorica-Almeida 1996; Garcia-Cabrera 2007; Rangel-Peraza *et al.* 2009; Ibarra-Montoya *et al.* 2010) and other tropical reservoirs located close to the study area (Lind *et al.* 1992; López and Dávalos-Lind 1998; Figueroa *et al.* 2007). This makes my results from the GCC effects evaluation for Aguamilpa reliable within their limitations.

6 CONCLUSIONS

There are a large number of studies related to GCC effects in rivers, streams and lakes/reservoirs. However, they mainly focus their analyses on evaluating quantity and salinity effects. In this study, I used GCC projected values for the temperate Deer Creek and tropical Aguamilpa areas and evaluated their impacts on in-reservoirs water quality. I constructed, calibrated, validated and then used two-dimensional hydrodynamic and water quality models (CE-QUAL-W2) to assess and quantify GCC effects in these two contrasting reservoirs. The Deer Creek model was used to evaluate the GCC effects in a temperate reservoir while Aguamilpa model outputs were used to quantify the GCC effects in a tropical reservoir. To assess these GCC effects in both reservoirs I developed new modeling assessment tools that can be used to analyze total normalized concentrations of biological and physicochemical parameters in the entire reservoir including lotic, transitional and lentic zones. Without these tools the output profiles obtained from the model provide an incomplete picture.

I identified the biological and physicochemical parameters that are more sensitive to GCC changes. One of these responsive parameters was total normalized algal concentration which included the total sum of three different algae groups (diatoms, green and cyanophyta). Also, total normalized DO and TDS concentrations were used as primary indicators of GCC effects together with total nutrients. These three parameters can be considered the most sensitive to GCC effects and anthropogenic induced changes. The use of Chl-A concentrations profiles

for analysis and evaluation was not conclusive because they did not clearly display the differences among simulated scenarios and they only exhibited the effects in a particular zone.

At the beginning of this study I established my hypothesis; I wanted to test if GCC effects in a tropical reservoir were more severe than in a temperate reservoir. After finishing my evaluations and comparisons, I observed that Aguamilpa, a large tropical reservoir, can be affected with a higher severity by GCC than Deer Creek when only the increase of total normalized algal concentration is considered. Yet, it is important to mention that both reservoirs can be affected by GGC, particularly during the warm season when they are most sensitive. Deer Creek exhibited increases in total normalized algal concentration when T_{AIR} was decreased 3°C; these changes were due to the increase of diatoms at lower temperatures, which are the dominant algae group. On the other hand, diatoms were replaced by other algae groups at higher temperatures (spring-summer) causing a deterioration of Deer Creek's water quality. Aguamilpa was more affected by GCC during the dry warm season and beginning of the cold dry season when total normalized algal concentrations displayed their highest peaks for warmer T_{AIR} and drier conditions represented by low Q values.

The results obtained from this study suggested that the impacts produced by the projected GCC for both reservoirs can be considered small, with changes due to land use change and reservoir management being larger. I observed that nutrients continue being the main factor for improving or worsening water quality in both reservoirs. For instance, if BMP's are not correctly applied to control TMDL's, then Aguamilpa's and Deer Creek's water quality will be deteriorated. According to my findings, GCC will affect water quality during warm seasons especially when combined with high levels of nutrients. Deer Creek should be able to handle the projected GCC and land use changes impacts because several projects have been implemented in

the area to reduce nutrient inflows. For instance, the construction of Jordanelle Reservoir upstream and its selective withdrawal can prevent nutrients coming into Deer Creek or can discharge water from different layers that can control water temperatures downstream. These practices can both mitigate GCC and land use changes impacts. Also, the Deer Creek W2 model can serve as tool to know how and when these mitigation practices should be applied.

Contrary to Deer Creek, Aguamilpa reservoir is not well prepared to handle and mitigate GCC and land use changes effects. Santiago River and Huaynamota River, the two main inflows of Aguamilpa (Figure 4-4), and other main tributaries flowing into the reservoir transport high concentration of nutrients due to the lack of BMP's designed to manage point and nonpoint sources discharged into Aguamilpa (Garcia-Cabrera 2007). If these high levels of nutrients continue flowing into Aguamilpa, the projected GCC effects will increase the impacts to the in-reservoir water quality. The recent construction of El Cajon and La Yesca reservoirs, upstream of Aguamilpa, can help reduce the amount of nutrients flowing into the Santiago River. However, the other tributaries surrounding Aguamilpa still discharge high levels of nutrients together with the nonpoint sources. This is why there is a need to design and implement plans that include controlling/decreasing point and nonpoint nutrient sources, and managing discharges from existing and projected reservoirs in the region to affront and mitigate the potential effects of GCC and land use changes in Aguamilpa. The W2 model constructed for Aguamilpa and tools developed in this study together with well-designed, implemented and constant monitoring campaigns can assist water managers to control TMDL's by designing and implementing BMP's in a large tropical Aguamilpa reservoir and its surrounding watersheds.

In this work, I highlighted the importance of collecting accurate and frequent field data because it will keep providing historical trends and giving the basis to develop more accurate

hydrodynamic and water quality models. Nevertheless, I showed in this study how water quality models played an important role in evaluating GCC and land use changes impacts in reservoirs from two contrasting regions.

Finally, this study and the developed tools can be used as guidelines for local and international institutions to predict how climate changes and land used changes could impact reservoirs used for drinking water supplies, agriculture, and other uses in temperate, tropical, developed and developing areas. This research work and its results opened new research paths in this field that are enlisted as follows.

6.1 New Paths for Research

The results from Deer Creek and Aguamilpa did not represent all temperate and tropical reservoirs and their response to GCC effects. However, they are good examples of two reservoirs with different physical characteristics, sources and infrastructure that can be affected by GCC effects. This research effort, like any other research, points to additional research areas that need more investigation. Possible research lines include but are not limited to:

- Extend the existing models for Deer Creek and Aguamilpa to evaluate GCC changes for longer periods. This will require better efforts related to data collection, particularly in Aguamilpa.
- Use statistical models to evaluate GCC effects in both reservoirs followed by a comparison of the results obtained from the W2 models. These statistical modeling efforts have been started for Deer Creek and preliminary results exhibited similar results to the two-dimensional computational model (Gonzalez *et al.* 2012, *Statistical and Temporal Analysis of Water Quality Patterns in a*

Small Temperate Supply Reservoir, EWRI 2012 Conference, May 20-24, Albuquerque, NM, unpublished work).

- Build, calibrate, validate and then use two-dimensional hydrodynamic models to evaluate GCC effects for different tropical and temperate reservoirs. For instance, La Yesca, El Cajon, San Rafael and other reservoirs located in the zone can be modeled at the same time to evaluate GCC effects in regional reservoirs. On the other hand, Jordanelle, Echo, Strawberry and other reservoirs located in Utah can be used to assess GCC effects in regional temperate reservoirs. This will provide a more general analysis related to how regional reservoirs will respond to GCC impacts.
- Other reservoirs such as ones located in subtropical zones can be used to assess GCC impacts on water quality. Comparisons of responses to GCC effects from different locations would be valuable. For example, evaluate GCC effects in tropical, subtropical, and temperate reservoirs from different countries but similar characteristics.

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APPENDIX A. DEER CREEK

In this appendix, I provide animations generated from the CE-QUAL-W2 model built for Deer Creek. Also, additional material, not included in the main text, is presented such as the developed scripts used to extract water quality indicators of GCC effects in Deer Creek.

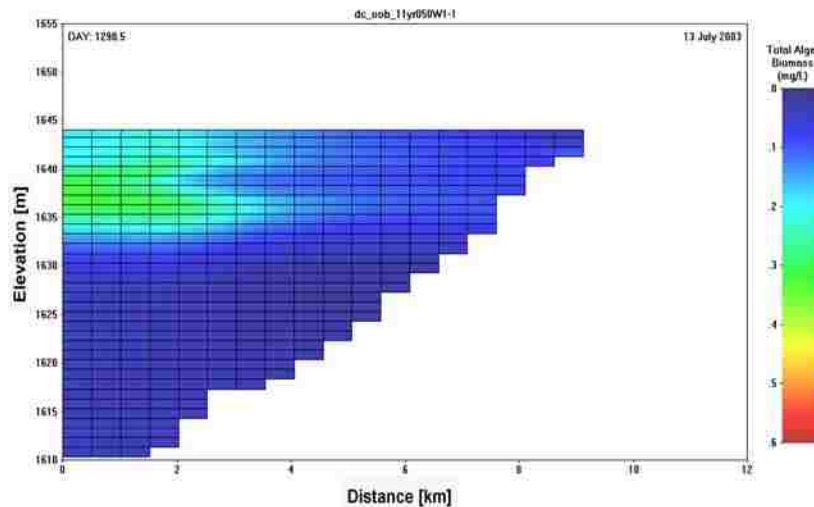


Figure A-1: Example Total Algal Concentration Simulation from the W2 Deer Creek Model (Provo River).

A.1 CE-QUAL-W2 Deer Creek Animations

The following figures illustrate example water quality animations from the long-term Deer Creek W2 model. They were generated by using the Animation and Graphics Portfolio Manager (AGPM-2D). This W2 post-processor includes options for plotting animations,

profiles, time-series and depths profiles for W2 modeled water quality constituents (Hauser *et al.* 2000).

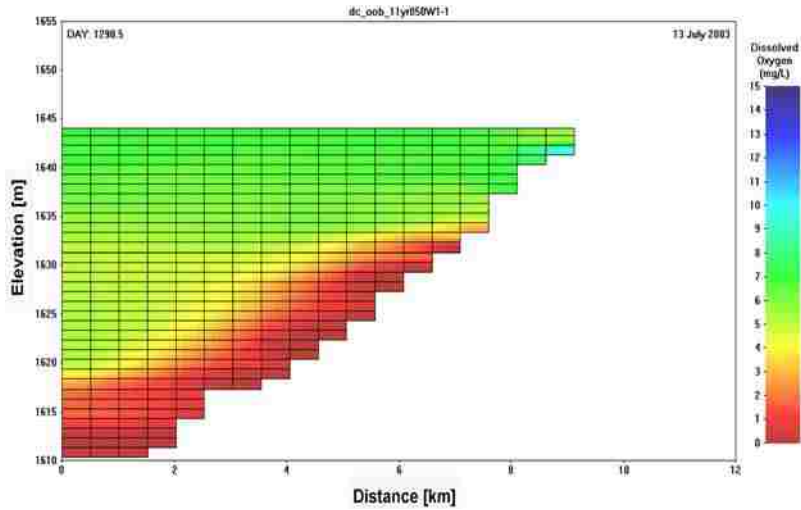


Figure A-2: Example Dissolved Oxygen Concentration Simulation from the W2 Deer Creek Model (Provo River).

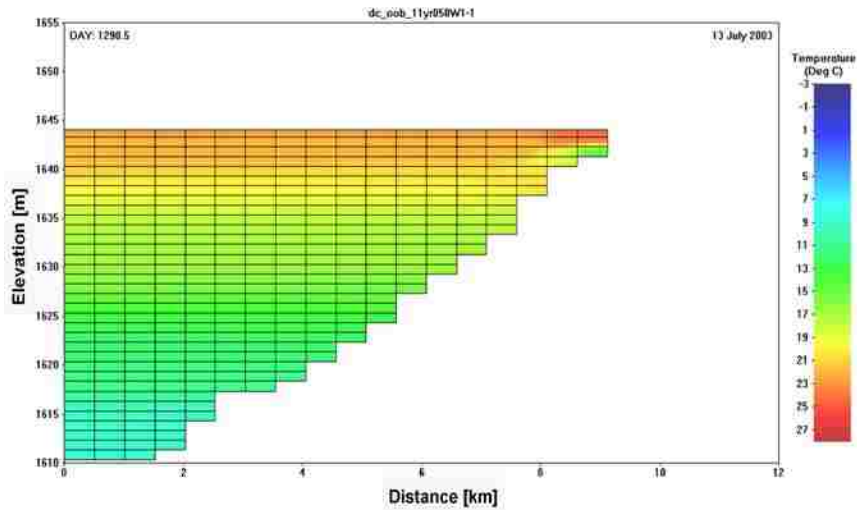


Figure A- 3: Example Water Temperature Simulation from the W2 Deer Creek Model (Provo River).

A.2 Scripts-Deer Creek

I created the following scripts to run several simulations (GCC scenarios) by using the best calibrated-validated W2 Deer Creek model. Extraction scripts are also enlisted in this section.

A.2.1 GCC Simulation Scripts

A.2.1.1 Air Temperature

```
#!/bin/sh
i=-30
end=30
step=30
j=1

while [ "$i" -le "$end" ]
do
echo $i, $j

gawk -v x=$i '{printf "%8s%8s%8s%8s%8s%8s%8s\n", $1, ($2 + x/10), $3, $4, $5, $6, $7}'
./Work/met.inp > ./Work/tmp # Meteorological data
sed 's/xxx/ /g' ./Work/tmp > ./Work/tmp1
cat ./Work/Head ./Work/tmp1 > ./Model/met.npt
rm -rf ./Work/tmp ./Work/tmp1

echo "Done creating input files"
echo "starting CE-QUAL-W2 Runs"

# Change into the Model directory and run w2_generic

cd ./Model
./w2OOB6.exe
mkdir ../DataRuns/Run$j
mv ./tsr_1_seg21.opt ../DataRuns/Run$j/
mv ./spr.opt ../DataRuns/Run$j/
mv ./snp.opt ../DataRuns/Run$j/
mv ./cwo_21.opt ../DataRuns/Run$j/
mv ./dwo_21.opt ../DataRuns/Run$j/
mv ./two_21.opt ../DataRuns/Run$j/
mv ./pre.opt ../DataRuns/Run$j/
mv ./dc_oob_11yr050W1.W2P ../DataRuns/Run$j/
```



```

cd ..

# Increment the counters

i=$((i + step))           # increment the i variable
j=$((j + 1))             # increment the j variable

echo "Looping to top"
done

echo "Loop is done"

```

A.2.1.2 Worst Case Scenarios

```

#!/bin/sh

# Program to add 3 degrees in 1 degree increments during worst cast
# there are two worst case scenarios, one low flows and high nutrients, the other
# with high flows and high nutrients
# using Deer Creek as a base
# There are 6 temperature input files
# met.npt Provo River temp

# The model is in /Model (includes model code to run CE-QUAL-W2)
# Working files in /Work
# This script is in ./
#
# Input for temp data is in *.inp (doesn't have 3 row header)
# Header for temp input data in ./Work/Head (3 rows)
#
# Temperature range from $i to $end by $step
# $i, $end, and $step need to be integers (whole degrees)
#
# $j is a counter used to name files
# The CE-Qual-W2 batch executable is called w2_generic.exe
# The post processor AGPM executable is called w2.exe

#-----CREATE THE +50% Nutrient File-----
#
#
#

```

```

i=150          # amount of Phosphates to increase x 10

# adding $i/100 value to the Third colum (Phosphates)
# the .inp files are the same as the .npt files with the 3 line header removed.
# cdt_br1.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cdt_br1.inp >
./Work/tmp # Provo distrib WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/cdt_br1.npt
rm -rf ./Work/tmp
# cdt_br2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cdt_br2.inp >
./Work/tmp # Branch 2 distrib WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/cdt_br2.npt
rm -rf ./Work/tmp
# cin_br1.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cin_br1.inp >
./Work/tmp # Provo WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/cin_br1.npt
rm -rf ./Work/tmp
# cin_br2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cin_br2.inp >
./Work/tmp # Main Creek WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/cin_br2.npt
rm -rf ./Work/tmp
# ctr_tr1.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/ctr_tr1.inp >
./Work/tmp # Snake creek WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/ctr_tr1.npt
rm -rf ./Work/tmp
# ctr_tr2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, ($4 *
x/100), $5, $6, $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/ctr_tr2.inp >
./Work/tmp # Daniel's creek WQ
cat ./Work/HeadConc ./Work/tmp > ./Model/ctr_tr2.npt
rm -rf ./Work/tmp

```

```

echo "Done creating input files"
echo "starting CE-QUAL-W2 Runs"

#
#
#-----DONE CREATING HIGH NUTRIENT LOAD FILES
echo " "
echo " "
echo "finished creating Nutrient input file, starting runs"

#-----Changing Flow at -10% and +10%

iflow=90          #Si is the begining value x 10
endflow=110      #Send is the ending value x 10
stepflow=20      #Sstep is the step size x 10
jflow=1

while [ "$iflow" -le "$endflow" ]
do
echo "flow values", $iflow, $jflow

# Multiply $iflow/100 value to the second colum (inflow)
# the .inp files are the same as the .npt files with the 3 line header removed.
# qdt_br1.opt
gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qdt_br1.inp > ./Work/Tmp
# Provo distrib inflow
cat ./Work/Head ./Work/Tmp > ./Model/qdt_br1.opt
rm -rf ./Work/Tmp
# qdt_br2.opt
gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qdt_br2.inp > ./Work/Tmp
# Branch 2 distrib inflow
cat ./Work/Head ./Work/Tmp > ./Model/qdt_br2.opt
rm -rf ./Work/Tmp
# qin_provo.npt
gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qin_provo.inp >
./Work/Tmp # Provo River inflow
cat ./Work/Head ./Work/Tmp > ./Model/qin_provo.npt
rm -rf ./Work/Tmp
# qin_man.npt
gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qin_man.inp > ./Work/Tmp
# Main Creek inflow
cat ./Work/Head ./Work/Tmp > ./Model/qin_man.npt
rm -rf ./Work/Tmp
# qtr_snake.npt

```

```

gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100) }' ./Work/qtr_snake.inp > ./Work/Tmp
# Snake's creek inflow
cat ./Work/Head ./Work/Tmp > ./Model/qtr_snake.npt
rm -rf ./Work/Tmp
# qtr_daniel.npt
gawk -v x=$iflow '{printf "%8s%8s\n", $1, ($2 * x/100) }' ./Work/qtr_daniel.inp >
./Work/Tmp # Daniel's creek inflow
cat ./Work/Head ./Work/Tmp > ./Model/qtr_daniel.npt
rm -rf ./Work/Tmp
# qot_br1.npt
gawk -v x=$iflow '{printf "%8s%8s%8s\n", $1, ($2 * x/100), ($3 * x/100) }'
./Work/qot_br1.inp > ./Work/Tmp # Provo River outflow
cat ./Work/Head ./Work/Tmp > ./Model/qot_br1.npt
rm -rf ./Work/Tmp

```

```

echo "Done creating flow input files"

```

```

#-----Changing Air Temperature and running

```

```

i=0          #i is the begining value x 10
end=30       #Send is the ending value x 10
step=10      #Step is the step size x 10
j=1

```

```

while [ "$i" -le "$end" ]
do
  echo $i, $j

  # adding $i/10 value to the second colum (tempertature)
  # the .inp files are the same as the .npt files with the 3 line header removed.
  # met.npt
  gawk -v x=$i '{printf "%8s%8s%8s%8s%8s%8s%8s\n", $1, ($2 + x/10), $3, $4, $5, $6,
$7}' ./Work/met.inp > ./Work/tmp # Meteorological data
  sed 's/xxx/ /g' ./Work/tmp > ./Work/tmp1
  cat ./Work/HeadMet ./Work/tmp1 > ./Model/met.npt
  rm -rf ./Work/tmp ./Work/tmp1

```

```

echo "Done creating input files"
echo "starting CE-QUAL-W2 Runs"

```

```

# Change into the Model directory and run w2_generic

```

```

cd ./Model
./w2OOb6.exe
mkdir ../DataRuns/Run$jflow$j

```

```

mv ./tsr_1_seg21.opt ../DataRuns/Run$jflow$j/
mv ./spr.opt ../DataRuns/Run$jflow$j/
mv ./snp.opt ../DataRuns/Run$jflow$j/
mv ./cwo_21.opt ../DataRuns/Run$jflow$j/
mv ./dwo_21.opt ../DataRuns/Run$jflow$j/
mv ./two_21.opt ../DataRuns/Run$jflow$j/
mv ./pre.opt ../DataRuns/Run$jflow$j/
mv ./dc_oob_11yr050W1.W2P ../DataRuns/Run$jflow$j/

```

```
cd ..
```

```
# Increment the counters
```

```
i=$((i + step))
```

```
# increment the i variable
```

```
j=$((j + 1))
```

```
# increment the j variable
```

```
echo "Looping to top of temperature loop"
```

```
done
```

```
echo "inner Loop is done"
```

```
# Increment the counters
```

```
iflow=$((iflow + stepflow))
```

```
# increment the iflow variable
```

```
jflow=$((jflow + 1))
```

```
# increment the jflow variable
```

```
echo "Looping to top of flow loop"
```

```
done
```

```
echo "All done"
```

A.2.2 Extraction and Concentration Outputs Calculation Scripts

A.2.2.1 Total Algal Mass Extraction

```
#!/bin/sh
```

```
#Algal Mass
```

```
grep 'Elevation' snp.opt | awk '{print $4}' > Elev.dat
```

```
grep -A140 'Mass Balance' snp.opt | grep -A60 'Branch 1' | grep -A1 'Algae' | grep
CMBRS | awk '{print $6}' > AlgB1.dat
```

```
grep -A140 'Mass Balance' snp.opt | grep -A60 'Branch 2' | grep -A1 'Algae' | grep
CMBRS | awk '{print $6}' > AlgB2.dat
```

```

grep -A160 'Mass Balance' snp.opt | grep -A80 'Branch 1' | grep -A1 'Green' | grep
CMBRS | awk '{print $6}' > GreenB1.dat
grep -A160 'Mass Balance' snp.opt | grep -A80 'Branch 2' | grep -A1 'Green' | grep
CMBRS | awk '{print $6}' > GreenB2.dat

```

```

grep -A160 'Mass Balance' snp.opt | grep -A85 'Branch 1' | grep -A1 'Cyanophyta' | grep
CMBRS | awk '{print $6}' > CyaB1.dat
grep -A160 'Mass Balance' snp.opt | grep -A85 'Branch 2' | grep -A1 'Cyanophyta' | grep
CMBRS | awk '{print $6}' > CyaB2.dat

```

```

paste Time.dat Elev.dat AlgB1.dat AlgB2.dat GreenB1.dat GreenB2.dat CyaB1.dat
CyaB2.dat > tmp1.dat
awk '{print $1, $2, $3+$4+$5+$6+$7+$8}' tmp1.dat > MassOut2.dat #Add
octave /cygdrive/f/cygwin/home/DC_OOB_PO4_00-11_001/bin/OctProg6.m
paste T.dat E.dat V.dat At.dat Ct.dat > Conc2.dat
rm -rf tmp1.dat AlgB1.dat AlgB2.dat GreenB1.dat GreenB2.dat CyaB1.dat CyaB2.dat
Time.dat Elev.dat
rm -rf T.dat E.dat V.dat At.dat Ct.dat

```

A.2.2.2 Total Algal Concentration Calculation

```

% program to interplot water volume from elevation and capacity curve
% uses the capacity curver 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/f/cygwin/home/DC_OOB_PO4_00-11_001/bin/DrCrkVol.dat');

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

Elv = Crv(:,2);
Stor = Crv(:,5);

% next load the data point you want to interpolate from a file
% the file is ElevIn.dat

Data = load('./MassOut2.dat');
Time = Data(:,1);

```

```

WtrElv = Data(:,2);
AlgT = Data(:,3);

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

Vol = interp1(Elv,Stor,WtrElv);
ConcAlgT = AlgT./Vol./1000000;

%open a file to send the answer to, the 'w' means for writing
%write the Vol to the output file uses 8 places, 6 before the decimal
% 1 for the decimal, and 1 after

Tfile=fopen('T.dat','w');
Efile=fopen('E.dat','w');
Vfile=fopen('V.dat','w');
Atfile=fopen('At.dat','w');
Ctfile=fopen('Ct.dat','w');

fprintf(Tfile,'%8.4f\n',Time);
fprintf(Efile,'%8.4f\n',WtrElv);
fprintf(Vfile,'%8.4f\n',Vol);
fprintf(Atfile,'%8.4f\n',AlgT);
fprintf(Ctfile,'%8.4f\n',ConcAlgT);

fclose(Tfile);
fclose(Efile);
fclose(Vfile);
fclose(Atfile);
fclose(Ctfile);

```

APPENDIX B. AGUAMILPA

Additional material related to Aguamilpa and not included in the main text is enlisted in this appendix. This comprises W2 example simulations and scripts used to evaluate GCC effects in Aguamilpa.

B.1 CE-QUAL-W2 Aguamilpa Animations

In this section, I show example water quality animations from the Aguamilpa W2 model. They were generated by using the AGPM-2D (Hauser *et al.* 2000). Several water quality parameters were simulated but I only present DO, water temperature and total algal concentration simulations for branch 1 (Santiago River).

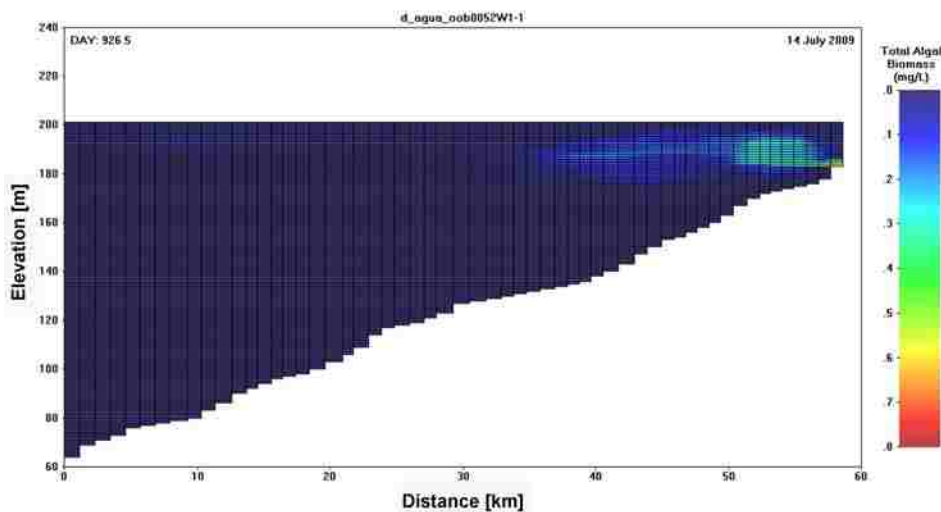


Figure B-1: Example Total Algal Concentration Simulation from the Aguamilpa W2 Model (Santiago River).

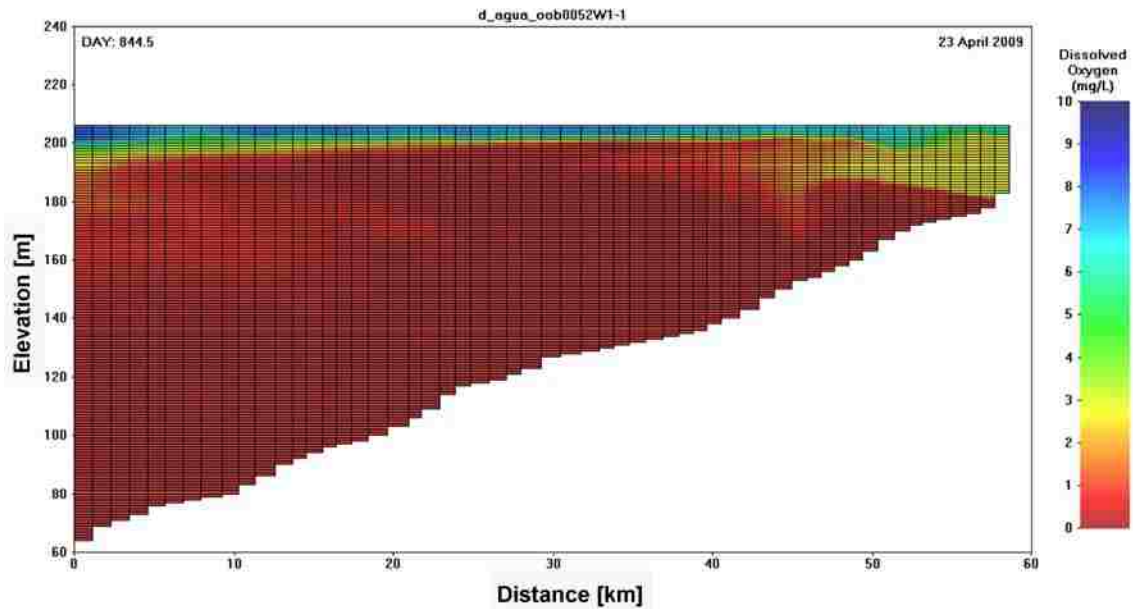


Figure B-2: Example Dissolved Oxygen Concentration Simulation from the Aguamilpa W2 Model (Santiago River).

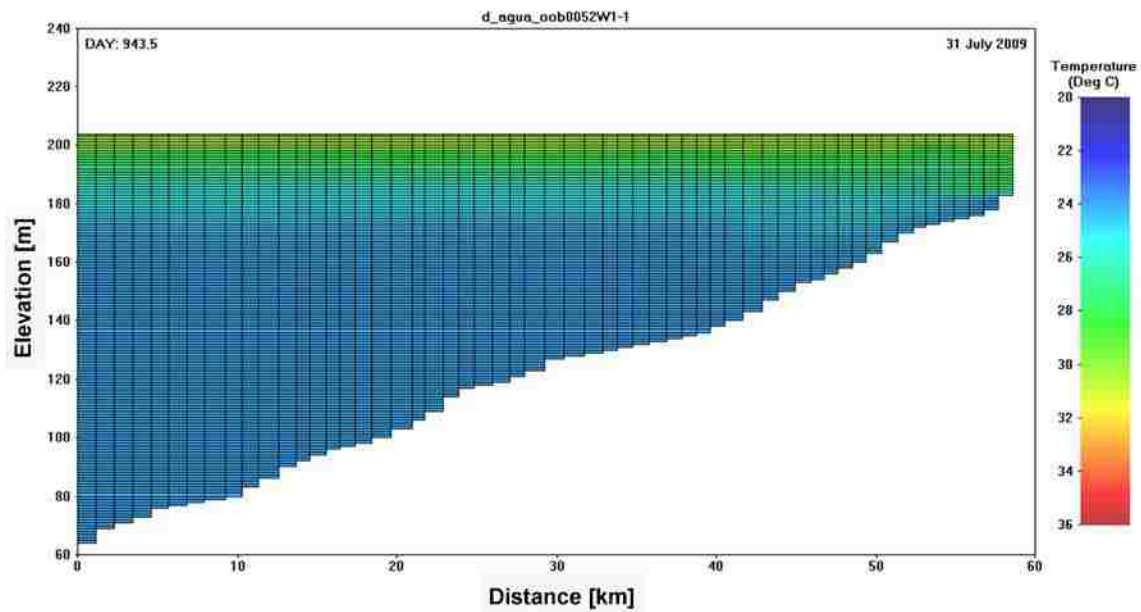


Figure B-3: Example Water Temperature Simulation from the Aguamilpa W2 Model (Santiago River).

B.2 Scripts-Aguamilpa

I created the following scripts to run several simulations (GCC scenarios) by using the best calibrated-validated W2 Deer Creek model. Extraction scripts are also enlisted in this section.

B.2.1 GCC Simulation Scripts-Tropical

B.2.1.1 Flow

```
#!/bin/sh

i=90          # $i is the beginning value x 10
end=110       # $end is the ending value x 10
step=10       # $step is the step size x 10
j=1

while [ "$i" -le "$end" ]
do
echo $i, $j

# Multiply $i/100 value to the second column (inflow)
# the .inp files are the same as the .npt files with the 3 line header removed.
# qdt_br1.opt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qdt_br1.inp > ./Work/Tmp #
Branch 1 distrib inflow
cat ./Work/Head ./Work/Tmp > ./Model/qdt_br1.opt
rm -rf ./Work/Tmp
# qdt_br2.opt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qdt_br2.inp > ./Work/Tmp #
Branch 2 distrib inflow
cat ./Work/Head ./Work/Tmp > ./Model/qdt_br2.opt
rm -rf ./Work/Tmp
# qdt_br3.npt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qdt_br3.inp > ./Work/Tmp #
Branch 3 distrib inflow
cat ./Work/Head ./Work/Tmp > ./Model/qdt_br3.opt
rm -rf ./Work/Tmp
# qin_man.npt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qin_br1.inp > ./Work/Tmp #
Branch 1 inflow
cat ./Work/Head ./Work/Tmp > ./Model/qin_br1.npt
```

```

rm -rf ./Work/Tmp
# qtr_snake.npt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qin_br2.inp > ./Work/Tmp #
Branch 2 inflow
cat ./Work/Head ./Work/Tmp > ./Model/qin_br2.npt
rm -rf ./Work/Tmp
# qtr_daniel.npt
gawk -v x=$i '{printf "%8s%8s\n", $1, ($2 * x/100)}' ./Work/qin_br3.inp > ./Work/Tmp #
Branch 3 inflow
cat ./Work/Head ./Work/Tmp > ./Model/qin_br3.npt
rm -rf ./Work/Tmp
# qot_br1.npt
gawk -v x=$i '{printf "%8s%8s%8s\n", $1, ($2 * x/100), ($3 * x/100)}' ./Work/qot_br1.inp >
./Work/Tmp # Branch 1 outflow
cat ./Work/Head ./Work/Tmp > ./Model/qot_br1.npt
rm -rf ./Work/Tmp

echo "Done creating input files"
echo "starting CE-QUAL-W2 Runs"

# Change into the Model directory and run w2_generic

cd ./Model
./w2agpmoob.exe
mkdir ../DataRuns/Run$j
mv ./tsr_1.opt ../DataRuns/Run$j/
mv ./spr.opt ../DataRuns/Run$j/
mv ./snp.opt ../DataRuns/Run$j/
mv ./dwo_58.opt ../DataRuns/Run$j/
mv ./cwo_58.opt ../DataRuns/Run$j/
mv ./two_58.opt ../DataRuns/Run$j/
mv ./qwo_58.opt ../DataRuns/Run$j/
mv ./pre.opt ../DataRuns/Run$j/
mv ./d_agua_oob0060_12YRS_CW1.W2P ../DataRuns/Run$j/

cd ..

# Increment the counters

i=$((i + step)) # increment the i variable
j=$((j + 1)) # increment the j variable

echo "Looping to top"
done

echo "Loop is done"

```

B.2.1.2 NO₃-NO₂-N

```
#!/bin/sh
```

```
i=50          # $i is the beginning value x 10
end=150       # $end is the ending value x 10
step=50       # $step is the step size x 10
j=1
```

```
while [ "$i" -le "$end" ]
do
echo $i, $j
```

```
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cdt_br1.inp >
./Work/tmp # Branch 1 distrib WQ
cat ./Work/Head ./Work/tmp > ./Model/cdt_br1.npt
rm -rf ./Work/tmp
# cdt_br2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cdt_br2.inp >
./Work/tmp # Branch 2 distrib WQ
cat ./Work/Head ./Work/tmp > ./Model/cdt_br2.npt
rm -rf ./Work/tmp
# cin_br1.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cdt_br3.inp >
./Work/tmp # Branch 3 distrib WQ
cat ./Work/Head ./Work/tmp > ./Model/cdt_br3.npt
rm -rf ./Work/tmp
# cin_br2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cin_br1.inp >
./Work/tmp # Branch 1 WQ
cat ./Work/Head ./Work/tmp > ./Model/cin_br1.npt
rm -rf ./Work/tmp
# ctr_tr1.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cin_br2.inp >
./Work/tmp # Branch 2 WQ
cat ./Work/Head ./Work/tmp > ./Model/cin_br2.npt
```

```

rm -rf ./Work/tmp
# ctr_tr2.npt
gawk -v x=$i '{printf
"%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s%8s\n", $1, $2, $3, $4, $5,
($6 * x/100), $7, $8, $9, $10, $11, $12, $13, $14, $15, $16, $17 }' ./Work/cin_br3.inp >
./Work/tmp # Branch 3 WQ
cat ./Work/Head ./Work/tmp > ./Model/cin_br3.npt
rm -rf ./Work/tmp

```

```

echo "Done creating input files"
echo "starting CE-QUAL-W2 Runs"

```

```
# Change into the Model directory and run w2_generic
```

```

cd ./Model
./w2agpmoob.exe
mkdir ../DataRuns/Run$j
mv ./tsr_1.opt ../DataRuns/Run$j/
mv ./spr.opt ../DataRuns/Run$j/
mv ./snp.opt ../DataRuns/Run$j/
mv ./two_58.opt ../DataRuns/Run$j/
mv ./cwo_58.opt ../DataRuns/Run$j/
mv ./dwo_58.opt ../DataRuns/Run$j/
mv ./qwo_58.opt ../DataRuns/Run$j/
mv ./pre.opt ../DataRuns/Run$j/
mv ./d_agua_oob0060_12YRS_CW1.W2P ../DataRuns/Run$j/

```

```
cd ..
```

```
# Increment the counters
```

```

i=$((i + step))           # increment the i variable
j=$((j + 1))             # increment the j variable

```

```

echo "Looping to top"
done

```

```
echo "Loop is done"
```

APPENDIX C. RESEARCH OUTCOMES

In addition to this dissertation, the findings and outcomes from this research effort are shared with water resources scientific communities through publications including peer-reviewed journal articles, books chapters, conference proceedings/presentations and master's theses. All these outcomes are enlisted below.

C.1 Journal Articles

- Obregon, O., G.P. Williams, E.J. Nelson, J. de Anda, J. Miller, D. Erickson, F. Gonzalez-Farias and J. Rangel-Peraza, 2011. Early Water Quality Modeling with Minimal Data to Support Management Decisions: A Case Study of Aguamilpa Reservoir. *Journal of Environmental Science and Engineering* **5**:667-681.
- Obregon, O., R.E. Chilton, G.P. Williams, E.J. Nelson, C.A. Buahin and J.B. Miller “Quantitative Evaluation of Water Quality Sensitivity in Deer Creek Reservoir to Predicted Changes from Global Climate Change and Other Drivers Using Water Quality Modeling” *Journal Of American Water Resources Association* (WILEY-BLACKWELL) **submitted 2011**.
- Rangel-Peraza, Jesús G., O. Obregon, E. J. Nelson, G.P. Williams, J. de Anda, F. A. González-Faría, and J.B. Miller. “Modeling Approach for Thermal Stratification, Characterization and Water Quality Assessment in a Large Tropical Reservoir” *Lakes &*

Reservoirs: Research and Management (WILEY-BLACKWELL) **submitted 2011 (LRE-11-036.R1).**

- Obregon, O., G.P. Williams, E.J. Nelson, J.B. Miller, and C.A. Buahin “A Two-Dimensional Water Quality Model to Evaluate Changes Produced by Climate Change Effects in a Tropical Reservoir” *Journal Of Climatic Change* (Springer) **in review.**
- Obregon, O., G.P. Williams, E.J. Nelson, J.B. Miller, C.A. Buahin, and J.G. Rangel-Peraza “Comparison of Climate Change Effects in Two Contrasting Reservoirs with Water Quality Modeling” *Lakes & Reservoirs: Research and Management* (WILEY-BLACKWELL) **in review.**

C.2 Book Sections

- Jesus Gabriel Rangel-Peraza, Oliver Obregon, James Nelson, José de Anda, Gustavious P. Williams, Yazmín Jarquín-Javier, Jerry Miller and Michael Rode (2012). The Use of Digital Elevation Models (DEMs) for Bathymetry Development in Large Tropical Reservoirs, Bathymetry and Its Applications, Philippe Blondel (Ed.), ISBN: 978-953-307-959-2, InTech, Available from: <http://www.intechopen.com/articles/show/title/the-use-of-digital-elevation-models-dem-for-bathymetry-development-in-large-tropical-reservoirs>

C.3 Conference Papers/Proceedings/Presentations

- Obregon, Oliver, Nicolas A. Gonzalez, Gustavious P. Williams, E. James Nelson, Jerry B. Miller, and Nathan R. Swain, “Long-Term Water Quality Modeling To Evaluate Climate Change Effects in a Temperate Water Supply Reservoir” *47th Annual Water*

Resources Conference of the American Water Resources Association Albuquerque, NM, November 7-10, 2011.

- Obregon, Oliver, Nicolas A. Gonzalez, Gustavious P. Williams, E. James Nelson, and Blake D. Buehler, “Statistical Modeling to Assess Potential Climate Change Induced Impacts to Water Quality in Deer Creek Reservoir” *31st International Symposium of the North American Lake Management Society* Spokane, WA, October 26-28, 2011
- Obregon, Oliver, Reed E. Chilton, Gustavious P. Williams, E. James Nelson, and Jerry Miller, “Climate Change Effects in a Tropical Reservoir with a Two-Dimensional Water Quality Model” *AWRA 2011 Spring Specialty Conference: Managing Climate Change Impacts on Water Resources: Adaptation Issues, Options and Strategies*, Baltimore, MA, April 18-20, 2011.
- Lounsbury, Derek, Oliver Obregon, Reed Chilton, Rolando F. Velasquez, Gustavious P. Williams, and E. James Nelson “Sediment Oxygen Demand and Pore Water Phosphate Flux: Measurement, Characterization, and Monitoring in Deer Creek Reservoir” *proceedings of the American Society of Civil Engineers (ASCE) Environmental and Water Resources Institute (EWRI) 2011 Congress*, Palm Springs, CA, May 22-26 , 2011.
- Obregon, Oliver, Reed E. Chilton, Gustavious P. Williams, E. James Nelson, and Jerry Miller “Assessing Climate Change Effects in Tropical and Temperate Reservoirs by Modeling Water Quality Scenarios” *proceedings of the American Society of Civil Engineers (ASCE) Environmental and Water Resources Institute (EWRI) 2011 Congress*, Palm Springs, CA, May 22-26 , 2011.
- Stephens, Ryan, Oliver Obregon, Reed E. Chilton, Gustavious P. Williams, and E. James Nelson “Field Algae Measurements Using Empirical Correlations At Deer Creek

Reservoir” *proceedings of the American Society of Civil Engineers (ASCE)*

Environmental and Water Resources Institute (EWRI) 2011 Congress, Palm Springs, CA, May 22-26 , 2011.

- Obregon, Oliver, Reed Chilton, Gustavious Williams, E. James Nelson, and Jerry Miller (2010). “A two-dimensional hydrothermal model to evaluate water quality changes in Deer Creek Reservoir due to climate change.” *Society of Hispanic Professional Engineers Annual Conference Proceedings*, Cincinnati, OH October 27 – 31, 2010.
- Nelson, E. James, Caleb Buahin, *Rushit Hila, Tamara Rabadi, Oliver Obregon, Reed Chilton, Ashley Childers, and Gustavious P. Williams (2010) “ArcGIS Tools for Importing, Storing, and Analyzing Reservoir Vertical Profile and Other Water Quality Data” *proceedings of the 2010 AWRA Spring Specialty Conference GIS & Water Resources VI* March 29 – 31, 2010, Orlando, Florida.
- Obregon, O., Nelson, E.J., Williams, G.P., and Miller, J.B. “Assessing water quality modeling in tropical regions.” Technical paper competition. Society of Hispanic Professional Engineers (SHPE) 2009 National Conference, Washington D.C. Oct. 2009.
- Obregon, O., Gustavious Paul Williams, E. James Nelson, Jerry Miller, and Reed Chilton, (2010) “Applying a two-dimensional hydrothermal model to evaluate water quality changes in Deer Creek Reservoir due to climate change and best management practice implementations” *30th International Symposium of the North American Lake Management Society* Oklahoma City, OK, November 3 - 5, 2010.
- Obregon, O., E.J. Nelson, G.P. Williams, J.B. Miller, and J. de Anda. “CE-QUAL-W2 Modelo de Calidad del Agua para la Presa Aguamilpa, Nayarit, México.” 4°. Congreso de la Asociación Mexicana de Limnología. Oct 22-24,2008. Xalapa, Veracruz, Mexico.

C.4 Master's Theses

- Gonzalez, N.A. “Spatial and Temporal Statistical Analysis of Water Quality Patterns in a Small Temperate Supply Reservoir.” Brigham Young University, (in-process).
- Chilton, R.E. “Applying a two-dimensional hydrothermal model to evaluate water quality changes in Deer Creek Reservoir due to climate change and best management practice implementations.” Brigham Young University, (2011).
- Stephens, R. “Field algae measurements using empirical correlations at Deer Creek Reservoir.” Brigham Young University, (2011).