



University of
Massachusetts
Amherst

2-D Spill Modeling in the Wachusett Reservoir with CEQUAL-W2 for Years 2003-2006

Item Type	Master Projects
Authors	Sojkowski, Bryan R.
DOI	10.7275/AN5F-5147
Download date	2026-03-13 05:17:16
Link to Item	https://hdl.handle.net/20.500.14394/4803

**2-D SPILL MODELING IN THE WACHUSETT RESERVOIR WITH CEQUAL-W2
FOR YEARS 2003-2006**

A Master's Project Presented By
Bryan R. Sojkowski

Submitted to the Department of Civil and Environmental Engineering of the
University of Massachusetts in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Environmental Engineering

May 2011

Department of Civil and Environmental Engineering
University of Massachusetts
Amherst, MA 01003

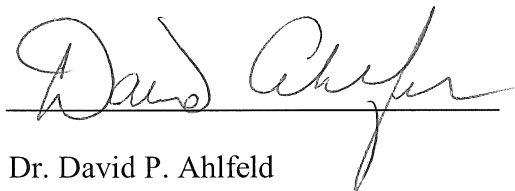
**2-D SPILL MODELING IN THE WACHUSETT RESERVOIR WITH CEQUAL-W2
FOR YEARS 2003-2006**

A Master's Project Presented by

Bryan R. Sojkowski

Environmental Engineering Program
Department of Civil and Environmental Engineering
University of Massachusetts

Approved as to style and content by:



Dr. David P. Ahlfeld
Committee Chairperson



Dr. John E. Tobiason
Committee Member



Dr. David P. Ahlfeld
Graduate Program Director
MS Environmental Engineering

Acknowledgements

This research was funded by the Massachusetts Department of Conservation and Recreation (DCR). Data was supplied by DCR, the Massachusetts Water Resources Authority (MWRA), the National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS). Thank you to the DCR and MWRA teams for supplying all of the data and answering e-mails in a timely fashion when issues arose. You played a major role in my understanding and familiarity of how the Wachusett Reservoir functions and my desire to fish for smallmouth bass in the coves has increased dramatically.

Thank you to the faculty at the University of Massachusetts. My stay was rather short but I immediately felt comfortable. Every professor had their own effective teaching style and I never felt like I couldn't ask for help. I came in with a mechanical background and have left a well-rounded engineer thanks to all of the professors I had classes with. This field has always interested me but I now have a special appreciation for it. I am extremely thankful for choosing to enter into this fantastic program. To all the graduate students that I met during the 1.5 years, thank you for all the help on homework when something didn't make sense, the laughter when I needed a break, and of course all the disc golf which has now become an addiction. You have truly made ELab II feel like a home.

This project would not have been possible without the amazing team I entered into. Thank you to Christina for making my transition into CEQUAL W2 an easy one. Thanks to Mikaela for all your guidance, especially when struggling with subsurface hydrogeology. Thank you to Cory for all of your post processing help, there is no way I would have had all of these plots in this project without your help. And of course, thank you to both Dr. Tobiason and Dr. Ahlfeld for all of your support, guidance, and knowledge of the reservoir, water resources, and modeling. I enjoyed all of our DCR meetings and never felt too overwhelmed due to your encouragement and advice.

I could not ask for a better advisor than Dr. Ahlfeld. Thank you for being supportive throughout my three semesters. You have an amazing skill of explaining things in a very clear manner so that even I can understand. You were extremely inviting from the start and have made my stay an absolute pleasure. I am also forever grateful to you for recommending me for the Fish

Passage Engineering program which I hope one day will become my career. Thank you for everything you have done for me.

Thank you to my family for always being supportive! thanks mom for calling me most days out of the week to make sure I am still alive. Thank you dad for always reminding me to, "just get it done." Last but not least, thanks to my soon to be wife Shannon. Thank you for your constant support and patience. You mean the world to me, and I couldn't have done it without you. Our decision to come to UMass will only make our future brighter; I can't wait to enjoy the rest of my life with you.

Executive Summary

This study examines the effects of various environmental conditions on the behavior of a contaminant spill as it travels across the Wachusett Reservoir. The reservoir, located in central Massachusetts, is a 65 billion gallon water body that supplies drinking water to the Boston Metropolitan area and consists of numerous inflows and outflows. The Quabbin Reservoir, a 412 billion gallon system, accounts for close to half of the inflow. The Wachusett Reservoir receives Quabbin water through the Quabbin aqueduct located on its eastern side. CEQUAL W2, a two-dimensional, laterally averaged, hydrodynamic and water quality model was utilized to perform numerous simulations. The current version, version 3.6, was used due to its computational speed and ability to apply past years data without changing input files.

Four years were analyzed, 2003-2006, in order to examine similarities and differences from year to year. Simulations for years 2005 and 2006 were calibrated to measured temperature and conductivity profiles within the North Basin of the Wachusett Reservoir (Years 2003 and 2004 were completed prior to this research). Simulations were performed in order to better understand the behavior of the spill under three main scenarios: 1) seasonal change, 2) variation of spill temperature, and 3) turning the Quabbin transfer on or off. Spill characteristics and location were kept the same for each simulation to allow for comparison. The date of the spill was chosen based on similar wind conditions for each season of every year. The behavior of the spill was evaluated by analyzing conductivity versus time at the withdrawal of the reservoir, the Cosgrove intake. Profiles of conductivity versus water depth at some locations along the reservoir were observed in order to better understand spill behavior.

Model results demonstrated that similarities between years existed. The arrival time of the spill was affected by the seasonal change. Spring spills consistently arrived at the withdrawal within 2-3 days, fall spills within approximately 7-10 days, and summer spills took 10-15 days. The summer spills showed more variability, having larger peaks than the other seasons. Changing the temperature of the spill displayed minimal effect for the spring and fall seasons. The summer of 2004 showed a faster arrival time at the intake for a warm spill whereas the summers of 2003, 2005 and 2006 displayed negligible differences in spill behavior when changing the spill temperature. Altering the condition of the Quabbin transfer showed the most effect during the summer months for all four years. Turning the transfer off for a period of two weeks after the

spill caused the variability of spill concentration measured at the withdrawal to dampen significantly. CEQUAL W2 V3.6 proved to be an effective tool in examining the behavior of a contaminant spill within the Wachusett Reservoir under various scenarios.

Table of Contents

1.0 INTRODUCTION	10
1.1 Scope.....	10
1.2 Wachusett Reservoir.....	10
1.2.1 Reservoir Water Quality Data	12
1.2.2 Major Inflows/Outflows	13
1.2.3 All Inflows/Outflows.....	16
1.3 OBJECTIVES.....	17
2.0 BACKGROUND	18
2.1 Modeling	18
2.2 CEQUAL W2	18
2.3 Other Applications of CEQUAL W2	19
2.4 Past Work for Wachusett Reservoir.....	21
2.5 CEQUAL W2 Grid and Segments.....	21
3.0 CE QUAL W2 MODEL DEVELOPMENT	23
3.1 Data Collection and Preparation	23
3.1.1 Water Balance.....	23
3.1.2 Input Files	27
3.2 Calibration	30
3.2.1 Initial Conditions	31
3.2.2 WSC – Wind Sheltering Coefficient.....	33
3.2.3 AX, DX – Dispersion Coefficients.....	36
3.2.4 BETA, EXH2O.....	42
3.2.5 FRICT – Chezy Coefficient or Manning’s N	43
3.2.6 Temperature and Conductivity Profiles	45
3.3 Spill Modeling	53
3.3.1 Spill Characteristics and Location	54
3.3.2 Spill Dates	55
4.0 Results.....	58
4.1 Seasonal Effect on Spill Behavior.....	58
4.2 Effect of Varying Spill Temperature.....	66
4.2 Effect of Quabbin Transfer On/Off	72

5.0 Summary and Conclusions 78

6.0 References **Error! Bookmark not defined.**

List of Figures

Figure 1.1 – Wachusett Reservoir Location (Google Maps)	11
Figure 1.2 – MWRA Water Supply System (MWRA, 2008)	11
Figure 1.3 - Location of tributaries, Quabbin transfer, Cosgrove Intake, and Nashua River	12
Figure 1.4 - Major inflows into the Wachusett Reservoir in the year 2005.....	14
Figure 1.5 - Major outflows out of the Wachusett reservoir in the year 2005.....	15
Figure 1.6 – Conductivity Profile (Quabbin Interflow), July 24, 2006_Measured at North Basin.....	15
Figure 2.1 - CEQUAL W2 segments, top view	22
Figure 2.2 - CEQUAL W2 layers, side view	22
Figure 3.1 - Calibrated Plot of Water Surface Elevation for 2005	25
Figure 3.2 - Calibrated Plot of Water Surface Elevation for 2006	26
Figure 3.3 – Absolute Difference between Calibrated and Measured Elevations for 2005 & 2006	26
Figure 3.4 - Effect of Increase of Initial Conductivity Value by 15 $\mu\text{S}/\text{cm}$ _North Basin_JD201_2005.....	32
Figure 3.5 – Effect of Increase of Initial Temperature_North Basin_2006	33
Figure 3.6 – Effect of Wind Sheltering Coefficient on Temperature_North Basin_JD200_2006.....	34
Figure 3.7 – Julian Day 206_2006, Calculated Compared to Measured for WSC=0.727	35
Figure 3.8 – Julian Day 216_2006, Calculated Compared to Measured for WSC=0.727	35
Figure 3.9 – Effect of Increase of DX on Temperature_JD206_2006_North Basin	37
Figure 3.10 – Effect of Increase of DX on Conductivity_JD206_2006_North Basin	37
Figure 3.11 – Effect of Increase of DX on Temperature_JD216_North Basin for 2006.....	38
Figure 3.12 – Effect of Increase of DX on Conductivity_JD216_2006_North Basin	39
Figure 3.13 - Effect of Increase of DX on Temperature_JD243_2006_North Basin	39
Figure 3.14 – Effect of Increase of DX on Conductivity_JD243_North Basin.....	40
Figure 3.15 – Effect of AX Change on Temperature_JD206_2006_North Basin.....	41
Figure 3.16 – Effect of AX Change on Conductivity_JD206_2006_North Basin.....	41
Figure 3.17 – Effect of Increase of BETA on Temperature_JD200_2006_North Basin.....	42
Figure 3.18 – Effect of Default Values of EXH2O on Temperature_JD200_2006_North Basin	43
Figure 3.19 – Effect of Increase of Friction Coefficient on Temperature_JD206_2006_North Basin	44
Figure 3.20 - Temperature Profiles for 2005 at North Basin, segment 42	49
Figure 3.21 - Temperature Profiles for 2005 at North Basin, segment 42	49
Figure 3.22 - Conductivity Profiles for 2005 at North Basin, segment 42	50
Figure 3.23 - Conductivity Profiles for 2005 at North Basin, segment 42	51
Figure 3.24 - Temperature Profiles for 2006 at North Basin, segment 42	52
Figure 3.25 - Temperature Profiles for 2006 at North Basin, segment 42	52
Figure 3.26 - Conductivity Profiles for 2006 at North Basin, segment 42	53
Figure 3.27 - Conductivity Profiles for 2006 at North Basin, segment 42	53
Figure 3.28 - Spill Location at Rt. 140 Bridge, represented by segment 7 in	54
CEQUAL W2.....	54
Figure 3.29 - Wind Direction Key	57
Figure 4.1 - Spill behavior at Cosgrove intake due to seasonal changes for a cold spill in 2004_Rte 140_Segment 7	59

Figure 4.2 - Seasonal spill behavior at Cosgrove intake 30 days after spill date for 2004_Rte 140_Segment 7.....	60
Figure 4.3 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in the spring	61
Figure 4.4 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in summer.....	62
Figure 4.5 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in fall.....	63
Figure 4.6 - Diagram of flow field around the Cosgrove intake for a wind direction towards intake (Not to Scale)	64
Figure 4.7 - Diagram of flow field around the Cosgrove intake for a wind direction away from intake (Not to Scale)	64
Figure 4.8 - Comparison of Spill Concentration at Segment 30, seven days after the spill for 2006 (Medium Temperature Spill).....	65
Figure 4.9 - Comparison of Spill Concentration at Segment 44, seven days after the spill for spring and fall, 12 days after the spill for summer (Medium Temperature Spill).....	66
Figure 4.10 - Comparison of spill behavior at Cosgrove for spring of 2004 for different spill temperatures	67
Figure 4.11 - Comparison of spill behavior at Cosgrove for fall of 2004 for different spill temperatures .	68
Figure 4.12 - Comparison of spill behavior at Cosgrove for summer of 2004 for different spill temperatures	69
Figure 4.13 - Comparison of spill behavior at Cosgrove for summer of 2003 for different spill temperatures	70
Figure 4.14 - Comparison of spill behavior at Cosgrove for summer of 2005 for different spill temperatures	70
Figure 4.15 - Comparison of spill behavior at Cosgrove for summer of 2006 for different spill temperatures	71
Figure 4.16 - Comparison of Spill Concentration Profiles for segment 30 for 2005 and 2006, 10 days after the spill	71
Figure 4.17 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2003 cold spill	73
Figure 4.18 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2004 cold spill	74
Figure 4.19 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2005 cold spill	74
Figure 4.20 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2006 cold spill	75
Figure 4.21 - Comparison of Spill Concentration Profile at Segment 44 for the summer of 2005 and 2006, 20 Days after the spill	75
Figure 4.22 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2004 warm spill	76
Figure 4.23 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2005 warm spill	77

List of Tables

Table 1.1 - Percentage of Total Flow for all Inflows/Outflows	17
Table 3.1 - 2005, 2006 and Prior Model Calibration Factors.....	25
Table 3.2 - Root Mean Squared Error for Years 1994-2006.....	27
Table 3.3 - Simplified List of Required Input Files.....	28
Table 3.4 - Default Values for CEQUAL-W2 Model Parameters Affecting Thermal Calibration.....	31
Table 3.5 - Temperature Errors for 2005 at the North Basin.....	46
Table 3.6 - Temperature Errors for 2006 at the North Basin.....	47
Table 3.7 - Conductivity Errors for 2005 at the North Basin.....	47
Table 3.8 - Conductivity Errors for 2006 at the North Basin.....	48
Table 3.9 - Wind Comparison of all Four Years and Seasons.....	57
Table 4.1 - Base Model Parameters Used for Simulations.....	58
Table 4.2 - Summary of Quabbin Transfer Simulations for all Four Years.....	72

1.0 INTRODUCTION

This report describes the results of two-dimensional modeling within the Wachusett Reservoir utilizing a modeling package called CEQUAL W2, conducted at the University of Massachusetts (UMass) during the period of January 2009 to May 2010. The project is a collaborative effort between UMass, the Department of Conservation and Recreation (DCR), and the Massachusetts Water Resources Authority (MWRA). The focus of research was to better understand the behavior of potential contaminant spills into the reservoir under a variety of conditions. Analyses were performed for years 2003-2006 in order to assess similarities and differences from year to year.

1.1 Scope

CEQUAL W2 V3.6 was utilized to analyze the behavior of spills within the Wachusett Reservoir. The focus of this project was to examine spills for four calendar years, 2003-2006, under conditions such as seasonal change, variation of spill temperature, and state of the Quabbin transfer. The spill of a non-reactive substance was assessed as this represents a worst case scenario which would provide vital information to the DCR team.

1.2 Wachusett Reservoir

The Wachusett Reservoir, completed in 1908, is located in central Massachusetts, northeast of Worcester as shown in Figure 1.1. It contains approximately 65 billion gallons of water making it the second largest body of water in the Commonwealth of Massachusetts. It has a maximum depth of 120 feet (36.6 meters), a length of 8.4 miles, and a surface area of 6.3 square miles. The reservoir is part of the MWRA's water supply system (Figure 1.2) which includes the Quabbin Reservoir, completed in the 1930s, and provides 2.2 million people, as well as 5,500 industrial users, with high quality water. It is the main water supply for the Boston, MA metropolitan area. Water leaves the Quabbin Reservoir at specific times during the year and enters the Wachusett reservoir via the Quabbin Aqueduct. Water exits the Wachusett Reservoir via the Cosgrove intake to be disinfected at the John J. Carroll water treatment facility and then distributed. Along with the MWRA, DCR manages the system by assessing water quality and managing the surrounding watershed.



Figure 1.1 – Wachusett Reservoir Location (Google Maps)

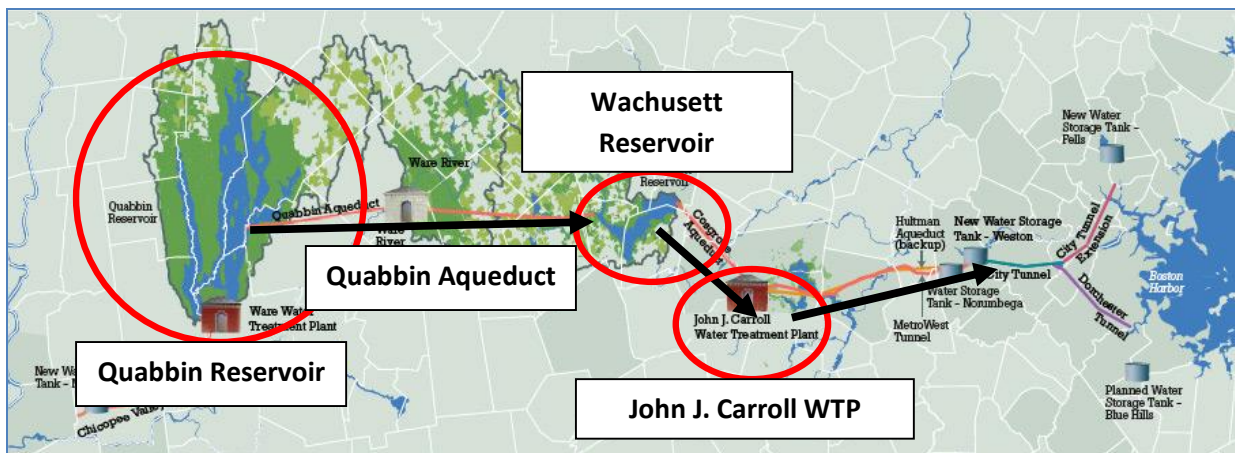


Figure 1.2 – MWRA Water Supply System (MWRA, 2008)

The Wachusett Reservoir can be segmented into three distinct basins, displayed in Figure 1.3. The Thomas Basin is the narrow section on the western side, the South Basin represents the southern portion, and the North Basin is located on the northeastern side of the reservoir. Water enters the Wachusett Reservoir naturally through direct precipitation and runoff from nine tributaries that feed into the reservoir, as well as the Quabbin transfer, shown in Figure 1.3. The two largest tributaries are the Stillwater River, which enters from the north into the Thomas basin, and the Quinapoxet River, which comes into the reservoir near the Quabbin transfer. These are also the only two tributaries that are gauged to measure flow. The other seven tributaries are small brooks that are not gauged. These include the Washacum, Malden, West Boylston, Gates, Muddy, Malagasco, and French Brooks. Water primarily exits the system

through the Cosgrove Intake and the Nashua River, which are located on the eastern side, along with minor town water supply withdrawals and evaporation.

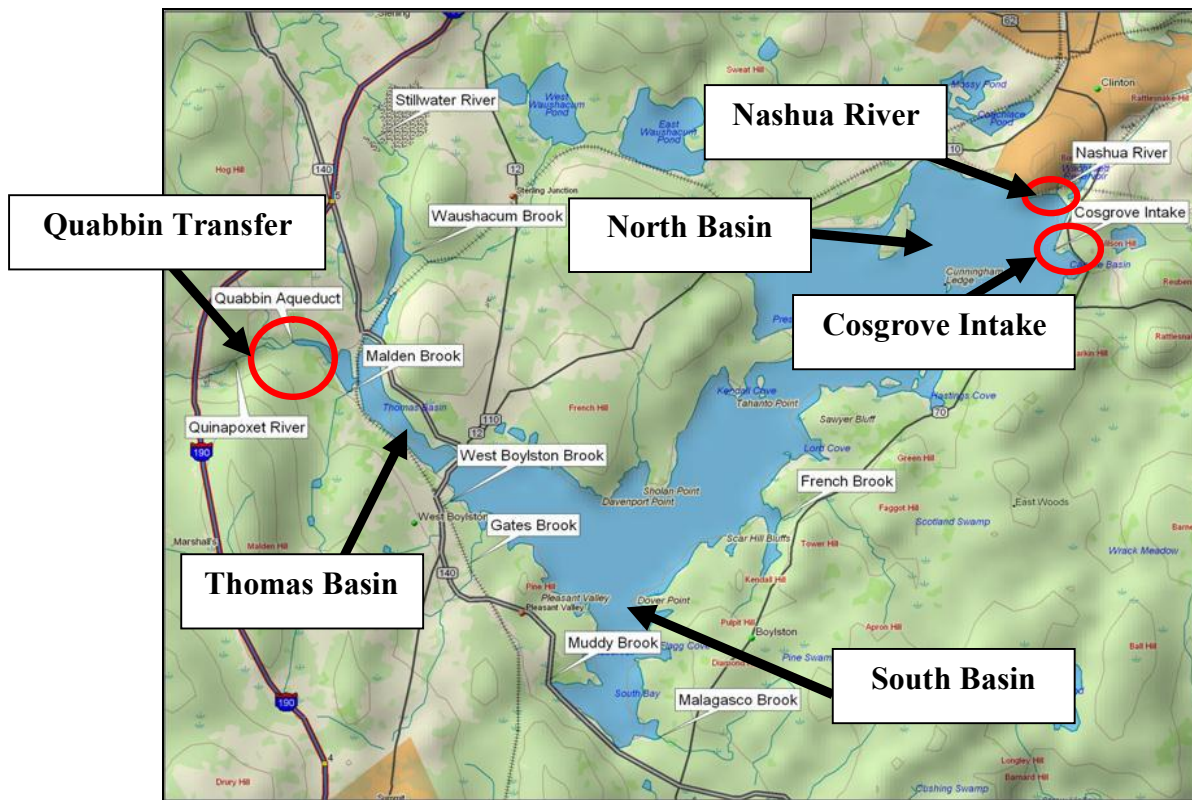


Figure 1.3 - Location of tributaries, Quabbin transfer, Cosgrove Intake, and Nashua River

1.2.1 Reservoir Water Quality Data

In-reservoir water quality data are collected by the DCR team periodically throughout the year. Parameters include temperature, conductivity, dissolved oxygen (DO), and pH which are gathered from one location within each basin. The frequency of collection depends on weather conditions as well as specific sampling needs. In 2005 and 2006 samples were taken within the North Basin on a monthly basis from May to October which captured the stratification and de-stratification periods. One sample was recorded for each month, each sample including all four parameters mentioned above, at multiple locations across the depth of the reservoir.

1.2.2 Major Inflows/Outflows

Figure 1.4 displays the major inflows and Figure 1.5 shows the major outflows of the Wachusett Reservoir for year 2005 (Similar information for other years are found within Appendix A, Figures A.1 through A.6). 2005 is a typical representation of the reservoir; the magnitudes of flows vary from year to year but the basic operation does not change significantly. The left y-axis of both figures displays the flows in units of m^3/s , the right y-axis shows the water surface elevation in m, and x-axis are the dates for the year 2005. The major inflows consist of the Stillwater and Quinapoxet Rivers, and Quabbin transfer. As shown in Figure 1.4, Stillwater and Quinapoxet flows spike in the spring when winter snowmelt occurs followed along by an increase in water surface elevation. During times of low flow, as witnessed during the summer, the Quabbin transfer is turned on in order to maintain the water surface elevation within a desired range. The Quabbin water that enters the reservoir typically has lower conductivity and temperature than the Wachusett Reservoir. This creates what is called, the Quabbin interflow which can be tracked as the water moves towards the Cosgrove intake. The interflow is characterized by a region of layers, approximately 10-15m below the surface, of water of lower conductivity. The interflow occurs when the reservoir is stratified as shown in Figure 1.6. Figure 1.6 represents a conductivity profile measured by DCR in the North Basin in July of 2006. The state of stratification during the summer months allows for the interflow to form when the Quabbin transfer is on. For this date, the Quabbin interflow exists between depths of approximately 8 and 12 m where the specific conductivity is, on average, 16.3 units below the ambient value of 140 $\mu S/cm$. If the Quabbin transfer was not on, the conductivity profile would look more like a vertical line, equal conductivity across the depth of the reservoir, due to the absence of the lower conductivity water from the transfer.

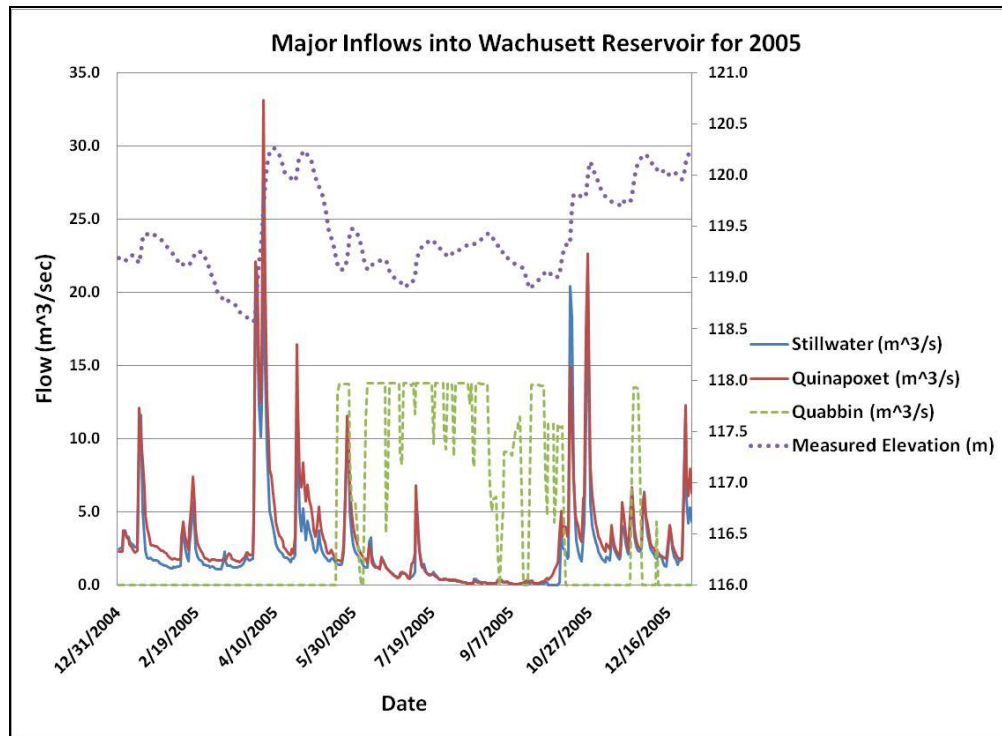


Figure 1.4 - Major inflows into the Wachusett Reservoir in the year 2005

The Cosgrove intake is a relatively steady outflow, sometimes discharging more than 300 MGD towards the John J. Carroll WTP. The intake consists of two inlets, one at an elevation of 343 ft (104.5m) and the other at 363 ft (110.6m). The other major outflows consist of the Nashua River and Spillway which are located in the North Basin. The spillway is used to release water from the surface of the reservoir during times of high water elevation. This is shown to occur in the spring of 2005 which correlates with the increase of surface elevation in Figure 1.5. 1.8 MGD of water is discharged to the Nashua River on a daily basis from an intake structure located on the dam face. High flows are periodically discharged to allow for a larger inflow of better quality Quabbin water while maintaining the desired water surface elevation.

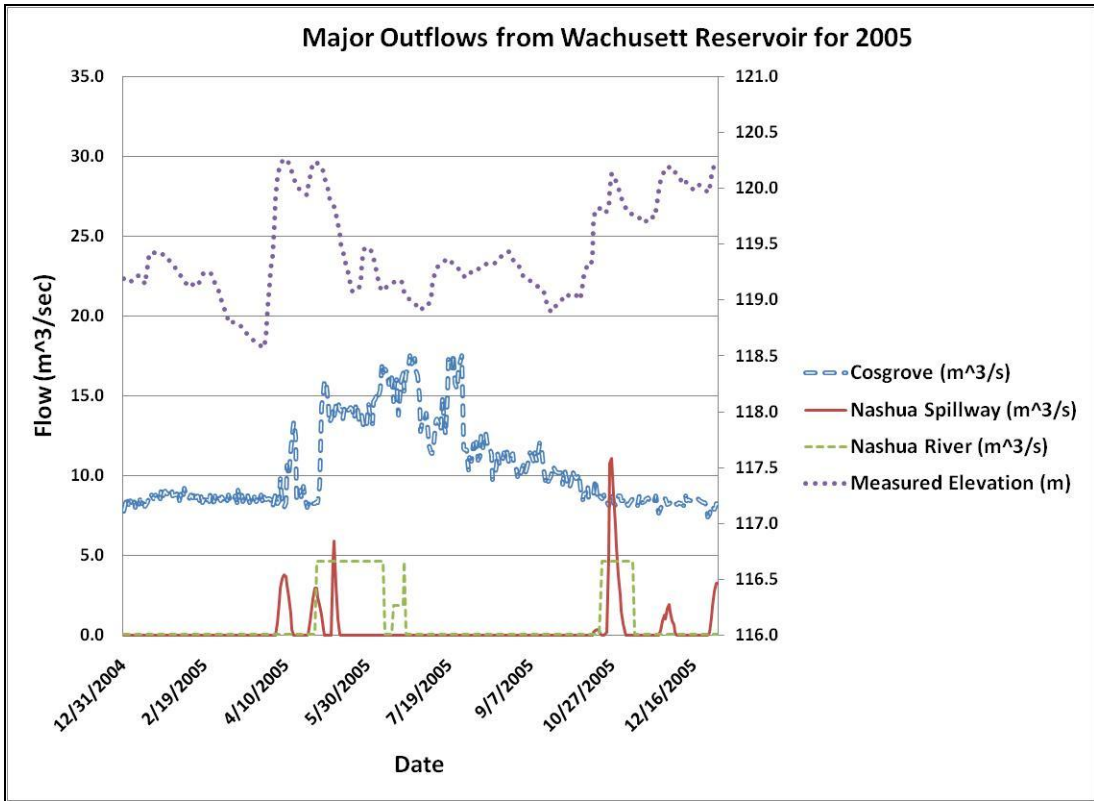


Figure 1.5 - Major outflows out of the Wachusett reservoir in the year 2005

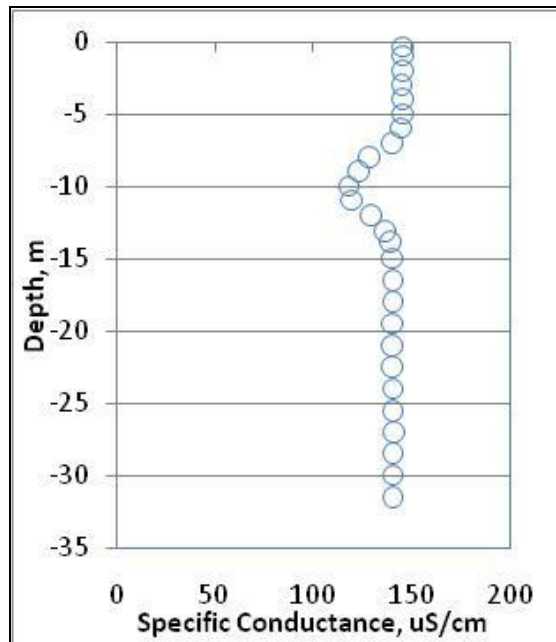


Figure 1.6 - Conductivity Profile (Quabbin Interflow), July 24, 2006_Measured at North Basin

1.2.3 All Inflows/Outflows

Table 1.1 presents a list of all the inflows and outflows that occur around the Wachusett Reservoir with associated percentage of total flow for the years 2003-2006. The percentage represents the portion of the total inflow or outflow that each inflow or outflow accounts for. The Quabbin Aqueduct, although not used year round, accounts for over 30% of the inflow due to the fact that it discharges, at specific times, over 300 MGD. This table also validates that the Stillwater and Quinapoxet Rivers are two major inflows, which combined account for over 30% of the inflow. The other seven tributaries each provide less than 3% of the inflow, the majority less than 1%. Precipitation makes up approximately 5% of the total inflow, and direct runoff, which is directly affected by the amount of precipitation ranges from 5 to 11%.

The Wachusett Aqueduct is not utilized every year. It was used towards the end of 2003 and beginning of 2004 due to repairs being performed on the Cosgrove intake and new corrections to the Carroll WTP. The Nashua Spillway displays an asterisk for 2003 because the data was not available for that year. Table 1.1 also validates that the Cosgrove accounts for most of the outflow from the Wachusett Reservoir, ranging from 60 to 84% of the total outflow. The Nashua River is also a major outflow with percentages ranging from 7 to 15%. An outflow that cannot be neglected when calculating water surface elevations is the evaporation which makes up for approximately 4% of the total outflow. The outflow labeled "other" accounts for dike seepage and water that was taken from the Quinapoxet River.

Table 1.1 - Percentage of Total Annual Flow for all Inflows/Outflows

		2003	2004	2005	2006
Inflows:	Quabbin Aqueduct	43.5	59.1	34.5	37.5
	Precipitation	5.2	4.7	6.0	4.9
	Direct Runoff	9.2	5.3	11.4	9.9
	Waushacum	2.9	1.6	3.5	3.1
	Stillwater River	14.0	8.3	17.7	15.8
	Quinapoxet River	21.4	18.7	22.1	24.7
	Malden Brook	0.6	0.3	0.7	0.6
	Boylston Brook	0.2	0.1	0.2	0.2
	Gates Brook	1.4	0.8	1.8	1.5
	Muddy Brook	0.3	0.2	0.4	0.3
	Malagasco Brook	0.4	0.2	0.5	0.4
	French Brook	0.9	0.5	1.1	1.0
	Outflows:	Wachusett Aqueduct	13.8	16.6	0.0
Nashua Spillway		*	1.8	3.0	5.5
Nashua River		14.1	15.3	7.1	12.7
Town Withdrawals		0.7	0.7	0.7	0.6
Cosgrove		66.0	60.2	84.0	76.7
Evaporation		3.7	3.7	4.0	4.5
Other		1.7	1.6	1.3	0.0

1.3 OBJECTIVES

The objectives of this research project were two-fold. The first was to develop 2-D models representing the Wachusett Reservoir for years 2005 and 2006 using CE QUAL W2. The second was to utilize V3.6 of CEQUAL W2 to perform spill simulations for years 2003-2006 under various conditions in order to assess year to year variability. Conditions evaluated included seasonal changes, variation of spill temperature, and effect of turning the Quabbin transfer on/off. The overall goal of the study was to better understand the behavior of spills within the reservoir in order to provide guidance on potential outcomes to help DCR better manage the reservoir if a spill were to occur.

2.0 BACKGROUND

2.1 Modeling

Water quality and hydrodynamic models are utilized to understand the behavior of various systems under a range of conditions. They can be used to analyze concentrations of contaminants or natural organic matter in order to determine the quality of the water due to a mixture of inputs. Models can also be applied to study changes in water surface elevation, velocities, and temperatures within the system caused by changes in inflows and outflows. They allow the user to examine several different scenarios in a time efficient manner because instead of inducing these conditions physically a computer can quickly simulate many different scenarios. The information provided can be used to develop responses to potential emergencies, such as contaminant spills, or to analyze a system over time to better understand water quality changes. It must be noted that model application can be complicated and knowledge in areas such as numerical modeling and hydrodynamics is required in order to recognize if the output is valid. Models can be a very effective tool when used correctly but if not careful, results may not be applicable.

2.2 CEQUAL W2

CEQUAL W2 is a two-dimensional (longitudinal and vertical) hydrodynamic and water quality model. It is best suited for relatively long and narrow water bodies because it assumes lateral homogeneity but has been applied to a combination of rivers, lakes, and reservoirs (Cole and Wells, 2008). CEQUAL W2 was first developed in 1975 by Edinger and Buchak, known back then as LARM (Laterally Average Reservoir Model) (Cole and Wells, 2008). It has been continuously developed with the most current modification released as version 3.6.

CEQUAL W2 was chosen for this research project because of the long, thin shape of the Wachusett Reservoir. It was also chosen for its simplicity as a two-dimensional model which saves time in development compared to a 3-dimensional. Version 3.6 was utilized due to its improved computational speed over version 3.5. Also, the input files created for V3.5 are compatible with V3.6 and therefore past files could be rerun without making any changes. Many other updates were made for V3.6 but are not discussed here; for more information see the CEQUAL W2 user manual (Cole and Wells, 2008).

2.3 Other Applications of CEQUAL W2

The purpose of this section is to present past literature pertaining to spill modeling using CEQUAL W2. The intention of this portion of the project was to better understand how CEQUAL W2 has been utilized in the past for spill modeling in fresh water systems such as lakes and reservoirs as well as for modeling of hydrodynamics. Contaminant spills into water supply reservoirs, such as the Wachusett Reservoir, are important to understand in order to best manage the water supply and protect water consumers.

Effectively managing the risks associated with accidental or intentional contaminant releases into the environment is of concern. A Spill Management Information System (SMIS) was developed by Vanderbilt University's Department of Civil and Engineering in conjunction with the Nashville District of the U.S. Army Corps of Engineers (USACE) which incorporated CEQUAL W2 V3.1 as its surface water contaminant transport model (Martin et al, 2004). The purpose of the SMIS is to aid responders in mitigating the effects of chemical incidents within the environment. This particular system was utilized on the Cheatham Reach, part of the Cumberland River, and simulated a 50,000 L spill of benzene, that occurred over a 1 hour period. The overall simulation time was set for one day, with an hourly temporal resolution, in which the plume of the spill was tracked as it traveled within the river. Although the focus of this section of the report is spill modeling into reservoirs, this type of model could be adapted to other waterways (Martin et al, 2004).

The transport of a contaminant within a reservoir is controlled by the hydrodynamics of the system and needs to be well understood in order to properly predict transport behavior. CEQUAL W2 was used to study the fate and transport of atrazine, an herbicide, in the Saylorville Reservoir located in Iowa (Se-Woong, 2009). The program was modified in order to incorporate a submodel for the fate and transport of atrazine. The reservoir was divided into 31 segments with an average length of 2.3 km and 28 vertical layers with 0.8-1.0 m thickness. The model was used to simulate the time period beginning on March 1 and ending on September 30, with a time step of 1088 seconds, in order to capture the corn growing season in which atrazine concentrations are elevated. Measured water temperatures and atrazine concentrations were used to verify simulation results. CEQUAL W2 proved to be a sufficient model for predicting temperature contours and determining the distribution of atrazine for different seasons (Chung

S., 2009). This displays a good example in which CEQUAL W2 could be integrated into reservoir management in order to better understand the behavior of contaminants under different scenarios.

CEQUAL W2 has also proved to be an important tool for simulating water quality components in many reservoirs. Eutrophication was modeled in two reservoirs located in Taiwan in which CEQUAL W2 was used to simulate temperature distributions as well as key water quality constituents such as dissolved oxygen and algal biomass (Kuo et al, 2005). Each of the reservoirs was divided into 15 longitudinal segments which were divided into 2 meter layers within the water column. A time step of 406 seconds was used to simulate the period starting on January 1, 1998 and ending on December 31, 1999. The model was calibrated using measured data and was used to evaluate watershed management techniques. It was found that a 30-55% reduction in the phosphorous load would improve the water quality from a eutrophic to an oligotrophic status (Kuo Jan-Tai et al, 2005). This study demonstrates yet another application of CEQUAL W2 in better managing a water system.

Another example of CEQUAL W2 being used to simulate the hydrodynamics of a reservoir was described in an article about Shasta Lake, located in northern California. In this case, CEQUAL W2 was utilized to simulate the limnological effects of a temperature control device (TCD) (Bartholow, J. et al, 2001). The purpose of the TCD is to improve downstream temperatures to improve the habitat for salmonids by releasing epilimnetic waters in the winter/spring and hypolimnetic waters in the summer/fall (Bartholow et al, 2001). Model predictions were compared to measured values throughout the water column at several locations for a two-year time period. Model predictions for water temperature had an R^2 value of 0.97 and predictions for DO had an R^2 value of 0.75. CEQUAL W2 successfully achieved the objective which was to predict in-reservoir effects of the TCD under various scenarios such as reduced summer stratification and delayed onset of stratification in the spring. All of these examples prove that CEQUAL W2 is a valid model that can be used to simulate the hydrodynamics of many different systems. Results for 68 reservoir temperature simulations in the US and throughout the world show that that the model is capable of reproducing a variety of reservoir thermal regimes with minimum adjustment of hydrodynamic/temperature calibration parameters (Cole, 2000).

2.4 Past Work for Wachusett Reservoir

The Wachusett Reservoir was originally modeled using CE QUAL W2 by Camp Dresser & McKee Inc. and FTN Associates, LTD. and calibrated for 1987, 1990, and 1992 (CDM, 1995). A revised model that computes the water budget on a daily time scale was constructed for years 1998 and 1999 by Alejandro Joaquin (Tobiason *et al.*, 2002). The model was used to observe the effect of Quabbin transfers on Wachusett Reservoir composition. Buttrick (2005) calibrated the model for 2001 and 2002 and modeled natural organic matter; the program code was modified to include light induced decay of UV₂₅₄ absorbance. Matthews (2007) calibrated the model for 2003 and 2004 and modeled coliform contamination that might occur from a wastewater pump station overflow. The CE QUAL W2 code was edited by Matthews to include light induced coliform decay. The 2004 version of the model (i.e. data input files and parameter values) was used for the majority of the research in this report. Stauber (2009) utilized the CEQUAL W2 models for 2003 and 2004 created by Matthews in order to examine contaminant spill behavior in general and specific aspects of spills of ammonium nitrate and fuel oil number 1. V3.5 of the program was used to better understand how these substances would behave within the reservoir under different wind conditions, temperatures of the spill, and state of the Quabbin transfer. The CEQUAL W2 code was altered by Stauber (2009) to include volatilization in order to better simulate benzene.

2.5 CEQUAL W2 Grid and Segments

The original grid for the Wachusett Reservoir was created by Camp Dresser & McKee Inc. (CDM) and modified by Joaquin (2001). The reservoir was divided into 63 segments as shown in Figure 2.1, with each segment containing a number of layers (Figure 2.2) associated with the depth at that location. The segments and layers represent the bathymetry of the reservoir. Each segment has a different number of layers, 47 being the maximum. The top surface layer through layer 31 are 0.5 m thick, layers 32 and 33 are 0.75 m thick, and bottom layers through 47 are 1.5 m thick. Figure 2.1 displays the location of the Cosgrove intake which is represented by a small segment, number 46. Each tributary is modeled as a flow into the specific segment representative of its physical location around the reservoir.

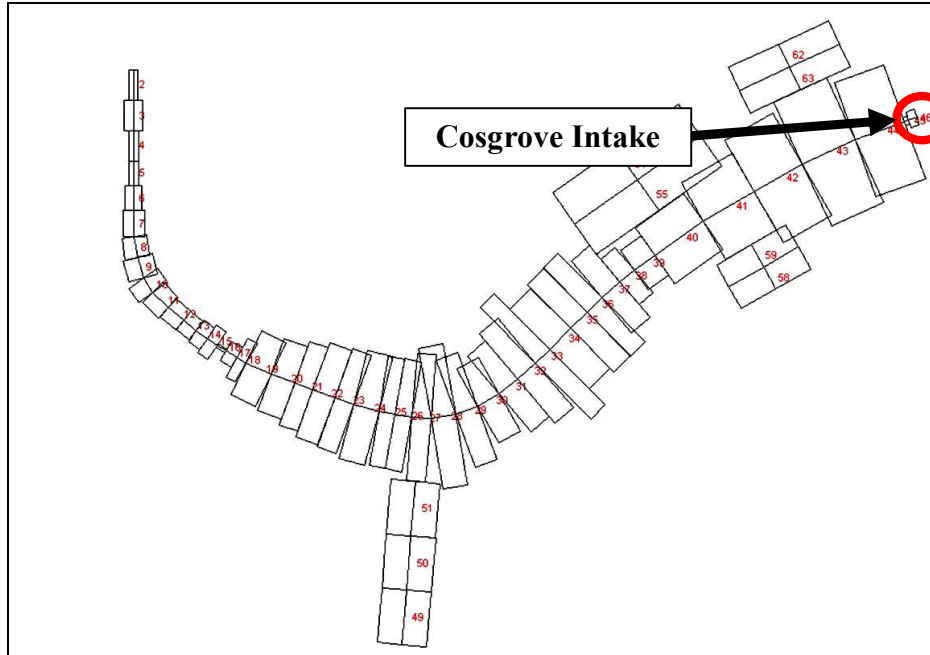


Figure 2.1 - CEQUAL W2 segments, top view

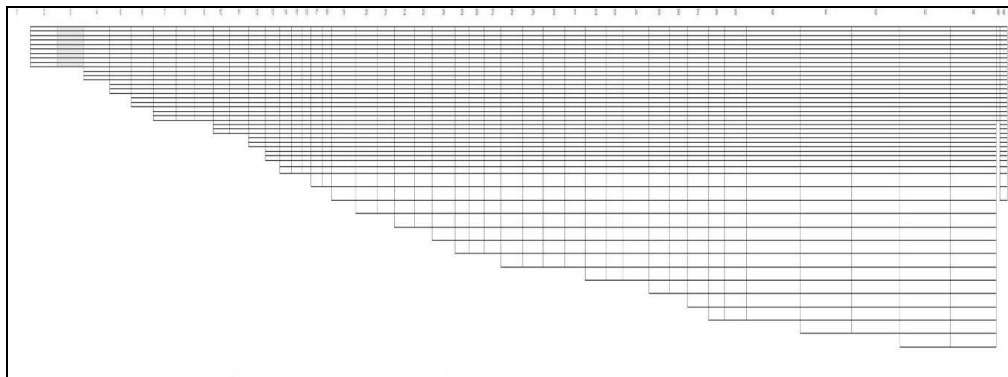


Figure 2.2 - CEQUAL W2 layers, side view

3.0 CE QUAL W2 MODEL DEVELOPMENT

The purpose of this section is to present the methods used to develop the CEQUAL W2 Wachusett Reservoir models for years 2005 and 2006. The model development and calibration portion of this project encompasses a large part of the work conducted at UMass. These steps are critical for generating a model which will produce valid output. As described previously, if the model is not created or used properly the output will be invalid. The first step in developing the model was to match water surface elevation to ensure that water was being added and taken out properly over the entire year. CEQUAL W2 model parameters were then adjusted to match measured temperature and conductivity profiles in order to ensure that the system is being heated and cooled correctly as well as contains appropriate levels of total dissolved solids (TSS). A description of each parameter is given within this section. These calibration procedures ensured that the model was acceptable to use in order to simulate spill behavior within the system.

3.1 Data Collection and Preparation

There were several steps involved in preparing and eventually calibrating the data that CEQUAL W2 utilizes in order to generate valid output. The first step was to collect the required data in order to complete a water balance, second was to generate the necessary input files, and the last step was calibration of the CE QUAL W2 model by adjusting parameters within the program.

3.1.1 Water Balance

The water balance, an Excel spreadsheet developed by Kennedy (2003), is an important tool used to minimize the error between measured and calculated water surface elevations by applying calibration factors to each of the inflows. This first step identifies any instances in which data is incorrect or missing in order to conduct a proper calibration. The data (daily-averaged) consists of measured inflows and outflows gathered from sources such as the National Oceanic and Atmospheric Administration (NOAA), MWRA, and the United States Geological Survey (USGS). Changes in total reservoir volume are calculated for each day by adding the total inflow volume and subtracting the total outflow. This value is then converted to a water surface elevation which can then be compared to measured values taken by the DCR team. A more thorough discussion of the correlation between volume and water surface elevation is presented in Buttrick (2005).

As described previously, flow data are only available for the Stillwater and Quinapoxet tributaries. The flow of the other tributaries is estimated by multiplying the Stillwater discharge by an areal ratio of the tributary watershed to the area of the Stillwater watershed. Calibration factors are then determined for each inflow, including the Quabbin Aqueduct. These factors are found through the utilization of SOLVER within the water balance Excel spreadsheet. The daily flows of each tributary inflow are multiplied by its associated calibration factor in order to determine daily inputs. Solver adjusts calibration parameters to minimize the square errors between calculated and measured water surface elevation. Once the calibration is complete and error between the measured and calculated water surface elevation is acceptable, the inflow and outflow data are used to create a portion of the CEQUAL W2 input files, which are described in the following section.

Table 3.1 displays the final calibration factors for 2005 and 2006 along with prior model values and ranges. The 2005 calibration factors are all within the historical ranges. They are also close to a value of 1 which demonstrates that the provided data for 2005 are accurate. For example, if a factor is adjusted to a value of 1.3, an additional 30% of flow for each day is added for that tributary. The closer the value is to 1, the smaller the adjustment had to be in order to minimize the error. Figure 3.1 displays a plot of water surface elevation for 2005 that illustrates the adjustment made in the water balance in order to make the model as close as possible to the measured data. The un-calibrated values represent the original data obtained from MWRA and other sources. The calibrated dataset are the elevations obtained after utilizing the SOLVER portion of the water balance spreadsheet. Most of the 2006 calibration factors are towards the low end of the historical ranges. This shows that in order to minimize the error, flows had to be reduced by approximately 22%. Figure 3.2 displays the elevation plot for 2006. As shown, the un-calibrated elevation values were greater than the measured for the entire year. Therefore, the raw data flows were producing higher elevations than measured which would be the reason for the low calibration factors. In order to correct for this, the Stillwater River flows were reduced as shown by the value of 0.80, a 20% reduction. The tributaries, as described previously, are estimated by multiplying the Stillwater River flow by an areal ratio. Therefore, each of the tributary flows was reduced accordingly.

Table 3.1 - 2005, 2006 and Prior Model Calibration Factors

Inflow	Annual Average (1994-2004)	Range (1994-2004)	2005	2006
Quabbin	1.03	0.93 - 1.10	0.99	1.00
Stillwater	1.01	0.70-1.28	0.94	0.80
Quinapoxet	1.10	0.82-1.30	0.92	1.05
Waushacum	1.19	0.79-1.65	0.93	0.78
Nashua Sleeve Valve	1.01	0.98-1.04	1.01	0.76
Direct Runoff	1.19	0.79-1.62	0.93	0.78
Malden	1.13	0.79-1.35	0.93	0.78
W. Boylston	1.16	0.79-1.35	0.93	0.78
Gates	1.22	0.79-2.0	0.93	0.78
Muddy	1.13	0.79-1.35	0.93	0.78
Malagasco	1.13	0.79-1.35	0.93	0.78
French	1.13	0.79-1.35	0.93	0.78

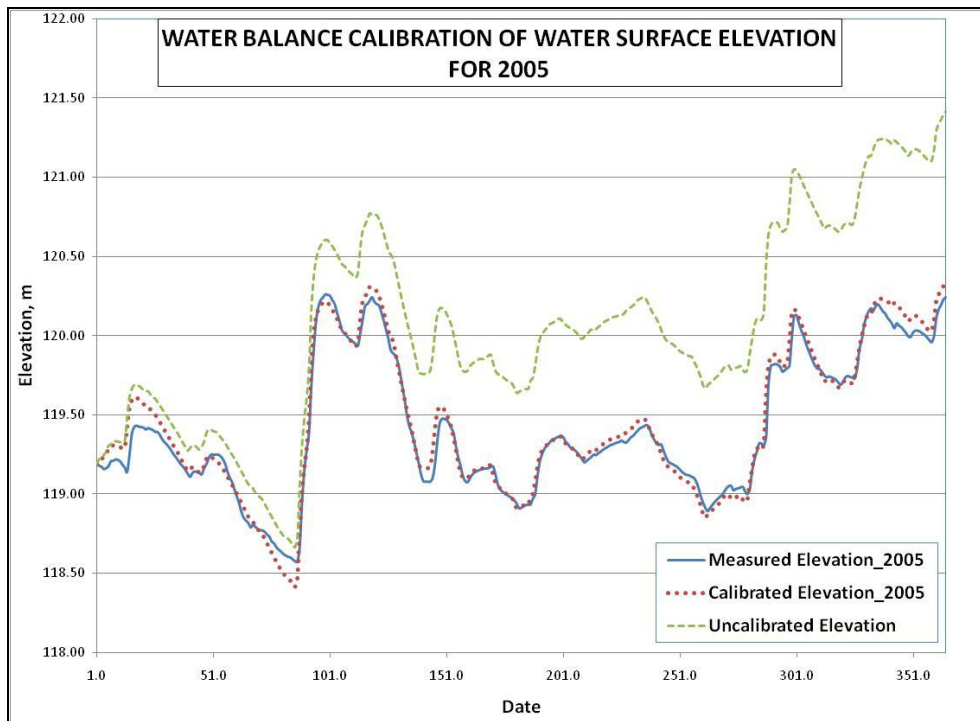


Figure 3.1 - Calibrated Plot of Water Surface Elevation for 2005

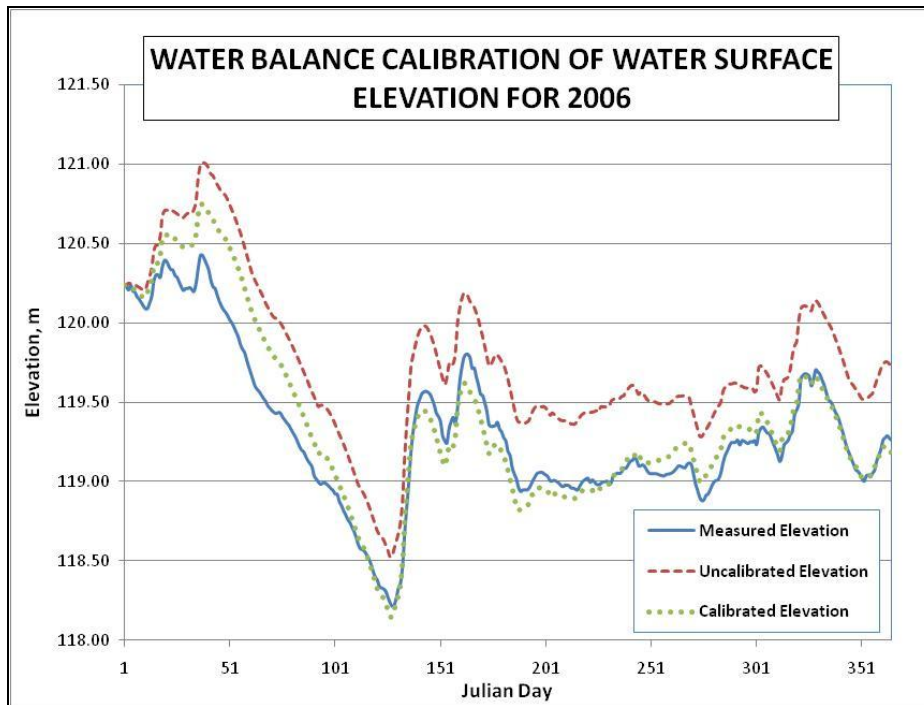


Figure 3.2 - Calibrated Plot of Water Surface Elevation for 2006

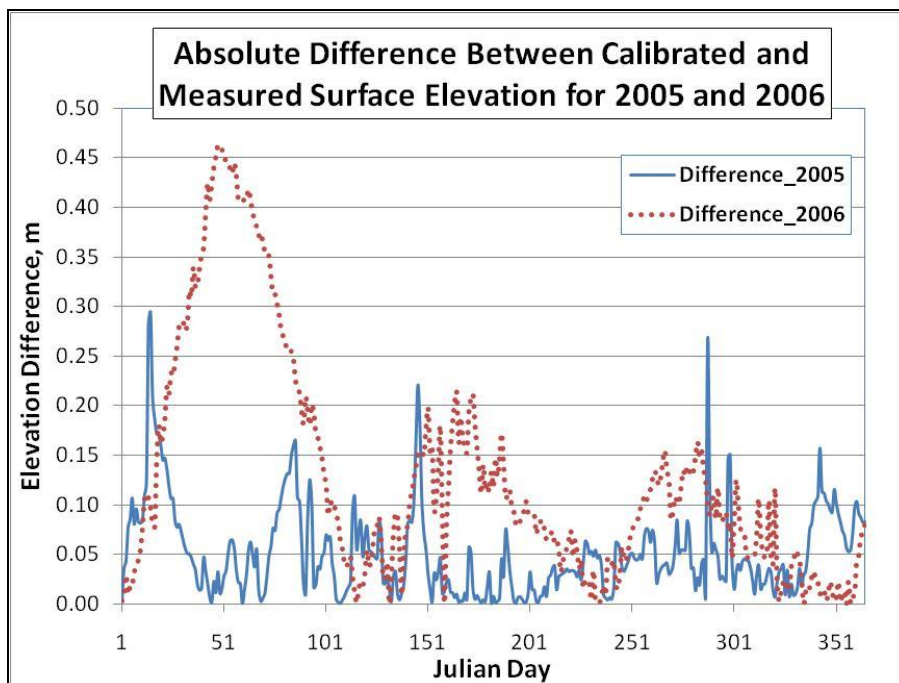


Figure 3.3 - Absolute Difference between Calibrated and Measured Elevations for 2005 & 2006

A comparison of root mean squared (RMS) errors between measured and calculated elevations for 2005, 2006, and historical values is presented in Table 3.2. 2005 had one of the lowest RMS errors where 2006 had a rather high error. This error is attributed to the adjustment made to the Stillwater River and tributaries. The difference between measured and calibrated water surface elevations for 2005 and 2006 is displayed in Figure 3.3. There is a peak of error in 2006 that occurs between Julian days 1 and 101 which correlates with Figure 3.2. The calibrated elevation values are greater than the measured until Julian day 101 in which the errors become more acceptable.

Table 3.2 - Root Mean Squared Error for Years 1994-2006

Year	RMS Error, m
1994	0.07
1995	0.17
1996	0.23
1997	0.11
1998	0.10
1999	0.06
2000	0.08
2001	0.07
2002	0.07
2003	0.06
2004	0.11
2005	0.07
2006	0.17

3.1.2 Input Files

Table 3.3 is a simplified table which is used to describe the input files that were created and the necessary manipulation of data. Table 3.3 lists the name of each input file along with a brief description and source of the data. The proper preparation of all the input files is required in order for CE QUAL W2 V3.6 to run correctly. The file extension for all the listed input files is .nptö.

Table 3.3 – Simplified List of Required Input Files

File (.npt)	Description	Source
cdt_br1	Weekly constituent data for daily runoff	MWRA supplied
cin_br1	Weekly Stillwater inflow constituents	MWRA supplied
cpr_br1	Weekly precipitation concentrations - Avg. of Lexington & Quabbin	GOOGLE - National Atmospheric Deposition Prog
ctr_tr1 to ctr_tr9	Weekly inflow constituents for all tributaries	MWRA supplied
*ctr_tr3	Quabbin weekly inflow constituents	MWRA website
met	Hourly Meteorological Data	NOAA
pre-br1	Daily precipitation - Worcester Airport	NOAA
qin_br1	Stillwater daily inflow	USGS website
qdt_br1	Direct runoff discharge	Waterbalance
qot_br1	Cosgrove Withdrawal	Waterbalance
qtr_tr1 to qtr_tr9	Daily inflows of tributaries	Waterbalance
*qtr_tr2	Quinapoxet daily inflow	USGS website
*qtr_tr3	Quabbin daily inflow	MWRA website
qwd	Withdrawals: Dike seepage + town +nashua + wachusett aqueduct	MWRA supplied
tdt_br1	Weekly direct runoff temperature	MWRA supplied
tin_br1	Weekly Stillwater temperature	MWRA supplied
tpr_br1	Hourly dew point temperature	NOAA
ttr_tr1 to ttr_tr9	Weekly inflow temperatures for all tributaries	MWRA supplied
*ttr_tr3	Quabbin weekly inflow temperature	MWRA website
w2_con	Control File	
wsc	Wind Sheltering Coefficient File	

The input file containing weekly constituent data for daily runoff is labeled cdt_br1. Weekly constituent data for daily runoff represents the average concentration of constituents entering the reservoir from the runoff of all tributaries excluding the Stillwater and Quinapoxet Rivers. For this study the only water quality constituent modeled was the concentration of total dissolved

solids (TDS). TDS values were converted to conductivity for comparison with measured conductivity data obtained by DCR. Therefore, the input files must contain TDS values. The weekly constituents entering from the Stillwater River are in a separate input file, `cin_br1`. Input files `ctr_tr1` through `ctr_tr9` represents all other weekly inflow constituents including the Quabbin transfer. All constituent data, except for the Quabbin transfer, are obtained from MWRA and DCR personnel. The Quabbin weekly inflow constituent data, `ctr_tr3`, can be obtained from the MWRA website (drm.mwra.com). The Quabbin daily inflow, `qtr_tr3`, can also be found at this website.

The input file `cpr_br1` has the weekly precipitation TDS concentrations which are calculated by averaging TDS values of Lexington and Quabbin precipitation. This data is thus the constituents entering the reservoir through precipitation and is gathered from the National Atmospheric Deposition Program which can be found through a simple Google search. The `met` file contains all the critical meteorological data such as air temperature in degrees Celsius, dew point temperature in degrees Celsius, wind speed in m/s, wind direction in radians, and cloud cover. Cloud cover is represented by a value from 0 to 10. A value of 0 means there is no cloud cover while a 10 symbolizes a clear condition. It is pertinent that this file have an hourly temporal resolution in order to capture realistic physical conditions occurring around the reservoir. The temperature and velocity of the water are affected by meteorological conditions. The data found in the `met` file and `pre_br1` file, which contains daily precipitation, are acquired from the NOAA website. The data are from the Worcester Airport and can be found by utilizing the "Search by Map" function within the NOAA website.

The Stillwater and Quinapoxet Rivers, as described earlier, are gaged by the USGS. The Stillwater and Quinapoxet daily inflow input files, `qin_br1` and `qtr_tr2` respectively, are created by gathering the appropriate data from the USGS website. The daily inflows of all other tributaries, `qtr_tr1` through `qtr_tr9` (excluding `qtr_2` and `qtr_tr3`), are calculated within the water balance as described in the following section. All inflow input files are in units of m^3/s . Two other input files created from the water balance are `qdt_br1`, direct runoff discharge, and `qot_br1` which represents the Cosgrove intake withdrawal. The `qwd` input file contains values which represent the total daily withdrawals from other sources such as dike seepage, town withdrawals from Clinton, MA, Nashua River discharge, and Wachusett Aqueduct

withdrawals. All data within this file are gathered from personnel at the MWRA. The Wachusett Aqueduct is only used when necessary, such as in 2003 when the Cosgrove intake was shut down for repair. Flow values within these files are also in units of m³/s.

The temperature of water for each inflow is also required in order to properly run CEQUAL-W2. The weekly direct runoff temperature, $\bar{o}tdt_br1\bar{o}$, as well as the Stillwater River weekly inflow temperature, $\bar{o}tin_br1\bar{o}$, are obtained from MWRA personnel. The weekly inflow temperatures for all other tributaries, $\bar{o}tr_tr1\bar{o}$ through $\bar{o}tr_tr9\bar{o}$ (excluding $\bar{o}tr_tr3\bar{o}$), are also obtained from MWRA personnel. The input file labeled $\bar{o}tr_tr3\bar{o}$ represents the Quabbin transfer weekly inflow temperature which can be obtained from the MWRA website. The hourly dew point temperature, $\bar{o}tpr_br1\bar{o}$, is obtained from the NOAA website for the Worcester Airport. All temperatures are in units of degrees Celsius.

The last input file listed in Table 3.3, $\bar{o}wsc\bar{o}$, contains the wind sheltering coefficient which is described in the calibration section of this report. Simply, it is a unit-less factor that is multiplied by the wind speed to best represent the terrain around the reservoir. The control file, $\bar{o}w2_con\bar{o}$, is the file that CEQUAL W2 requires to run. It is the location of values for all the program parameters which affect how a simulation will perform. Parameters can be turned on or off within this file as well as used to adjust the number of tributaries and their locations. The control file also identifies the individual input files in order to utilize the correct data when performing simulations.

3.2 Calibration

*****NOTE*****

It was discovered after the completion of this report that the met file contained values for visibility rather than cloud cover. This affected the amount of cloud cover and therefore was the reason for the temperature difference within the epilimnion of the reservoir. The Results section of this report contains simulations that were rerun, the plots and descriptions in the following section were not changed. This did not affect the overall conclusions of the project.

Calibration of temperature and conductance is important in order to generate a model that accurately simulates reservoir hydrodynamics and energy balance. The optimization of agreement between measured and modeled data is key to best model the reservoir hydrodynamics and utilize the model for further studies. There are numerous parameters within the model that have an effect on simulated temperature and conductivity profiles. There are specific coefficients that directly affect the thermal calibration of the model and may need to be adjusted from their default values (default values for all parameters discussed in this section are presented in Table 3.4). The wind sheltering coefficient (WSC) is a calibration parameter and therefore is not given a default value. The purpose of this section is to analyze and better understand the effects of adjusting these parameters. Tables of errors between measured and simulated temperature and conductivity values were created in order to obtain an optimal combination of parameters; profiles of water temperature and conductivity were generated from the model.

Table 3.4 – Default Values for CEQUAL W2 Model Parameters affecting Thermal Calibration

Parameter	Default Value	Units
AX	1	m ² /s
DX	1	m ² /s
WSC	Calibration	
BETA	0.45	
EXH2O	0.45	m ⁻¹
FRICT	70	m ² /s

3.2.1 Initial Conditions

There are several initial conditions that are required for model application, with an underlying assumption that the reservoir is initially homogenous and completely mixed. Two of these are the initial temperature, designated $\delta T2I\delta$ within the control file, and the initial constituent concentration, designated $\delta C2IWB\delta$, for January 1st of the modeled year. These values are

estimated by utilizing temperature and conductivity data from the Cosgrove intake. Figure 3.4 displays the results of changing the initial conductance by 15 S/cm at the North Basin for Julian Day 201 of 2005. The initial conductivity value, or best estimate on that date, was 79 S/cm which was increased to a value of 94 S/cm.

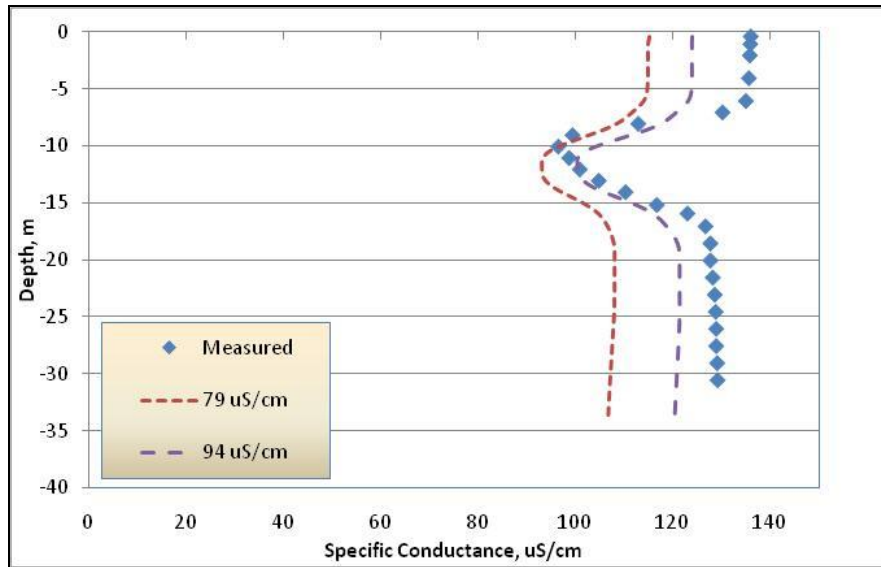


Figure 3.4 - Effect of Increase of Initial Conductivity Value by 15 μ S/cm_North Basin_JD201_2005

Figure 3.4 shows that there is a linear change to the epilimnion and hypolimnion conductivity values; an increase of 15 S/cm to the initial condition showed an increase of approximately the same within those layers. A smaller change occurs within the depths in which the Quabbin interflow is located, roughly 10 meters. This is attributed to water mixing with lower conductivity Quabbin water at this location, which does not occur within the epilimnion or hypolimnion. This proves the importance of the role that the initial conductivity plays when trying to match calculated and measured values. Adjusting this value correctly is critical in order to output a calibrated conductivity profile.

Two separate simulations were created to analyze the effect of changing the initial temperature as shown in Figure 3.5. Output was generated for the calculated surface temperatures at the North Basin for every day during the year for 2006.

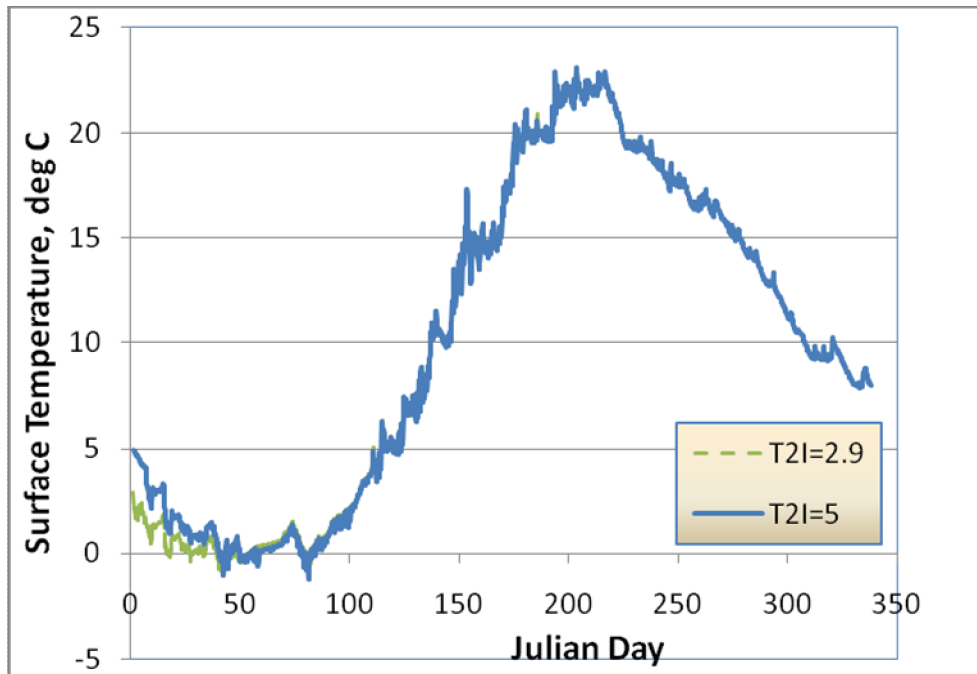


Figure 3.5 – Effect of Increase of Initial Temperature_North Basin_2006

The dashed line in Figure 3.5 represents an initial temperature of 2.9 deg C and the blue line represents an initial temperature of 5 deg C. As the figure shows, the initial temperature only affects the early temperatures (day 0-40) but does not have any effect on later days. This demonstrates that drivers such as air temperature, wind, and in-reservoir circulation dominate changes from the initial conditions. It must be noted that the temperatures realistically cannot reach temperatures below 0°C. The negative values reflect times when ice would have formed but was not explicitly modeled in order to accurately compare to previous years simulations.

3.2.2 WSC – Wind Sheltering Coefficient

WSC within the control file represents the wind sheltering coefficient. This value is a fraction which is multiplied by the wind speed to reduce the effects of the wind and account for the type of terrain that surrounds the water body. The wind sheltering coefficient, according to the CE QUAL W2 manual, has the most effect on temperature during calibration and therefore should be adjusted first. This parameter can be adjusted from a value of 0.0 to 1.0. A value of 1.0 would be representative of open terrain and typical values range from 0.5 to 0.9 for mountainous and/or dense vegetative canopy. The wind sheltering coefficient can be a function of segment if

segment by segment wind velocity is input. The 2005 and 2006 models used a constant value in order to simplify the process. Figure 3.6 is a plot that displays the effect of changing the wind sheltering coefficient from a value of 0.95 to 0.503 on the water temperature profile for the North Basin. The measured values are for the North Basin (Segment 42) and the Julian day was chosen to be 200 (7/17/06) in order to compare model output and the measured values during the period of stratification.

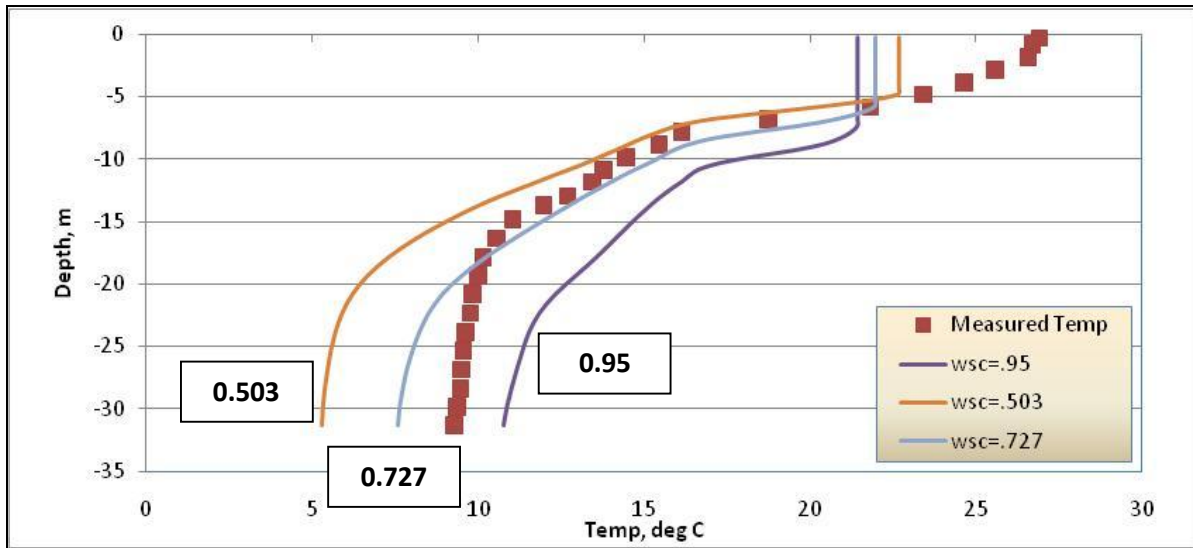


Figure 3.6 – Effect of Wind Sheltering Coefficient on Temperature_North Basin_JD200_2006

Figure 3.6 shows that the agreement between calculated and measured values improved as the coefficient was lowered until reaching the value of 0.503 in which case the difference in hypolimnion temperatures began to increase from the measured. The analysis showed that the wind sheltering coefficient has a substantial effect on the temperature profile within the reservoir during the summer.

It was observed that the simulated epilimnion temperatures were colder than the measured temperatures by a few degrees, as shown in Figure 3.6. The measured values showed a less mixed epilimnion as well, whereas the simulated showed the same temperature throughout a depth of approximately 5-7 m. More dates in 2006 were analyzed to better understand if this day was unique or if the epilimnion temperatures behaved in that manner consistently. Figures 3.7 and 3.8 represent Julian days 206 and 216, or 7/24/06 and 8/3/06, at the North Basin.

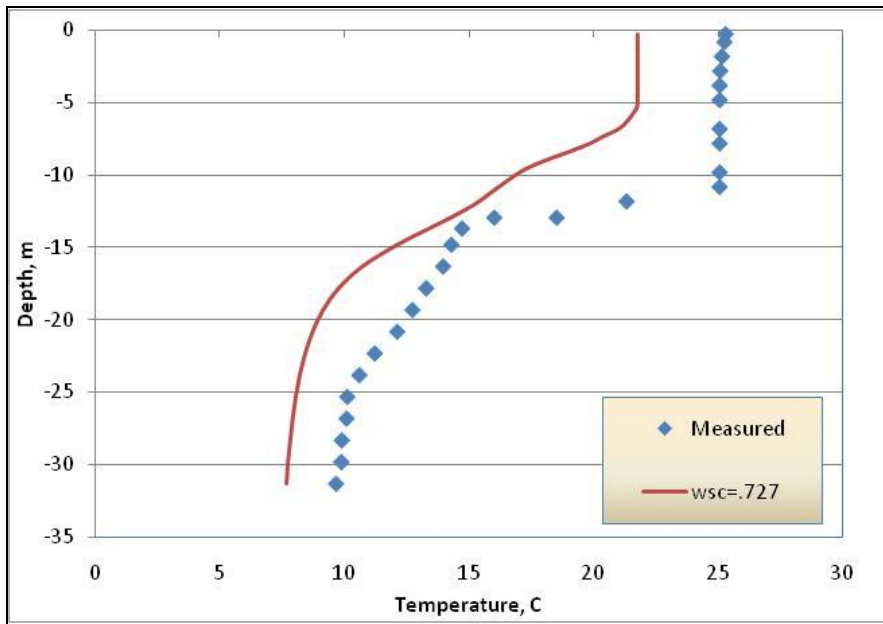


Figure 3.7 - Julian Day 206_2006, Calculated Compared to Measured for WSC=0.727

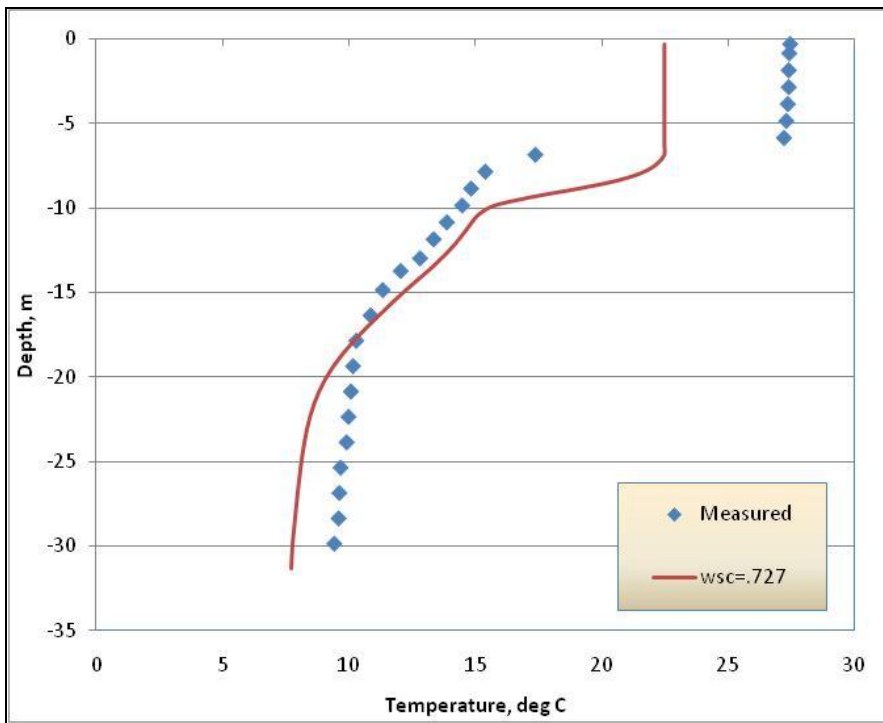


Figure 3.8 - Julian Day 216_2006, Calculated Compared to Measured for WSC=0.727

Figures 3.7 and 3.8 prove that the measured epilimnion temperatures for other days in the summer are constant throughout depths of 10 m. The figures also show that the calculated epilimnion temperatures are about 5 degrees cooler than the measured and therefore other thermal calibration factors should be analyzed to try and obtain a better fit.

3.2.3 AX, DX - Dispersion Coefficients

The δAX parameter represents the horizontal eddy viscosity, or the dispersion of momentum in the x-direction. The δDX parameter is the horizontal dispersion coefficient for temperature and constituents. Both can be found within the control file under the designations of δAX and δDX and affect the hydrodynamics that affect heat and constituent transport. The default values for these coefficients are 1, with units of m^2/s , and can vary up to 10-30 m^2/s for AX in some estuaries and can vary even more significantly for DX ranging from 10-100 m^2/s (Cole and Wells, 2008). The values for DX and AX were adjusted during calibration in order to better understand the effects on the temperature and conductivity profiles. In each test, all other parameters were set to their default values, while the parameter in question was adjusted. Figure 3.9 demonstrates the effect on the temperature profile of increasing the DX value from 1 to 8 m^2/s for Julian day 206 of 2006 at the North Basin and Figure 3.10 shows the change in the conductivity profile. The WSC values in figures 3.9 and 3.10 are different but it must be noted that results were consistent for all values. The intent of these figures is to demonstrate the affect of the DX parameter.

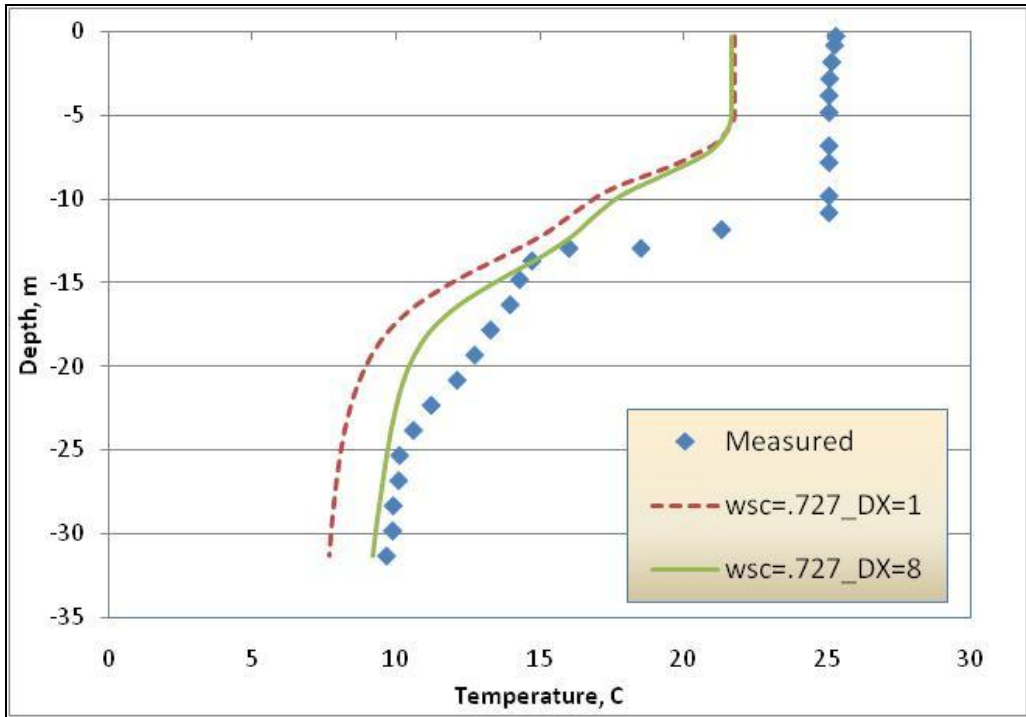


Figure 3.9 – Effect of Increase of DX on Temperature_JD206_2006_North Basin

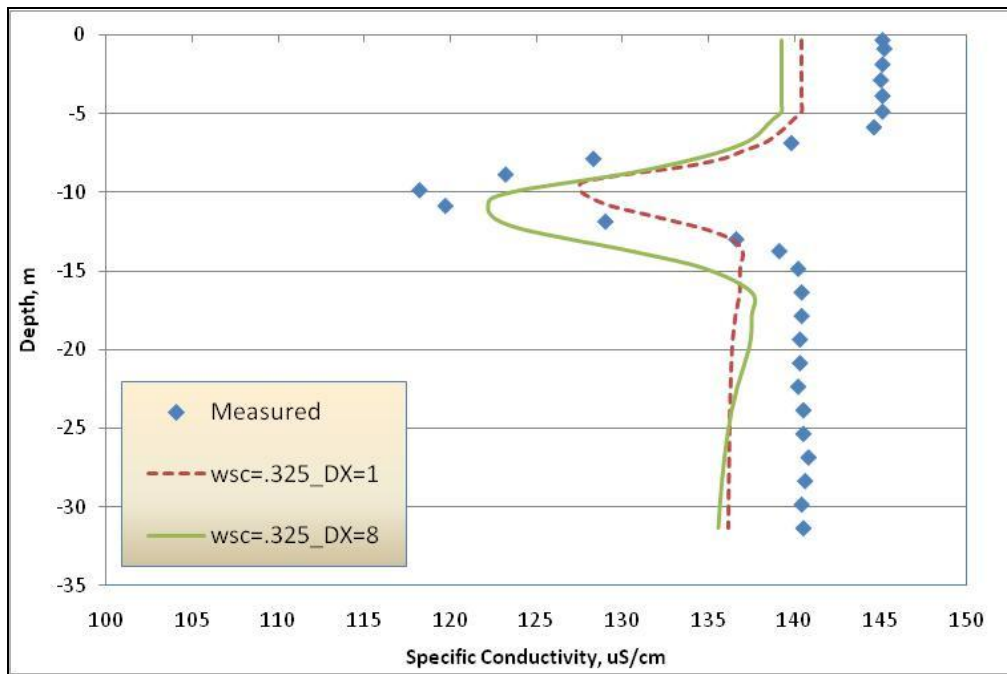


Figure 3.10 – Effect of Increase of DX on Conductivity_JD206_2006_North Basin

Figure 3.9 shows that there was an increase in temperature from a depth of approximately 10 m to the bottom for the increased DX value, generating a better fit between hypolimnion temperatures. Figure 3.10 shows that for the same Julian day and location the conductivities decreased slightly towards the middle but demonstrated small changes in the epilimnion and hypolimnion. Again, to better understand if these effects were consistent for other days, more dates were observed as shown in Figures 3.11, 3.12, 3.13, and 3.14 for Julian days 216 (8/3/06) and 243 (8/30/06).

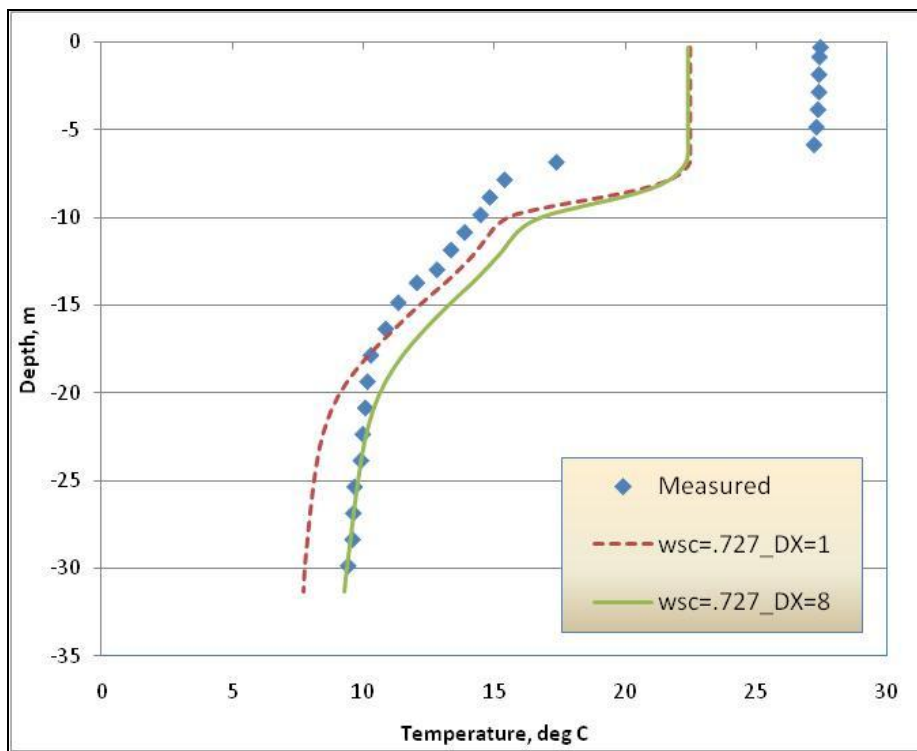


Figure 3.11 – Effect of Increase of DX on Temperature_JD216_North Basin for 2006

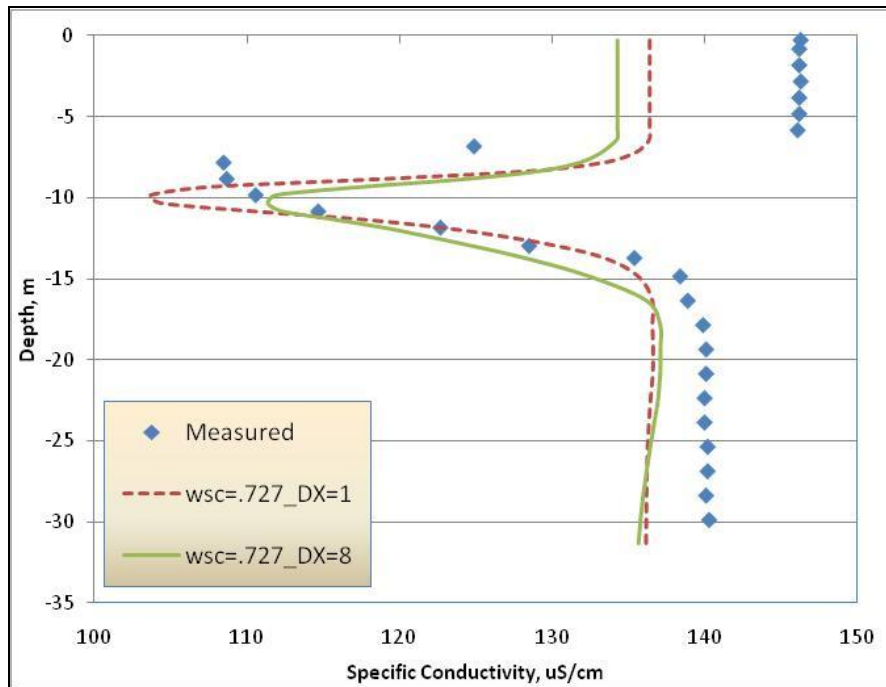


Figure 3.12 - Effect of Increase of DX on Conductivity_JD216_2006_North Basin

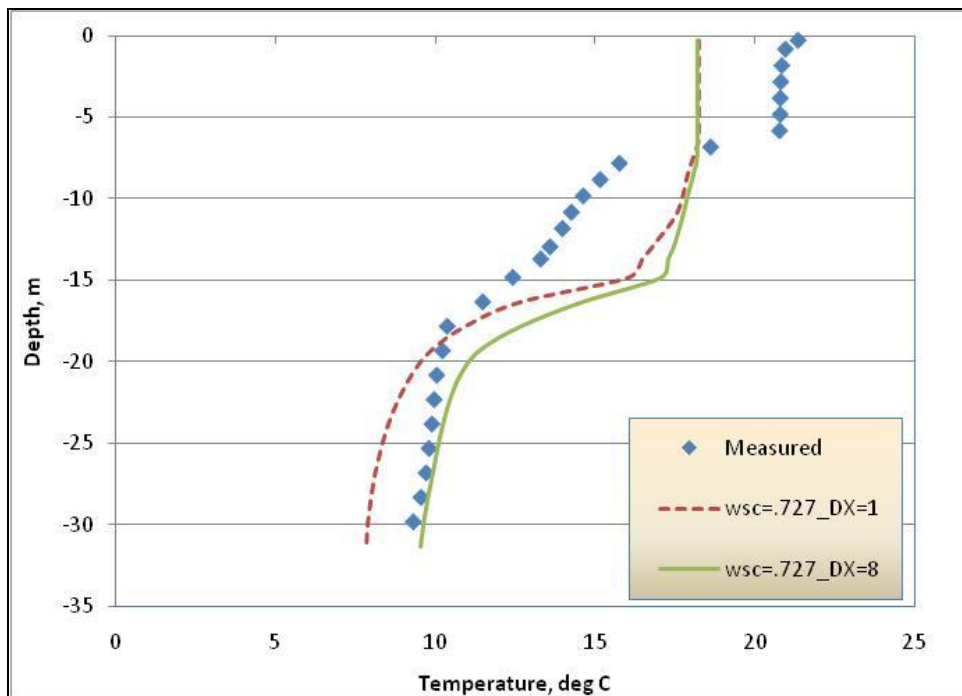


Figure 3.13 - Effect of Increase of DX on Temperature_JD243_2006_North Basin

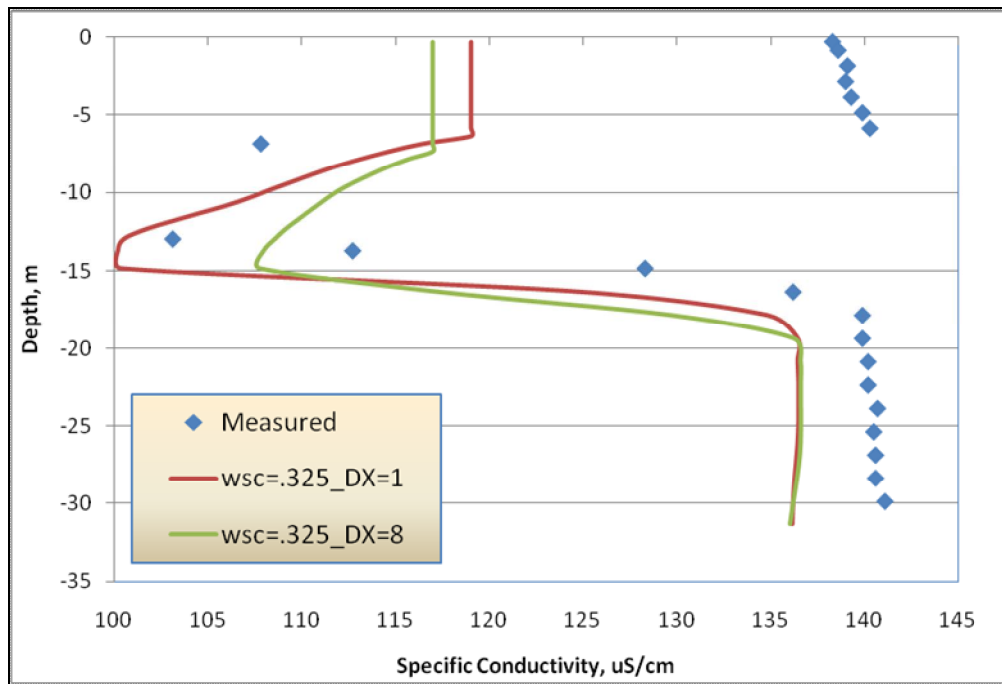


Figure 3.14 – Effect of Increase of DX on Conductivity_JD243_North Basin

Figures 3.11 and 13 show that the effect of increasing the DX parameter on the temperature profile is consistent. Both figures show that below a depth of 10 m, an increase of 2 to 5 degrees Celsius occurs. In all cases, the calculated hypolimnion temperatures showed better agreement for the higher DX value. The conductivity profiles, as shown in Figures 3.10, 3.12, and 3.14 show very little change in the calculated conductivity values versus the measured. Figure 3.10 shows a slight decrease in conductivity towards the middle depth of the North Basin and Figures 3.12 and 3.14 show a slight increase but neither showed any dramatic effect.

The AX parameter was decreased from the default value of $1 \text{ m}^2/\text{s}$ to a value of $0.25 \text{ m}^2/\text{s}$ and increased to $5 \text{ m}^2/\text{s}$ to examine the effects on the temperature and conductivity profiles for Julian day 206 of 2006 as shown in Figure 3.15, and 3.16.

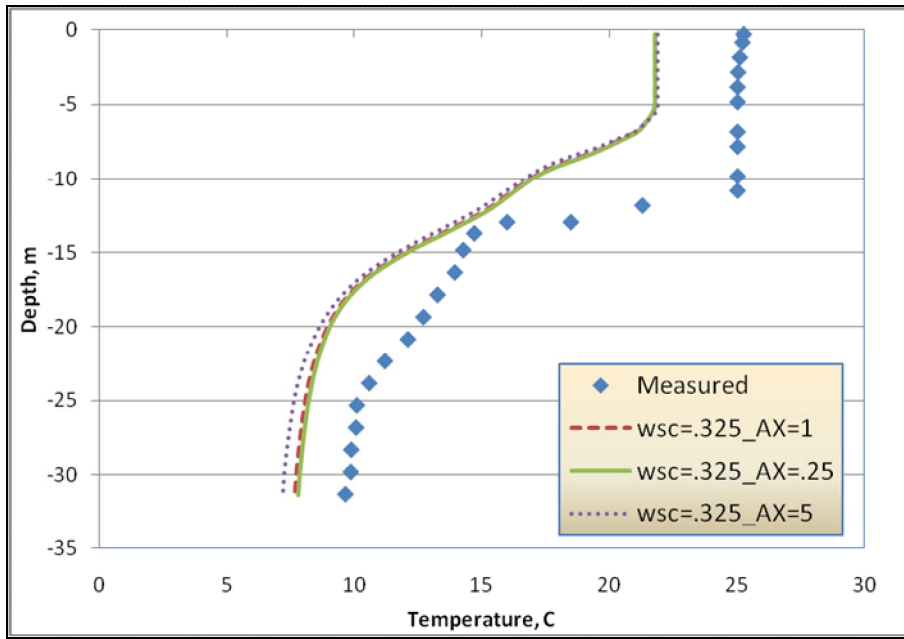


Figure 3.15 - Effect of AX Change on Temperature_JD206_2006_North Basin

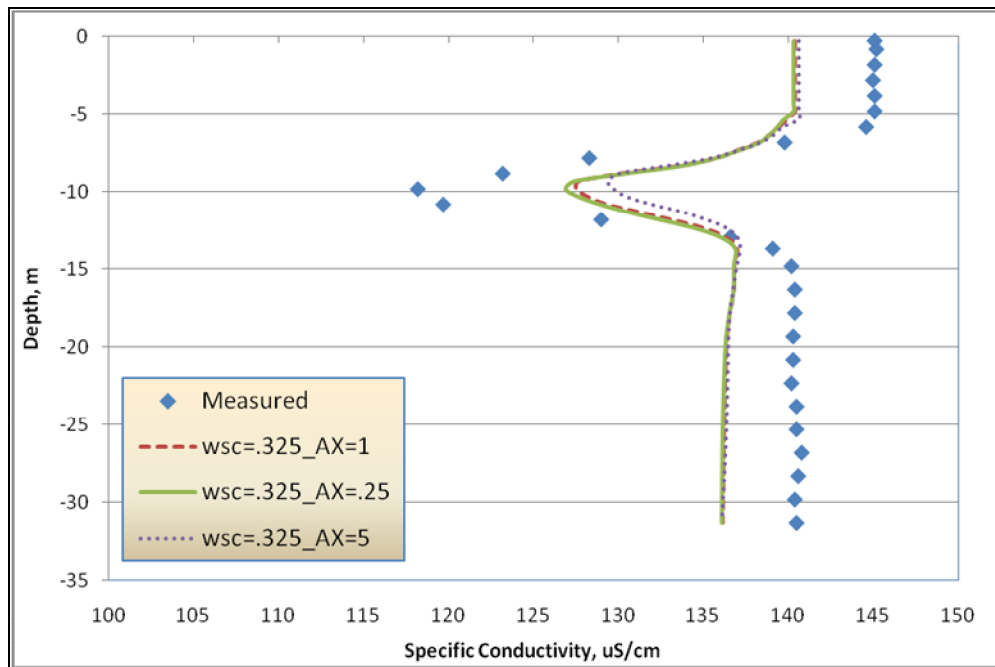


Figure 3.16 - Effect of AX Change on Conductivity_JD206_2006_North Basin

Figures 3.15 and 3.16 show that an increase or a decrease in the AX parameter has minimal effect on the simulated temperature and conductivity profiles.

3.2.4 BETA, EXH2O

CE QUAL W2 uses a parameter, designated as β , to describe the fraction of solar radiation absorbed in the surface layer. This fraction controls the distribution of solar radiation within the water column. Another factor that controls the distribution is the attenuation rate due to water, or extinction coefficient of water, designated as α . The default value for BETA is 0.45 and the manual shows that there are two different defaults for EXH2O, 0.25 or 0.45 m^{-1} . Figure 3.17 shows the results of an increase in BETA and the effect it has on the temperature profile during Julian day 200 of 2006 at the North Basin. This test was performed with the EXH2O default value of 0.25.

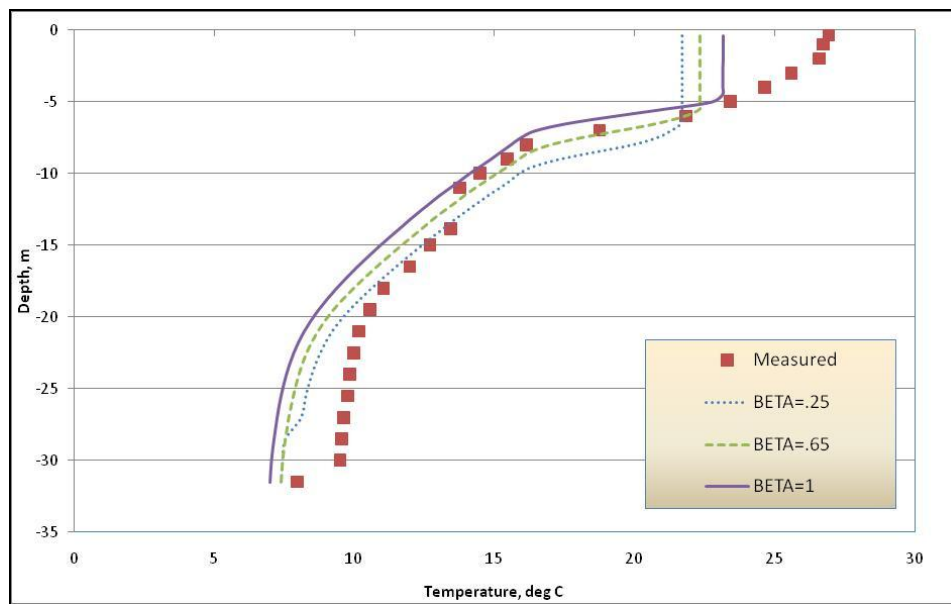


Figure 3.17 - Effect of Increase of BETA on Temperature_JD200_2006_North Basin

Figure 3.17 shows that as the BETA coefficient increases from 0.25 to 0.65 and then to 1.0, the epilimnion temperatures increase by almost a full degree. The hypolimnion temperatures however, decrease slightly. This analysis showed that even with a BETA value of 1.0, meaning 100% of the solar radiation is being absorbed in the surface layer, the temperature in the epilimnion is still a few degrees cooler than the measured. Realistically, the fraction would

never reach 1.0 because of various environmental factors. BETA was then set to its default and the EXH2O parameter was set at both defaults. The results of this test are shown in Figure 3.18.

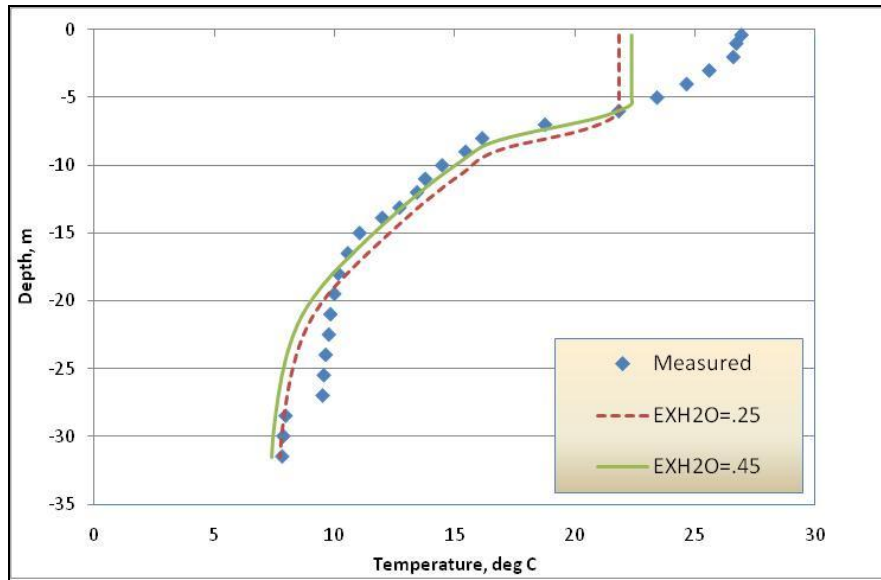


Figure 3.18 – Effect of Default Values of EXH2O on Temperature_JD200_2006_North Basin

Figure 3.18 shows that both default values for EXH2O had very similar output with a difference of only about half of a degree. This analysis of the BETA and EXH2O parameters showed that these parameters have small effects on the predicted epilimnion temperatures.

3.2.5 FRICT – Chezy Coefficient or Manning’s N

CE QUAL W2 gives the user the option of specifying a Chezy coefficient or a Manning’s n value for bottom friction. The default is set for Chezy which can be found under FRICC in the control file. These values are utilized within the program to calculate boundary friction and are specified in the bathymetry file. A typical value for the Chezy coefficient is 70 m²/s and 0.35 for Manning’s n. The Chezy coefficient is related to the Manning’s n in the following manner (SI Units):

$$C = (1/n) * R^{1/6}$$

where: C ó Chezy Coefficient

n ó Manning's friction factor

R ó Hydraulic Radius

The Chezy friction coefficient was increased from the default of 70 m²/s to 350 m²/s and the effect of this change on the temperature profile for Julian day 206 of 2006 is shown in Figure 3.19.

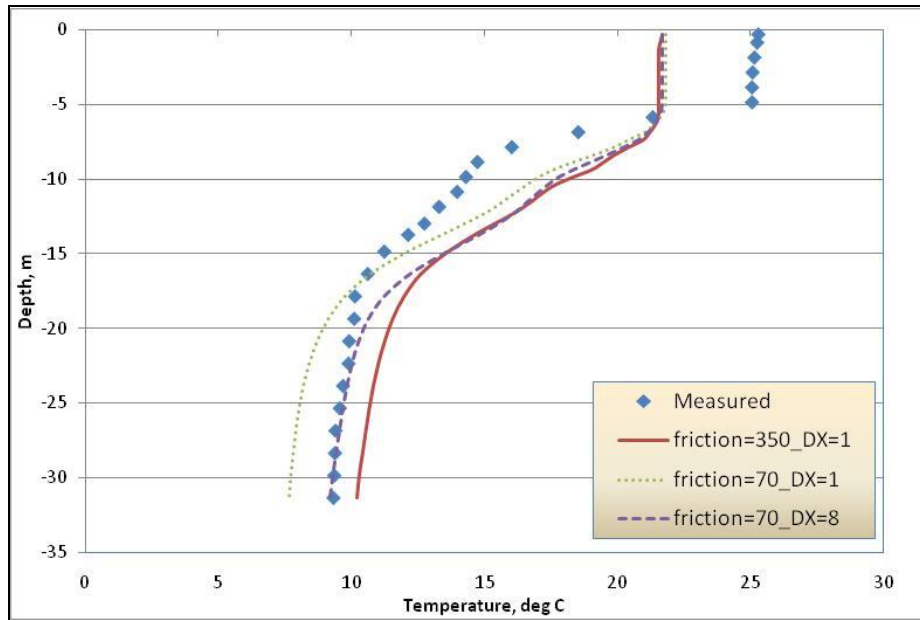


Figure 3.19 – Effect of Increase of Friction Coefficient on Temperature_JD206_2006_North Basin

Figure 3.19 shows that the increase of the Chezy coefficient value caused an increase in water temperature starting from a depth of approximately 10 m. This was a similar result to the effect of an increase in DX and therefore both results were shown. As displayed above, the results from increasing the friction coefficient are very similar to the effect of an increase of the DX parameter having a slightly better fit to the measured values when adjusting DX. According to the CE QUAL W2 manual the bottom friction parameter has a significant effect on the water level. Because typical DX values had a much larger range, it was decided to hold the bottom friction value at its default and only adjust DX.

3.2.6 Temperature and Conductivity Profiles

In-reservoir measurements of temperature and conductivity profiles were recorded by DCR in the North Basin (Station 3417) for years 2005 and 2006. This station is located towards the center of the North Basin, represented by segment 42 within CEQUAL W2. The data received from DCR were temperature and conductivity profiles measured once per month from May to October of both years. CEQUAL W2 does not model conductivity as a constituent. However, it models TDS, which is a closely related parameter. The relationship between TDS and specific conductance is affected by the types of dissolved solids in the water; however, for modeling purposes a constant relative ionic composition is assumed (Matthews, 2007). TDS can be estimated using the following equation (TDS in mg/L and conductivity in microsiemens per centimeter, uS/cm):

$$\text{TDS} = 0.6 * \text{Conductivity}$$

This equation was utilized to convert CEQUAL W2 output of TDS to conductivity values in order to compare simulated values to measured.

It was determined that the wind sheltering coefficient would have the most significant effect on the agreement of measured and simulated values within the temperature and conductivity profiles, as described previously. Adjustment of the dispersion coefficient, $\delta DX\ddot{o}$, had an effect on the hypolimnion temperatures and therefore had potential of improving the agreement as well. Multiple simulations were performed in order to adjust the wind sheltering coefficient and $\delta DX\ddot{o}$ value. The output of each run was compared to measured temperature and conductivity values evaluated at the North Basin of the Wachusett Reservoir. The measurements were taken on specific dates throughout the year and therefore the simulated values for the corresponding date were compared. Temperature and conductivity values were obtained for each layer of segment 42 (representative of the North Basin), associated with the depth at which the measurements were taken, from CEQUAL W2 output for the same dates. A squared error was calculated for each pair of simulated and measured temperature and conductivity values at the corresponding depth. The squared errors along the entire depth of segment 42 were then averaged and linked into a table under the specific date after taking the square root of the value. Two separate tables were generated, one for temperature and the other for conductivity for 2005 and 2006 in order to examine the effect of altering the wind sheltering coefficient and $\delta DX\ddot{o}$ parameters. The purpose

of this analysis was to select parameter values which would produce temperature and conductivity profiles that were as similar to measured data as possible before modeling contaminant spills.

Table 3.5 displays the errors between measured and simulated temperature values, in degrees Celsius, for 2005 at the North Basin. The left hand side column displays each simulation that was performed. The runs that do not have the δDX value listed use the default value of 1.0 m^2/s . Each date for which measured data was available is listed along with the associated error value in degrees Celsius. This value represents the square root of the average of all the squared errors along the depth of segment 42. The average error, which is simply the average of the error values, was also calculated in order to better understand the magnitude of error. Table 3.5 shows that a wind sheltering coefficient of 0.56 produced the minimal amount of error with an average temperature error across the entire depth at segment 42 of approximately 2.1 degrees Celsius. Increasing the δDX parameter for two runs produced a slightly higher error and was therefore not chosen. Table 3.6 displays the results of the 2006 simulations with associated errors. A wind sheltering coefficient of 0.626 and a δDX value of 1.0 were chosen. This combination did not produce the least amount of error for temperature but as shown in the next table (Table 3.8), produced the least amount of error between measured and simulated conductivity values and was therefore chosen. The average temperature error for 2006 was found to be 2.4 degrees Celsius.

Table 3.5 - Temperature Errors for 2005 at the North Basin

Temperature Errors_North Basin_Segment 42_2005								
Simulation	5/2/2005	5/19/2005	6/16/2005	7/19/2005	8/18/2005	9/19/2005	10/18/2005	Average Error
wsc=.727	1.8	2.9	1.3	2.7	3.5	3.0	1.7	2.4
wsc=.671	1.8	3.0	1.5	2.3	3.3	2.6	1.4	2.3
wsc=.56	1.4	2.8	1.7	1.8	3.1	2.3	1.4	2.1
wsc=.671_DX=5	2.0	3.0	1.4	2.6	3.4	2.8	1.6	2.4
wsc=.56_DX=5	1.9	3.0	1.6	1.9	3.1	2.3	1.3	2.1

Table 3.6 - Temperature Errors for 2006 at the North Basin

Temperature Errors_North Basin_Segment 42_2006							
Simulation	5/18/2006	6/12/2006	7/24/2006	8/3/2006	9/18/2006	10/5/2006	Average Error
wsc=.727_DX=1	1.6	1.5	2.4	3.3	2.6	2.2	2.3
wsc=.727_DX=8	1.4	1.5	2.7	3.5	2.8	2.4	2.4
wsc=.727_DX=10	1.3	1.5	2.8	3.5	2.9	2.6	2.4
wsc=.895_DX=1	1.2	1.8	3.5	4.2	3.2	3.1	2.8
wsc=.895_DX=5	1.1	2.1	3.8	4.6	3.7	3.4	3.1
wsc=.626_DX=1	2.0	2.1	2.4	3.1	2.6	2.3	2.4

Errors between measured and simulated conductivity values at the North Basin were also calculated for 2005 and 2006 as shown in Table 3.7, and 3.8. This was completed in order to observe if the wind sheltering coefficient value that produced the minimal amount of error for the temperature profile would do the same for the conductivity profile. The initial conductivity was changed from 94 uS/cm to 104 uS/cm for 2005 as shown in Table 3.7 under the column labeled "Simulation" which generated a reduced average error for the same WSC and DX parameters. The simulation that produced the least amount of error for 2005 had a WSC of 0.56 with an initial conductivity value of 104 uS/cm. The average error across the entire depth of segment 42 was 11.2 uS/cm. The optimal run for 2006 had a WSC of 0.626 with a DX value of 1 which resulted in an average error of 7.5 uS/cm. These simulations proved to be most favorable to utilize for spill modeling for 2005 and 2006 due to the fact that they resulted in the least amount of error between measured and simulated temperature and conductivity values.

Table 3.7 - Conductivity Errors for 2005 at the North Basin

Conductivity Errors_North Basin_Segment 42_2005									
Simulation	5/2/2005	5/19/2005	6/16/2005	7/19/2005	8/18/2005	9/19/2005	10/18/2005	Average Error	
C2I=94	wsc=.727	16.0	19.7	18.4	11.2	16.7	22.5	24.9	18.5
	wsc=.671	15.8	19.7	18.5	10.0	15.6	21.9	23.5	17.9
	wsc=.56	15.8	20.5	19.3	8.4	14.7	19.5	20.4	16.9
	wsc=.671_DX=5	15.8	19.6	18.0	10.1	16.0	22.3	24.0	18.0
	wsc=.56_DX=5	15.5	19.9	18.2	7.6	14.5	19.7	20.6	16.6
C2I=104	wsc=.56	5.8	10.7	10.8	6.3	14.6	14.9	15.1	11.2
	wsc=.671	6.0	10.4	10.5	8.5	16.2	17.9	18.8	12.6
	wsc=.56_DX=5	5.7	10.4	10.1	6.8	14.6	15.6	15.7	11.3

Table 3.8 - Conductivity Errors for 2006 at the North Basin

Conductivity Errors_North Basin_Segment 42_North Basin							
Simulation	5/18/2006	6/12/2006	7/24/2006	8/3/2006	9/18/2006	10/5/2006	Average Error
wsc=.727_DX=1	3.7	2.3	5.0	8.5	14.3	13.7	7.9
wsc=.727_DX=8	3.0	2.5	5.7	9.3	14.8	14.6	8.3
wsc=.727_DX=10	2.9	2.5	6.0	9.5	14.9	14.8	8.4
wsc=.895_DX=1	3.0	2.6	6.7	12.1	15.6	17.4	9.6
wsc=.895_DX=5	2.8	3.0	7.4	12.0	16.1	18.4	10.0
wsc=.626_DX=1	3.9	1.8	5.8	6.6	13.7	13.0	7.5

The following plots represent the temperature and conductivity profiles generated using the final calibrated parameter values. Each plot displays how the temperature or conductivity changes across the entire depth of segment 42 located within the North Basin. The title of each graph represents the date of comparison; measured and simulated values are defined within the legend. Figures 3.20 and 3.21 demonstrate the behavior of the temperature profile in segment 42 from May to October for 2005. May (5/2/2005) displays a well mixed reservoir in which the temperature gradient is small from layer to layer, approximately zero to a depth of 15 meters. The June (6/16/2005) and July (7/19/2005) plots show the reservoir becoming stratified, matched well by simulated output. August (8/18/2005) demonstrates the most drastic stratification in which the temperature changes from a surface temperature of approximately 25°C to 9°C at a depth of 15 meters and below. Both the August and September (9/19/2005) plots show that simulated epilimnion values are underestimated by about 4°C and 3°C respectively. Hypolimnion values are also slightly underestimated. October (10/18/2005) then displays the reservoir de-stratifying with the temperature gradient across the depth decreasing from the September plot.

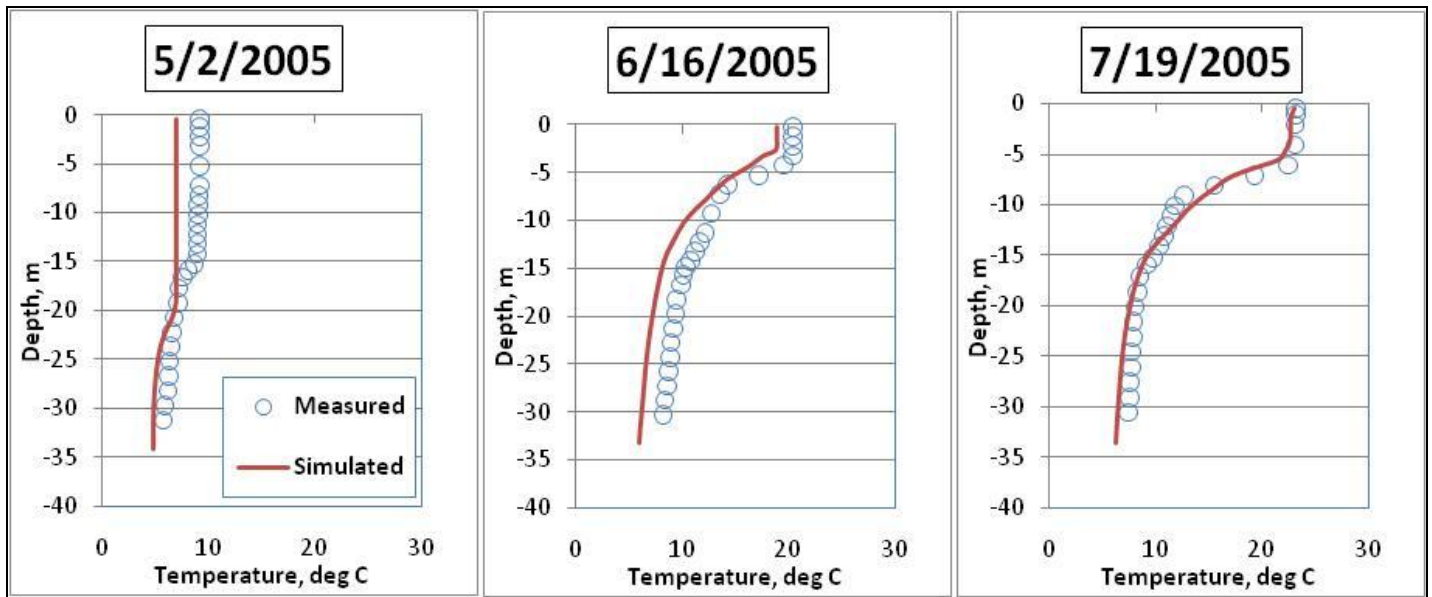


Figure 3.20 - Temperature Profiles for 2005 at North Basin, segment 42

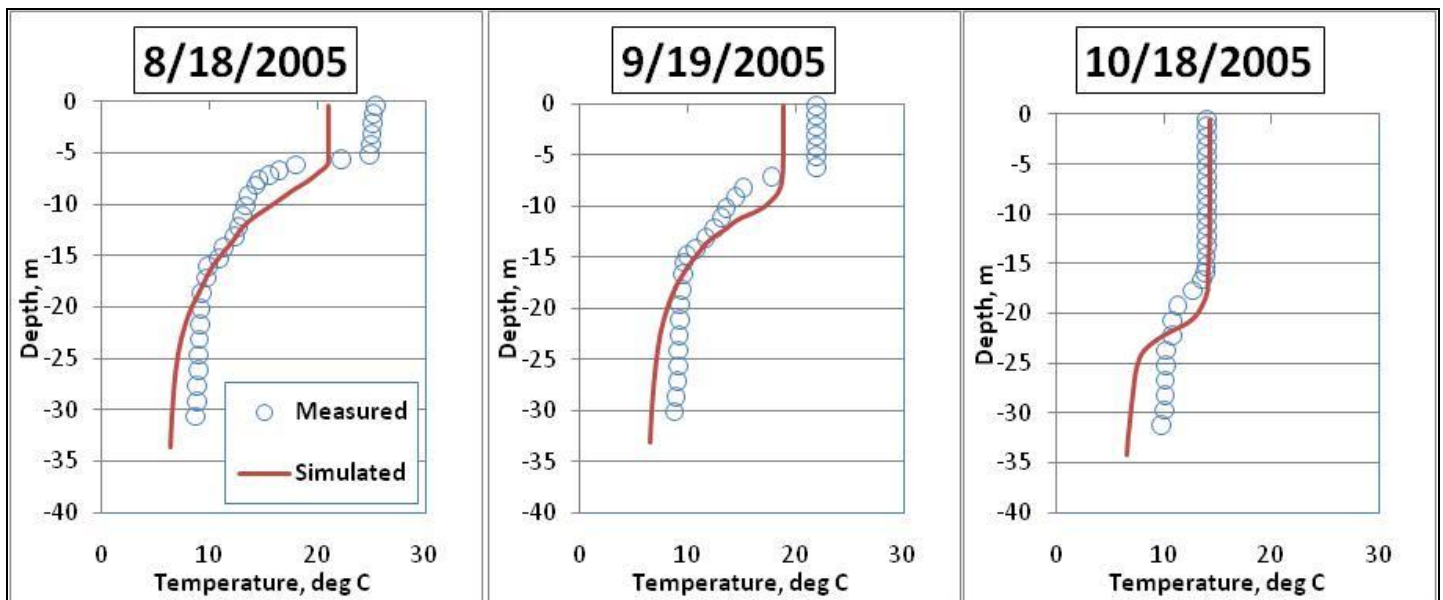


Figure 3.21 - Temperature Profiles for 2005 at North Basin, segment 42

Figures 3.22 and 3.23 display the conductivity profiles from May to October for 2005 at the North Basin. Again, the well mixed state of the reservoir is represented by the May plot.

Conductivity remains unchanged throughout the depth of segment 42 for this month. The Quabbin transfer was turned on starting 5/20/2005. The June graph, on 6/16/2005, shows the interflow beginning to develop at segment 42 and continues until it is fully developed in August where there is a change from an epilimnion conductivity value of approximately 128 uS/cm to a minimum value of 74 uS/cm within the interflow. The simulated values struggle to match the exact profile of the interflow as it changes from month to month but do well with predicting the epilimnion and hypolimnion conductivities. The September plot illustrates the dissipating interflow as the change from epilimnion to interflow conductivity values become 112 uS/cm to 96 uS/cm. October then shows the reservoir back to its well mixed state where the conductivity gradient is small.

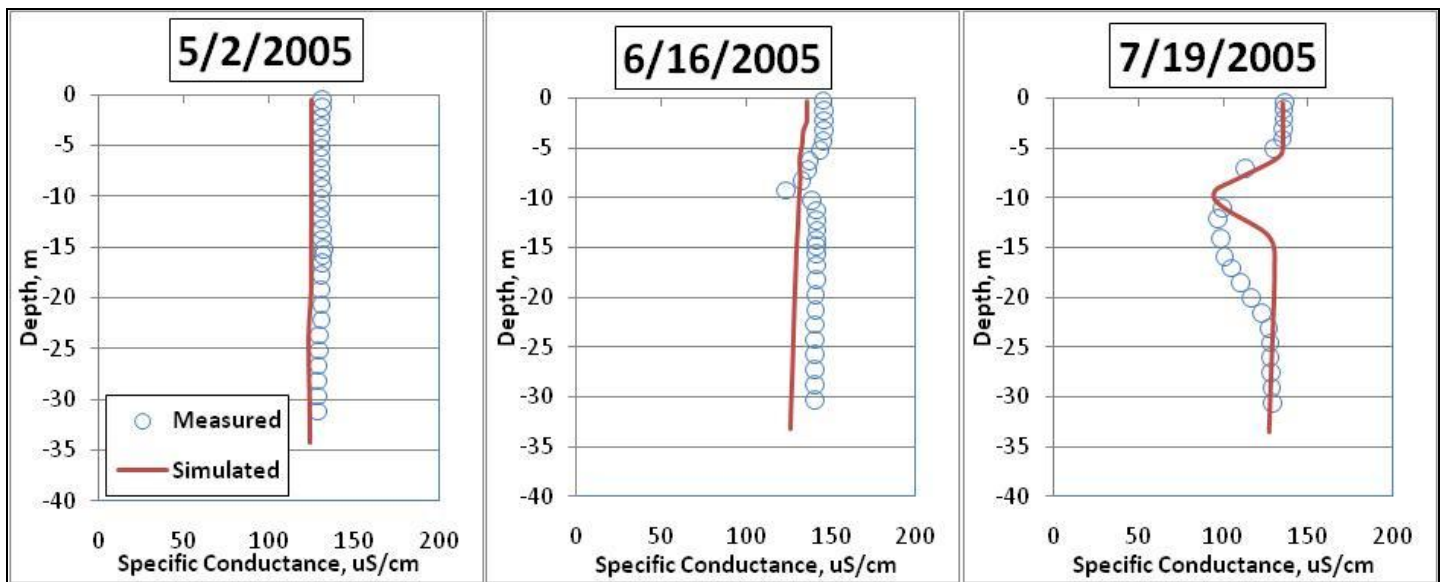


Figure 3.22 - Conductivity Profiles for 2005 at North Basin, segment 42

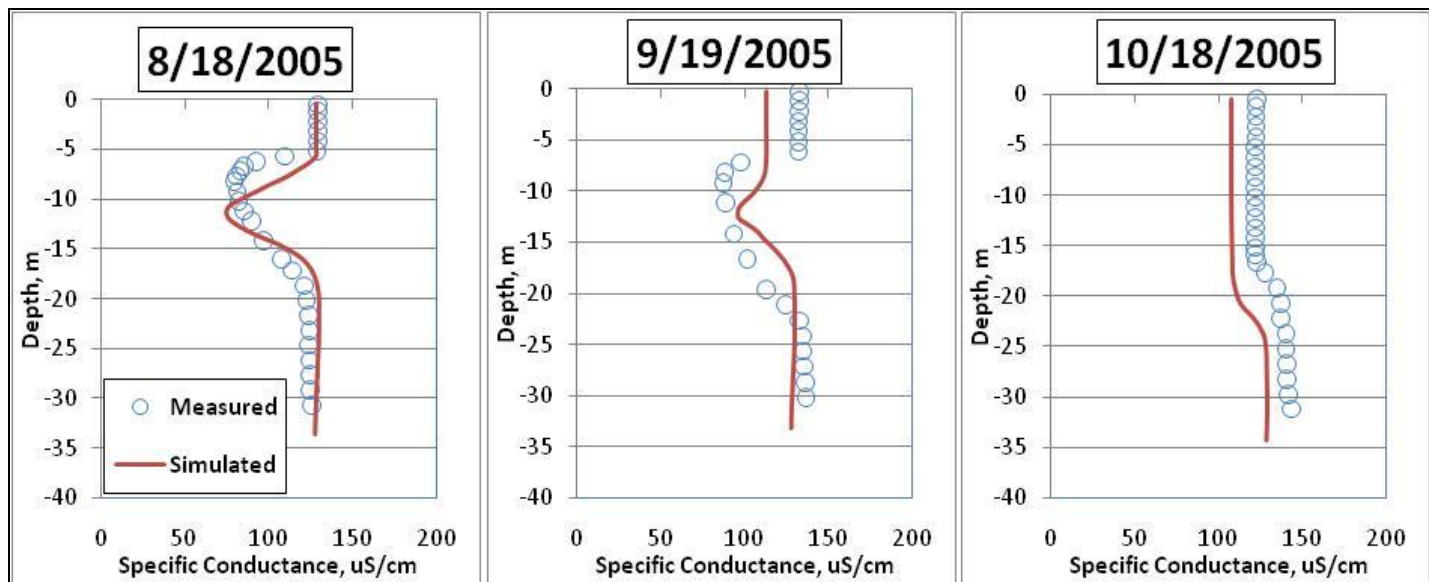


Figure 3.23 - Conductivity Profiles for 2005 at North Basin, segment 42

Figures 3.24 and 3.25 demonstrate the progression of the temperature profile for 2006 at the North Basin. The development of stratification within the reservoir is very similar to 2005. May (5/18/2006) is well mixed with a small temperature gradient. June (6/12/2006) shows the reservoir beginning to stratify and by August (8/3/2006) it is fully stratified representing a temperature change from a surface temperature of 27°C to 10°C starting at a depth of 15 meters. As shown in the 2005 plots, the 2006 simulated values also underestimate the epilimnion values by 2 to 4°C. The 2006 conductivity profiles at the North Basin are represented in Figures 3.26 and 3.27. In this case, the Quabbin transfer was not turned on until 7/7/2006 and therefore is not observed in the May and June results. The interflow shows up in the July (7/24/2006) plot. The behavior of the interflow is matched better than 2005 for the months of July and August but misses it in September (9/18/2006). The average error between measured and simulated conductivity values for 2006 was better than for 2005, 8.6 uS/cm versus 11.8 uS/cm, as described in the above tables. Overall, both years performed similarly in predicting temperature and conductivity values across the depth of segment 42 in the North Basin.

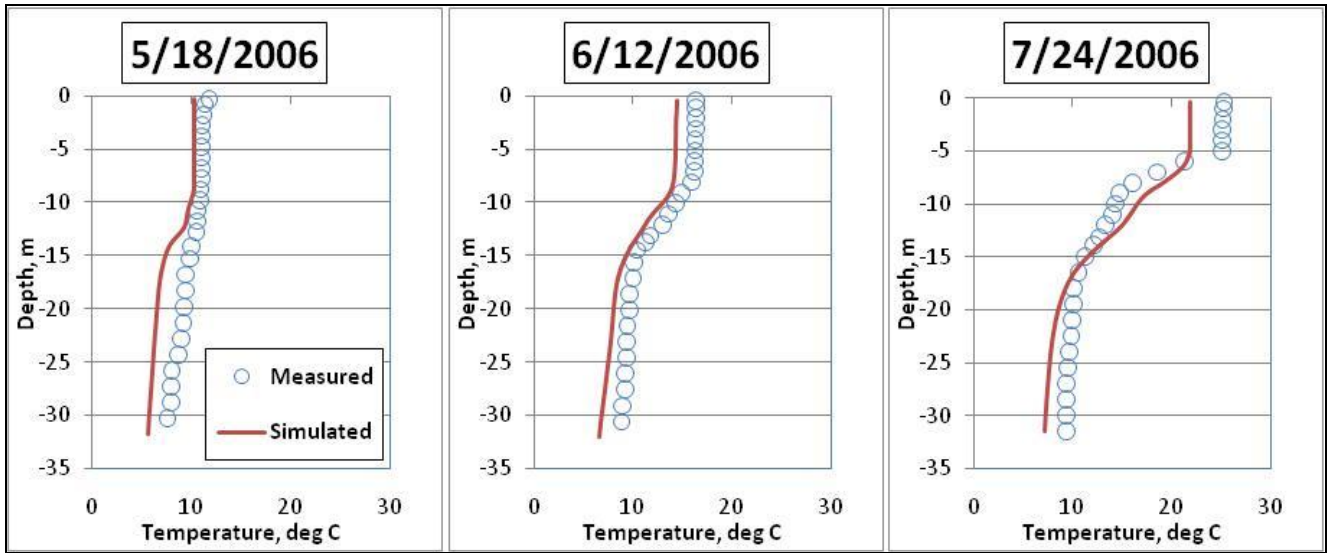


Figure 3.24 - Temperature Profiles for 2006 at North Basin, segment 42

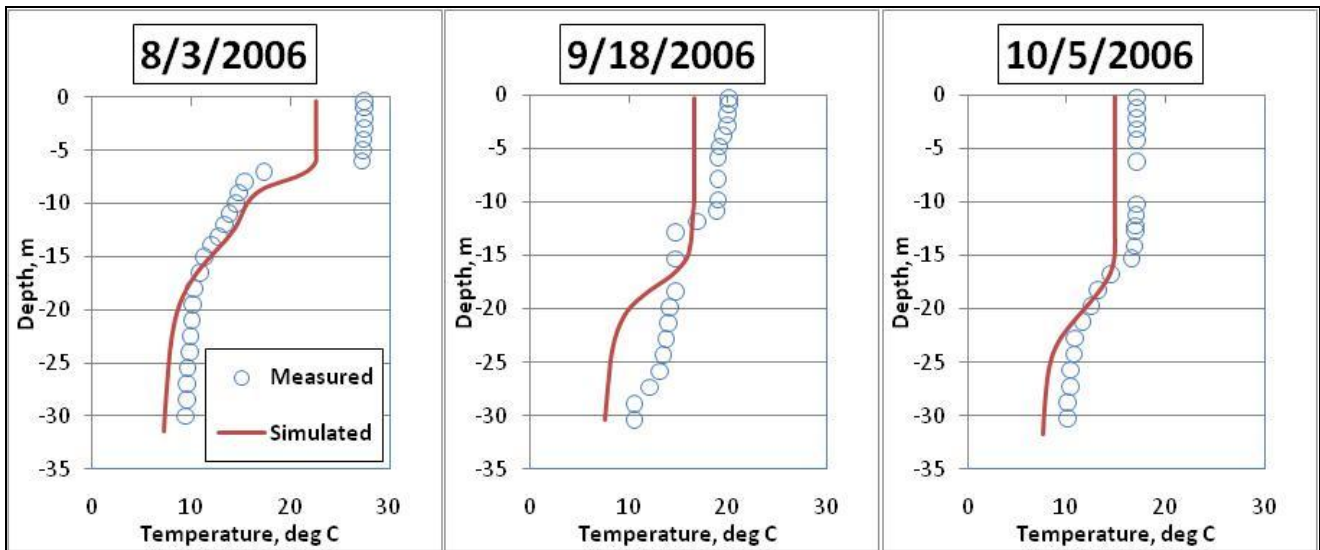


Figure 3.25 - Temperature Profiles for 2006 at North Basin, segment 42

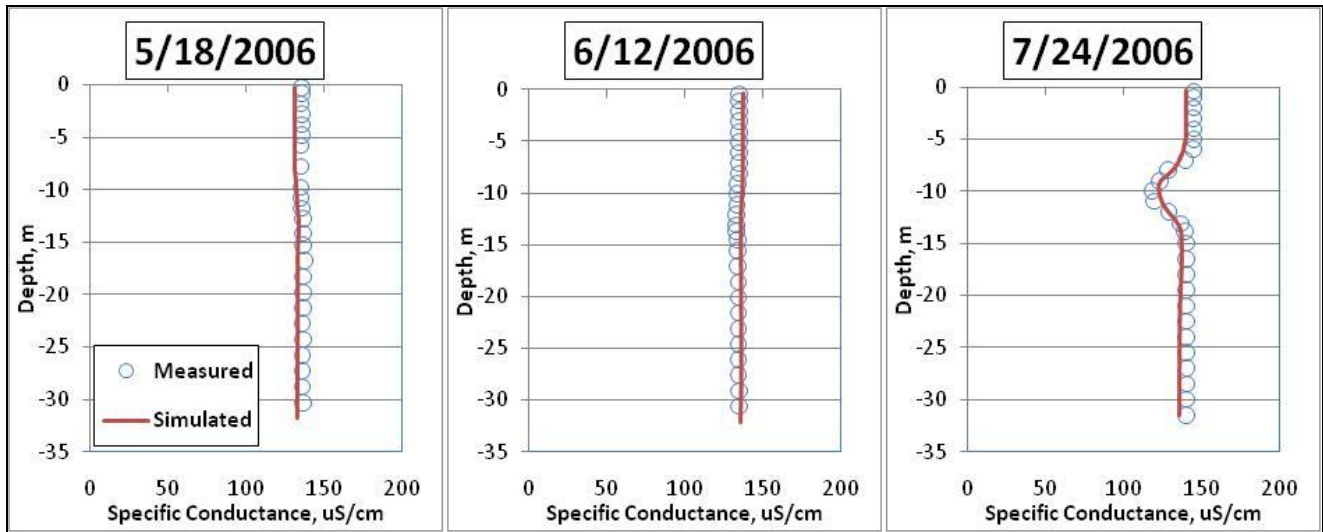


Figure 3.26 - Conductivity Profiles for 2006 at North Basin, segment 42

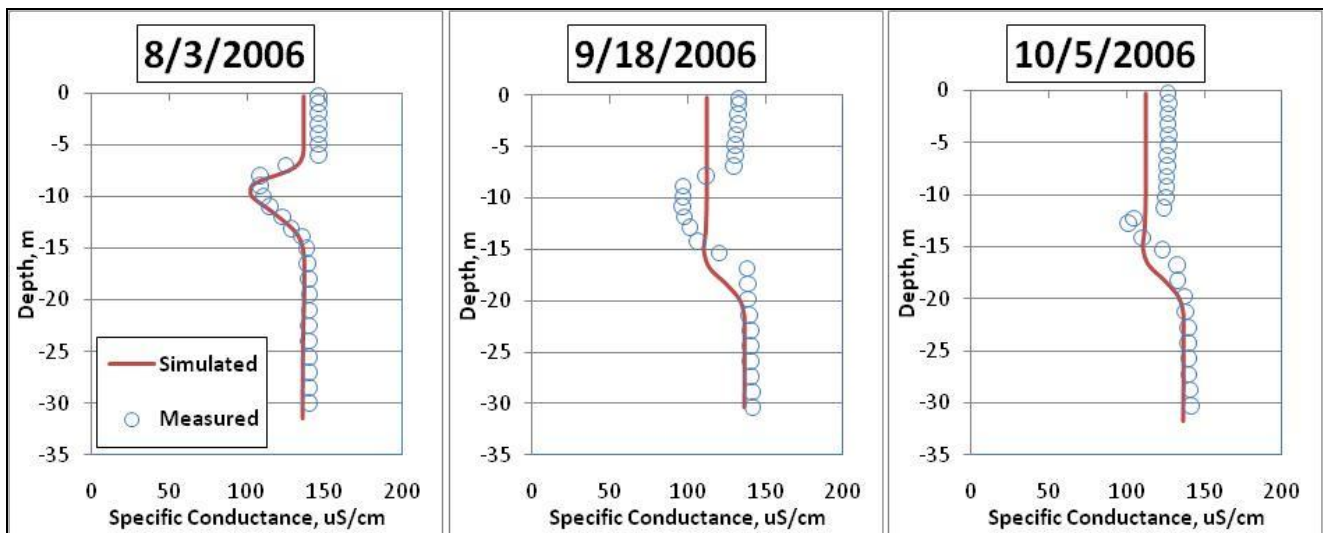


Figure 3.27 - Conductivity Profiles for 2006 at North Basin, segment 42

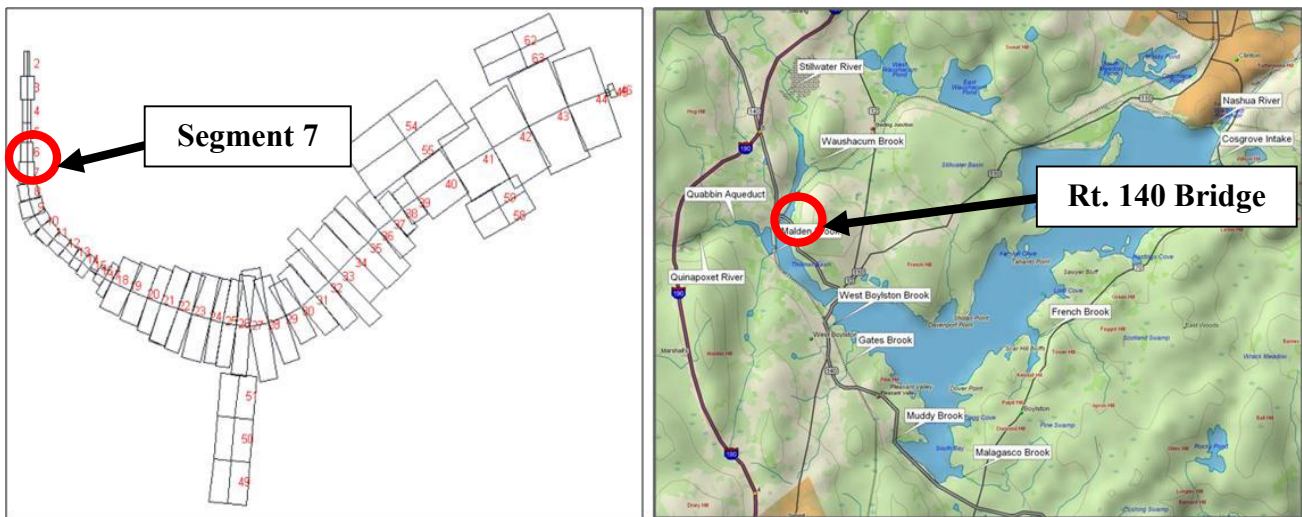
3.3 Spill Modeling

The purpose of this section is to describe how spill modeling was performed using V3.6 of CEQUAL W2 for the Wachusett Reservoir. The goals of modeling a spill in the reservoir were to better understand the effects of seasonal change, how the temperature of the spill would affect the behavior, and if turning the Quabbin transfer on/off had an effect. This was performed in a

methodical manner for each year from 2003-2006 in order to appropriately compare results. The following discussion will describe how the spill was characterized, location of the spill, and the dates chosen for each year in which the spill would occur.

3.3.1 Spill Characteristics and Location

The spill was characterized the same way each year as well as applied to the same location in order to ensure year to year consistency. The spill was modeled as a conservative, non-reactive, tracer and therefore did not decay or volatilize. This represents a worst case scenario because all of the contaminant that spills into the reservoir would stay within it until removed by the reservoir personnel or naturally through the system. The spill was modeled as a low flow tributary ($0.02 \text{ m}^3/\text{s}$) with a high concentration ($1 \times 10^8 \text{ mg/L}$) that entered the reservoir at segment 7, representing the location of the Rt. 140 Bridge as shown in Figure 3.28. This site was chosen due to the high vulnerability of a crash causing a vehicle, such as a tanker, to enter the water due to the bridge crossing over the reservoir at that point. The spill was allowed to enter segment seven for a period of twelve hours, beginning at 12 noon on the day of the spill.



**Figure 3.28 - Spill Location at Rt. 140 Bridge, represented by segment 7 in
CEQUAL W2**

CEQUAL W2 is capable of modeling spills with various densities by substituting temperature for density. Thus the temperature of the contaminant affects the layer within the water column where the spill would settle based on density. For the purpose of simplicity, three generic terms were used to describe the temperature of the spill. A warm spill represents a surface spill

because it would sit on top of the water column. A cold spill is a "sinking" spill that will drop to the bottom layer of the reservoir. A medium spill represents a temperature that would be located in between the warm and cold, somewhere in the middle of the water column. These temperatures were chosen by observing the CEQUAL W2 output files of temperature profiles for each segment across the entire length of the reservoir. A temperature that best represented the surface, middle, and bottom layers of the reservoir was chosen as the warm, medium, and cold spills. These temperatures varied for each season and differed from year to year.

For simplicity, the concentrations measured at the Cosgrove were expressed as a relative concentration. This term was developed by Stauber and Tobiason (Stauber, 2009) and has been used in the 2003 models to present. It represents a normalized tracer concentration, calculated by dividing the simulated concentration value by the completely mixed value. The completely mixed value represents the total mass of the spill divided by the full reservoir volume. Simulations have shown that variations in absolute spill concentration do not alter the simulated relative contaminant concentrations.

3.3.2 Spill Dates

The dates for which a spill was simulated changed from year to year for each season. It was determined from Stauber (2009) that wind direction had a substantial effect on the behavior of the spill as it travels across the reservoir. Therefore, a spill date was chosen for each season of each year based on similar wind conditions. A span of 20 days of wind data for each season was analyzed in order to find four days in which the wind direction was consistent. Table 3.9 displays the results of this analysis which include the four chosen days, wind direction, and magnitude of the wind speed in m/s. The earliest Julian day represents the chosen date of the spill, for example, Julian day 117 for the spring of 2003. It must be noted that in 2003 the Cosgrove intake was shut down starting on Julian day 305 and remained shut down for the remainder of the year. The chosen spill date for the Fall of 2003 was Julian day 311. The Fall 2003 simulation was not performed because the input file, which contains the Cosgrove withdrawals, contained zero values of flow for the days in which it was shut down. The Cosgrove intake is represented by segment 46 where values of spill concentration are taken and therefore would cause readings of zero. The location of spill measurement within the reservoir

as well as the elevation of the inlet would have had to be altered within the control file. This season (Fall 2003) was not used because it would have hindered the consistency of results.

The wind directions were determined by converting the angle from degrees to a direction using the key as shown in Figure 3.29. The terms ðNW, NE, SW, and SEö represent the direction from which the wind is coming from. For example, a ðSWö or southwestern wind is approaching the reservoir from the southwest, not moving towards the southwest. As shown in Table 3.9, the four days for each season do not match perfectly. It was difficult to find four days for each season that had the exact same wind direction. The most important factor was if the wind was moving in an easterly or westerly direction and therefore was used as the main criteria for selecting the days. For instance, the summer of 2004 had three days in a row of ðSWö wind whereas the summer of 2005 had three days of ðNWö wind. This was determined to be acceptable due to the fact that the wind direction for each season was westerly. Table 3.9 also shows that the average wind speeds over the four days for each season of each year were similar ranging from 3.80 m/s to 8.32 m/s.

Table 3.9 - Wind Comparison for All Four Years and Seasons

WIND COMPARISON FOR ALL FOUR YEARS											
2003 SPRING			2004 SPRING			2005 SPRING			2006 SPRING		
JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag	JDAY	Wind Dir	Wind Mag (m/s)
117	SW	4.03	120	SW	6.67	114	SE	6.78	115	NW	6.04
118	SW	4.23	121	SW	6.73	115	SW	5.10	116	SW	5.28
119	NW	4.72	122	SW	6.65	116	SW	5.26	117	SW	4.21
120	SW	4.00	123	SW	6.08	117	SE	3.78	118	SE	3.82
Avg.		4.24	Avg.		6.53	Avg.		5.23	Avg.		4.84
2003 SUMMER			2004 SUMMER			2005 SUMMER			2006 SUMMER		
JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)
237	SW	4.30	230	SE	2.56	233	SW	8.27	222	SW	4.67
238	SW	3.84	231	SW	4.21	234	NW	9.54	223	NW	5.01
239	SW	5.28	232	SW	4.79	235	NW	8.21	224	NW	4.59
240	SW	3.38	233	SW	3.63	236	NW	7.25	225	NW	4.32
Avg.		4.20	Avg.		3.80	Avg.		8.32	Avg.		4.65
2003 FALL			2004 FALL			2005 FALL			2006 FALL		
JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)	JDAY	Wind Dir	Wind Mag (m/s)
311	NW	3.40	319	NW	6.47	323	SW	3.32	318	SE	4.36
312	NW	7.21	320	NW	4.48	324	SW	4.99	319	SE	3.20
313	NW	4.61	321	NW	2.96	325	SW	3.47	320	SE	5.66
314	SW	4.00	322	SW	2.42	326	SE	6.98	321	SW	7.28
Avg.		4.81	Avg.		4.08	Avg.		4.69	Avg.		5.12

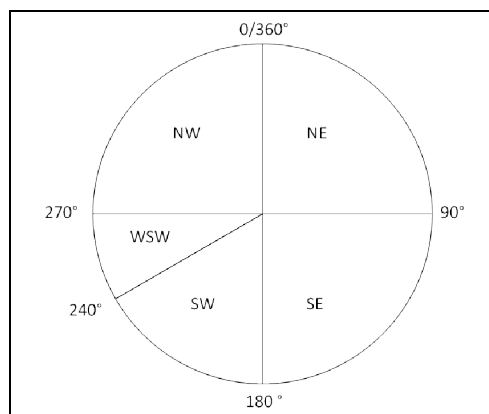


Figure 3.29 - Wind Direction Key

4.0 Results

This section of the report presents results for spill behavior for years 2003, 2004, 2005, and 2006 as a function of seasonal changes, variation of spill temperature, and turning on/off the Quabbin transfer. The CE QUAL W2 model was assembled and calibrated by Matthews for years 2003 and 2004 (Matthews, 2007). All model results were produced from V3.6 of CE QUAL W2 for spill characteristics and location as described earlier. Output was generated every tenth of a day or every 2.4 hours. Table 4.1 displays the model parameters used for each simulation.

Table 4.1 - Base Model Parameters Used for Simulations

Parameter	Description	2003	2004	2005	2006
WSC	Wind Sheltering Coefficient	0.625	0.625	0.559	0.626
AX	Horizontal Eddy Viscosity, m ² /s	1	1	1	1
DX	Horizontal Dispersion Coefficient, m ² /s	1	1	1	1
BETA	Fraction of Solar Radiation Absorbed in Surface	0.45	0.45	0.45	0.45
EXH2O	Light Extinction Coefficient for Water, m ⁻¹	0.25	0.29	0.25	0.25
Spring Spill Date	Date of the spring spill, Julian Day	117	120	114	115
Summer Spill Date	Date of the summer spill, Julian Day	237	230	233	222
Fall Spill Date	Date of the fall spill, Julian Day	N/A	319	323	318

4.1 Seasonal Effect on Spill Behavior

Seasonal changes affect the state of the reservoir by altering vertical water temperature gradients. This was witnessed when observing the temperature profiles during the calibration stage of this project. Fall and spring were well mixed with little to no temperature change through the entire depth whereas during the summer, large temperature gradients were observed. This transformation from season to season has the potential to alter the behavior of a spill as demonstrated in Figure 4.1.

Figure 4.1 represents a cold spill occurring at the Rt. 140 Bridge for the spring, summer, and fall of 2004. This plot demonstrates typical results for all four years. The x-axis displays the Julian days for the entire year and y-axis shows the simulated relative concentration at the Cosgrove intake. Fall and spring spill behaviors are very similar in that contaminant concentrations increase to a well mixed relative concentration value of 1 and then begin to decrease. The summer behavior is different because concentration peaks to a higher relative value of 3 and exhibits a highly variable behavior for a period of time before eventually decreasing. The

variability of spill behavior for summer and the similar behavior for the spring and fall demonstrates the effect that the temperature gradient has on the contaminant concentration as it moves through the reservoir.

The x-axis was changed to days after the spill in order to better display the behavior 30 days after the spill, such as arrival time and summer variability. Figure 4.2 displays the arrival times at the Cosgrove intake for a cold spill for the spring, summer, and fall of 2004. The results provide a closer comparison of seasonal spill behavior than found in Figure 4.1, showing the similar behavior in the spring and fall, and variability in the summer. The spill occurring in the spring arrives most quickly in 2 to 3 days, fall takes longer at about 7 days, and in summer arrival is the slowest at approximately 10 days. It is important to note that the average residence time, or the amount of time a particle resides within a system, of the Wachusett Reservoir is approximately 206 days. This value is calculated by dividing the reservoir volume (62 billion gallons) by the average outflow (300 MGD). The seasonal simulations show that it only takes 2-10 days for a contaminant to reach the Cosgrove intake and therefore is critical to understand how the hydrodynamics of the reservoir affect the behavior of the spill.

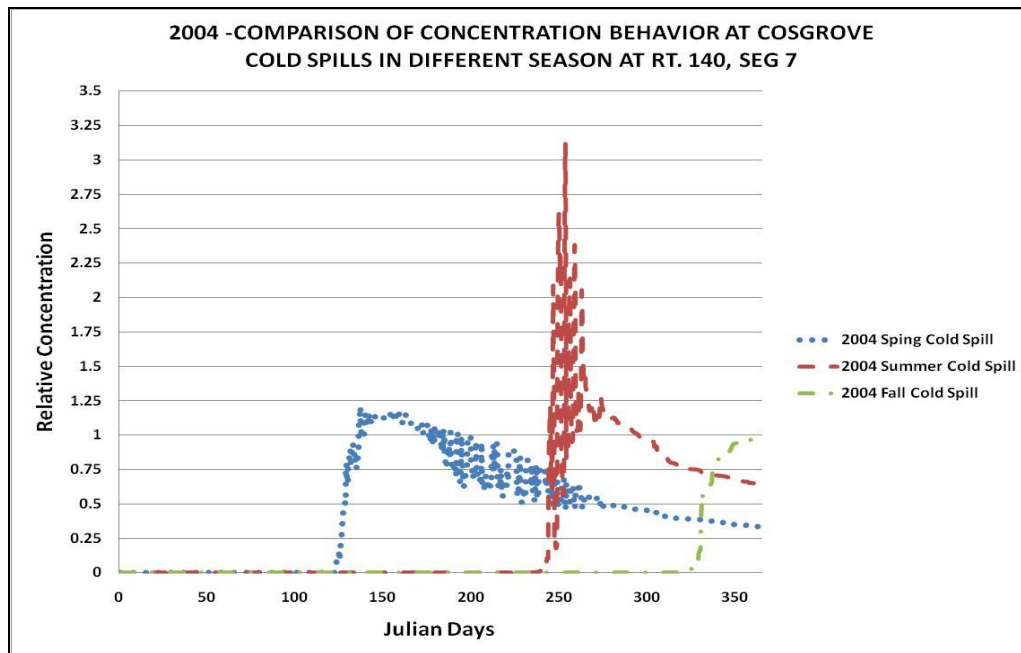


Figure 4.1 - Spill behavior at Cosgrove intake due to seasonal changes for a cold spill in 2004_Rte 140_Segment 7

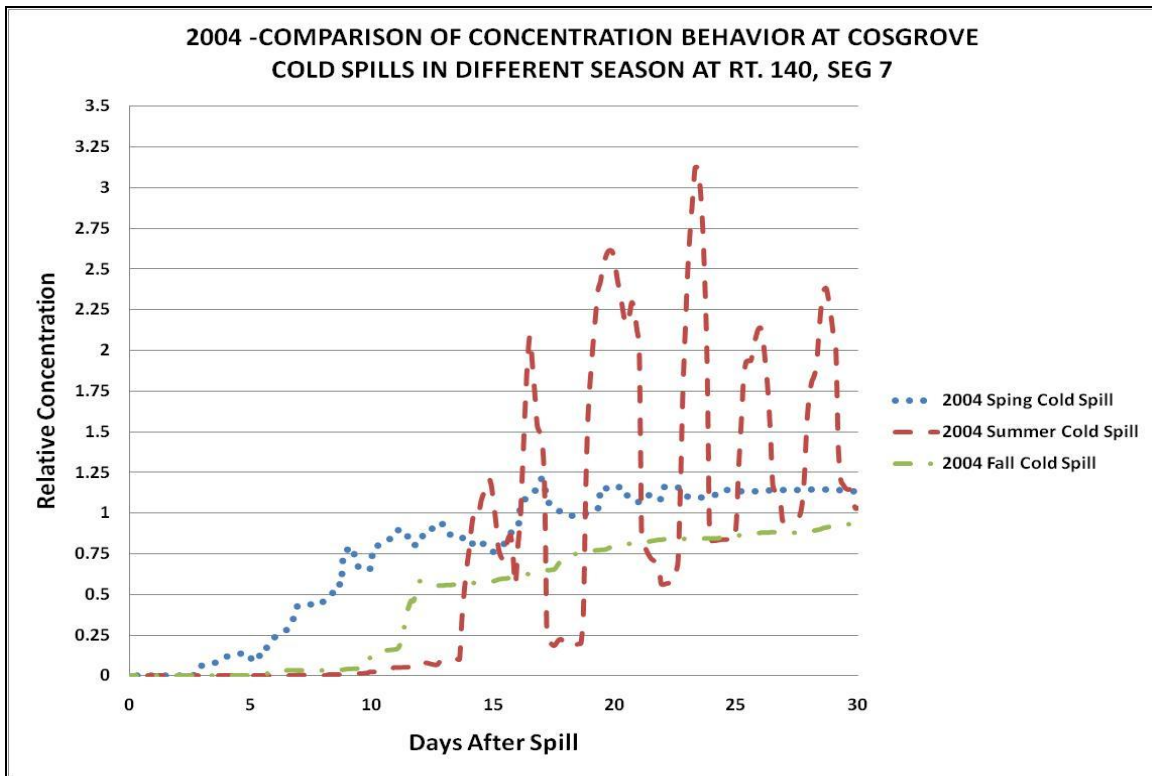


Figure 4.2 - Seasonal spill behavior at Cosgrove intake 30 days after spill date for 2004_Rte 140_Segment 7

The introduction of a spill into the Wachusett reservoir, if analyzed as a tracer entering a reactor, behaves in a manner that is between a plug flow reactor (PFR) and a continuous stirred tank reactor (CSTR). The PFR and CSTR systems characterize two different extremes. In CSTRs, the fluid mixing is very intense in which any parcel of contaminant or tracer that enters the reactor would mix and dilute instantaneously into the water within the entire volume. The behavior of a tracer within a PFR is very different in that the fluid would move through the reactor along a defined path without mixing with parcels of water ahead or behind of it in the axial direction (Benjamin and Lawler, 2010). If the Wachusett reservoir acted as a PFR, in which the mass of tracer was input at time zero, the tracer would only be detected at the Cosgrove intake at a time equivalent to the average residence time because mixing is non-existent. For a CSTR system, with the same mass of tracer input at time zero, the concentration of tracer would be the same in all locations due to instantaneous mixing of the total mass of tracer being mixed instantly into the entire volume of the system. Therefore, the plot of concentration versus time would begin with a value of 1 at time zero and then decline over time

due to the continuous influent of water which would dilute the tracer concentration. As observed from the seasonal plots of relative concentration versus time, the tracer in the Wachusett reservoir reaches the Cosgrove intake many days prior to the average residence time which demonstrates that mixing is present and the reservoir is not a PFR. The concentration reaches a relative value of 1, representing the completely mixed value, days after the spill, which shows that the reservoir is not a CSTR either. The behavior of the spill lies between these two extremes due to the hydrodynamics of the system.

Simulations were performed for years 2003, 2004, 2005, and 2006 in order to examine similarities of spill behavior between all four years. Each season is presented separately, starting with spring as shown in Figure 4.3. It can be observed from this figure that for all four years the time it takes for the spill to first arrive at the Cosgrove intake is consistently 2-3 days. The results also show that the spill behavior for all four years peaks at a relative concentration around 1 which indicates that spring spill behavior might be predictable from year to year.

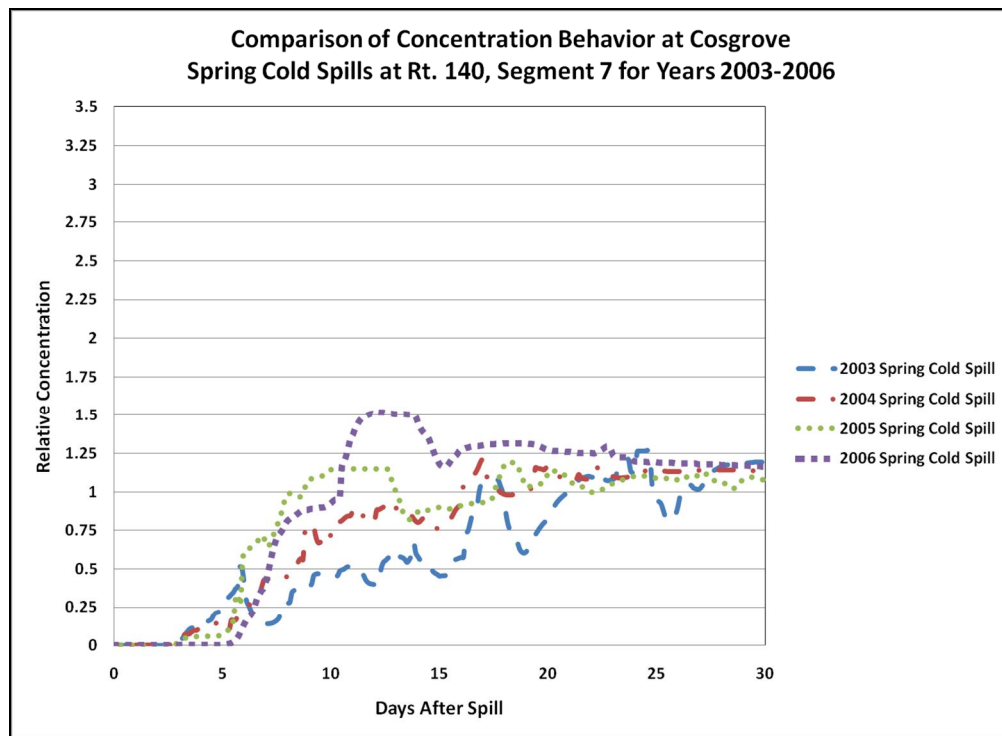


Figure 4.3 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in the spring

Figure 4.2 showed that summer spill behavior was variable over the 30 day period after the spill for 2004, and peaked to relative concentration values above 3. Similar results were witnessed for the years of 2003, 2005, and 2006 as well, as demonstrated in Figure 4.4. The time it took for the spill to reach the Cosgrove intake varied more than spring at 10-15 days. Fall spill behavior also showed similar behavior for all years. 2003 is not included in this plot due to the shutdown of the Cosgrove intake in which water was rerouted to the Wachusett Aqueduct on Julian day 305. Figure 4.5 shows that the spill concentrations for the fall of each year approached values of approximately 1 over the 30 day period. The arrival time was also very consistent at approximately 7 days.

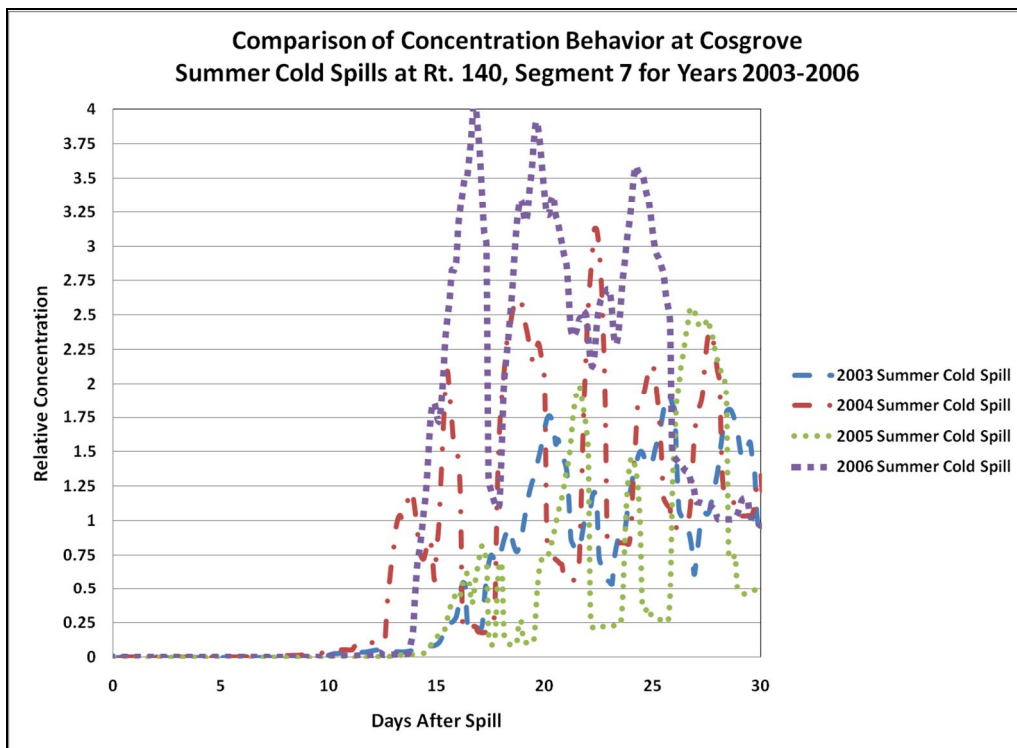


Figure 4.4 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in summer (*Note change of scale)

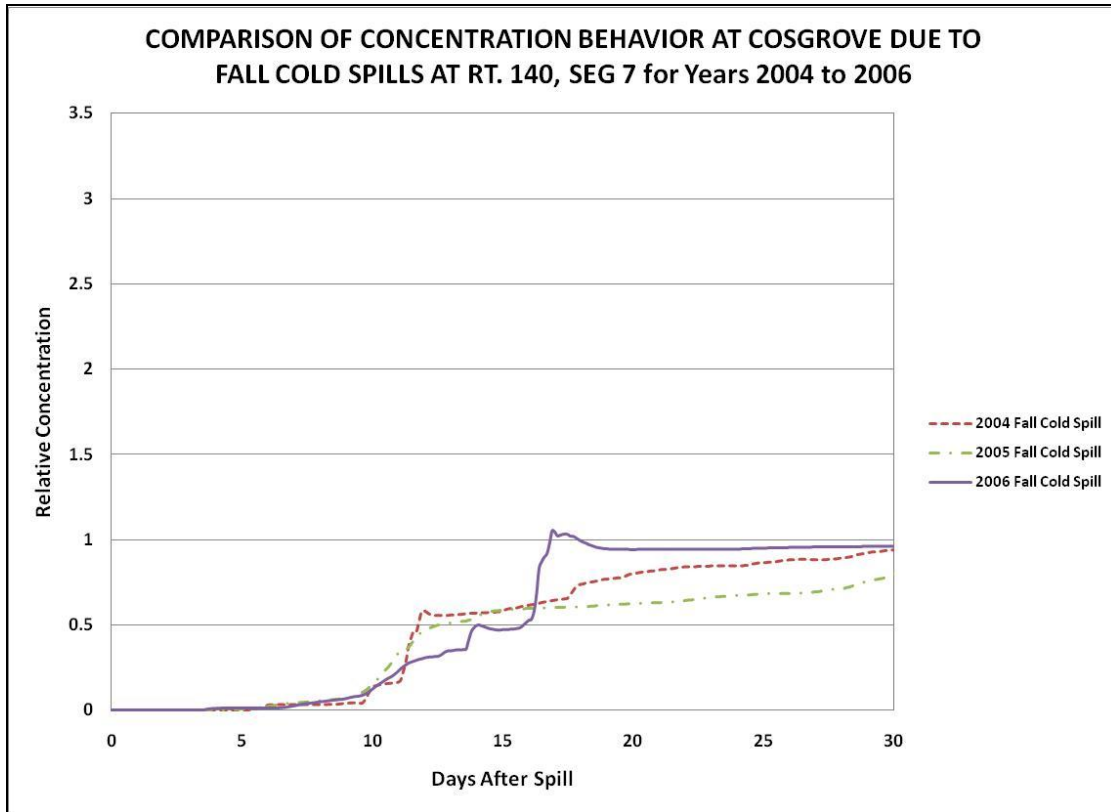


Figure 4.5 - Comparison of concentrations for all 4 years at Cosgrove, cold spill in fall

Summer variability of contaminant concentrations is attributed to the stratification of the reservoir during this time. Water can leave the reservoir at two depth locations along the water column at the Cosgrove intake; there are two inlets, one at an elevation of 104.5m (14.6 m below the surface) and a second at an elevation of 110.6 m (8.5 m below the surface). Only one inlet, the one located at an elevation of 104.5 m, was operating within the model. The spill concentration at this location depends on the flow field occurring around the intake. For example, for a specific wind direction, the surface water might be pushed down towards the intake as shown in Figure 4.6. The wind may also cause the surface water to pull away from the intake causing deeper water to be pulled in as demonstrated in Figure 4.7. In both figures, the wind is characterized by the topmost bold arrow and the Cosgrove intake is represented simply as two pipes leaving the reservoir.

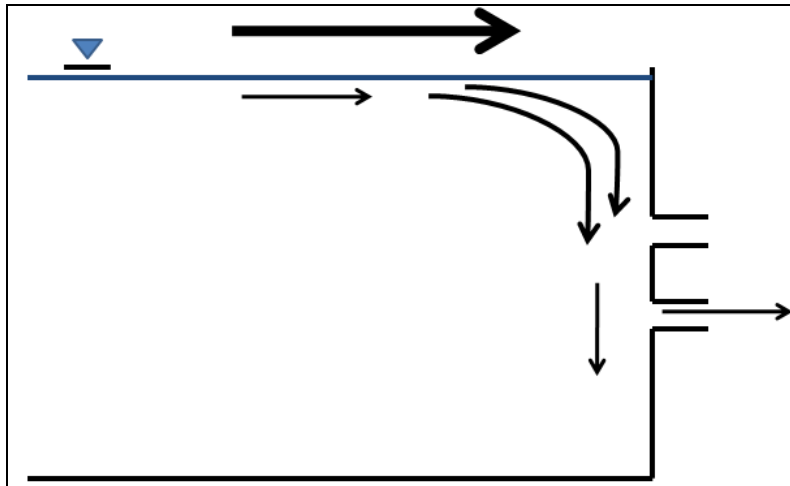


Figure 4.6 - Diagram of flow field around the Cosgrove intake for a wind direction towards intake (Not to Scale)

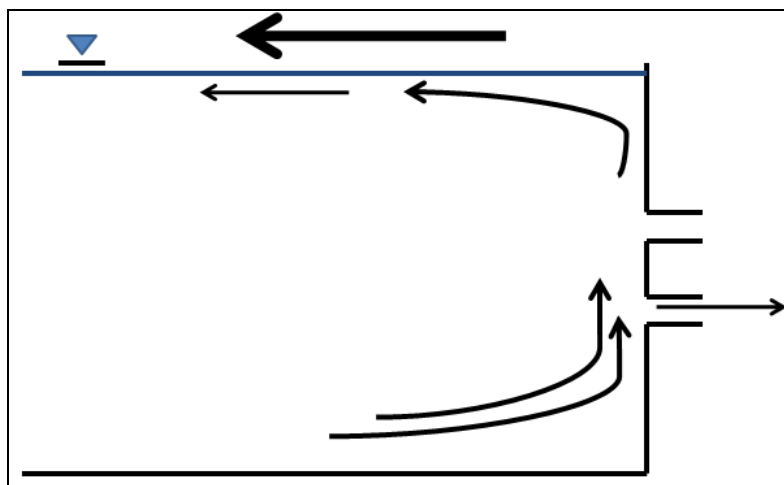


Figure 4.7 - Diagram of flow field around the Cosgrove intake for a wind direction away from intake (Not to Scale)

The variation of spill concentration across the depth near the Cosgrove intake directly affects the measured Cosgrove intake value. The surface water may contain a lower concentration than the deeper water or vice versa and the intake value depends on which part of the water column is being drawn into the intake. During the fall and spring months the reservoir is well mixed. By the time the spill reaches the Cosgrove intake the concentration is the same across the entire depth of the reservoir. Therefore, the Cosgrove concentration would not depend on the flow field because the concentration is the same in each layer of the water column. This is represented in Figure 4.8 which displays spill concentration, as output by CEQUAL W2, across the depth of

segment 30, seven days after a medium temperature spill for 2006. The dashed lines symbolize the center lines of the inlets at the Cosgrove intake. As shown, the spring and fall concentrations do not change across the depth whereas the summer shows a large gradient between inlets.

Spring shows a constant concentration of approximately 380 and fall shows a consistent value of 544. The spring value is smaller in magnitude than fall because, as represented previously, the highest concentration for spring occurs 2-3 days after the spill. Therefore, after seven days the highest concentration has already been observed at the Cosgrove intake.

Summer stratification inhibits dispersion of the spill due to the large temperature gradients. Some of the spill will disperse into other layers, but slower than in the fall and spring months. Most of the spill will sit in a specific layer until reaching the Cosgrove intake as shown in Figure 4.8. This figure shows concentration values of zero in the epilimnion and hypolimnion of segment 30. The entire mass of the spill is located between depths of 10 and 15 meters. In this case, the flow field around the intake has a major impact on the measured value because it depends on the layer where it is located and the direction of the wind. The mass of spill could be pushed down, towards the intake, or pulled away from the intake.

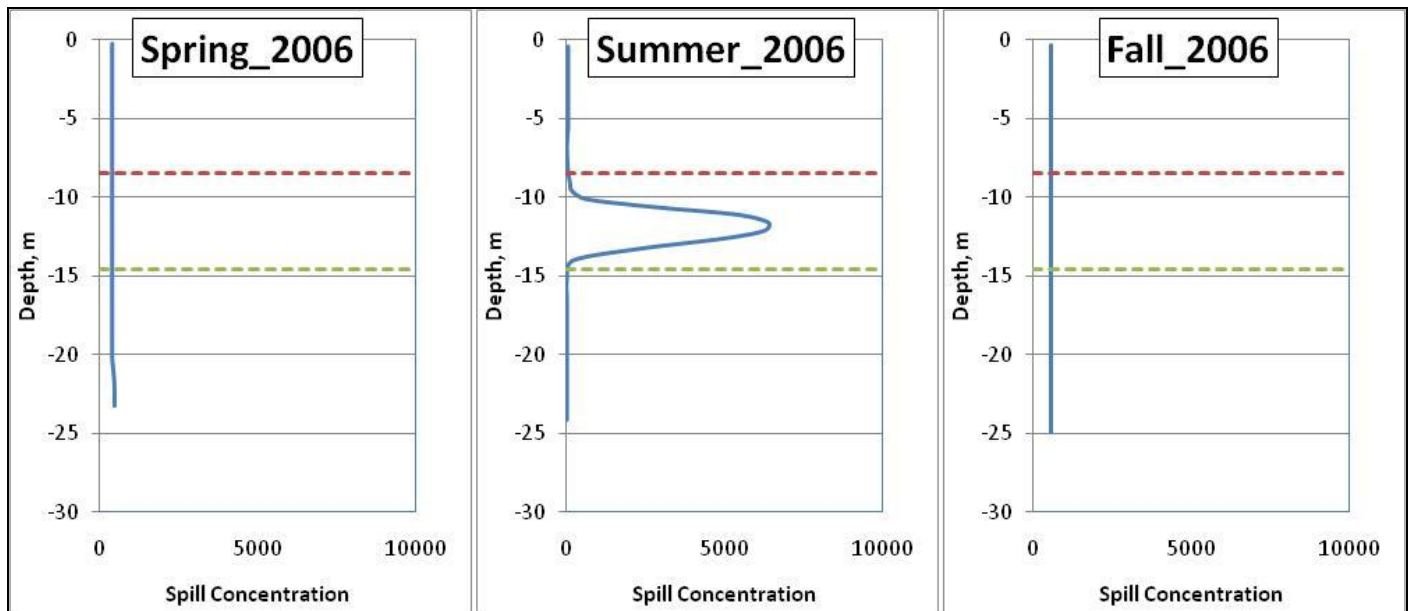


Figure 4.8 - Comparison of Spill Concentration at Segment 30, seven days after the spill for 2006 (Medium Temperature Spill)

Output from the spring, summer, and fall simulations were observed at segment 44, as shown in Figure 4.9, in order to confirm that the spill concentration profile did not change drastically as it reached the intake. The spring and fall plots represent the behavior seven days after the spill and the summer profile shows output 12 days after the spill in order to capture the behavior as it begins to arrive at the intake. As shown, the spring and fall spill concentrations remain consistent throughout the depth of segment 44. In this case, the spring shows a constant concentration of approximately 323 whereas the fall has a value of 14. This demonstrates that less mass reaches the intake during the fall seven days after the spill, which validates the earlier arrival time during the spring. The summer concentration profile 12 days after the spill is similar to the plot seven days after the spill. This verifies that the mass of the spill sits at a depth between 10 and 15 meters as it travels across the reservoir to the intake and confirms the reason for summer variability in the behavior of the spill.

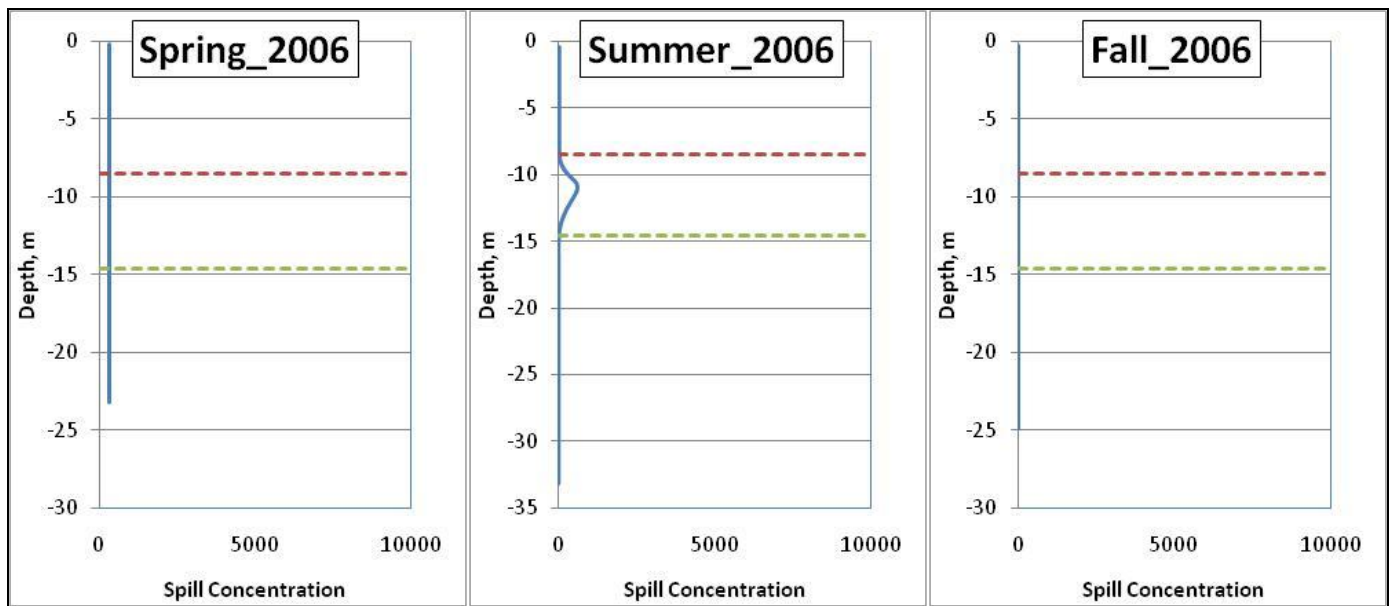


Figure 4.9 - Comparison of Spill Concentration at Segment 44, seven days after the spill for spring and fall, 12 days after the spill for summer (Medium Temperature Spill)

4.2 Effect of Varying Spill Temperature

The purpose of this portion of the project was to evaluate if the temperature of the spill would affect the behavior witnessed at the Cosgrove intake. This was performed for all four years and

for each season except for the fall of 2003. The following figures show model output for 2004 which demonstrate typical results found for all years. Figure 4.10 shows the effect of varying the spill temperature for the spring of 2004. In this case, the Cosgrove concentration does not change dramatically and the arrival time was not affected. The same results were observed for the fall of 2004 as displayed in Figure 4.11. Again, the arrival time remains consistent and the Cosgrove concentration does not change. The similar behavior for each spill temperature is attributed to the well mixed condition of the reservoir during the spring and fall. The lack of in-reservoir temperature gradients allows the spill, at any temperature, to disperse throughout the reservoir in the same manner.

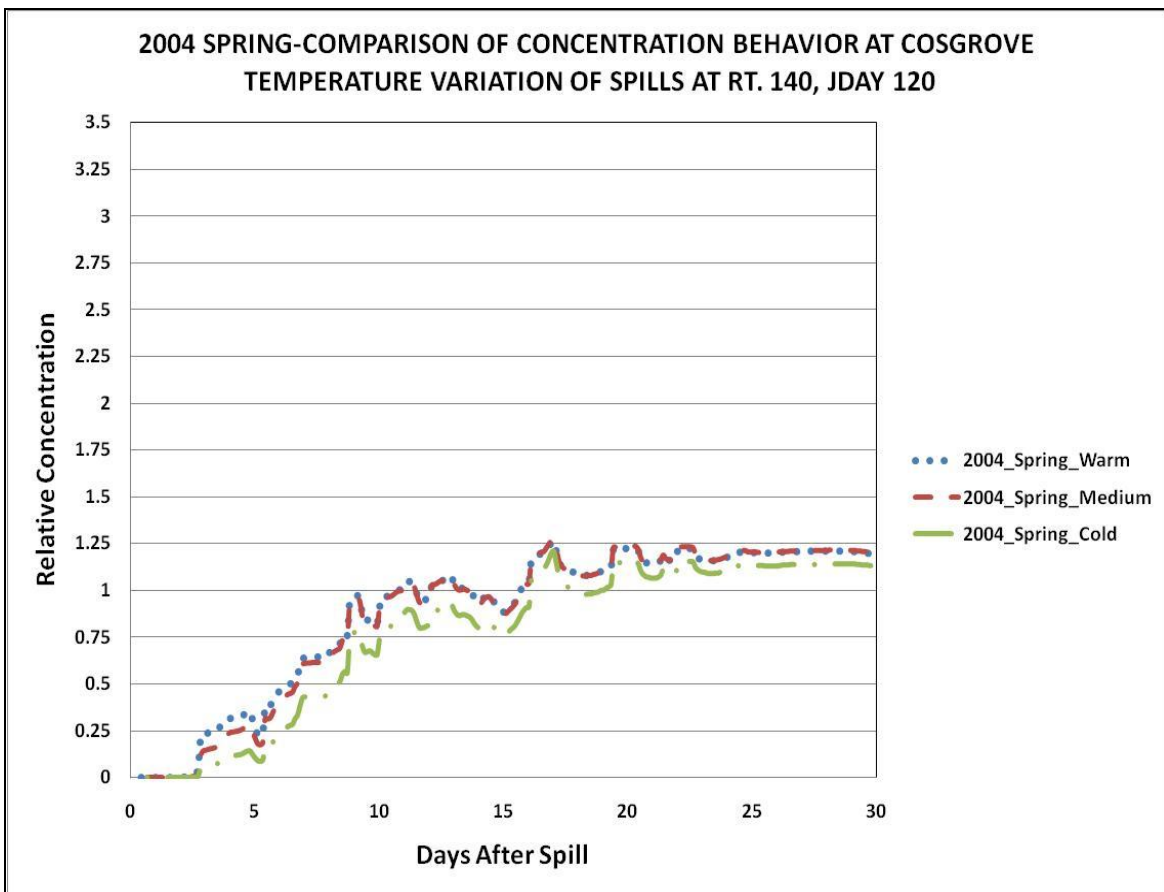


Figure 4.10 - Comparison of spill behavior at Cosgrove for spring of 2004 for different spill temperatures

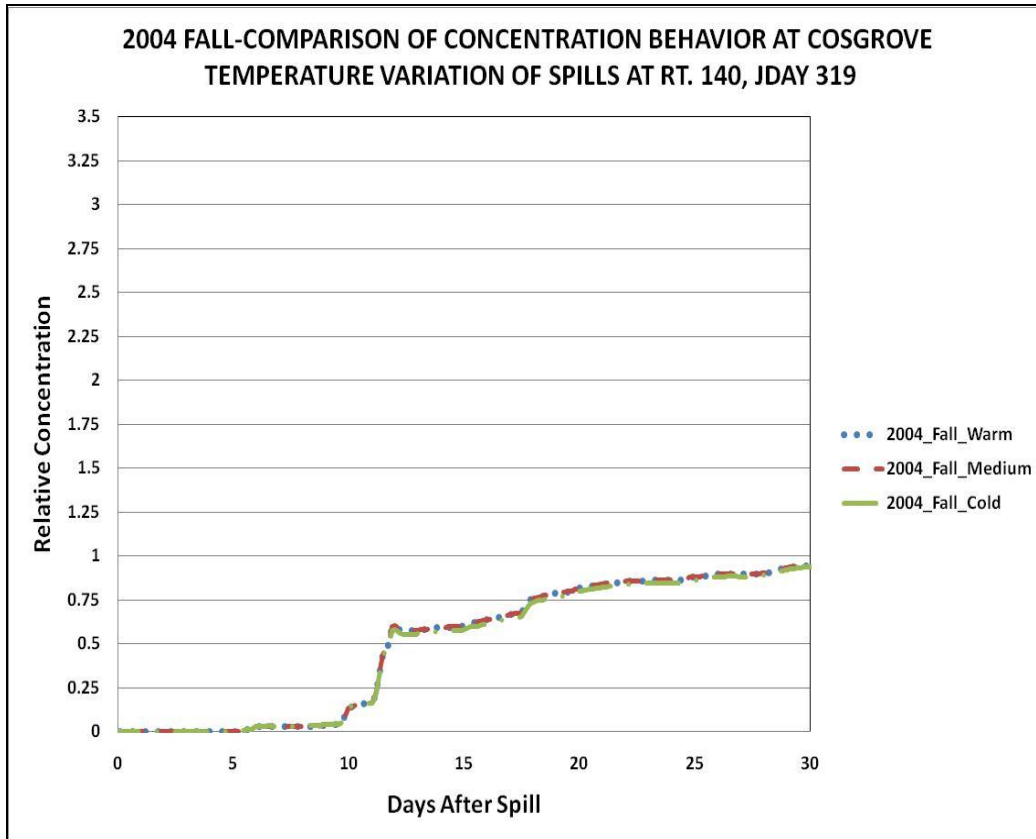


Figure 4.11 - Comparison of spill behavior at Cosgrove for fall of 2004 for different spill temperatures

The summer of 2004 showed different results than the spring and fall as shown in Figure 4.12. The medium and cold spills demonstrate similar concentration variability and the same arrival time. These spills would be located in the middle layers of the reservoir within the interflow and would therefore experience larger temperature gradients than a warm spill. The warm spill, which sits on the surface, arrived earlier by approximately 5 days and the concentration variability was dampened. This validates the notion of stratification having a major impact on the behavior of spills during the summer. The behavior of the spill witnessed at the Cosgrove intake depends on where the bulk of the mass sits. A warm spill, sitting on the surface, may not disperse into deeper layers as much as the medium and cold spills. The reservoir is never well mixed during the summer and therefore the contaminant concentration will be affected by the flow field for any spill temperature.

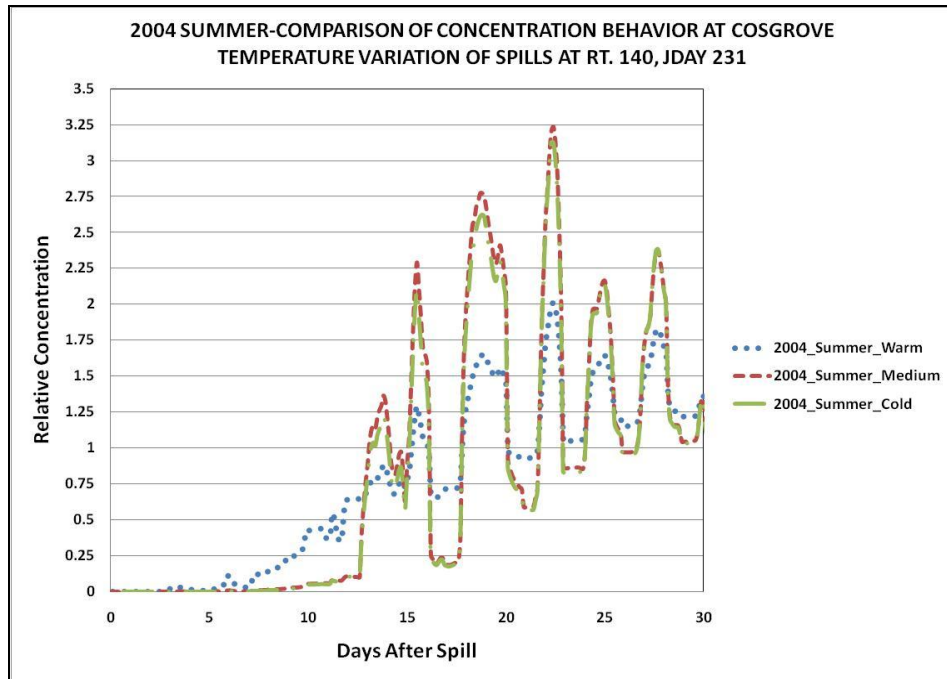


Figure 4.12 - Comparison of spill behavior at Cosgrove for summer of 2004 for different spill temperatures

The summer of 2003, 2005 and 2006 showed no significant change in the spill behavior due to a change in spill temperature as shown in Figures 4.13, 4.14 and 4.15. This again validates that the spill behavior is affected by where the mass of the spill is located and the amount of dispersion into the deeper layers or interflow. Figure 4.16 compares the spill concentration profile 10 days after the spill at segment 30 for 2006. The 2006 warm spill disperses into the interflow like the medium spill and therefore has similar behavior at the intake.

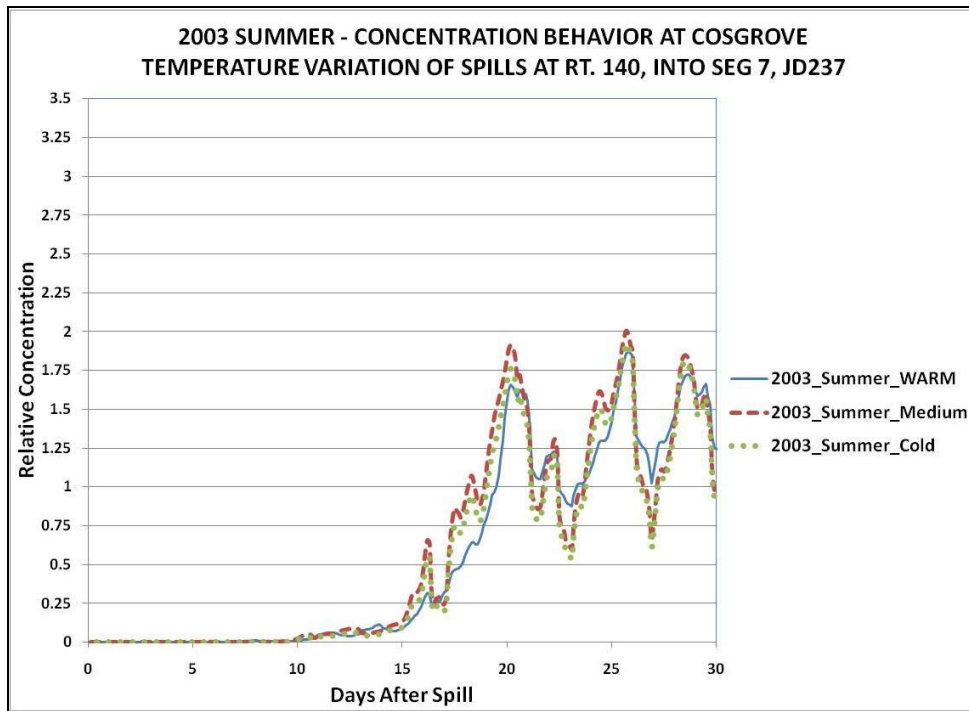


Figure 4.13 - Comparison of spill behavior at Cosgrove for summer of 2003 for different spill temperatures

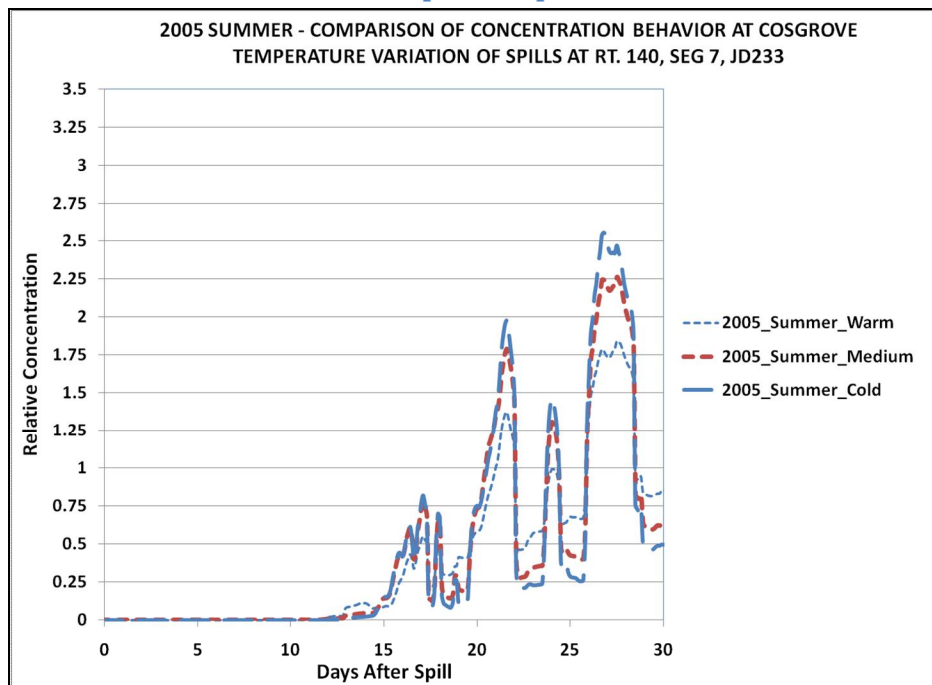


Figure 4.14 - Comparison of spill behavior at Cosgrove for summer of 2005 for different spill temperatures

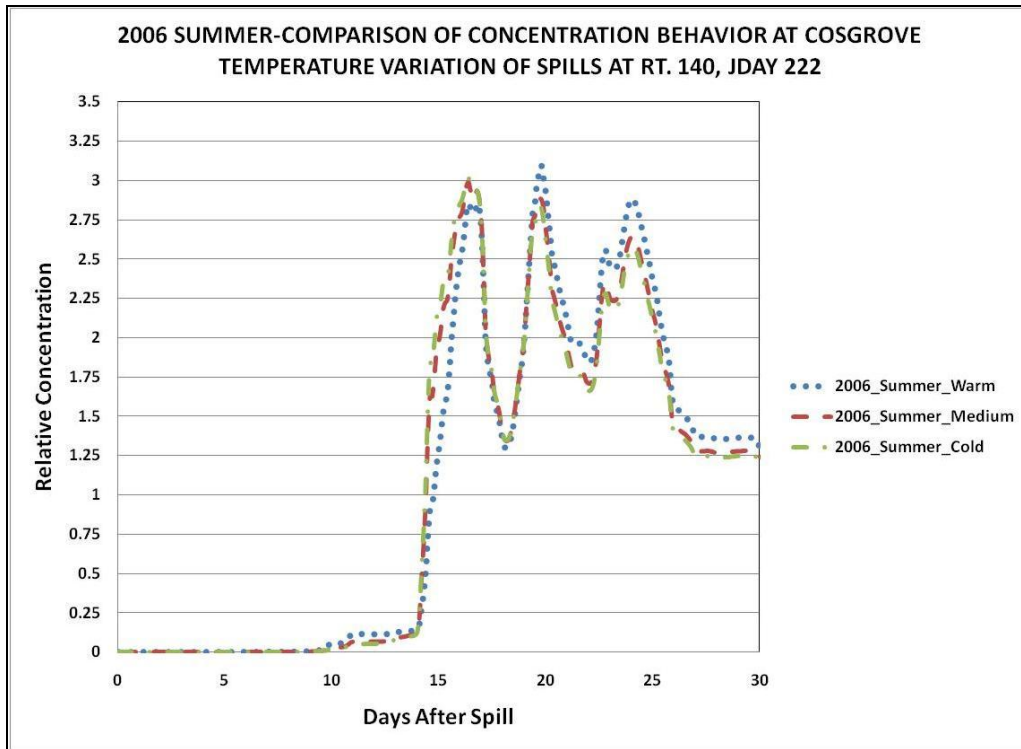


Figure 4.15 - Comparison of spill behavior at Cosgrove for summer of 2006 for different spill temperatures

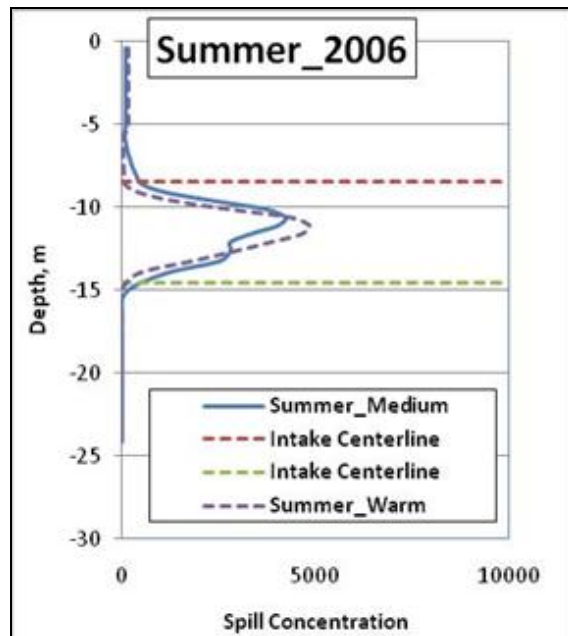


Figure 4.16 - Comparison of Spill Concentration Profiles for segment 30 for 2005 and 2006, 10 days after the spill

4.2 Effect of Quabbin Transfer On/Off

CEQUAL W2 was utilized to alter Quabbin transfer flows in order to investigate the effect of turning the transfer on or off on contaminant concentration at the Cosgrove intake. Two runs for each season of all four years for each temperature (warm, medium, and cold) were performed, as summarized in Table 4.2. One run represented the normal activity of the Quabbin transfer. For example, if the transfer was on during or after the spill it was allowed to remain on. The second run consisted of adjusting the transfer by turning it on if it was off and turning it off if it was on. Each adjustment of the transfer was made the same way. For instance, if turning it on or off, the change was put into effect for a period of two weeks and started twelve hours after the spill occurred. Twelve hours was selected in order to best represent the time it would take for the reservoir managers to turn the transfer on or off. The most significant effects of altering the Quabbin transfer were witnessed in the summer for the cold and medium temperature spills for all four years when turning the transfer off. For simplicity, only the cold spills are presented in this section due to the close similarities in behavior to the medium temperature spills.

Table 4.2 - Summary of Quabbin Transfer Simulations for All Four Years

Year	Season	Normal Condition of Quabbin Transfer	Altered Condition of Quabbin Transfer for 2 Weeks
2003	Spring	OFF	ON
2003	Summer	ON	OFF
2004	Spring	OFF	ON
2004	Summer	ON	OFF
2004	Fall	ON	OFF
2005	Spring	OFF	ON
2005	Summer	ON	OFF
2005	Fall	OFF	ON
2006	Spring	OFF	ON
2006	Summer	ON	OFF
2006	Fall	OFF	ON

Results for summer spills for all four years showed a dampening effect on the variability of spill concentration at the Cosgrove intake due to shutting the Quabbin transfer off for a period of two weeks after the spill (Figures 4.17, 4.18, 4.19, 4.20). In all four figures, the runs are labeled as "Quabbin_ACTUAL_ON" and "Quabbin_TURNED_OFF". The term "ACTUAL" was used to

signify the normal state of the Quabbin transfer and the term δ TURNED δ represents the run in which the normal activity was adjusted. For all four summers, the Quabbin transfer was normally on and a second run was completed in order to turn the transfer off. All four years display very similar behavior in which turning the transfer off for a period of two weeks dampens the variability of the spill concentration. As discussed previously, the state of stratification during the summer causes the Quabbin interflow when the transfer is on which creates layers of lower conductivity, affecting the spill concentration as it travels across the reservoir. Turning the transfer off eliminates the zone of lower conductivity and allows the spill to disperse throughout the water column as validated by the spill concentration profile for the summer of 2006, Figure 4.21. This figure shows the spill concentration profile 20 days after a medium temperature spill at segment 44 near the Cosgrove intake during the summer. It displays profiles for the normal, on condition, of the Quabbin transfer, δ Quabbin_ON δ , and when it is shut off for a period of two weeks, δ Quabbin_OFF δ . As shown in Figure 4.21, when the transfer is on, the bulk of the spill mass is located at depths between 10-15 m within the Quabbin interflow. The spill mass becomes more dispersed throughout the water column when the transfer is turned off for two weeks which validates the dampening of spill concentration variability at the Cosgrove intake.

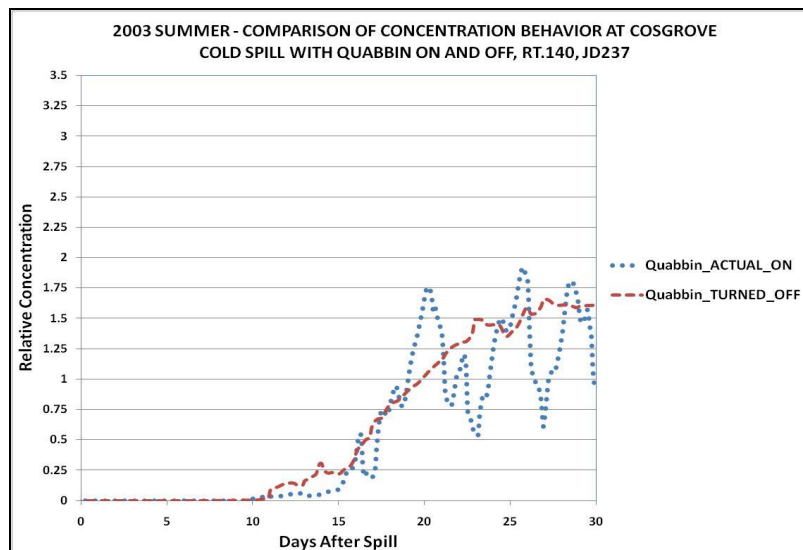


Figure 4.17 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2003 cold spill

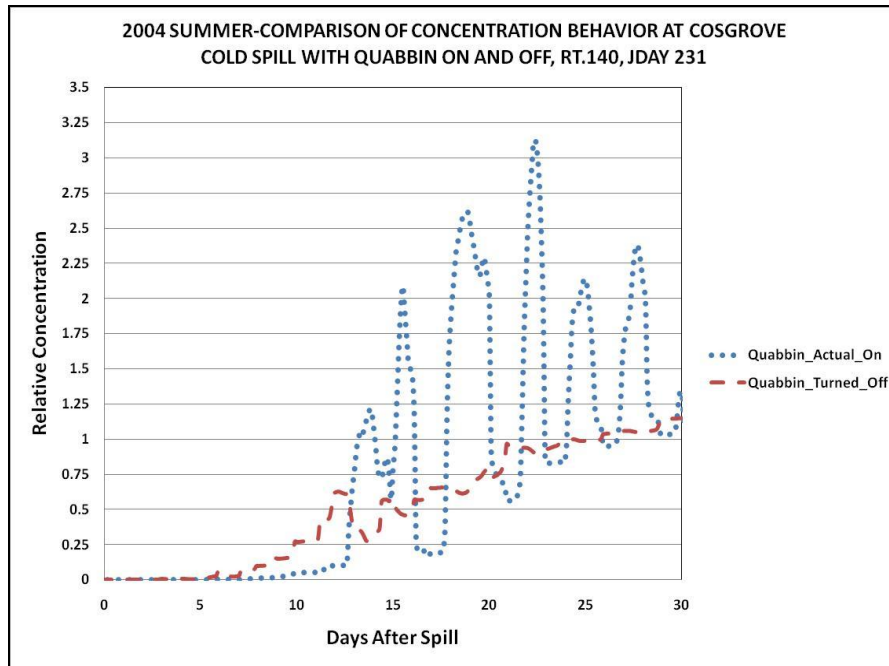


Figure 4.18 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2004 cold spill

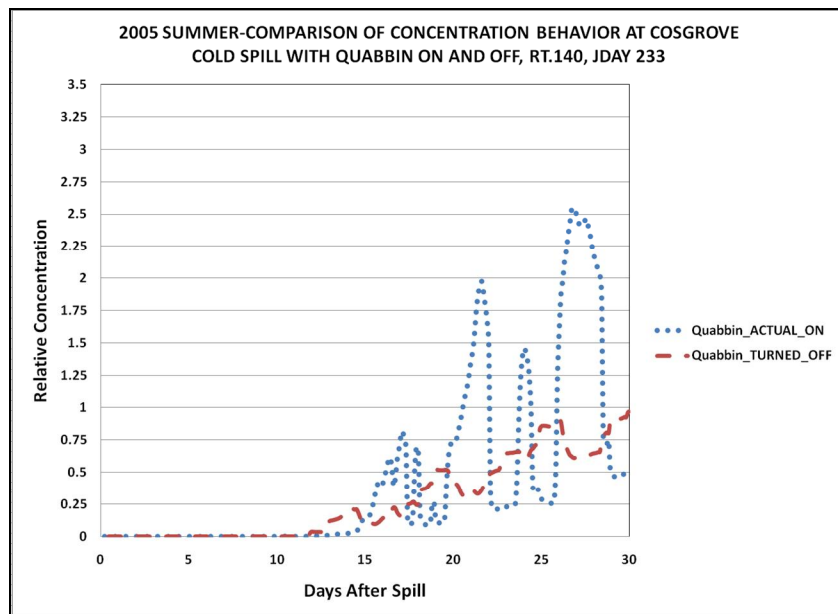


Figure 4.19 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2005 cold spill

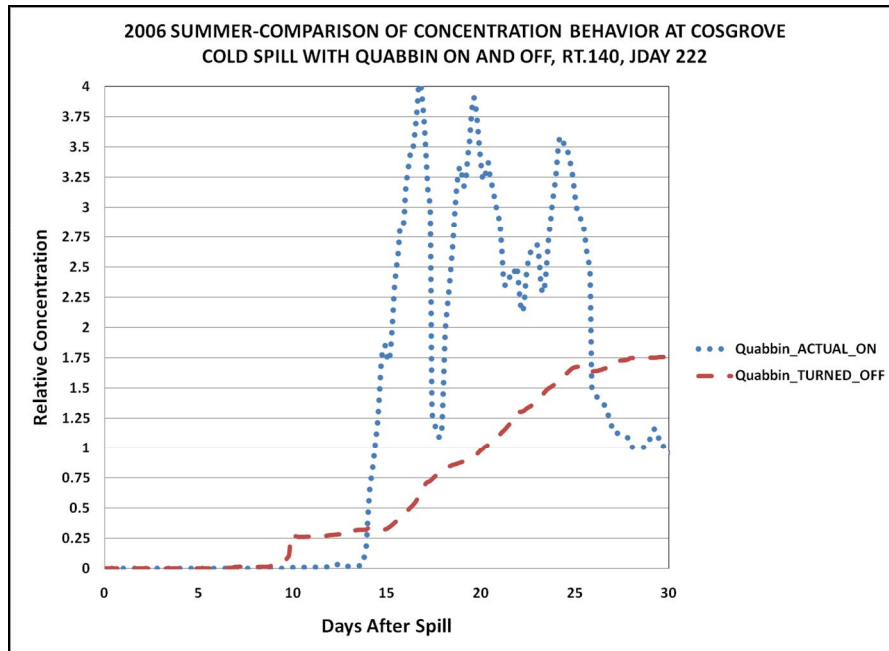


Figure 4.20 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2006 cold spill (*Note change of scale)

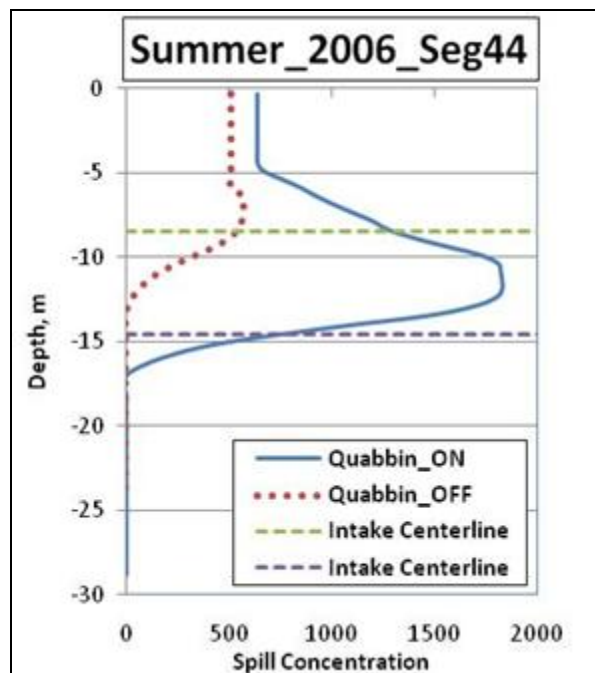


Figure 4.21 - Comparison of Spill Concentration Profile at Segment 44 for the summer of 2005 and 2006, 20 Days after the spill

All four years also showed similar spill behavior at the Cosgrove for a warm spill in the summer. In this case, the behavior remained the same as shown for years 2004, and 2005 in Figures 4.22, and 4.23. The warm spills represent surface spills which have less significant variability as described previously. This variability does not change when the Quabbin transfer is turned off for a period of two weeks. This is again attributed to the location of the spill in that it does not enter into the Quabbin interflow and therefore behaves in a similar manner.

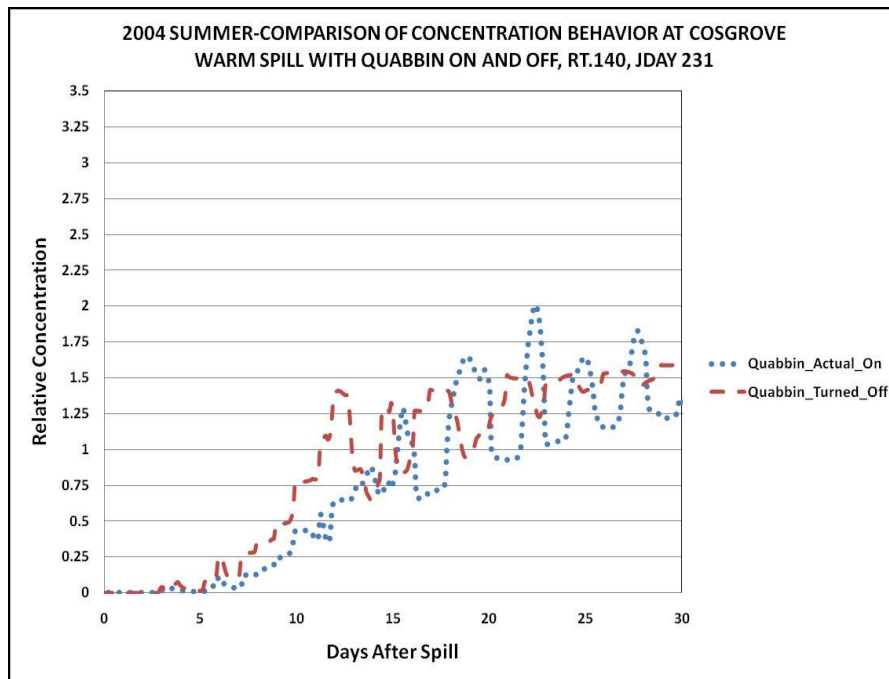


Figure 4.22 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2004 warm spill

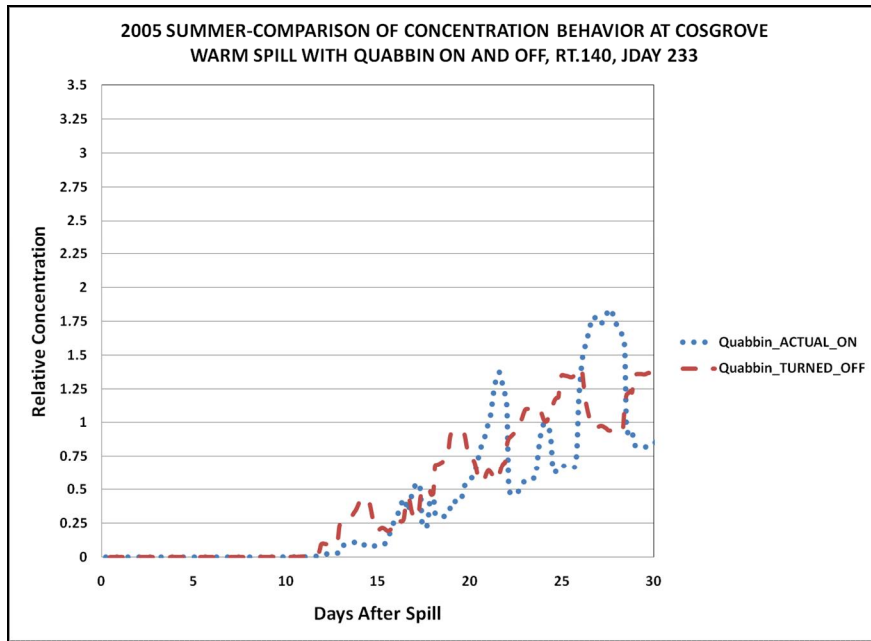


Figure 4.23 - Effect of turning Quabbin transfer off on spill behavior at Cosgrove, summer 2005 warm spill

5.0 Summary and Conclusions

Summary

A CEQUAL W2 model of years 2005 and 2006 was successfully generated. This was completed through a calibration process which involved matching water surface elevation as well as temperature and conductivity measurements taken within the Wachusett Reservoir by DCR. Error between measured and calculated water surface elevation was minimized by adjusting calibration factors attached to inflows and outflows within the water balance spreadsheet. A combination of CEQUAL W2 model parameters that would produce the least amount of error between measured and simulated temperature and conductivity profiles located in the North Basin of the Wachusett Reservoir were obtained. This was accomplished by performing several simulations, making alterations to specific parameters in each run, and comparing root mean squared errors.

V3.6 of CEQUAL W2 was effectively utilized to model spill behavior within the Wachusett Reservoir for years 2003, 2004, 2005, and 2006 under various conditions. These conditions included: seasonal changes, variation of spill temperature, and turning the Quabbin transfer on/off. The spill location was determined to be the Rt. 140 Bridge due to the high vulnerability of an accident, leading to a contaminant to enter the reservoir. The contaminant was modeled as a non-reactive tracer. The output of numerous simulations was evaluated in order to compare results from year to year.

Conclusions

It was determined through the many simulations that the spill behaved differently for each season. The spill traveled the quickest in the spring, and slowest in the summer. Spring spills consistently arrived at the withdrawal within 2-3 days, fall spills within approximately 7-10 days, and summer spills took 10-15 days. Stratification of the reservoir during the summer led to variability of the spill concentration measured at the Cosgrove intake. The summer spills showed more variability, having larger peaks than the other seasons. Varying the spill temperature showed little effect on the behavior during the spring and fall in which the reservoir is well mixed. The summer of 2004 showed a faster arrival time at the intake for a warm spill

whereas the summers of 2003, 2005 and 2006 displayed negligible differences in spill behavior when changing the spill temperature. Altering the condition of the Quabbin transfer showed the most effect during the summer months for all four years. Turning the transfer off for a period of two weeks after the spill caused the variability of spill concentration measured at the intake to dampen significantly. This behavior is associated with the absence of the Quabbin interflow which inhibits the dispersion of the spill within the reservoir.

References

- Barthlow J., Hanna R. B., Saito L., Lieberman D., and Horn M. (2001) "Simulated Limnological Effects of the Shasta Lake Temperature Control Device." *Environmental Management* 27(4): 609-626
- Buttrick D.R. (2005) "Modeling Natural Organic Matter in an Unfiltered Surface Water Supply," M.S. Thesis, University of Massachusetts, Amherst. Department of Civil and Environmental Engineering.
- Camp, Dresser and McKee (CDM) (1995) "Wachusett Reservoir Water Treatment Plan EIR Conceptual Design Task 2.3: Wachusett Reservoir Draft Modeling Report," submitted to Massachusetts Water Resources Authority.
- Chung S., Gu R. R. (2009) "Prediction of the Fate and Transport Processes of Atrazine in a Reservoir." *Environmental Management* 44: 46-61.
- Cole T.M. (2000) "Reservoir Thermal Modeling using CEQUAL W2." *Environmental Studies Series* 4: 237-246.
- Cole T.M. and S. A. Wells (2008) "CE-QUAL-W2: A two-dimensional, laterally averaged, Hydrodynamic and Water Quality Model, Version 3.6," Department of Civil and Environmental Engineering, Portland State University, Portland, OR.
- Joaquin A.L. (2001) "Modeling the Effect of Quabbin Transfers on Wachusett Reservoir Composition," M.S. Thesis, University of Massachusetts, Amherst Department of Civil and Environmental Engineering.
- Kennedy M.G. (2003) "Three-Dimensional Numerical Modeling of Hydrodynamics and Transport in a Reservoir." M.S. Thesis, University of Massachusetts, Amherst. Department of Civil and Environmental Engineering.
- Kuo J., Lung W., Yang C., Liu W., Yang M., Tang T. (2005) "Eutrophication Modeling of Reservoirs in Taiwan." *Environmental Modelling and Software* 21: 829-844
- Lawler D.F., and Benjamin M.M. (2010), Water Quality Engineering: Physical-Chemical Treatment Processes, a text in the process of being written
- Martin P.H., LeBoeuf E.J, Daniel E.B., Dobbins J.P., Abkowitz M.D. (2004) "Development of a GIS-based Spill Management Information System." *Journal of Hazardous Materials* B112: 239-252.

Matthews T.P. (2007) "Modeling Fate and Transport of Fecal Coliform in Wachusett Reservoir", M.S. Thesis, University of Massachusetts, Amherst Department of Civil and Environmental Engineering.

Stauber C.L. (2009) "Contaminant Spill Modeling for Wachusett Reservoir", M.S. Thesis, University of Massachusetts, Amherst Department of Civil and Environmental Engineering.

Tobiason J.T., Ahlfeld D.P., Joaquin A. and Mas D. (2002) "Water Quality in MDC Reservoirs. Project 1: Wachusett Reservoir Water Quality Modeling", University of Massachusetts, Amherst Department of Civil and Environmental Engineering, prepared for Metropolitan District Commission, West Boylston, MA.

APPENDIX A - Time Series of Major Inflows/Outflows

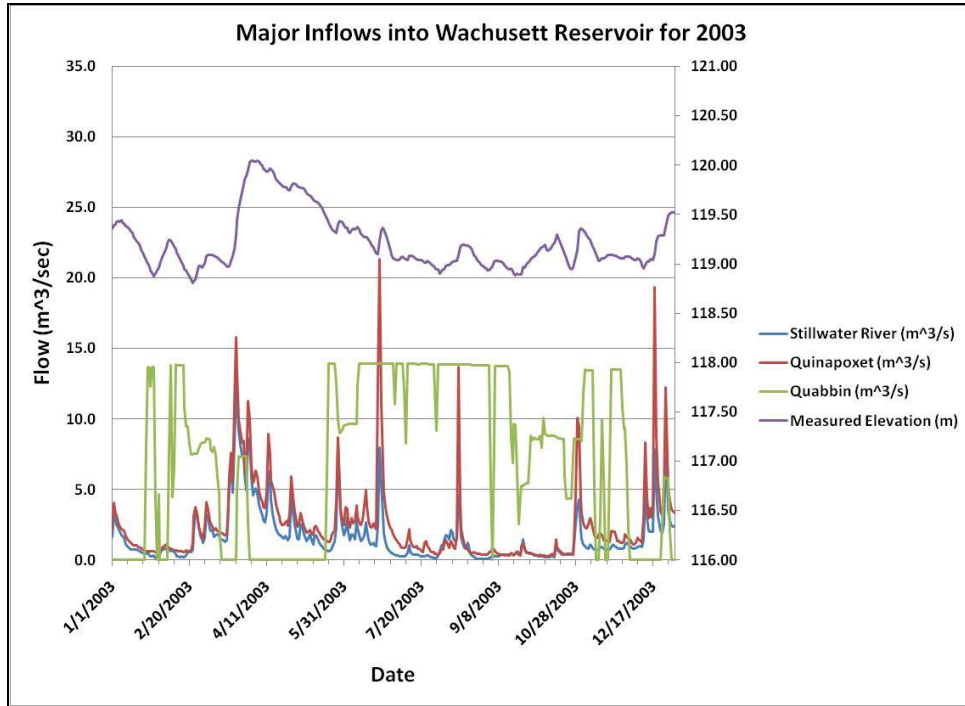


Figure A.1 – Major Inflows into the Wachusett Reservoir for 2003

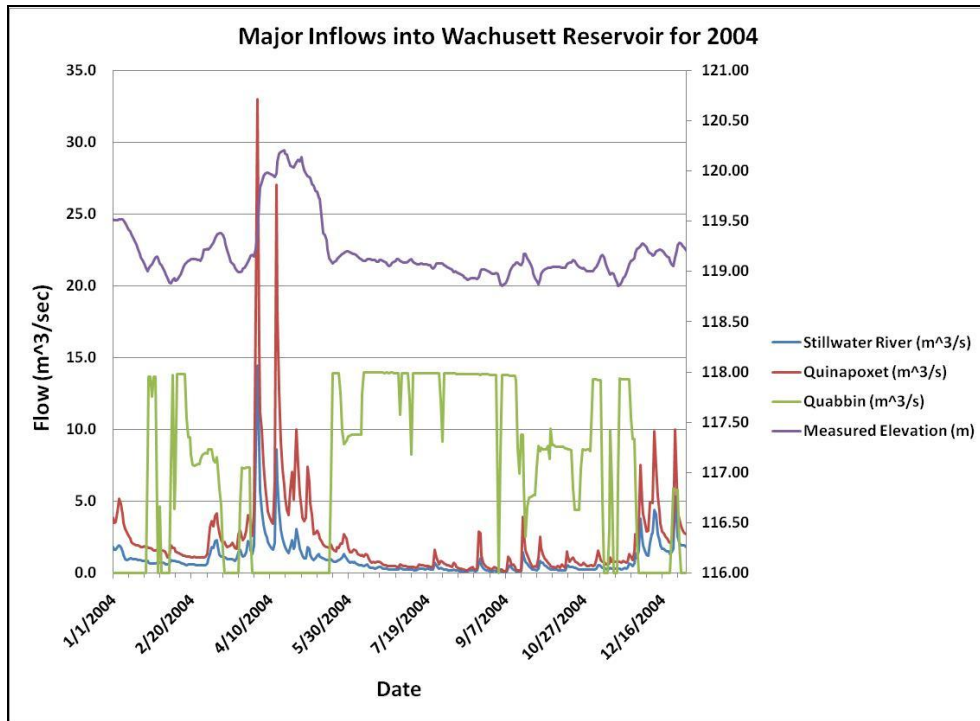


Figure A.2 – Major Inflows into the Wachusett Reservoir for 2004

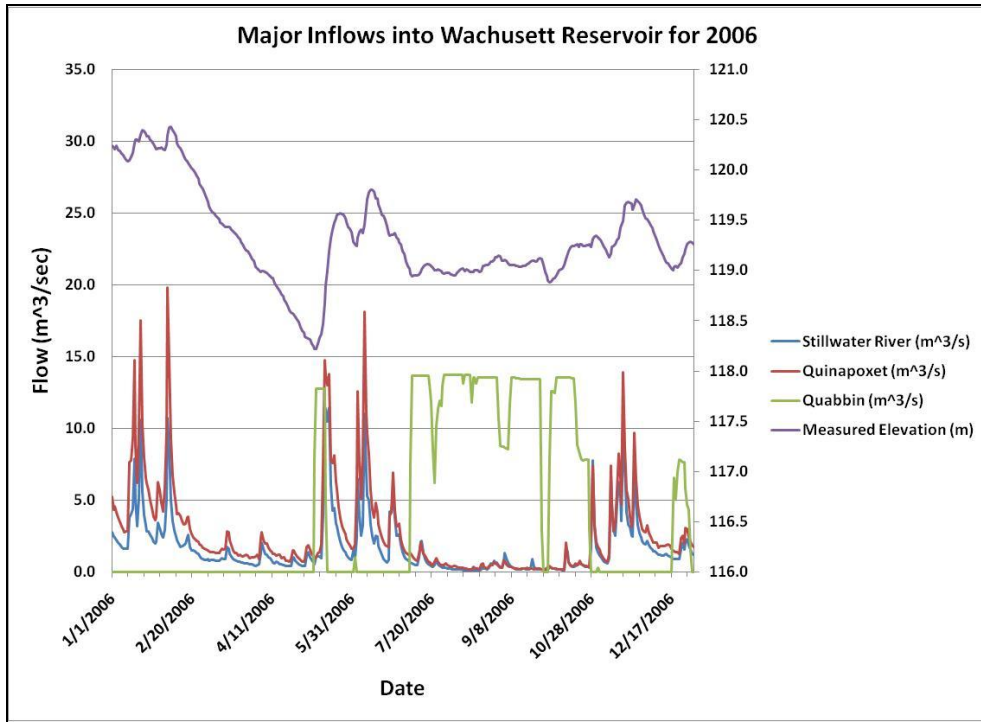


Figure A.3 – Major Inflows into the Wachusett Reservoir for 2006

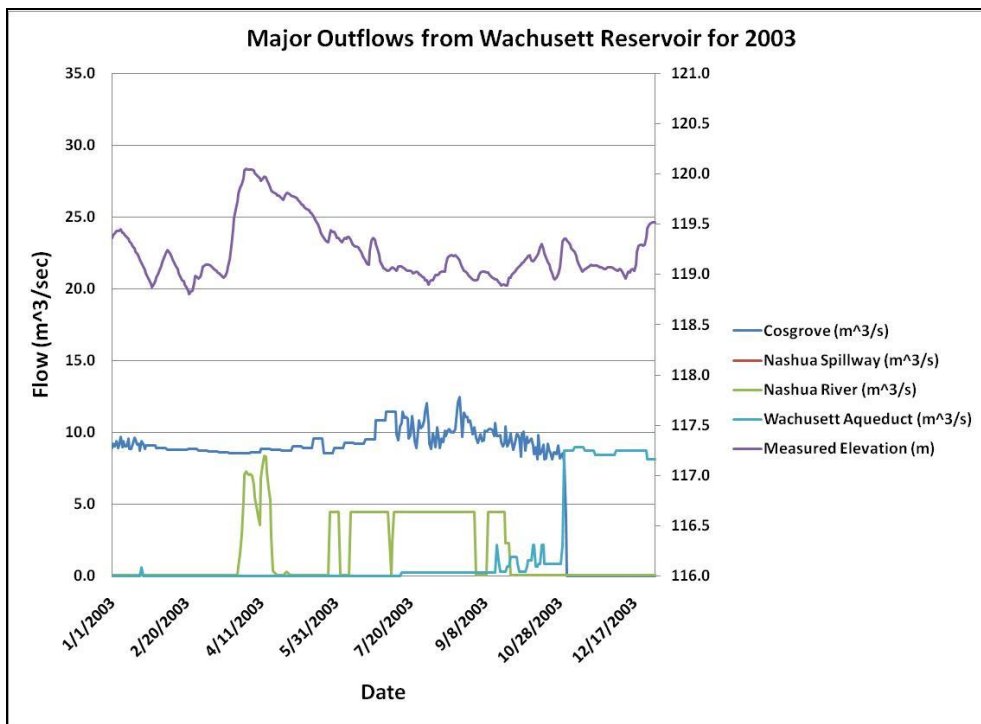


Figure A.4 – Major Outflows into the Wachusett Reservoir for 2003

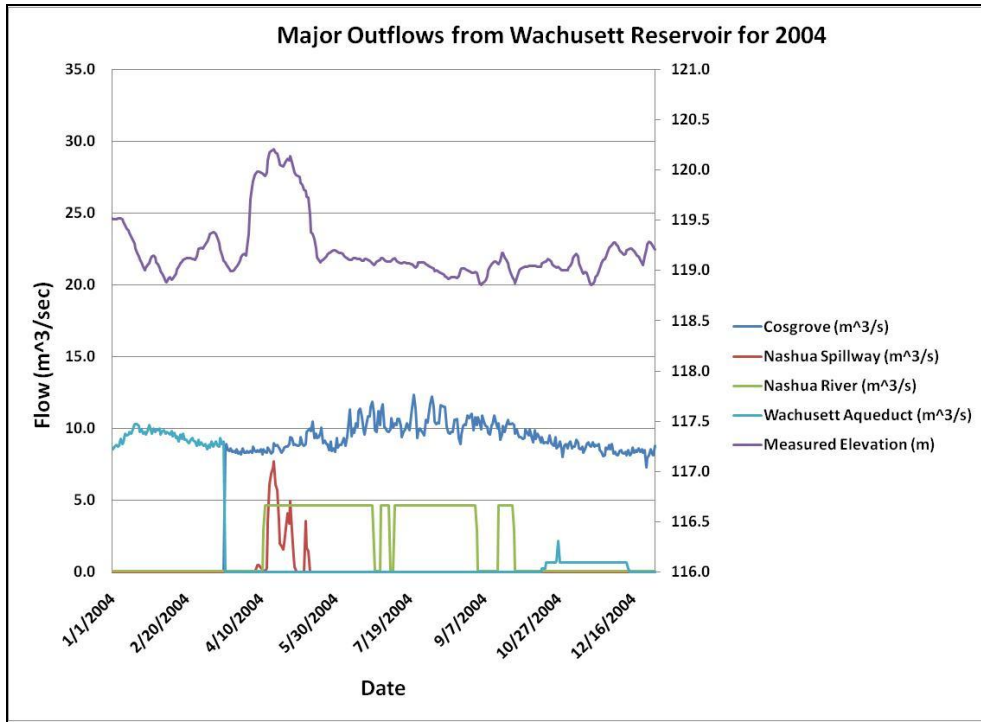


Figure A.5 – Major Outflows into the Wachusett Reservoir for 2004

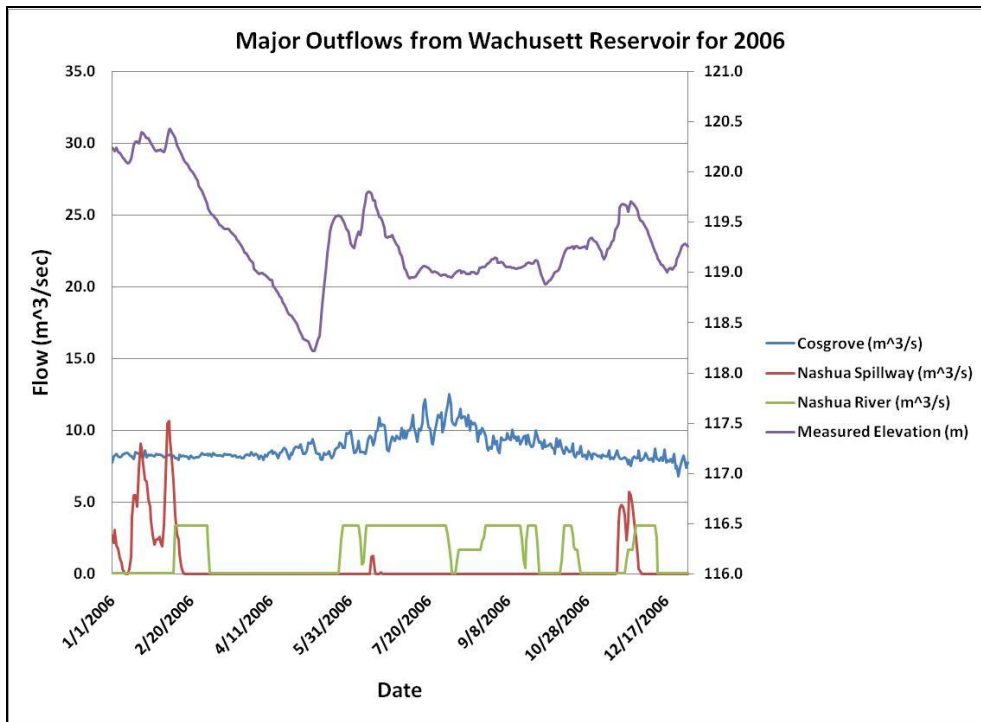


Figure A.6 – Major Outflows into the Wachusett Reservoir for 2006