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Using Ce-Qual-W2 to Model A Contaminant Spill Into the Wachusett Reservoir

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USING CE-QUAL-W2 TO MODEL A CONTAMINANT SPILL INTO THE WACHUSETT RESERVOIR

A Masters Project Presented by

Lillian M. Clark

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

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Acknowledgements

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Thank you also to Mikaela Laverty, for your ideas and answers to my modeling questions. Your knowledge and experience have been so helpful and I have really enjoyed getting to know you, and your daughter Annika, over the past year and a half.

To my friends and fellow graduate students at UMass, thank you for making this experience a great one. It’s a pleasure working with such intelligent and inspiring people. Finally, I would especially like to thank my family, and fiancé Chris, who have continued to support me throughout the years in whatever I have pursued. I am so grateful for your love and encouragement.
Executive Summary

This research was done to understand the potential fate and transport of a contaminant spill into the Wachusett Reservoir utilizing the model CE-QUAL-W2 V3.6. The Wachusett Reservoir, located in central Massachusetts, is the main water supply for the Boston, MA metropolitan area. The reservoir has a capacity of approximately 65 billion gallons and receives about half of its total inflow from the Quabbin Reservoir, which has a capacity of 412 billion gallons. Water is transferred from the Quabbin Reservoir to the western end of the Wachusett Reservoir intermittently through the Quabbin Aqueduct typically from June through November to meet higher water demands, maintain the water level, and mitigate water quality concerns in Wachusett. The largest outflow from the Wachusett Reservoir is the Cosgrove drinking water intake, located at the most eastern end of the waterbody.

CE-QUAL-W2 is a two-dimensional, longitudinal and vertical, hydrodynamic and water quality model. The model is suitable for simulating water quality and hydrodynamics in Wachusett because the reservoir is relatively long and narrow. Therefore, longitudinal and vertical gradients in velocities, temperatures, and constituents are much larger than lateral gradients. For this study, a model of the reservoir was developed for the year 2009 using inputs for meteorology, bathymetry, initial flow and constituent conditions, inflow quantity and quality, outflow quantity, and outlet descriptions. The 2009 simulation was successfully created and calibrated to match temperature and specific conductivity profile measurements in the reservoir. Models for the years 2003-2008 had been created and calibrated during previous UMass research by Matthews (2007), Sojkowski (2011), and Devonis (2011).

The calibrated CE-QUAL models for the years 2003-2009, verified by the temperature and specific conductivity profiles, were used to simulate potential contaminant spills into the Wachusett Reservoir. Contaminant spills were modeled as a conservative substance to study the effects of seasonal change, various spill densities (temperatures), and turning the Quabbin transfer on and off. Spill dates for each season were chosen based on days with similar meteorological conditions. The approximate contaminant spill arrival time, maximum relative concentrations, and behavior at the Cosgrove Intake were observed and compared for various analyzed scenarios.
During the spring and the fall seasons, the density of a contaminant spill does not typically have an effect on the arrival time or relative concentration of the contaminant at the Cosgrove Intake. Spring spills arrive between 2 and 7 days after the spill occurred, reaching an average maximum relative concentration of 1.0 to 2.9. Fall spills typically arrive between 4 and 11 days with an average maximum concentration of approximately 1.0 to 1.2. During the summer months, when the reservoir is stratified, contaminant spill behavior is more variable, arrival time is usually later, and the average maximum relative concentration is greater. The average arrival times for warm, medium, and cold spills during the summer are 8.4, 11.6, and 12.3 days respectively. The average maximum relative concentration at the Cosgrove for warm spills is 1.9, while for medium and cold spills the average are about 2.6 during the summer months.

Impacts of the Quabbin transfer on spill behavior and relative contaminant concentration were also investigated for the spring, summer, and fall. Turning the Quabbin Aqueduct off after a spill in the summer, when it is normally on, generally does not impact the arrival time of the contaminant at the Cosgrove. However, turning the Quabbin transfer off reduces the variability in the concentration of the contaminant at the intake. Changes in the Quabbin transfer during the spring and the fall have minimal impacts on contaminant arrival time and behavior.

A combined two year model developed from the data for years 2008 and 2009 demonstrates that a conservative contaminant can remain in the reservoir for more than three times the mean hydraulic residence time of 206 days. In contrast, a contaminant with a first order decay rate of 0.02 day$^{-1}$ results in a 99% decay of contaminant concentration in the outflow after one mean hydraulic residence time. Model results for decaying contaminants show that relatively rapid decay rates (0.10 to 0.66 day$^{-1}$) are needed to decrease the peak outflow concentration by 99% for a range of peak concentration arrival times of 7 to 46 days for all simulated model years. Additionally, a combined two year model is useful producing more realistic boundary conditions for a 3-D model of the North Basin in the Wachusett Reservoir.
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1 INTRODUCTION

This report describes the results of two-dimensional modeling of the Wachusett Reservoir conducted at the University of Massachusetts (UMass) during the period of summer 2011 to fall 2012 utilizing a modeling package called CE-QUAL-W2. This research is a product of the collaboration between UMass, the Massachusetts Department of Conservation and Recreation (DCR), and the Massachusetts Water Resources Authority (MWRA). Simulation results for the 2003 to 2009 calendar year models were analyzed to assess similarities and differences from year to year.

1.1 Objective and Scope

The objective of this research was to better understand the behavior of potential contaminant spills from the Route 140 Bridge into the reservoir under different conditions. The scope of work involved using CE-QUAL-W2 V3.6 to model the hydrodynamics and water quality of the Wachusett Reservoir to simulate a contaminant spill. Scenarios for hypothetical contaminant spills into the Wachusett Reservoir from the Route 140 Bridge were modeled for years 2003-2009 to determine arrival times and relative contaminant concentrations at the Cosgrove Intake. Scenarios investigated include the impacts of changing seasons, spill density, and the Quabbin transfer. The model results provide useful information to reservoir operators regarding how to respond to a potential spill under various conditions.

1.2 Wachusett Reservoir System

The Wachusett Reservoir is located in central Massachusetts, northeast of Worcester, and is the main water supply for the Boston, MA metropolitan area (Figure 1.1). In 1897 the Nashua River above the town of Clinton was impounded by the Wachusett Dam and six and a half square miles of land were flooded to create the reservoir. Work was completed on the reservoir in 1905 and it was filled in May 1908 (MWRA, 2006). The reservoir has a capacity of about 65 billion gallons, which makes it the second largest water body in the state 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 MWRA maintains the water surface elevation between 390 feet (118.9 m) and 391.5 feet (119.3 m) above the Boston base. The Cosgrove Intake is the major withdrawal from the reservoir and
is used to supply drinking water to metropolitan Boston. Water also leaves the reservoir to supply the Nashua River by a controlled release and a sleeve valve below the Wachusett Dam, as well as a spillway, which water flows over during times of high water surface elevation. Water is routinely released from the base of the Wachusett Dam to the Nashua River, with flows varying from near 2 to greater than 100 million gallons per day (MGD) as controlled by a valve.

The Wachusett Reservoir can be divided into three separate basins: Thomas Basin, South Basin, and North Basin, as seen in Figure 1.2. Water enters the reservoir by direct precipitation, runoff, nine tributaries, and the Quabbin transfer. The two largest tributaries are the Stillwater River and the Quinapoxet River, which both enter from the north end of the reservoir into the Thomas Basin. Water from the Quabbin reservoir is transferred via the Quabbin Aqueduct and discharges into the Quinapoxet River, just upstream of the reservoir. These two tributaries are gauged for flow by the United States Geological Survey (USGS). Seven other tributaries entering the reservoir include the Washacum, Malden, West Boylston, Gates, Muddy, Malagasco, and French Brooks. Gates Brook was recently gauged by the USGS as of December 2011. Water exits the reservoir on the eastern side via the Cosgrove Intake, the Nashua River, minor withdrawals to nearby towns, and evaporation.

Figure 1.1  Wachusett Reservoir Location (Google Maps)
The reservoir is part of the MWRA’s water supply system (Figure 1.3) including the Carroll Water Treatment Plant (CWTP), the Metrowest Water Supply Tunnel (MWWST), and the Quabbin Reservoir, completed in the 1930’s, which is the largest water body in Massachusetts with a 412 billion gallon capacity. Since 1985, the MWRA has distributed water to 46 communities in the Boston area. The water system is managed in partnership with the Department of Conservation and Recreation (DCR), which has the responsibility of managing the watersheds. Modeling the movement of the water through the reservoirs can improve management and operational procedures to maintain excellent quality water for the metropolitan Boston area.
1.2.1 The Quabbin Transfer

Water transferred from the Quabbin Reservoir to the Wachusett Reservoir intermittently through the Quabbin Aqueduct has a large impact on the hydrodynamics and water quality of Wachusett reservoir. This aqueduct is 24.6 miles long, 11 feet wide, and 12 feet 9 inches tall, making it one of the longest tunnels in the world. The Quabbin Aqueduct is the largest outflow from the Quabbin Reservoir and on average accounts for more than 60% of the water that leaves the 412 billion gallon reservoir. The MWRA can also divert water from the Ware River watershed to either the Quabbin Reservoir or the Wachusett Reservoir through the Quabbin Aqueduct, but these diversions are rare. Historically, water transfers from the Quabbin into the Wachusett account for over 50% of the average annual inflow to the Wachusett Reservoir. Transfers generally occur from June through November and can last for weeks at a time to meet higher water demands, maintain the water level, and mitigate water quality concerns in the Wachusett Reservoir (DCR, 2007).

During periods of stratification a phenomenon occurs in the Wachusett Reservoir known as the Quabbin Interflow, which is water from the Quabbin travelling through the Wachusett Reservoir at a certain depth. Water is withdrawn from depths of 13 to 23 meters in the Quabbin Reservoir and the temperature ranges from 9 to 13°C. The water gains some heat while travelling through
the aqueduct but when it reaches the Wachusett Reservoir it usually cooler than the surface water in the Wachusett Reservoir, depending on when the transfer occurs. The region of significant Quabbin water influence is typically 10 m thick and this water is found to predominantly travel at a depth of 5 to 15 meters below the surface of the Wachusett Reservoir (DCR, 2011). Water from the Quabbin Reservoir is also lower in specific conductivity (at about 40 µS/cm) than water in the Wachusett Reservoir, and the signature of the Quabbin water travelling through the thermocline of the Wachusett Reservoir can be observed in measured water quality profiles from the North Basin, as seen in Figure 1.4. The Quabbin water travelling through the Wachusett Reservoir during stratification is detected by a region of lower conductivity and intermediate temperature. This so called density current is most easily identified in the specific conductivity profiles where the epilimnion and the hypolimnion are higher in specific conductivity than the thermocline. The Quabbin Interflow travels throughout the Wachusett Reservoir until it reaches the Cosgrove Intake, where a combination of the Quabbin and Wachusett water is withdrawn and sent to the Carroll Water Treatment Plant to be disinfected and distributed.

![Conductivity Profile, July 20, 2009 (JDay 201) at North Basin (CE-QUAL-W2 Segment 44)](image)

**Figure 1.4** Conductivity Profile, July 20, 2009 (JDay 201) at North Basin (CE-QUAL-W2 Segment 44)

### 1.2.2 Major Inflows and Outflows

Table 1.1 shows the relative distribution of inflow and outflows for the years 2003 through 2009. The inflows to the reservoir include the Quabbin Aqueduct, direct precipitation, direct runoff,
and nine tributaries. About 93% of the inflows to the Wachusett in the years 2003 to 2009 are from the Quabbin Aqueduct, direct precipitation, direct runoff, the Stillwater River, and the Quinapoxet River. Minor tributaries include Washacum Brook, Malden Brook, West Boylston Brook, Gates Brook, Muddy Brook, Malagasco Brook, and French Brook. Smaller intermittent streams including Potash Brook, Hastings Cove Brook, Oakdale Brook, Meadow Brook, and Lawson Brook are included as direct runoff area for the purposes of completing the water budget because they contribute less than 1% of the inflow to the reservoir. Direct runoff is estimated using the Stillwater yield, as discussed in Tobisayan et al. (2002). Outflows include the Cosgrove Intake, the Nashua River Release, town withdrawals, the Nashua Spillway, the Wachusett Aqueduct, and evaporation. The three major outflows from the Wachusett are the Cosgrove, the Nashua River, and the Nashua Spillway, which is displayed as an asterisk for 2003 because data were not available for that year. In the years 2003 to 2009 these major outflows average about 87% of the total outflow from the reservoir.

Table 1.1 Percentage Distribution of Total Inflow and Outflows (By Volume)

<table>
<thead>
<tr>
<th>Inflows:</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quabbin Aqueduct</td>
<td>43.5</td>
<td>59.1</td>
<td>34.5</td>
<td>37.5</td>
<td>52.8</td>
<td>38.1</td>
<td>42.0</td>
</tr>
<tr>
<td>Direct Precipitation</td>
<td>5.23</td>
<td>4.74</td>
<td>6.04</td>
<td>4.91</td>
<td>4.62</td>
<td>6.10</td>
<td>5.27</td>
</tr>
<tr>
<td>Direct Runoff</td>
<td>9.20</td>
<td>5.29</td>
<td>11.4</td>
<td>9.95</td>
<td>8.09</td>
<td>11.1</td>
<td>10.2</td>
</tr>
<tr>
<td>Stillwater River</td>
<td>14.0</td>
<td>8.3</td>
<td>17.7</td>
<td>15.8</td>
<td>12.4</td>
<td>17.0</td>
<td>15.5</td>
</tr>
<tr>
<td>Quinapoxet River</td>
<td>21.4</td>
<td>18.7</td>
<td>22.1</td>
<td>24.7</td>
<td>16.3</td>
<td>19.8</td>
<td>19.7</td>
</tr>
<tr>
<td>Washacum Brook</td>
<td>2.86</td>
<td>1.65</td>
<td>3.55</td>
<td>3.09</td>
<td>2.52</td>
<td>3.44</td>
<td>3.16</td>
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<tr>
<td>Malden Brook</td>
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<td>0.33</td>
<td>0.71</td>
<td>0.62</td>
<td>0.50</td>
<td>0.69</td>
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<td>Boylston Brook</td>
<td>0.19</td>
<td>0.11</td>
<td>0.24</td>
<td>0.21</td>
<td>0.17</td>
<td>0.23</td>
<td>0.21</td>
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<tr>
<td>Gates Brook</td>
<td>1.42</td>
<td>0.82</td>
<td>1.76</td>
<td>1.53</td>
<td>1.25</td>
<td>1.70</td>
<td>1.57</td>
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<tr>
<td>Muddy Brook</td>
<td>0.31</td>
<td>0.18</td>
<td>0.39</td>
<td>0.34</td>
<td>0.27</td>
<td>0.37</td>
<td>0.34</td>
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<tr>
<td>Malagasco Brook</td>
<td>0.40</td>
<td>0.23</td>
<td>0.49</td>
<td>0.43</td>
<td>0.35</td>
<td>0.48</td>
<td>0.44</td>
</tr>
<tr>
<td>French Brook</td>
<td>0.90</td>
<td>0.52</td>
<td>1.11</td>
<td>0.97</td>
<td>0.79</td>
<td>1.08</td>
<td>0.99</td>
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</table>

<table>
<thead>
<tr>
<th>Outflows:</th>
<th>2003</th>
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<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<tr>
<td>Cosgrove Intake</td>
<td>66.0</td>
<td>60.2</td>
<td>84.0</td>
<td>76.7</td>
<td>72.3</td>
<td>69.2</td>
<td>64.5</td>
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<tr>
<td>Nashua River Release</td>
<td>14.1</td>
<td>15.3</td>
<td>7.1</td>
<td>12.7</td>
<td>9.7</td>
<td>15.2</td>
<td>21.1</td>
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<tr>
<td>Town Withdrawals</td>
<td>0.74</td>
<td>0.71</td>
<td>0.65</td>
<td>0.58</td>
<td>0.53</td>
<td>0.61</td>
<td>0.56</td>
</tr>
<tr>
<td>Nashua Spillway</td>
<td>*</td>
<td>1.83</td>
<td>2.99</td>
<td>5.53</td>
<td>5.78</td>
<td>0.80</td>
<td>4.62</td>
</tr>
<tr>
<td>Wachusett Aqueduct</td>
<td>13.8</td>
<td>16.6</td>
<td>4.01</td>
<td>4.52</td>
<td>4.32</td>
<td>3.96</td>
<td>3.66</td>
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<tr>
<td>Evaporation</td>
<td>3.71</td>
<td>3.75</td>
<td>4.01</td>
<td>4.52</td>
<td>4.32</td>
<td>3.96</td>
<td>3.66</td>
</tr>
<tr>
<td>Other</td>
<td>1.72</td>
<td>1.64</td>
<td>1.31</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 1.5 shows the major daily inflows into the Wachusett Reservoir for the year 2009 on the y-axis as well as the daily change in water surface elevation throughout the year on the secondary y-axis. The inflows for this year are representative of typical inflows for a particular year. Inflows from the Quabbin Aqueduct usually occur from the spring through the fall. For the year 2009, the Quabbin transfer accounted for about 42.0% percent of the total water volume entering the reservoir. The Stillwater River water provided an additional 15.5% of the total water volume and the Quinapoxet provided another 19.7%. Large increases in the flows from the Stillwater and Quinapoxet Rivers represent large rain events, which led to an increase in the water surface elevation, as shown in Figure 1.5. During periods of lower runoff, Quabbin transfer flow is used to maintain the water surface elevation while meeting water demands and Nashua River discharges.

Figure 1.5  Major Inflows into the Wachusett Reservoir in the Year 2009

Figure 1.6 shows the major daily outflows from the reservoir and the daily change in water surface elevation for the year 2009. The Wachusett Reservoir supplies the headwaters to the Nashua River on the downstream side of the Wachusett Dam throughout the year. Nashua River
releases are often at a minimum level of 2 MGD (0.09 m³/s), but periodically the discharge is increased to about 100 MGD (4.38 m³/s) to control water surface elevation and to allow for transfer of additional Quabbin water to improve Wachusett reservoir’s water quality. Outflows over the Nashua Spillway to the Nashua River also occur to maintain the water surface elevation after large rainstorms and high inflows into the reservoir, as seen in July and August of 2009. The primary outflow from the reservoir is the water withdrawn daily from the reservoir at the Cosgrove Intake to meet the drinking water demands of the metropolitan Boston area. About 60 to 84% of the water from the reservoir leaves via the Cosgrove Intake, with the highest demand for water during the month of August. In 2009, the average daily Cosgrove demand was approximately 187 MGD (8.2 m³/s) while the average daily demand during just the month of August was approximately 217 MGD (9.5 m³/s) Water from the intake is treated by disinfection at the Carroll Water Treatment Plant before it is distributed. Additional minor withdrawals supply the municipalities of Worcester, Clinton, and Leominster. Water is also lost from seepage through the North Dike and evaporation. A full account of the inflow and outflow graphs for the years 2003 to 2008 are presented in Appendix A.

Figure 1.6 Major Outflows into the Wachusett Reservoir in the Year 2009
2 BACKGROUND

The following section provides an overview of water quality modeling and describes the CE-QUAL-W2 model used for this research. The potential applications of this model for hydrodynamic and water quality modeling are discussed, including the modeling efforts done in previous years by students at UMass.

2.1 Modeling

Hydrodynamic and water quality models use analytical or numerical methods to simulate behaviors of water bodies under a range of conditions. Models can be used to understand water velocities, changes in water surface elevation, and temperature responses to changes in the inflows and outflows of a system. Models can also be used to determine water quality when used as a tool to analyze concentrations of contaminants, nutrients, microbes, or natural constituents in a water body. Water quality models allow the user to rapidly investigate many scenarios if sufficient data are collected to calibrate and validate the model. It is necessary to have knowledge of the capabilities and limitations of various reservoir models. One-dimensional (1-D) models are appropriate for long, narrow, and shallow water bodies where transport along the length of the reservoir dominates lateral and vertical movement. A 1-D model could be used to model the Wachusett during times when it is completely mixed, because it is essentially laterally and vertically homogeneous. Two-dimensional (2-D) models can predict hydrodynamics in a reservoir during periods of stratification better than a 1-D model because they are more applicable to water bodies where longitudinal and vertical variability dominates lateral variability. Three-dimensional (3-D) models are used when 1-D or 2-D models can not accurately simulate waterbodies with strong vertical, lateral, and longitudinal gradients. However, 3-D models are much more computationally demanding than a 1-D or 2-D model.

Models can be used to simulate and predict the fate of contaminants and to evaluate the potential impacts of inputs on water quality. This information is particularly useful for developing responses to potential emergencies, such as contaminant spills into surface water bodies. However, it is also important to note that proper background data and reasonable estimations of parameters are required to produce applicable results for 1-D, 2-D, and 3-D models. Models should be calibrated and verified prior to use in predicting unknown behavior.
2.2 CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional, longitudinal and vertical, hydrodynamic and water quality model. The model is best used for relatively long and narrow water bodies that have longitudinal and vertical water quality gradients because the model assumes that lateral variations in velocities, temperatures, and constituents are negligible. This makes the model applicable to a combination of rivers, lakes, reservoirs, and estuaries (Cole and Wells, 2008). CE-QUAL-W2 directly couples hydrodynamics and water quality algorithms. To model water hydrodynamics and mass transport, CE-QUAL-W2 solves six laterally and layer averaged equations for six unknowns using the finite difference method. The governing equations for the model are for horizontal-momentum, constituent transport, free water surface elevation, hydrostatic pressure, continuity, and density (Cole and Wells, 2008). The six dependent variables are the water surface elevation, pressure, horizontal velocity, vertical velocity, constituent concentrations, and temperature/density. The governing equations are described in detail by Cole and Wells (2008). The original model was developed in 1975 by Edinger and Buchak and was known as LARM (Laterally Averaged Reservoir Model) (Cole and Wells, 2008). The model has been under continuous development since 1975 and the release used for this research is Version 3.6. Documentation on the versions of this model can be found in the CE-QUAL-W2 user manual and on the website (Cole and Wells, 2008).

CE-QUAL-W2 was chosen for this project due to the long and narrow geometry of the Wachusett Reservoir. The reservoir has a length-to-width ratio of about 11, making it appropriate for the application of a laterally averaged model (Ahlfeld et al., 2003). This model was also chosen for its simplicity as a two-dimensional model with a relatively short model run time.

2.3 Other Applications of CE-QUAL

The CE-QUAL-W2 model has a wide range of potential applications for hydrodynamic and water quality modeling. The model has been successfully applied to over 200 different systems within the United States and the world (Cole and Wells, 2008). It is the reservoir model of choice for the Tennessee Valley Authority (TVA), U.S. Bureau of Reclamation (USBR), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), and the U.S. Environmental Protection Agency (USEPA) (Cole and Tillman, 2001). UMass projects and
Master’s theses have used CE-QUAL to model the hydrodynamics and water quality of the Quabbin Reservoir and the Wachusett Reservoir and to examine worst case scenarios of a potential spill using a conservative tracer. Developing these models is useful for understanding contaminant spills in water bodies and important for developing strategies to best manage water quality.

There have been many studies of various contaminant spills into reservoirs using CE-QUAL-W2 as well as other models similar to it. Chung and Gu (1998) used a two-dimensional generalized longitudinal-vertical hydrodynamics and transport model (GLVHT) to simulate contaminated density currents in the stratified Shasta Reservoir after a chemical spill into the Sacramento River. GLVHT was developed from the laterally averaged reservoir model (LARM) which was later used to develop CE-QUAL (Chung and Gu, 1998). Simulations were conducted for varying water temperatures, densities, flow velocities, and concentrations of methyl isothiocyanate (MITC) throughout the reservoir over time. MITC was simulated as a conservative tracer to evaluate the effects of mixing on the material distributions and to predict the transport behavior of the contaminant plume. The simulations and measurements of the contaminant in the reservoir compared well to each other and the study concluded that the seasonal stratification in the reservoir played a large role in the transport of the contaminant.

Gelda et al. (1998) also successfully captured seasonal stratification in the Cannonsville Reservoir in New York using CE-QUAL. The model was calibrated and verified using temperature data collected in the reservoir and the completed model compared well to in reservoir measurements. The model captured the timing and duration of the seasonal stratification as well as the variations of temperatures in the layers of the model. After good agreement between measured and modeled temperatures in the reservoir, the model was used to simulate the longitudinal transport of a conservative tracer (Gelda et al., 1998). Knowledge of the response of this reservoir at the water supply intake to a conservative tracer spill was useful information to water managers when determining the best response plan for emergencies.

The use of CE-QUAL and a Spill Management Information System (SMIS) can help to effectively manage the risks of a potential spill into a water body (Martin et al., 2004). SMIS was developed by Vanderbilt University’s Department of Civil and Environmental Engineering in conjunction with the Nashville District of the U.S. Army Corps of Engineers (USACE). The GIS
based system incorporates CE-QUAL W2 V3.1 as its surface water contaminant transport model and Computer-Aided Management of Emergency Operations (CAMEO), which models atmospheric dispersion. The SMIS application was designed to evaluate the short-term impacts of a chemical spill and to facilitate the development of a comprehensive response plan. This application was tested on the Cheatham Reach, a part of the Cumberland River, where the model simulated a 50,000 L spill of benzene that occurred over 1 hour. The combination of model results from CE-QUAL and CAMEO, and information from GIS layers, provides real-time planning and analysis capabilities for first-responders, facility operators, and emergency response organizations (Martin et al., 2004).

CE-QUAL has also been an important tool in simulating water quality in water bodies. A model was developed for Lake Erie for the year 1994 by Boegman et al. (2001) that accurately reproduced lake-wide hydrodynamics and water quality of the lake for that year. The model was then used in a study done by Boegman et al. (2008) to understand the relative roles of changes in nutrient loading on Lake Erie because the model coupled hydrodynamics and the dynamics of water quality and biota. This information was used to quantify the effects of dreissenid mussels in the western basin of the lake because these animals are influenced by both physical and biological processes in the lake.

Another example of CE-QUAL-W2 applied to a water quality study is the research done by Kuo et al. (2005) modeling eutrophication in the Te-Chi Reservoir and the Tseng-Wen Reservoir, both located in Taiwan. The model was used to simulate temperature distributions and concentrations of nutrients, dissolved oxygen, and algal biomass. Water temperature data were used to evaluate the hydrodynamic results from a one-year model run and the simulation closely matched the measured values in the reservoirs throughout the year. A number of phosphorous reduction scenarios were tested using the model to develop best management practices. It was found that a 30-55% reduction in the phosphorous load would improve the water quality in the reservoir from a eutrophic state to an oligotrophic state (Kuo et al., 2005). This study demonstrates another application of the model that can provide valuable information for managing a water system.
2.4 Past Work for Wachusett Reservoir

The CE-QUAL-W2 model of the Wachusett Reservoir was originally developed and calibrated by Camp, Dresser, and McKee Inc. and FTN Associates, LTD. for the years 1987, 1990, and 1992 (CDM, 1995). Work on the model was then done at UMass, where Alejandro Joaquin (2001) developed a water budget on a daily time scale and developed new models for the calendar years 1998 and 1999 to model the effects of the Quabbin transfer on Wachusett Reservoir water composition (Tobiason et al., 2002). Buttrick (2005) developed the model for the calendar years 2001 and 2002. The program code was modified to include light induced decay of UV254 absorbance so that natural organic matter in the reservoir could be modeled. Matthews (2007) calibrated the model for the calendar years 2003 and 2004 and modeled fecal coliform contamination due to a sewage pump station overflow. The code was also modified to include light induced coliform decay. Model years 2003 and 2004 were used by Stauber (2009) to examine the behavior of a spill of ammonium nitrate and fuel oil number 1 under different wind conditions, spill temperatures, and Quabbin transfer scenarios. Stauber also modified the source code to include volatilization to better simulate benzene. In 2011, Sojkowski developed models for the calendar years 2005 and 2006 using the latest and current version of the model (Sojkowski, 2011). Devonis (2011) developed the model for the calendar years 2007 and 2008 to investigate the effects of season, the Quabbin transfer, and wind on conservative spill behavior in the reservoir.
3 CE-QUAL MODEL DEVELOPMENT

The use of CE-QUAL-W2 requires inputs for the reservoir bathymetry, initial flow and constituent conditions, inflow quantity and quality, outflow quantity, and descriptions of the outlets. The model also requires time series of inflow rates and water quality, meteorological data, an initial water surface elevation, and values for various kinetic parameters when appropriate. Field measurements are used to calibrate modeled water surface elevation, water quality, and temperature by comparisons to model predictions for these parameters.

3.1 CE-QUAL-W2 Grid and Segments

The modeling grid for the Wachusett Reservoir was originally developed by Camp, Dresser, and McKee (CDM) (1995) and calibrated for the years 1987, 1990, and 1992. The model was later updated by Joaquin (2001) to better capture some of the reservoir’s key features. In the current grid, the reservoir is divided into 63 laterally averaged segments, as seen in Figure 3.1. Each segment consists of up to 47 layers as seen in Figure 3.2. The main body of the reservoir, Branch 1, is made up of Segments 2 through 46. Branch 2 represents the South Bay and consists of Segments 49-51. Branches 3-5 represent the wider portions of the reservoir or coves. The top surface layer through layer 31 are 0.5 meters thick, layers 32 and 33 are 0.75 meters thick, and the bottom layers 34 through 47 are 1.5 meters thick.

The Route 140 Bridge, under which the Sillwater River flows, is represented by Segment 7. The Route 12 Bridge is represented by Segment 15 and it separates the Thomas Basin (Segments 2-14) from the main basin. Segment 39 is smaller than the surrounding segments and represents the Narrows, which separates the South Basin from the North Basin. A cofferdam was constructed to keep water out of the construction area during the installation of the Cosgrove Intake. The remains of the cofferdam are represented by Segment 45. Segment 46 represents the Cosgrove Intake, where CE-QUAL withdraws water using a selective withdrawal algorithm which calculates the layers water is taken from based on total outflow, structure type and elevation, and computed upstream gradients (Cole and Wells, 2008). The actual Cosgrove has two 4 ft by 6 ft intakes with centerline elevations of 343 ft (104.3 m) and 363 ft (110.6 m) (CDM, 1995). The shallower intake is typically used and is included in the model. The Cosgrove Intake is modeled as two selective line sinks at an elevation of 104.3, within layer 33. Layer 35 is the bottom layer
below which selective withdrawal cannot occur. The configuration of the two segments simulates how warmer water from the upper layers is often withdrawn through the Cosgrove Intake.

Other minor withdrawals can include withdrawals for the towns of Clinton, Leominster, and Worcester, seepage from the North Dike, spills and releases to the Nashua River, and the Wachusett Aqueduct. These withdrawals are defined in the model at a specific segment and elevation, as noted in Table 3.1. The elevation of the lower spillway to the Nashua River is at 119.6 m and the upper spillway is at an elevation of 120.4m. The lower elevation spillway is typically used in the actual reservoir and therefore the elevation used for the CE-QUAL modeled spillway withdrawal. Approximately 1.8 MGD of water is released daily to the Nashua River from below the Wachusett Dam, in addition to water that is sometimes released to maintain the water surface elevation and water quality in the reservoir. The North Dike seepage and the town withdrawals occur in the same layer and segment and are combined to be one withdrawal in the model.

<table>
<thead>
<tr>
<th>Withdrawal</th>
<th>Layer</th>
<th>Elevation (m)</th>
<th>Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dike / Town Withdrawals</td>
<td>11</td>
<td>115.95</td>
<td>44</td>
</tr>
<tr>
<td>Nashua Spillway</td>
<td>4</td>
<td>119.63</td>
<td>44</td>
</tr>
<tr>
<td>Nashua River Release</td>
<td>35</td>
<td>101.35</td>
<td>44</td>
</tr>
<tr>
<td>Wachusett Aqueduct</td>
<td>35</td>
<td>101.35</td>
<td>44</td>
</tr>
</tbody>
</table>
Figure 3.1 CE-QUAL-W2 Segments (Top View)

Figure 3.2 CE-QUAL-W2 Layers (Side View)
Tributaries that contribute more than 1% of the annual water budget are modeled as a flow into a specific segment at its physical location on the reservoir. The Quabbin Aqueduct is also modeled as a tributary. All tributaries, excluding the Stillwater River and including the Quabbin Aqueduct, enter the reservoir at a depth that corresponds to an equivalent water density, based on water temperature. The Stillwater River is an exception because it enters the reservoir at the first segment and is therefore represented as a branch inflow. Tributaries that contribute less than 1% to the inflow are modeled as direct runoff, or a distributed tributary in CE-QUAL. Flow is distributed to each segment of Branch 1 proportional to the segment surface area to represent this non-point source (Cole and Wells, 2008).

3.2 Data Collection and Preparation

Hydrodynamic and water quality data are needed to develop and calibrate the CE-QUAL model in order to generate a valid output. Model development first requires meteorological and water balance data. This information is used to generate the input files read by the model’s algorithm. For each of the inflows, the model requires a specified flow, temperature, and a constituent file if the water quality parameters are active. Data are supplied to the model at varying time steps and the program makes calculations at constant time intervals. If input data are not supplied at an interval, then the model interpolates between available data at specified intervals. Outlet flows must also be specified. Temperature and water quality data, such as specific conductivity, are used to calibrate the model to measured field data by adjusting parameters within the model. Water quality samples are routinely collected from stations on tributary streams and from boats in the reservoir. The MWRA also regularly records water quality at the Cosgrove Intake throughout the year.

3.2.1 Meteorological Data

Hourly meteorological data such as air temperature, dew point temperature, wind speed, wind direction, and cloud cover were acquired from the National Oceanic and Atmospheric Administration (NOAA) website. This website provides public access to meteorological data from around the world. The closest weather station to the Wachusett Reservoir is located at the Worcester Airport, about 10 miles southwest of the reservoir. It is assumed that the weather conditions at this station are approximately what occur at the reservoir. There is a weather station
operated by the MWRA next to the Cosgrove building. However, data have not yet been used for model development because of the stations susceptibility to local wind currents, making wind speed and direction data unreliable. Future data from this site may be more useful.

3.2.2 Water Balance

A water balance Excel spreadsheet model was developed by Kennedy (2003) to calculate changes in water surface elevation based on daily inflows and outflows for the Wachusett Reservoir in order to calibrate the water budget to the measured water surface elevation prior to use of the data in the CE-QUAL model. This tool is used in developing the flows for the inputs to the CE-QUAL model and minimizes the error between measured and calculated water surface elevations using the SOLVER function in Microsoft Excel. Daily mean discharge data from the Stillwater and Quinapoxet Rivers are measured by United States Geological Survey (USGS) gages. The other tributaries surrounding the reservoir are not gaged and their flows are calculated based on a runoff coefficient and tributary area (Equation 1).

\[
\text{Tributary Discharge} \left( \frac{m^3}{s} \right) = \left( \frac{\text{Stillwater Discharge} (m^3)}{\text{Stillwater Watershed Area} (m^2)} \right) \times \text{Tributary Area} (m^2) \quad \text{(Equation 1)}
\]

Direct runoff is calculated based on the ratio of Stillwater daily discharge to Stillwater watershed area multiplied by the entire direct runoff area. The inflows to the reservoir from Quabbin Aqueduct are measured daily by the MWRA. Precipitation is measured hourly at the Worcester Airport station and acquired from NOAA online.

All outflows including the Cosgrove Aqueduct, the Wachusett Aqueduct, and the Nashua River releases are also recorded daily by the MWRA. Withdrawals by the towns of Clinton, Leominster, and Worcester are recorded daily by the DCR. Evaporation is the only outflow that is not directly measured by the MWRA. This is calculated within the water balance spreadsheet to determine an approximate total outflow. Water balance evaporation calculations are based on calculations done internally by CE-QUAL. Evaporation for the Wachusett was estimated based on work by Edinger et al (1974) and was later discussed in Garvey’s work on the Quabbin Reservoir (Garvey, 2000). The rate of evaporative water loss, \( Q_e \) (m/s), from a body of water can be summarized by Equation 2.
\[ Q_e = \beta(T_s - T_d)f(W)/\rho \Delta e \]  

(Equation 2)

where \(T_s\) is the water surface temperature (°C), \(T_d\) is the dew point temperature (°C), \(\rho\) is the density of water (1000 kg/m³), \(\Delta e\) is the latent heat of evaporation (J/g at 20°C), and \(\beta\) is the slope (mm Hg/°C) of a chord on the saturated vapor pressure-temperature curve between the dew point temperature and the water surface temperature (Garvey, 2000). This slope can be expressed with Equation 3. The empirical wind speed function, \(f(W)\) (W/m² mm Hg), is defined in Equation 4, where \(W\) is wind speed measured at 2 m above the ground in m/s.

\[ \beta = 0.35 + 0.015\frac{T_s + T_d}{2} + 0.0012\left(\frac{T_s + T_d}{2}\right)^2 \]  

(Equation 3)

\[ f(W) = 9.2 + 0.46W^2 \]  

(Equation 4)

The daily water surface elevation in the reservoir is calculated in the water balance spreadsheet based on the daily inflows and outflows to and from the reservoir. The total outflow volume is subtracted from the inflow volume for a particular day, and then this is added to the total storage volume of the previous day. The computed storage volume can then be converted to a water surface elevation, using a stage to volume relationship measured by the DCR. Figure 3.3 shows the relationship between the reservoir volume and the water surface elevation that is used in the water balance model.

![Figure 3.3](image-url)  

**Figure 3.3** Relationship Between Volume and Water Surface Elevation for Wachusett Reservoir
Figure 3.4 shows the difference between the measured water surface elevation and the uncalibrated calculated water surface elevation from the water balance spreadsheet for the calendar year 2009. The values do not match exactly due to discrepancies and uncertainties in measured and calculated inflows and outflows. This is corrected in the calibration of the water balance, discussed in a later section of this report.

![Figure 3.4  Measured and Uncalibrated Calculated Water Surface Elevation for 2009](image)

### 3.2.3 Specific Conductivity

Specific conductivity (electrical conductivity normalized to 25°C) is a measurement of the ability of water to conduct electricity. Specific conductivity measurements are taken on a weekly basis by the DCR at French, Malagasco, Muddy, Malden, Waushacum, Gates, and West Boylston Brooks, as well as the Stillwater and Quinapoxet Rivers. Precipitation specific conductivity data are collected by two National Atmospheric Deposition Program (NADP) stations in Massachusetts. The precipitation data used for the CE-QUAL model are weekly averages of the data from the station located on the Prescott Peninsula of the Quabbin Reservoir and the station in Lexington, MA. CE-QUAL does not model specific conductivity as a constituent, but it does model total dissolved solids (TDS). The two water quality parameters are closely related based on the assumption that TDS in water consists mainly of inorganic ions that conduct electricity. Specific conductivity is relatively easier and less costly to directly measure than TDS and is
often converted to TDS based on a site specific relationship. For modeling purposes, it is assumed that there is a constant relative ionic composition in the reservoir. Therefore, Equation 5 can be used to convert measured specific conductivity in the Wachusett Reservoir to TDS for model inputs and to compare model results for TDS to profile measurements of specific conductivity taken by the DCR staff. This equation was used in the CDM model (1995) and was later confirmed by Tobiason et al. (2002) for Wachusett using data from Malagasco Brook. TDS in CE-QUAL is modeled as a conservative constituent.

\[
TDS \left( \frac{mg}{L} \right) = 0.6 \times \text{Specific Conductivity} \left( \frac{\mu S}{cm} \right) \quad \text{(Equation 5)}
\]

### 3.3 Calibration

Hydrodynamic and water quality calibrations were completed for the calendar years 2003 through 2009. Each year is calibrated separately because each year has unique hydrologic conditions. Discussions of calibrations in this section include the results from the 2009 calibration and a summary of the years 2003 through 2009. The hydrodynamics are calibrated first using the data and measurements of water surface elevations. Temperature calibration verifies that the total heat budget is correct and that the meteorological input data are adequate. The specific conductivity calibration verifies that the movements of the non-reactive constituents are accurate in the reservoir. Measurements of temperature and specific conductivity are then compared to simulated values. A sensitivity analysis is conducted to identify the effects of changes in parameter values on model outputs.

#### 3.3.1 Water Balance Calibration

Beginning with measured inflows and outflows, the discrepancies between the calculated and the measured water surface elevations are minimized with the use of the SOLVER algorithm package in Microsoft Excel. The differences in the calculated and measured values are minimized by multiplying each tributary inflow, the Quabbin transfer, direct runoff, and the Nashua River by a calibration factor, which is determined separately for each calendar year. The algorithm minimizes the sum of square residuals between the calculated and measured water surface elevation (Equation 6).
The sum of square residuals is used to calculate a root mean square error for each year (Equation 7). A comparison of root mean square errors (RMS) between measured and calculated elevations from 1994-2009 is presented in Table 3.2. The RMS values range from 0.06 to 0.23, and 2009 had an RMS value of 0.06.

\[
RMS = \sqrt{\frac{SSR}{Days \ in \ the \ Year}} \tag{Equation 7}
\]

Table 3.2 Root Mean Square Error for Years 1994-2009

<table>
<thead>
<tr>
<th>Year</th>
<th>RMS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>0.07</td>
</tr>
<tr>
<td>1995</td>
<td>0.17</td>
</tr>
<tr>
<td>1996</td>
<td>0.23</td>
</tr>
<tr>
<td>1997</td>
<td>0.11</td>
</tr>
<tr>
<td>1998</td>
<td>0.10</td>
</tr>
<tr>
<td>1999</td>
<td>0.06</td>
</tr>
<tr>
<td>2000</td>
<td>0.08</td>
</tr>
<tr>
<td>2001</td>
<td>0.07</td>
</tr>
<tr>
<td>2002</td>
<td>0.07</td>
</tr>
<tr>
<td>2003</td>
<td>0.06</td>
</tr>
<tr>
<td>2004</td>
<td>0.11</td>
</tr>
<tr>
<td>2005</td>
<td>0.07</td>
</tr>
<tr>
<td>2006</td>
<td>0.17</td>
</tr>
<tr>
<td>2007</td>
<td>0.07</td>
</tr>
<tr>
<td>2008</td>
<td>0.15</td>
</tr>
<tr>
<td>2009</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Using the SOLVER function in Excel, the calibration factors are allowed to vary within certain constraints. They are typically not varied by more than 30% (0.7-1.30). Table 3.3 compares the historical calibration factors used for the various inflows to the reservoir as well as the values for the 2009 calibration. The calibration factors for 2009 are all within the historical range of the values and close to 1.00, which means that little adjustment was needed to provide an accurate water balance for the year. For example, if a calibration factor is equal to 1.10, it means that 10% additional flow is needed for that inflow. Once the calibration factors are determined, the calibrated inflow and outflow data are used to create the input files for the CE-QUAL model.
Table 3.3 Comparison of Range of Historical Average Calibration Factors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quabbin</td>
<td>1.02</td>
<td>0.93-1.16</td>
<td>0.97</td>
</tr>
<tr>
<td>Stillwater</td>
<td>1.01</td>
<td>0.70-1.28</td>
<td>1.06</td>
</tr>
<tr>
<td>Quinapoxet</td>
<td>1.08</td>
<td>0.82-1.30</td>
<td>1.08</td>
</tr>
<tr>
<td>Waushacum</td>
<td>1.10</td>
<td>0.78-1.65</td>
<td>1.07</td>
</tr>
<tr>
<td>Nashua River</td>
<td>0.96</td>
<td>0.76-1.06</td>
<td>0.92</td>
</tr>
<tr>
<td>Direct Runoff</td>
<td>1.10</td>
<td>0.78-1.62</td>
<td>1.07</td>
</tr>
<tr>
<td>Malden</td>
<td>1.06</td>
<td>0.78-1.35</td>
<td>1.07</td>
</tr>
<tr>
<td>West Boylston</td>
<td>1.08</td>
<td>0.78-1.35</td>
<td>1.07</td>
</tr>
<tr>
<td>Gates</td>
<td>1.13</td>
<td>0.78-2.00</td>
<td>1.07</td>
</tr>
<tr>
<td>Muddy</td>
<td>1.06</td>
<td>0.78-1.35</td>
<td>1.07</td>
</tr>
<tr>
<td>Malagasco</td>
<td>1.06</td>
<td>0.78-1.35</td>
<td>1.07</td>
</tr>
<tr>
<td>French</td>
<td>1.06</td>
<td>0.78-1.35</td>
<td>1.07</td>
</tr>
</tbody>
</table>

After the water balance calibration, the calculated water surface elevation is more similar to the measured one, as seen in Figure 3.5. The maximum difference between the measured and the calculated water surface elevation after calibration for 2009 was 0.14 meters, which meets the goal for the differences to be less than 0.15 meters (0.5 feet).

![Figure 3.5 Measured and Calculated Water Surface Elevations for Wachusett 2009](image-url)
At the same time as the inflow data are adjusted with the calibration factors, a corresponding runoff coefficient for each tributary watershed is determined. These coefficients are constrained between 0.3 and 0.75. The dimensionless runoff coefficient for each tributary during a specific year is calculated using Equation 8.

\[
\text{Runoff Coefficient} = \frac{\sum \text{Tributary Inflows} \ell/\text{Tr}}{\sum \text{Direct Precipitation} \ell/\text{Ta} \times \text{Triburary Area} (m^2)} \quad (\text{Equation 8})
\]

3.3.2 Temperature Initial Conditions

Once there is good agreement between the measured and calculated water surface elevations in the water balance spreadsheet, the input files are created and the model is run to determine the best initial conditions for temperature and specific conductivity. A uniform temperature and specific conductivity are applied to the reservoir on January 1 (Julian Day 1) because the reservoir is assumed to be completely mixed at this point in the year. Temperature measurements are taken at the Cosgrove Intake by the MWRA every fifteen minutes and are available online. The temperature on January 1, 2009 was 2.4°C.

A sensitivity analysis was conducted by varying the initial reservoir temperature from 0°C to 7°C, a range which includes the actual temperature measurement at the Cosgrove intake on January 1. Figure 3.6 shows the effects of varying the initial temperature on the temperature profile for 4/7/2009. In this profile from the North Basin of the reservoir (Segment 42) there is less than a 1°C difference between the profiles for each initial temperature and the profile is uniform, implying a completely mixed reservoir. The measured data show a constant temperature of about 5.2 °C, similar to the model output.
The results for the North Basin surface temperature for two initial temperatures, 2.4°C and 5°C, are shown in Figure 3.7. The different initial temperature conditions produced slightly different surface water temperatures during the beginning of the year (days 1-30), but after that, the differences were negligible. This demonstrates that after the initial days of the model run, the more important factors that impact water temperature are wind, air temperature, and circulation throughout the reservoir. Therefore, 2.4°C was determined to be the best initial temperature for the reservoir since this was the actual temperature on January 1st of this year and there was little difference in simulated temperature profiles throughout the year with different initial temperatures.
Figure 3.7 Effect of Increase in Initial Temperature on Modeled North Basin Surface Temperature 2009

It can also be seen from Figure 3.7 that there are several days in the winter months when the temperature in the North Basin appears to be below 0°C. The negative values reflect times during the simulated year where ice formed in CE-QUAL. The model can calculate the onset, growth, and breakup of ice cover. When the surface water temperature becomes lower than the freezing point, the negative temperature is converted to an equivalent ice thickness and equivalent heat is added to the heat source and sink term for the water. Once there is a net gain of heat to the surface and the surface temperature becomes greater than the freezing temperature, the ice begins to melt. Ice cover, growth, and breakup depend on locations and temperatures of inflows and outflows, evaporative wind variations over the ice surface, as well as turbulence and water movement beneath the ice. Reservoir branches are more susceptible to ice formation than the main body. Ice growth or melt at the ice-water interface can be described by the following equation (Cole and Wells, 2008).

\[
\Delta \theta_{iw}^n = \frac{1}{\rho_i L_f} \left[ K_i \frac{T_f - T_s^n}{\theta_{n-1}} - h_{wi}(T_w^n - T_f) \right] 
\]

(Equation 9)

Where \( \theta_{iw} \) is ice growth/melt at the ice-water interface (m), \( \rho_i \) is density of ice (kg m\(^{-3}\)), \( L_f \) is latent heat of fusion (J kg\(^{-1}\)), \( K_i \) is thermal conductivity of ice (W m\(^{-1}\) °C\(^{-1}\)), \( T_f \) is freezing point temperature (°C), \( \theta \) is the ice thickness (m), \( T_s \) is ice surface temperature (°C), \( h_{wi} \) is coefficient
of water-to-ice heat exchange through the melt layer (W m$^{-2}$ °C), and $T_w$ is water temperature below the ice (°C).

3.3.3 Specific Conductivity Initial Conditions

A spatially uniform initial specific conductivity is assumed for the first day of the model run because the reservoir is essentially completely mixed on January 1. Also, there are no data available on which to base a non-uniform distribution assumption. Specific conductivity is used because it is measured frequently in the reservoir throughout the year and it is a relatively conservative water quality parameter. The average specific conductivity at the Cosgrove Intake on January 1, 2009 was about 116.6 µS/cm, which corresponds to a total dissolved solids value of 70 mg/L. A sensitivity analysis was conducted for a range of initial specific conductivity values from 75 µS/cm to 166.7 µS/cm. The results were compared to profile measurements taken in the North Basin of the reservoir. Figure 3.8 and Figure 3.9 show the results of the sensitivity analysis for April 4 and August 14 during the year 2009. From these results it was determined that the best initial condition that would most closely simulate the measured profiles was not the actual measured value of 116.6 µS/cm, but 91.7 µS/cm. This value produced model profiles that more closely matched measured profiles in the beginning and throughout the year 2009.

![Figure 3.8 Varying Initial Specific Conductivity (4/7/2009)](image)
The reason for why the initial lower specific conductivity value resulted in a better calibration to the measured profile data in the North Basin is unclear. An investigation into this issue led to a comparison of specific conductivity profile measurements to measurements taken every 15 minutes at the Cosgrove Intake and model results from the Cosgrove Intake withdrawal. Figure 3.10 shows the actual 15 minute measurements of specific conductivity at the Cosgrove Intake plotted alongside two sets of model results for the Cosgrove Intake (Segment 46). One model run has initial conditions equal to the actual Cosgrove measurement on January 1, 2009 (117 µS/cm) and the other model run has initial conditions based on the best fit to the profiles measured in the North Basin (91.7 µS/cm). The figure also includes results for two profile measurements from the North Basin when the reservoir was completely mixed, and therefore the specific conductivity was uniform along the vertical profile.
Figure 3.10 Comparing Specific Conductivity Measurements with Model Results for 2009

Figure 3.10, shows that when the model is calibrated to the initial condition of the actual measurement on January 1 at the Cosgrove, the modeled specific conductivity results at the Cosgrove are similar to the MWRA measured values. However, when the model is calibrated to best fit the profiles measured in the North Basin throughout the year, the model simulation for the Cosgrove does not compare well to the Cosgrove measurements. The discrepancies between measurements at the Cosgrove Intake and the completely mixed profile data are evident throughout the years 2004 to 2009. It was speculated by Matthews (2007) that the 2004 conductivity measurements from the Cosgrove did not take temperature into consideration and that this caused these measurements that year to be approximately 20 µS/cm too high. Another possibility for this discrepancy in measurements may be due to differences in calibration of the two instruments. Regardless of this difference, the initial value of 91.7 µS.cm was chosen for an initial specific conductivity because of its good fit to the profile measurements in the North Basin throughout the year. This was done so the results are comparable to the previous model year results, which used good profile data comparisons as a basis for a calibrated model. It should be noted that this calibration is for water quality data only and does not affect the calibration of the hydrodynamics of the reservoir.
### 3.3.4 Bottom Heat Exchange

The bottom heat exchange coefficient can be varied during calibration. The coefficient of bottom heat exchange (CBHE) is used to compute the heat at the ground-water interface. The default value for this coefficient in CE-QUAL is 0.3 W/m²-sec. A higher value for the CBHE increases the temperature of the bottom of the reservoir while a lower value decreases the temperature. Since the coefficient cannot be zero, the parameter was varied from $7 \times 10^{-7}$ W/m²-sec to a max value of 2.0 W/m²-sec. Figure 3.11 shows the impacts of varying the CBHE at the bottom of the temperature profile in the North Basin. The difference in values for the CBHE results in a temperature difference of about 2.5 °C at the bottom of the temperature profile. A value of 1.0 for the CBHE was determined the best overall fit for the entire year 2009. Model years 2007 and 2008 also used a value of 1.0 while prior to these years a value of $7 \times 10^{-7}$ was used to calibrate the model.

![Figure 3.11 Varying CBHE (8/27/2009)](image-url)
3.3.5 Water-Ice Heat Exchange

The coefficient of water-ice heat exchange (HWICE in the model code or $h_{wi}$ in Equation 9) is a parameter that specifies the rate of heat exchange between the water and ice on the reservoir. Therefore, this parameter has the most effect on the heat exchange during the colder months of the simulation. The coefficient is also dependent on turbulence and water movement under the ice. The default value for this parameter in CE-QUAL is 10.0 but a value of 1.0 had been historically used for Wachusett simulations. For this sensitivity analysis, values of 1.0, 5.0, and 10.0 were investigated. Figure 3.12 and Figure 3.13 illustrate the impact of changing this coefficient during a winter months when there is ice on the reservoir and two months later when there is no ice. Decreasing the coefficient decreases the rate of heat exchange between the water and ice, which results in a greater ice thickness. Increasing this coefficient increases the rate of heat exchange between the water and the ice and results in less ice formation. In the 2009 model, a HWICE value of 1.0 resulted in a maximum ice thickness of 0.43 meters in the North Basin while a coefficient of 10.0 resulted in a maximum thickness of 0.39 meters. The slightly warmer water temperatures produced when there is more ice in the North Basin is likely due to the ice insulating the water and preventing exposure to the cold air at the surface. Ice formation and melting occurred for approximately the same number of days in both scenarios investigated. A value of 10.0 was chosen because the model results more closely matched the measured temperature profiles in the North Basin during the colder months, compared to the value of 1.0 used in previous model years.
According to MWRA records, “ice-over” of the reservoir in 2009 was documented on the 14th of January. It was also noted that the southern part of the reservoir was completely covered in ice. The northern part of the reservoir had substantial ice cover, but holes remained all season.
The bird harassment program on the reservoir by boat ceased on January 14\textsuperscript{th} due to ice buildup. The thaw in 2009 was recorded as March 16\textsuperscript{th}. Results from the CE-QUAL model calculated that the ice formation in the North Basin began on January 7\textsuperscript{th} and was completely melted on March 9\textsuperscript{th}.

3.4 Calibrated Model

The final values for parameters determined during calibration for all model years are presented in Table 3.4. The initial temperature and initial specific conductivity in the reservoir at the beginning of the year can vary from year to year depending on the conditions in the reservoir. An initial specific conductivity value is also selected to produce the best fit to the measured data for the whole year. The CBHE, HWICE, and the wind sheltering coefficient (WSC) all reflect physical parameters of the reservoir and in theory should not vary much from year to year. The WSC is reflective of the landscape surrounding the reservoir and can vary from 0.0 to 1.0, where 0.0 represents mountains or structures that provide full shelter from the wind and a value of 1.0 is an open plain. Since all of the landscape around the reservoir is similar, there is only one value for the whole water body.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2I</td>
<td>Initial Temperature ($^\circ$C)</td>
<td>1.5</td>
<td>5.0</td>
<td>2.87</td>
<td>2.9</td>
<td>7.0</td>
<td>4.0</td>
<td>2.4</td>
</tr>
<tr>
<td>C2IWB-TDS</td>
<td>Initial Total Dissolved Solids (mg/L)</td>
<td>52.5</td>
<td>66</td>
<td>112</td>
<td>75.16</td>
<td>45</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>CBHE</td>
<td>Bottom Heat Exchange</td>
<td>7x10\textsuperscript{-7}</td>
<td>7x10\textsuperscript{-7}</td>
<td>7x10\textsuperscript{-7}</td>
<td>7x10\textsuperscript{-7}</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>HWICE</td>
<td>Water-Ice Heat Exchange</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>WSC</td>
<td>Wind Sheltering Coefficient</td>
<td>0.625</td>
<td>0.625</td>
<td>0.559</td>
<td>0.626</td>
<td>0.626</td>
<td>0.626</td>
<td>0.626</td>
</tr>
</tbody>
</table>

3.4.1 Temperature Profiles

Figure 3.14 shows model results for the temperature profiles in the North Basin (Segment 42) compared to measurements in the North Basin taken by the DCR staff. The model captures the seasonal changes in the water temperature and the stratification in the reservoir well. The
difference between measured and simulated temperatures is generally below 4°C. The model has
a slight tendency to under predict epilimnion and hypolimnion temperatures, but over predict the
temperatures in the thermocline during stratification. The depth of the thermocline however is
accurately simulated when it is present. Similar model results can be observed for other model
years, as noted by Buttrick (2005), Matthews (2007), Sojkowski (2011), and Devonis (2011).
Figure 3.14 2009 Temperature Profiles in Segment 42 (North Basin)
3.4.2 Specific Conductivity Profiles

Figure 3.15 presents the modeled and measured conductivity data for the North Basin of the reservoir for 2009. The model accurately simulates the specific conductivity in the epilimnion and hypolimnion throughout most of the year. There is a slight tendency for the model to over predict the conductivity in the thermocline. However, model results are generally within 20 µS/cm of the measured values. The model also simulates the depth and extent of the Quabbin interflow comparable to the measured values. The Quabbin is identified by its lower conductivity and medium temperature water as it travels through the reservoir, usually during the summer months.
Figure 3.15 2009 Specific Conductivity Profiles in Segment 42 (North Basin)
3.5 Spill Modeling

The calibrated CE-QUAL models, verified by the temperature and specific conductivity profiles previously described are used to simulate potential contaminant spills into the Wachusett Reservoir. Spills are modeled as a conservative substance to study the effects of seasonal change, various spill densities (temperatures), and turning the Quabbin transfer on and off. A conservative tracer spilled into the reservoir represents a worst case scenario, because the spill does not decay or volatilize. A conservative spill can be removed from the reservoir by natural hydrodynamic processes or by emergency response actions.

For this study, the spill is modeled by adding a tributary with a relatively insignificant flow of 0.02 m$^3$/s with a conservative tracer concentration of $1 \times 10^8$ mg/L that enters the reservoir at Segment 7, which is the location of the Route 140 Bridge as shown in Figure 3.16. The site for modeling the spills was chosen because the vehicle traffic on the bridge makes this area of the reservoir especially susceptible to a tanker truck accident and a chemical spill. For modeling purposes, the spills occurred at noon on the day of the spill and are allowed to enter the reservoir for 12 hours. The combination of the spill flow, tracer concentration, and spill duration results in a known mass input of conservative contaminant to the reservoir.

![Figure 3.16 Spill Location on the Reservoir at Rt. 140 Bridge](image)

Spill densities are modeled by different temperature contaminants. A warmer spill is less dense and will travel along the top of the water column. A cold spill, in contrast, will sink in the
reservoir and travel along the bottom. A medium spill is approximately the temperature of the thermocline and will therefore travel throughout the middle of the reservoir. Temperatures of the surface, middle, and bottom layers determined from modeled temperature profiles reflect the warm, medium, and cold temperature spills for the spill date selected in a specific year.

Contaminant spills into the reservoir have been modeled for the years 2003 to 2009. Three dates are chosen for each year, one each in the spring, summer, and fall, to represent the different seasonal conditions in the reservoir and the seasonal effects of a potential spill on contaminant concentration at the Cosgrove Intake. The dates chosen for spills vary from year to year and are based on three to four consecutive days with similar wind direction and magnitude in each season. Table 3.5 shows the spill dates selected for each season from 2003 to 2009.

<table>
<thead>
<tr>
<th>Year</th>
<th>Spring Spill Date</th>
<th>Summer Spill Date</th>
<th>Fall Spill Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>4/27/03 (JDay 117)</td>
<td>9/25/03 (JDay 237)</td>
<td>11/7/03 (JDay 311)</td>
</tr>
<tr>
<td>2004</td>
<td>4/29/04 (JDay 120)</td>
<td>9/17/04 (JDay 230)</td>
<td>11/14/04 (JDay 319)</td>
</tr>
<tr>
<td>2005</td>
<td>4/24/05 (JDay 114)</td>
<td>9/21/05 (JDay 233)</td>
<td>11/19/05 (JDay 323)</td>
</tr>
<tr>
<td>2006</td>
<td>4/25/06 (JDay 115)</td>
<td>9/10/06 (JDay 222)</td>
<td>11/14/06 (JDay 318)</td>
</tr>
<tr>
<td>2007</td>
<td>4/29/07 (JDay 119)</td>
<td>9/10/07 (JDay 222)</td>
<td>11/14/07 (JDay 318)</td>
</tr>
<tr>
<td>2008</td>
<td>5/1/08 (JDay 122)</td>
<td>9/14/08 (JDay 227)</td>
<td>11/9/08 (JDay 314)</td>
</tr>
<tr>
<td>2009</td>
<td>4/7/09 (JDay 97)</td>
<td>8/29/09 (JDay 210)</td>
<td>11/8/09 (JDay 312)</td>
</tr>
</tbody>
</table>

One method of analyzing the effects of different temperature spills, seasons, and the Quabbin transfer is by analyzing the simulated concentration of the contaminant at the Cosgrove Intake. Concentrations are expressed as a relative, or normalized, concentration as developed by Stauber (2009). The relative concentration is calculated by dividing the simulated concentration by the completely mixed concentration (368 g/m³). The completely mixed value is determined by the total mass (8.64x10¹⁰ g) of the spill divided by the full volume of the reservoir (62 billion gallons or 2.35x10⁸ m³). A relative concentration of 1.0 represents the concentration that would occur if the contaminant were to be instantly and completely mixed throughout the reservoir. The approximate spill arrival time, maximum relative concentration, and behavior can be observed and compared for various analyzed scenarios. Prior work has shown that the absolute amount of the conservative contaminant spill has no effect on the modeled relative concentrations in the reservoir.
4 RESULTS

The results of the CE-QUAL-W2 simulations for the years 2003 to 2009 using CE-QUAL-W2 V.3.6 are presented in the following section. Scenarios investigated include seasonal and Quabbin transfer impacts on spill arrival time, magnitude, and behavior at the Cosgrove Intake. This section also includes the results of the development of a combined two year model for the years 2008 and 2009. The potential residence times of a spilled conservative contaminant and decaying contaminant are demonstrated with the ability of this two year model to produce a longer model run. Additionally, there is a discussion of the application of the two year model to the development of GEMSS, a 3D hydrodynamic and water quality model of the Wachusett Reservoir.

4.1 Seasonal Influences (2003-2009)

Seasonal variations in reservoir temperatures and hydrology have an impact on spilled contaminant behavior in the reservoir and the relative concentrations at the Cosgrove Intake. Figure 4.1 shows the relative contaminant concentrations at the Cosgrove Intake for spring, summer, and fall cold temperature spills in 2009. The results represent typical model simulations for spring, summer, and fall spills throughout all years. Spills that occur in the spring and the fall exhibit similar behaviors and relative concentrations because the reservoir is approximately completely mixed with no stratification. For spills that occur in the summer months, contaminants reach a higher maximum relative concentration at the Cosgrove Intake and exhibit much more variable concentrations due to the stratification in the reservoir at this time of year. Instead of mixing throughout the entire reservoir, the high contaminant concentration becomes trapped within a layer of stratification, resulting in less vertical mixing and higher concentrations arriving at the intake.
Table 4.1 summarizes the average number of days it takes for a spilled contaminant to arrive at the Cosgrove Intake, as well as the average maximum relative concentration at the intake for all years modeled. Arrival time is defined as the number of days after the spill for the relative contaminant concentration to be 0.1 at the Cosgrove Intake. In general, spring spills arrive at the Cosgrove in the least amount of time, from 2 to 7 days, for all spill temperatures. Fall spills have the second shortest arrival time with a range of arrival times from 4 to 11 days. Summer spills have the longest arrival time of approximately 5 to 15 days. Spring and fall spills result in similar average relative concentrations at the Cosgrove Intake, while summer spills on average result in a relative concentration about twice as large. It is important to note that the average residence time, or the average amount of time that a fluid packet remains in the reservoir, is approximately 206 days, calculated from the full reservoir volume divided by the average throughput flow.

Table 4.1  Average Arrival Times and Relative Concentrations at Cosgrove 2003-2009

<table>
<thead>
<tr>
<th>Season</th>
<th>Average Arrival Time (days)</th>
<th>Average Maximum C/Co at Cosgrove</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warm</td>
<td>Medium</td>
</tr>
<tr>
<td>Spring</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Summer</td>
<td>8.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Fall</td>
<td>8.4</td>
<td>7.7</td>
</tr>
</tbody>
</table>
4.1.1 Spring

During the spring, the reservoir is not yet stratified and inflows to the reservoir are greater because of rain, frozen ground, less vegetation, and snow melting in the watershed. Warm, medium, and cold spills during this season usually exhibit similar behavior for arrival time and concentration because the reservoir is essentially completely mixed. Figure 4.2 shows relative contaminant concentration at the Cosgrove versus time expressed as days after the spill occurred. The results show the lack of effect of spill temperatures on relative concentrations at the Cosgrove for the spring of 2009, and are representative of results for a typical spring spill.

![Graph showing relative concentration at Cosgrove](image)

Figure 4.2 Comparison of Spill Temperatures on Relative Concentration at the Cosgrove for the Spring of 2009 (JDay 97, Rt. 140)

Figure 4.3 through Figure 4.5 show results for model years 2003 to 2009 for warm, medium, and cold spring spills, respectively. Spring spills usually have the shortest arrival times at the Cosgrove Intake, which are between 2 and 7 days after the spill occurred. The average maximum relative concentration at the Cosgrove for the years 2003 to 2009 is 1.0 to 2.9. During the spring and the fall seasons, the reservoir acts essentially like a continuous flow stirred tank reactor (CFSTR) with a uniform distribution of temperature and specific conductivity. Contaminant spills during these seasons typically exhibit behavior similar to the behavior of a non-ideal
CFSTR. The high relative concentration for the warm spill in 2003 is not a typical result for warm and medium spills in this season and is likely due to minor stratification in the reservoir during the time of the spill. The behavior is almost that of a delayed CFSTR, where the bulk of the pulse input of contaminant reaches the Cosgrove at the same time, as noted by Devonis (2011). This would cause the spill to travel along the top of the water column and to be influenced by the wind. In general however, spring spills of all temperatures arrive at the Cosgrove in approximately 2 to 7 days and level off at a relative concentration of approximately 1.0, indicating that the contaminant is essentially mixed throughout the reservoir. As shown in Figure 4.3 to Figure 4.5, the contaminant slowly washes out of the reservoir with time, as expected for a continuous flow stirred tank reactor.

Figure 4.3  Comparison of Relative Concentration at the Cosgrove Intake for Spring Warm Spills at Rt. 140 for Years 2003-2009
Figure 4.4  Comparison of Relative Concentration at the Cosgrove Intake for Spring Medium Spills at Rt. 140 for Years 2003-2009

Figure 4.5  Comparison of Relative Concentration at the Cosgrove Intake for Spring Cold Spills at Rt. 140 for Years 2003-2009
4.1.2 Summer

During the summer, the reservoir is characterized by thermal stratification. There is also a somewhat greater demand for water from the Cosgrove to supply the Boston metropolitan area. Water is transferred into the Wachusett from the Quabbin Aqueduct during this season to maintain the water level in the Wachusett. The introduction of this water into the reservoir causes an effect known as the Quabbin interflow and this has an impact on the behavior of spilled contaminants. The effects of altering the Quabbin interflow are discussed later in this report.

Figure 4.6 shows the effect of spill temperature on relative concentration at the Cosgrove for the summer of 2009, which is representative of the results for a typical modeled summer spill. Warm, medium, and cold spills during this season exhibit different arrival times due to the effects of thermal stratification and the Quabbin transfer phenomenon. Medium and cold spills also generally result in a slightly greater relative concentration than a warm spill.

Figure 4.6  Comparison of Spill Temperatures with Relative Concentration at the Cosgrove for the Summer of 2009 (JDay 210, Rt. 140)

Figure 4.7 through Figure 4.9 show results for model years 2003 to 2009 for warm, medium, and cold summer spills, respectively. Summer spills generally show a longer arrival time at the
Cosgrove Intake compared to spring and fall spills. The average arrival times for warm, medium, and cold spills are 8.4, 11.6, and 12.3 days respectively. Warm spills take the least time to reach the intake because they travel along the top of the water column and are affected more by wind along the top of the reservoir. The average maximum relative concentration at the Cosgrove for warm spills is 1.9, while for medium and cold spills the averages are approximately 2.6. Higher relative Cosgrove concentrations due to medium and cold spills are likely due to the stratification of the reservoir during the summer. Medium and cold temperature spills are at the same temperatures as the thermocline and hypolimnion in the reservoir, and as a result they are initially confined to traveling in these layers and are unable to mix as much as a warmer spill travelling in the epilimnion. The summer stratification causes contaminant concentrations to be much more variable at the Cosgrove compared to spring and fall spills. This variability at the Cosgrove is due to the stratification during the summer, resulting in water from layers at different temperature being drawn into the Cosgrove Intake.

Figure 4.7  Comparison of Relative Concentration at the Cosgrove Intake for Summer Warm Spills at Rt. 140 for Years 2003-2009
Figure 4.8 Comparison of Relative Concentration at the Cosgrove Intake for Summer Medium Spills at Rt. 140 for Years 2003-2009

Figure 4.9 Comparison of Relative Concentration at the Cosgrove Intake for Summer Cold Spills at Rt. 140 for Years 2003-2009
4.1.3 Fall

During the fall, the reservoir becomes completely mixed again after the surface cools and the turnover occurs. Inflows to the reservoir are generally lower and there is less of a demand for water from the Boston metropolitan area. Warm, medium, and cold spills during this season typically exhibit similar arrival times and relative Cosgrove concentrations because the reservoir is almost completely mixed. Figure 4.10 shows the effect of spill temperatures on relative concentration at the Cosgrove for the fall of 2009, where an unusual behavior is observed. For this day, a warm temperature spill was 12°C, a medium temperature spill was 9°C, and a cold spill was 5°C.

![Figure 4.10 Comparison of Spill Temperatures with Relative Concentration at the Cosgrove for the Fall of 2009 (JDay 312, Rt. 140)](image)

In this case the model showed that the relative contaminant concentration at the Cosgrove was sensitive to a narrow range of spill temperatures. Figure 4.11 illustrates the results of a further investigation into spill temperature effects for a spill occurring on Julian Day 312 in 2009. The results demonstrate the variation in Cosgrove modeled arrival times and behaviors for a small range of spill temperatures in the fall of 2009. On this particular day, a temperature difference of only one degree can result in varying contaminant concentrations at the Cosgrove Intake.
Contaminant spills modeled with a temperature greater than 10°C result in a greater maximum concentration at the Cosgrove compared to spills modeled with a temperature less than 10°C which result in a lower maximum concentration. The relative concentration results at the Cosgrove for a 10°C temperature spill fall between the results for the higher and lower spill temperatures. The differences in the warmer spills arrival times and behaviors compared to the colder spills are likely due to slight vertical temperature variations still existing in the reservoir during the time of the spill and meteorological influences on the warm spill travelling throughout the top portion of the water column. Temperature profiles from Segment 42 on the days following the simulated fall spill on Julian Day 312 indicate that in fact, the temperature of the water closest to the surface is just under 11°C and the temperature of the water at the bottom of the reservoir is just under 10°C.

Figure 4.11  2009 Model Sensitivity to Varying Spill Temperatures

Figure 4.12, Figure 4.13, and Figure 4.14 show results for model years 2003 to 2009 for warm, medium, and cold fall spills. The arrival times and contaminant concentration behavior for fall spills are similar to results during the spring because of the nearly uniform conditions throughout
the reservoir. The average arrival times for warm, medium, and cold spills during the fall are 8.4, 7.7, and 7.5 days respectively with a range for conditions of approximately 4 to 11 days. The average maximum relative concentrations at the Cosgrove for warm, medium, and cold spills are 1.0, 1.1, and 1.2, respectively. After the arrival of a fall spill, the relative concentration increases to approximately 1.0 and remains at this fully mixed concentration until new water is introduced into the reservoir and the spill is diluted.

Figure 4.12  Comparison of Relative Concentration at the Cosgrove Intake for Fall Warm Spills at Rt. 140 for Years 2003-2009
Figure 4.13  Comparison of Relative Concentration at the Cosgrove Intake for Fall Medium Spills at Rt. 140 for Years 2003-2009

Figure 4.14  Comparison of Relative Concentration at the Cosgrove Intake for Fall Cold Spills at Rt. 140 for Years 2003-2009
4.2 Quabbin Transfer Influences (2003-2009)

The impacts of varying the Quabbin transfer on the relative concentration of a spilled contaminant at the Cosgrove Intake were investigated using the CE-QUAL-W2 model for the years 2003 to 2009. Two model simulations were analyzed for each season for each year for all three spill temperatures (warm, medium, and cold). One run represents the spill day selected with the Quabbin operating as it did in reality, either on or off. Another run simulates a potential management response to a spill in the reservoir, in which the Quabbin transfer is turned on or off, depending on the original conditions, for a period of 2 weeks beginning twelve hours after the spill occurs. Twelve hours has been used in past Wachusett modeling work as the amount of time it could take the reservoir managers to respond to a spill and alter the flow of the Quabbin transfer. Table 4.2 is a summary of the Quabbin transfer impact simulations for the years 2003 to 2009. The transfer is always off for spring spill dates, always on for summer spill dates, and varies for fall spill dates.

<table>
<thead>
<tr>
<th>Year</th>
<th>Season</th>
<th>Actual Condition of Quabbin Transfer</th>
<th>Altered Condition of Quabbin Transfer for 2 Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Spring</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2003</td>
<td>Summer</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>2004</td>
<td>Spring</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>2004</td>
<td>Summer</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>2004</td>
<td>Fall</td>
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Past research by Sojkowski (2011) and Devonis (2011) investigated the impacts of varying the Quabbin transfer during all three seasons for the years 2003 to 2008. They concluded that turning the transfer off in the summer when it is normally on generally does not impact the Cosgrove arrival time of the contaminant, but this action reduces the variability of the concentration at the Cosgrove Intake. Minimal impacts in spill arrival time and behavior were observed for spring and fall contaminant spills, with the exception of the years 2005 and 2006 where there was some notable change.

The influence of the Quabbin transfer for the year 2009 is investigated in Figure 4.15 and Figure 4.16. The results are labeled as “Quabbin_Actual_ON” and “Quabbin_Turned_OFF” representing the actual condition of the Quabbin transfer and the altered condition, respectively. The figures show results for warm and cold spills in the summer and the impact of turning the Quabbin transfer off. In all three cases, the arrival time at the Cosgrove Intake is unaltered when the Quabbin transfer is turned off for two weeks. However, the variability of the relative contaminant concentration at the intake decreases, in agreement with results from previous year models, as seen in Appendix B. Variability in the spill is most likely reduced when the Quabbin was turned off because doing so dissipates the zone of cooler water and lower conductivity in the interflow and better disperses the spill throughout the reservoir (Sojkowski, 2011).

Figure 4.15 Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2009
Warm Spill by Varying the State of the Quabbin Transfer
Figure 4.16 Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2009 Cold Spill by Varying the State of the Quabbin Transfer

4.3 Two Year Model Simulation

Previous CE-QUAL-W2 models developed by the UMass team simulating contaminant spills into the Wachusett Reservoir have simulated hydrodynamics and water quality over a one calendar year period. The mean hydraulic residence time of the reservoir is approximately 206 days, yet conservative spill modeling results, and consideration of hydrodynamics, suggest that a contaminant could remain in the reservoir for longer than this time. To further understand the behavior and potential residence time of a conservative contaminant spill into the reservoir, a two year simulation was developed by combining data for 2008 and 2009. The development of this model also facilitates the simulation of more accurate velocity profile results at the entrance to the North Basin of the reservoir (CE-QUAL Segment 39) on January 1, 2009 for use as boundary conditions in the 3D GEMSS model. The water balance approach for the two year model was expanded to include two years and the difference between measured and calculated water surface elevation is minimized using the SOLVER function in Microsoft Excel, as described previously. Meteorological and total dissolved solids data for both years were also combined to produce the input files for the two year model. The model was calibrated using the same parameters as used for the 2008 model.
4.3.1 Potential Residence Time of a Conservative Contaminant Spill

Figure 4.17 shows the modeled relative contaminant concentration at the Cosgrove Intake for a cold spill in the spring, summer, and fall of 2008 using the combined 2008 to 2009 model. The spills occur on the 2008 Julian days 122 (5/1/08), 227 (8/14/08), and 314 (11/9/08). The results show that a conservative contaminant spilled into the reservoir can remain present for over 600 days after the spill has occurred if there is no emergency response to contain, remove, or dilute the spill. Based on the 2008 spring spill, a conservative contaminant can remain in the reservoir for about 600 days, which is about 3 times the mean hydraulic residence time of about 206 days.

![Figure 4.17 Potential Residence Time of a Spring, Summer, and Fall Cold Contaminant Spill in 2008](image.png)

After the initial peak in contaminant concentration, the reservoir exhibits behaviors similar to a complete mixed reactor. Therefore, the relative contaminant concentration at the Cosgrove after three hydraulic residence times can be described by Equation 10 for a pulse input into an ideal CFSTR where $C/C_0$ is the relative concentration at the Cosgrove, $t$ is the amount of time that the contaminant has been in the reservoir in days, and $\tau$ is the mean hydraulic residence time in days (Tchobanoglous and Schroeder, 1985). By definition, the concentration in an ideal CFSTR is the
same in all locations and the input is mixed instantaneously with the whole volume of fluid in the reactor. Based on Equation 10, the expected relative contaminant concentration after one hydraulic residence time (200 days) is equal to $e^{-1}$, or 0.37. Similarly, after three residence times in the reservoir (600 days) the relative concentration is expected to be approximately equal to $e^{-3}$, or 0.05. The two year simulation results for the spring 2008 spill are consistent with this type of behavior, as the relative concentration at the Cosgrove after 600 days is approximately 0.05.

$$\frac{c}{c_o} = e^{-t/\tau} \quad \text{(Equation 10)}$$

The results for a conservative contaminant using a two year model also illustrate the various behaviors of spills in each season. Spring and fall contaminant concentrations peak at a Cosgrove relative concentration of approximately 1.0, indicating a completely mixed reservoir, and then slowly decline as they are washed out of the reservoir. A summer spill has a higher maximum relative concentration and then stratification present in the reservoir at the time of the spill produces greater variability in concentration at the Cosgrove, as discussed previously. This summer variability can also be seen in the spring spill while it remains in the reservoir during the summer of 2008. The impacts of stratification during the summer of 2009, at approximately Julian Day 600, can also be seen in all the relative concentration results.

### 4.3.2 Potential Residence Time of a Decaying Contaminant

The fate and transport of contaminants in a reservoir is also dependent on whether or not they decay or settle. The chemical decay or microbial uptake of a contaminant can contribute to a contaminant’s potential residence time and concentration at the Cosgrove Intake. CE-QUAL allows for a generic constituent to have a zero or first order decay rate. The user can specify a zero and/or a 1st order decay coefficient with or without an Arrhenius temperature dependence function, and/or a settling velocity. The source/sink term for a generic constituent in CE-QUAL is modeled using Equation 11, where $S_g$ is the source/sink term, $\theta_g$ is the temperature rate multiplier, $T$ is water temperature ($^\circ$C), $\omega_g$ is settling velocity (m/s), $K_0$ is the zero order coefficient (g/m$^3$-d at 20$^\circ$C), $K_1$ is the first order decay coefficient (d$^{-1}$ at 20$^\circ$C), and $Y_g$ is the generic constituent concentration (g/m$^3$) (Cole and Wells, 2008).

$$S_g = -K_0 \theta_g^{(T-20)} - K_1 \theta_g^{(T-20)} Y_g - \omega_g \frac{\partial Y_g}{\partial z} \quad \text{(Equation 11)}$$
Stauber (2009) modeled a spill of ammonium nitrate from the railroad bridge (Segment 9) into the Wachusett Reservoir for the years 2003 and 2004 using a first order decay rate. She investigated the effects of ammonium and nitrate uptake rates by phytoplankton and algae in order to understand the effects of a potential ammonium nitrate spill on fertilizing the plant life in the reservoir, assuming that phosphorous was available and not a limiting reagent. The uptake rate for ammonium and nitrate was modeled as a “decay” rate applied to the generic constituent in CE-QUAL. Ammonium and nitrate were modeled separately because they have different uptake rates by plankton. As described in Stauber’s work, a concentration of ammonium (9,466 mg/L) and nitrate (32,533 mg/L) were modeled similarly to a conservative spill described previously, but with a first order decay (uptake) rate of 0.13 d⁻¹ for ammonium, and 0.023 d⁻¹ for nitrate, instead of a zero order decay rate added to the control file. Decay rates were chosen based on an average of values found in a literature review, as detailed in Stauber (2009).

To compare previous spill modeling results with those of a decaying contaminant spill, impacts of different decay coefficients (CG1DK in model code or K₁ in Equation 11) were investigated for a contaminant spill from the Route 140 Bridge (Segment 7). Figure 4.18 shows the results of a spill from the Route 140 Bridge on Julian Day 122 (5/1/08) for the two year model of 2008-2009. Three decay rates (0.025, 0.1, and 0.25 d⁻¹) are modeled and compared to a tracer spill with a zero order decay rate. As shown in the figure, the model results for the decaying constituent show significantly lower maximum concentrations at the Cosgrove Intake and throughout the 600 days of the washout. A constituent with a decay rate of zero has a maximum relative concentration of approximately 1.3 and 600 days after the spill occurs the relative concentration was approximately 0.06. Constituents with decay rates of 0.025, 0.1, and 0.25 d⁻¹ reach maximum relative concentrations of approximately 0.9, 0.5, and 0.2, respectively and by 200 days after the spills occur, they all have relative concentrations less than 0.006.
To validate that the CE-QUAL model is accurately reflecting the choices of the decay rates for the constituent spills, the values of the decayed concentrations at the Cosgrove Intake are divided by the conservative tracer concentrations and plotted versus time, as shown in Figure 4.19. An exponential decay trend line is fit to the data, with the exception of the very beginning data points. The observed decay rate for the constituent spill with the model decay rate CG1DK equal to 0.025 d\(^{-1}\) is appropriately 0.025 d\(^{-1}\) as determined from the exponential best fit line, or Equation 12. Based on this relationship, the relative conservative tracer concentrations can be used to determine concentrations of reactive constituents at the Cosgrove without using CE-QUAL with a reactive term, confirming a conclusion made by Stauber (2009) from ammonium nitrate decay modeling results.

\[
\frac{c}{c_0} = \exp(-K_1 \cdot t)
\]  

Equation 12
Equation 12 can be used to determine the decay rate required to decrease the maximum relative concentration at the Cosgrove by 99%. The range of modeled maximum contaminant concentration arrival times at the Cosgrove for years 2003 to 2009 is between 7 and 46 days. Therefore, relatively rapid decay rates (0.10 to 0.66 day\(^{-1}\)) are needed to decrease the maximum outflow concentration by 99%. In comparison, a slower decay rate (0.02 day\(^{-1}\)) results in a 99% decay of contaminant concentration in the outflow after 206 days.

### 4.4 Application to GEMSS

Two year CE-QUAL-W2 model simulations are also useful for the development of the 3D model of the Wachusett Reservoir using GEMSS (Generalized Environmental Modeling System for Surface Waters). The GEMSS system is comprised of four hydrodynamic modules: the 3-D model (GLLVHT), the 2-D longitudinal-vertical model (CE-QUAL), the 1-D model (GLHT), and the 0-D fully mixed model (RTC). The GEMSS model also includes various water quality constituent models. The current UMass GEMSS model for the Wachusett Reservoir includes only the Narrows (CE-QUAL Segment 39), the entire North Basin (CE-QUAL Segments 40-45) and the Cosgrove Intake (CE-QUAL Segment 46). Similar to CE-QUAL, the model requires spatial and temporal data. Spatial data include reservoir bathymetry and locations, elevations
and configurations of structures. Temporal data include time-varying boundary conditions that specify inflow rates and temperatures, inflow constituent concentration, outflow rate, and meteorological data.

The inflow rate boundary conditions that are needed for the GEMSS model of the Wachusett Reservoir North Basin are generated from the CE-QUAL model velocity profiles at the Narrows (Segment 39) for the model year. Figure 4.20 shows the CE-QUAL velocity profiles from 1/1/2009 to 1/3/2009 at Segment 39 for a one year simulation of the year 2009 beginning on 1/1/2009. The profile for 1/1/2009 shows essentially no velocity through the Segment 39 due to the initial zero velocity condition in all the segments. The profile for 1/2/2009 shows a profile of a moving reservoir and varying velocities throughout the profile. These results indicate that the model takes some time to become numerically stable and produce realistic profiles that can be used as the boundary conditions for the GEMSS model. Further investigation included running the CE-QUAL model with steady state flow and meteorological conditions to observe the length of time for the velocity profiles to become essentially stable. Results suggest that the model can take several months to produce stable results for consistent input conditions.

Figure 4.20  Velocity Profiles at the Narrows (CE-QUAL Segment 39) for the 2009 One Year Model, Julian Days 1-6

It was determined that more appropriate velocity profiles at Segment 39 in CE-QUAL for all of calendar year 2009 can be generated using a two year combined model of the years 2008 and 2009. Figure 4.21 shows the results for velocity profiles at Segment 39 for the combined model. It is evident from this figure that the profiles from the one year model of 2009 and from the two year model are different, especially on 1/1/09. Profiles for the combined model may produce
more realistic results that are more appropriate for use as the boundary conditions for the GEMSS model because the profile on 1/1/2009 is reflective of the impacts of all of the meteorological and flow conditions from the previous year. The profile from the two year model on 1/1/09 is more representative of what is happening in the actual reservoir than the one year model profile result on 1/1/09.

![Velocity Profiles](image)

**Figure 4.21** Velocity Profiles at the Narrows (CE-QUAL Segment 39) for the 2008-2009 Two Year Model Julian Days 364-372

After development and calibration is completed using the boundary conditions provided by CE-QUAL, the GEMSS model can be used to run spill simulations. Spilled contaminant concentration profiles are also taken from Segment 39 in CE-QUAL and used as the initial conditions to the GEMSS model. Spill profiles and concentrations at the Cosgrove Intake can then be compared to CE-QUAL contaminant concentration results. The GEMSS model will also be useful in determining how much lateral and longitudinal variability of spill concentrations there potentially is in the North Basin of the reservoir that is not currently captured by the CE-QUAL model due to its larger grid size and lateral averaging.
5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

A CE-QUAL-W2 model of the Wachusett Reservoir for the year 2009 was developed from meteorological data, stream flows, water quality data, and existing bathymetry data from previous models. The water balance parameters were calibrated by minimizing differences between measured and calculated water surface elevations by adjusting calibration factors related to inflow and outflow data within a water balance spreadsheet. CE-QUAL-W2 parameters were calibrated to match temperature and specific conductivity profiles measured in the North Basin of the reservoir throughout the year. Varying one parameter at a time and comparing the simulations to measurements minimized the difference between the data and the simulations.

The calibrated model was used to simulate scenarios for contaminant spills from the Route 140 Bridge into the Wachusett Reservoir. The Route 140 Bridge was chosen because its location on the reservoir has a higher vulnerability to a vehicle or truck accident. Contaminant spills for the calendar years 2003 to 2009 were analyzed by modeling different conditions that assessed the effects of seasonal trends and the Quabbin transfer on the behavior of the contaminant concentration at the Cosgrove Intake. A two year model was also developed and used to understand the potential residence time and behavior of a conservative and a decaying contaminant spill in the reservoir. All modeled years can be compared to determine overall trends in seasonal spills and conditions that the reservoir experiences throughout an entire year.

5.2 Conclusions

CE-QUAL-W2 contaminant spill simulations in the spring, summer, and fall for the calendar years 2003 to 2009 were evaluated to understand the behavior of different temperature (density) spills on contaminant concentrations at the Cosgrove Intake. It was determined that during the spring and the fall, the density of a contaminant does not typically have an effect on the arrival time or relative concentration at the Cosgrove because the reservoir is not stratified. Spring spills arrive 2 to 7 days after the spill occurs, reaching an average maximum relative concentration of 1.0 to 2.9. Fall spills typically arrive in 4 to 11 days with an average maximum relative concentration of approximately 1.0 to 1.2. Summer contaminant spills produce more variable
results at the Cosgrove Intake due to the stratification during this time of the year, and they usually have later arrival times at the intake compared to spring and fall spills. The average arrival times for warm, medium, and cold spills during the summer are 8.4, 11.6, and 12.3 days respectively. The average maximum relative concentration at the Cosgrove for warm spills is 1.9, while for medium and cold spills the average are about 2.6 during the summer months.

Impacts of the Quabbin transfer on spill behavior and relative contaminant concentration were also investigated for the spring, summer, and fall. It was determined that turning the transfer off for two weeks after a spill occurs in the summer, when it is normally on, generally does not impact the arrival time of the contaminant at the Cosgrove. However, turning off the Quabbin does reduce the variability in the concentration of the contaminant at the intake. Changes in the Quabbin transfer during the spring and the fall has minimal impacts on contaminant arrival time and behavior.

With the development of a 2 year model, the potential residence time of a contaminant in the reservoir can be observed. A model for the calendar years 2008 to 2009 demonstrated that a contaminant can remain in the reservoir for more than three times the mean hydraulic residence time of 206 days. In comparison, a contaminant with a decay rate of 0.025 d$^{-1}$ is essentially non-detectable at the Cosgrove Intake approximately 200 days after the spill event. The development of a two year CE-QUAL model was also necessary to produce realistic boundary conditions at Segment 39 on January 1, 2009 for the 3-D GEMSS model of the North Basin.

5.3 Recommendations

Future work should include incorporating more of the measured reservoir water quality data from the DCR and MWRA into the CE-QUAL model. A continued effort should also be made to relate available land use data and water quality data to the reservoir model. Additional work could include modeling NOM levels in response to different conditions that the reservoir experiences, such as differences in wet or dry years, and operation of the Quabbin transfer or Nashua River. The CE-QUAL model can also be used to model Giardia cysts in the Wachusett reservoir to better understand the fate and transport of these organisms in the system. There could also be an effort to investigate climate change induced extremes in precipitation on reservoir inputs.
REFERENCES


APPENDIX A – Major Inflows and Outflows for Years 2003-2009

Figure A.1: Major Inflows into Wachusett Reservoir for 2003

Figure A.2: Major Outflows from Wachusett Reservoir for 2003
Figure A.3: Major Inflows into Wachusett Reservoir for 2004

Figure A.4: Major Outflows from Wachusett Reservoir for 2004
Figure A.5: Major Inflows into Wachusett Reservoir for 2005

Figure A.6: Major Outflows from Wachusett Reservoir for 2005
Figure A.7: Major Inflows into Wachusett Reservoir for 2006

Figure A.8: Major Outflows from Wachusett Reservoir for 2006
Figure A.9: Major Inflows into Wachusett Reservoir for 2007

Figure A.10: Major Outflows from Wachusett Reservoir for 2007
Figure A.11: Major Inflows into Wachusett Reservoir for 2008

Figure A.12: Major Outflows from Wachusett Reservoir for 2008
APPENDIX B – Quabbin Transfer ON/OFF Results for Years 2003-2008

Figure B.1: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2003 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.2: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2003 Warm Spill by Varying the State of the Quabbin Transfer
Figure B.3: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2004 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.4: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2004 Warm Spill by Varying the State of the Quabbin Transfer
Figure B.5: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2005 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.6: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2005 Warm Spill by Varying the State of the Quabbin Transfer
Figure B.7: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2006 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.8: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2006 Warm Spill by Varying the State of the Quabbin Transfer
Figure B.9: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2007 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.10: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2007 Warm Spill by Varying the State of the Quabbin Transfer
Figure B.11: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2008 Cold Spill by Varying the State of the Quabbin Transfer

Figure B.12: Relative Spill Concentration at Cosgrove Intake for Summer Model Year 2008 Warm Spill by Varying the State of the Quabbin Transfer