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Application of CE-QUAL-W2: Wachusett Reservoir Contaminant Spill Modeling

A Masters Project Presented by

William M. Yan

Submitted to the Graduate School of the

University of Massachusetts Amherst in partial fulfillment

of the requirements for the degree of

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in

Civil Engineering

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Department of Civil and Environmental Engineering

University of Massachusetts

Amherst, MA 01002

Application of CE-QUAL-W2: Wachusett Reservoir Contaminant Spill Modeling

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Executive Summary

This research was done to investigate the fate and transport of a simulated contaminant spill into Wachusett Reservoir using the CE-QUAL-W2 model. The reservoir is located in central Massachusetts (north east of Worcester) and was first filled in 1908. The Massachusetts Water Resource Authority (MWRA) uses the reservoir as a primary source of drinking water for the metropolitan Boston area. The 65-billion-gallon reservoir is replenished by 9 tributaries and also supplemented by the transfer of water from Quabbin Reservoir (412 billion-gallon capacity) through the Quabbin Aqueduct. This transfer is used to meet system water demands, manage the water surface elevation at the Wachusett Reservoir and improve Wachusett water quality. The MWRA withdraws reservoir water at the Cosgrove Intake (CIT) where it flows by gravity to the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough.

CE-QUAL-W2 is a 2 dimensional longitudinal and vertical hydrodynamic and water quality model that has been used at UMass for over 15 years to simulate spills into the Wachusett Reservoir. The model assumes lateral homogeneity, thus is best suited for waterbodies that are relatively long and narrow. Wachusett Reservoir's length to width ratio is about 6 to 1, making the model suitable for the reservoir simulations. Wachusett Reservoir models for calendar years 2015 and 2016 were successfully developed using CE-QUAL-W2 Version 4.0. Model parameters were calibrated to simulate a good match between measured and modeled temperature and specific conductivity water profiles. Segment 42 in the model was used to compare to a Department of Conservation and Recreation (DCR) frequently sampled site in North Basin. Root mean squared error (RMSE) was used to determine the errors of calibration parameters.

Contaminant spill scenarios were simulated using the 2015 and 2016 Wachusett Reservoir models. Factors such as spill temperature/density, vertical shear stress formulation, and bathymetry were analyzed. Model results showed that contaminant arrival time and concentration at the CIT was mostly independent of spill temperature during the Spring and Fall. This was due to the completely mixed nature of the reservoir at those times. Spill temperature influenced contaminant characteristics at the intake during the Summer seasons, due to reservoir stratification.

The vertical shear stress formulation used resulted in different reservoir hydrodynamic behavior. UMass has historically utilized the W2 formulation, but recently switched to the turbulent kinetic energy formulation (TKE) for climate change models with high temporal resolution (Jeznach, 2016). The TKE formulation produced simulated water quality profiles that better match DCR measured profiles and consistently producing lower RMSE than W2. The W2 formulation simulated 30-80% faster contaminant arrival at the Intake, while TKE model results exhibited an average of 10% higher maximum intake relative concentration.

Reconsideration of the construction plan for the cofferdam built adjacent to the CIT suggested that adjustments to the model bathymetry might need to be considered. Simulations with the new bathymetry file produced model results that better match water quality data for water withdrawn at the intake. The adjustment also increased spill contaminant arrival time at the intake by 20-24% for all but the Spring spill using the TKE formulation. However, The TKE formulation with the new bathymetry simulated higher maximum intake concentration than models that used the old bathymetry file. The opposite is true for the W2 formulation.

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CHAPTER 1: INTRODUCTION

1.1 The MWRA Water System

The Massachusetts Water Resources Authority (MWRA) provides wholesale water to 48 communities in Massachusetts, 42 of which are located within the metropolitan Boston area. The system includes of four core components; the Quabbin Reservoir, Wachusett Reservoir, Carroll Water Treatment Plant (CWTP), and MetroWest Tunnels (Figure 1.1). Quabbin water is transferred into the Wachusett Reservoir and withdrawals from the reservoir are treated at the CWTP. The water system has a combined safe yield of 300 million gallons per day (MGD).

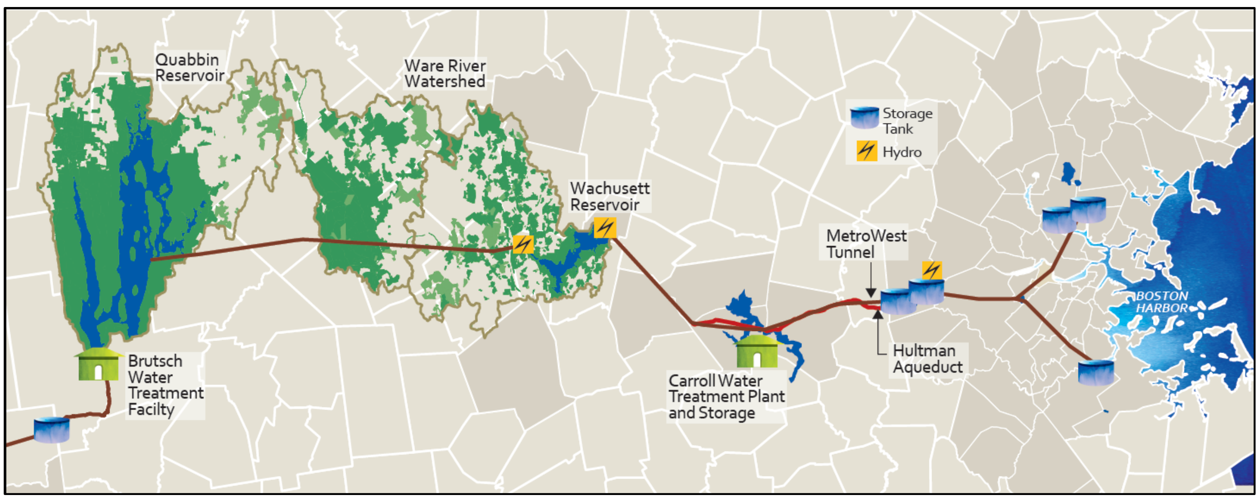

Figure 1.1 The MWRA Water System (Source: MWRA)

1.2 The Quabbin Reservoir and Aqueduct

The Quabbin Reservoir is currently the largest manmade reservoir in the state of Massachusetts. Located in Western Massachusetts, the 412-billion-gallon reservoir was completed and first started to fill in 1939 (Figure 1.2). Water is diverted through the 39.6 km long, 3.9 m tall, and 3.4 m wide Quabbin Aqueduct into the Wachusett Reservoir. The Quabbin Transfer historically occurred during periods of high water demand from Boston to meet demand and maintain high water quality in the Wachusett Reservoir.

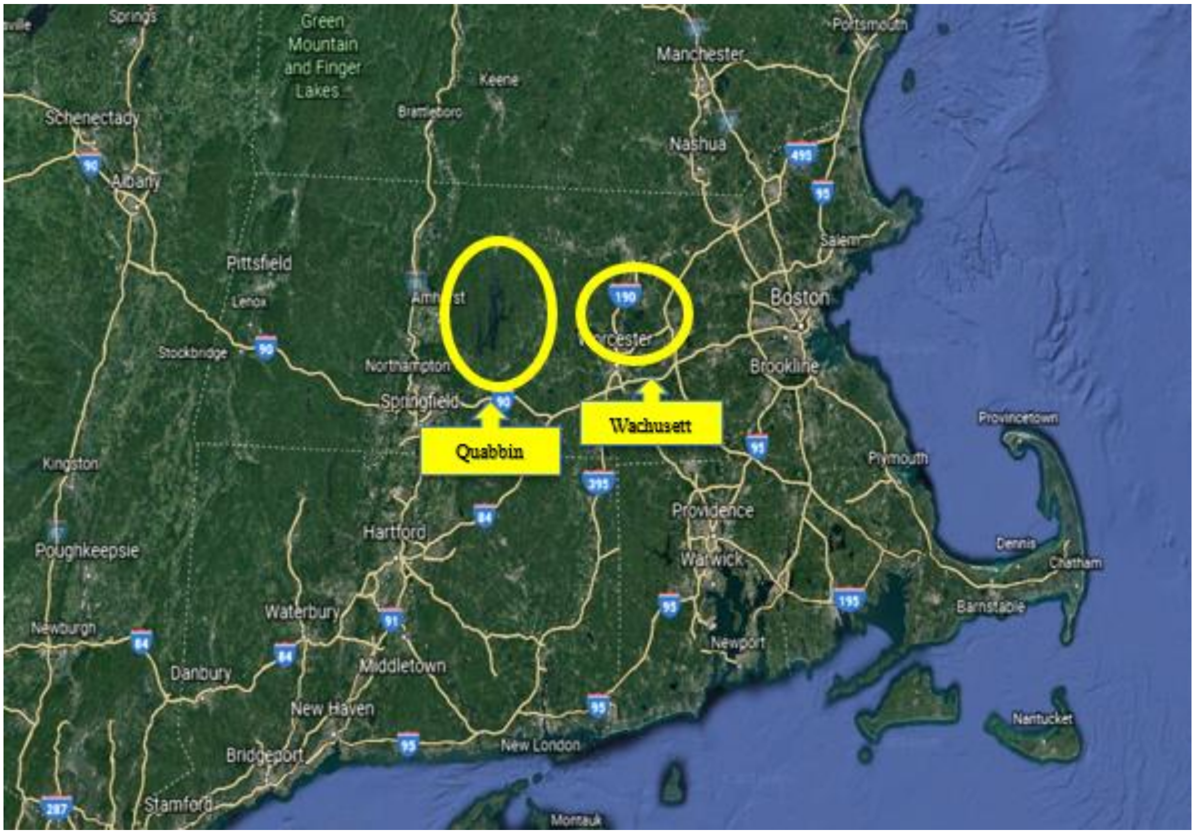

Figure 1.2 The Quabbin Reservoir (Left) and Wachusett Reservoir (Right) (Source: Google Earth)

1.3 The Wachusett Reservoir

Construction for the Wachusett Reservoir system began in 1897 with the impoundment of the Nashua River above the town of Clinton by the Wachusett Dam. Work on the system was completed in 1905 and the reservoir filled by 1908 to become the largest public water supply reservoir in the world at the time (MWRA, 2006). The reservoir is located northeast of Worcester in Central Massachusetts (Figure 1.3) and is currently the second largest manmade water system in the state with a length of 8.4 miles (13.5 km), a maximum depth of 129 feet (39.3m) and a surface area of 6.5 square miles (16.8 km^2). The 65 billion-gallon reservoir is maintained by the MWRA and its surrounding watershed is managed by the Division of Water Supply Protection, Office of Watershed Management, of the Massachusetts Department of Conservation and Recreation (DCR).

Figure 1.3 The Wachusett Reservoir (Source: Google Earth)

The Wachusett Reservoir is replenished by direct runoff, precipitation, nine inflow tributaries and the Quabbin Aqueduct transfer. Quabbin Aqueduct, Malden Brook, Waushacum Brook, Quinapoxet River and Stillwater River discharge into the Thomas Basin the northwest portion of the reservoir, where water mixes before passing through a narrow channel under the Sterling Street bridge on Route 12/140. West Boylston, Gates, Muddy, Malagasco, and French Brook discharge into the South Basin. Water is released to maintain the Nashua River flow, withdrawn by the Wachusett Aqueduct and nearby towns, and spilled through the Nashua spillway. Most of the water is withdrawn at the Cosgrove Intake (CIT) located in the North Basin to provide quite high-quality raw water to the Carroll Water Treatment Plant (CTWP), which in turn provides treated water to the metropolitan Boston area. The United States Environmental Protection Agency (USEPA) granted the Massachusetts Department of Environmental Protection (MassDEP) the authority to approve a filtration waiver for the MWRA water systems (MWRA, 2015). Water withdrawn at the intake is transported to the CWTP where treatment consists of primary disinfection by ozonation and ultraviolet light and secondary disinfection with chloramination prior to distribution. Water is released from the reservoir via the Wachusett Dam to not only maintain the Nashua River flow, but also to control the reservoir water surface elevation and impact the water quality. The average water residence time in the reservoir is an estimated 307 days based on average reservoir volume and average combined outflows.

1.4 Objective and Scope

The objective of this research was to develop CE-QUAL-W2 models for calendar years 2015 and 2016 and investigate spill contaminant behavior in Wachusett Reservoir under various conditions. Varying spill scenarios were simulated as an inflow near Beaman Street located on Route 140 using the water quality and hydrodynamic model CE-QUAL-W2 Version 4.0. Two eddy viscosity formulations along with two slightly varying bathymetry files were used to compare the arrival time and relative concentration of the contaminant at the Cosgrove Intake. The four model variations consisting of a historically used W2 eddy viscosity formulation with the old bathymetry, W2 with the new bathymetry, turbulent kinetic energy (TKE) formulation with the old bathymetry, and TKE with the new bathymetry were all examined. Scenarios of varying spill temperature and seasons were also investigated to provide a wide range of potential outcomes that reservoir management can reference to make informed contingency emergency response to a spill at the Wachusett Reservoir.

CHAPTER 2: BACKGROUND

This section introduces the CE-QUAL-W2 model and provides a brief summary of the previous modeling work done here at UMass. Some applications of the CE-QUAL-W2 model by other researchers are discussed here.

2.1 CE-QUAL-W2

CE-QUAL-W2 is a two dimensional, longitudinal and vertical, laterally averaged water quality and hydrodynamic model applicable to various waterbodies. It was previously known as the Laterally Averaged Reservoir Model (LARM), which was first developed in 1975 by Edinger and Buchak (1975). Currently the model is maintained by Scotts Wells and Chris Berger at Portland State University, Oregon and continuously improved for faster model run time, additional constituent modeling capabilities and a better user-friendly interface (Cole and Buchak, 1995). CE-QUAL-W2 assumes lateral homogeneity thus is best suited for dendritic lakes, estuaries, reservoirs and rivers by solving 6 governing laterally averaged equations based on finite difference solution. Algorithms within the model's source codes compute the governing equations and solves for free water surface, hydrostatic pressure, horizontal momentum, continuity, constituent concentrations, and temperature/density (Cole and Wells 2015).

CE-QUAL-W2 was selected for this project due to the long and narrow geometry of Wachusett Reservoir and relatively fast model run time on generic commercial desktops. Version 4.0 was the most updated version of the model at the start of the project for model year 2015 to 2016, thus it was used for the modeling analyses conducted in this report. Version 4.0 offers user friendly freeformatting of data input files in comma separated values as opposed to Version 3.6's eight column width fixed format, greatly reducing time spent on input data processing.

2.2 Previous Applications of CE-QUAL-W2

CE-QUAL-W2 has been applied to numerous waterbodies for water quality and hydrodynamic modeling purposes. The model has been used for various contaminant spill scenarios across a wide range of reservoirs, rivers, and lakes. The New York City Department of Environmental Protection Bureau of Water Supply has, and continues to, use the model extensively for turbidity simulation throughout their reservoir supply systems that supply an average demand of 1.5 billion gallons per day (BGD) (NYCDEP, 2017).

Atrazine is an herbicide commonly used during the spring as a form of weed control in cornfields in the Midwest. Storm events in late Spring flush a significant concentration of the herbicide from agricultural fields into different water bodies and rivers. Some of the rivers discharge into the Saylorville Reservoir in Iowa, resulting in concentrations of atrazine higher than USEPA's maximum contaminant levels. Chung and Gu (2009) used CE-QUAL-W2 with the incorporation of a sub-model for toxic contaminants to predict the fate and transport of atrazine in Saylorville Reservoir. The sub-model integrated a first order decay kinetics degradation rate for the herbicide that accounts for hydrolysis, photolysis and biotransformation in a natural waterbody. Partitioning coefficients between particulate and dissolved forms along with atrazine volatilization were also assimilated into the sub-model. Chung and Gu successfully modeled atrazine in the Saylorville Reservoir. The predicted atrazine arrival time and magnitude of peak concentrations from CE-QUAL-W2 closely matched the observed concentration measured throughout the reservoir.

A contaminant spill into a waterbody can result in significant financial burden for any government. Developing a Pollution Response Management Model (PSRMM) may result in a more effective management response to mitigate effects of an accidental spill. Saadatpout and Afshar (2013) focused on research associated with reservoir release as a strategy to control the fate and transport of a conservative pollutant incorporated with Pareto optimization for determining an optimal selective withdrawal scheme. The PSRMM utilized CE-QUAL-W2 to identify reservoir regions with highest contaminant concentrations for potential emergency cleanup response. A 12-hour spill into the Ilam Reservoir located in Iran with a concentration of 0.2 mg/L was simulated. Withdrawals from the reservoir were assumed to be suspended for 31 days after a spill with the only outflow source being planned reservoir release. Reservoir cleanup time, number of water quality violations and worst water quality concentrations were all objectives the research optimized.

Martin et al. (2004) created a spill management information system (SMIS) consisting of a marriage of Geographical Information Systems (GIS), Database Management Systems (DBMS), Computer-Aided Management of Emergency Operations (CAMEO), and a water quality model CE-QUAL-W2. SMIS creates a user-friendly interface with multi-functional data retrieval procedures for tributary inflows and outflows, meteorological, chemical and other background data needed for air quality model CAMEO and water quality model CE-QUAL-W2 model runs. Results from the water and air quality model were visualized within GIS giving users visual documentation of spatial and temporal variations of the concentration of a contaminant spill into the Cheatham Reach near Nashville, TN. Real-time data could also be inputted in CE-QUAL-W2 and CAMEO by DBMS for rapid parameter modifications offering the most updated post-spill scenarios for response and management solutions.

Kim and Kim (2006) successfully used CE-QUAL-W2 to model temperature and flow density for the 60 km long Lake Soyang in Korea. The reservoir acquires over 50% of its total inflows during the monsoon season between July and August with water that has a higher concentration of suspended solids and lower temperature than the reservoir. 1996 data with high volume of observed turbid density interflow during the wet season were used to calibrate the model. Despite the high inflow volume of water during the monsoon season, the model was able to predict temperature profiles to match the observed profile for the 118 m deep reservoir. Cold water inflows create an interflow across Lake Soyang similar to the Quabbin interflow in the Wachusett Reservoir. The model was able to accurately capture the distribution of the turbid density interflow during the wet season.

2.3 UMass Amherst and DCR Experiences with CE-QUAL-W2

The CE-QUAL-W2 model for Wachusett Reservoir was originally developed by Camp, Dresser, and McKee Inc along with FTN Associates, LTD. The model was originally calibrated for calendar years 1987, 1990 and 1992 (CDM, 1995). After UMass obtained the model, Joaquin (2001) developed a daily time scale water budget and constructed models for calendar years 1998 and 1999 to simulate effects of Quabbin transfer on Wachusett Reservoir. Buttrick (2005) developed model years 2001 and 2002 and updated the source code to include light induced decay of UV_{254} to model natural organic matter. Matthews (2007) introduced light induced coliform decay into model Version 3.5's source code and developed models for calendar years 2003 and

2004 to simulate fecal coliform contamination from a sewage pump station overflow. Stauber (2009) revisited model years 2003 and 2004 to examine the behavior of ammonium nitrate and fuel oil spills under various wind conditions, temperatures of spill and Quabbin transfer status. She also incorporated volatilization into the CE-QUAL-W2 source code to better simulate the fate of benzene. Sojkowski (2011) built the calendar years 2005 and 2006 models with Version 3.6 and converted the 2003 and 2004 models over to the latest model. Devonis (2011) developed calendar year 2007 and 2008 models to examine effects of seasonality, Quabbin transfer and wind spill behavior on relative concentration on CIT. Lillian Clark (2013) reexamined calendar year 2003 to 2008 and expanded to 2009 on spill temperature along with seasonal effects on spill arrival time and relative concentration at the Cosgrove Intake; models for 2010 through 2014 were also developed. In 2016, Lillian Clark Jeznach modeled the impacts of extreme precipitation events on water quality and future climate effects on the heat budget for the Wachusett Reservoir (Jeznach, 2016)

CHAPTER 3: WACHUSETT RESERVOIR MODEL DESCRIPTION AND CALIBRATION

CE-QUAL-W2 requires user defined inputs of bathymetry, tributary flows, water quality, precipitation, and outputs of water quantity to model the hydrodynamics and water quality for the waterbody of interest. A majority of the work for calendar year 2015 and 2016 models was directed at data collection and model calibration.

3.1 CE-QUAL-W2 Grid and Segments

The original model discretization grid for Wachusett Reservoir was developed by Camp, Dresser, and McKee (CDM, 1995). The model grid simulated the natural bathymetry and orientation of the Wachusett Reservoir. Layer and segment adjustments to the grid were introduced by Joanquin (2001) to further refine resolution of the model. The updated grid consists of 64 segments with the cofferdam (Segment 45) and Cosgrove Intake (Segment 46) addition as shown in Figure 3.1. The reservoir is separated into 5 branches within the grid. Branch 1 is the main body of the reservoir consisting of Segment 2 extended continuously to Segment 46. Branch 2 with segments 49 to 51 represents the South Bay. Branch 3, 4, and 5 are represented by Segments 54-55, Segments 58-59 and Segments 52-63, respectively. Layer assignments are shown in Figure 3.2. The top layers from 1 through 31 are designated to be half a meter thick for higher resolution to capture the thermocline layer, which includes the Quabbin transfer when the reservoir is stratified. Layers 32 and 33 are 0.75 meters thick while layer 34 through 47 are 1.5 meters thick as less vertical resolution is needed for the hypolimnion layer. Finer grid resolution for more accurate modeling is achievable by increasing the number of layers and reducing layer thickness.

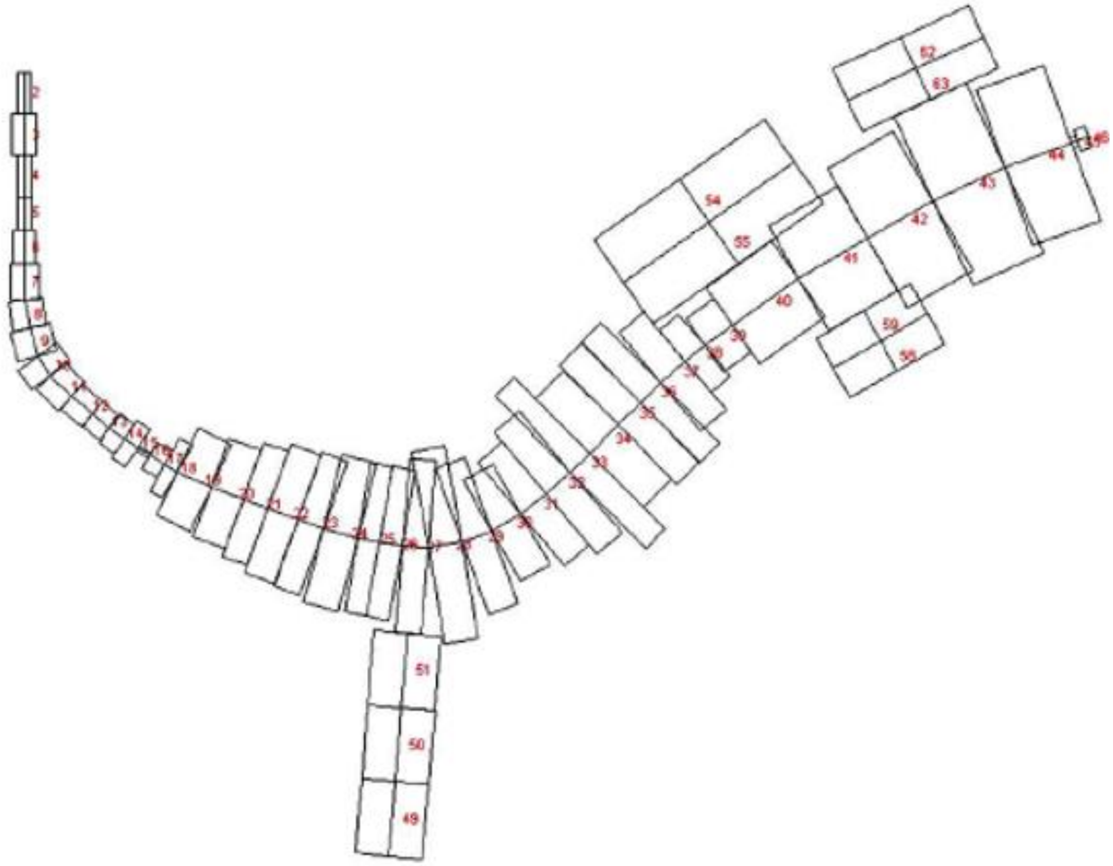

Figure 3.1 Plan View of CE-QUAL-W2 Model Segments.

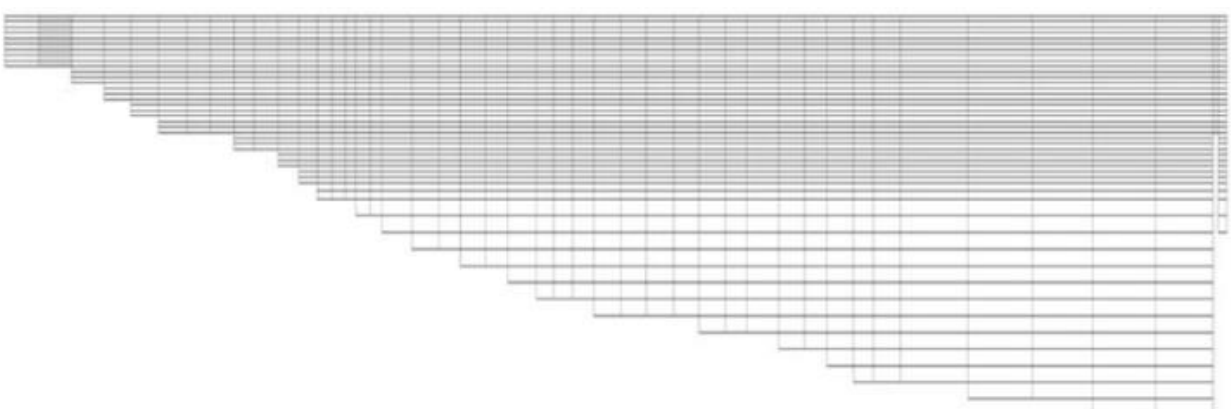

Figure 3.2 Profile View of CE-QUAL-W2 Model Layers

Segment 15 represents the short and narrow channel under the Sterling Street bridge on Route 140 that connects the Thomas Basin with the main body of the reservoir. The water elevation of the

Wachusett Reservoir was lowered, and a cofferdam was installed to enable dewatering, prior to the construction of the Cosgrove Intake; the intake area is represented by Segment 46. After the completion of the intake, cuts were made in the cofferdam to enable water withdrawal at two intakes at elevations 343 ft (104.3 m) and 363 ft (110.6 m) (MDC/DWM, 2001). The remainder of the uncut cofferdam was submerged underwater as the water surface elevation increased to restore storage volume. Segment 45 (the cofferdam opening) historically has been modeled as a rectangular cut with uniform width of 328 ft (100 m) and to a depth of 363 ft (110.7 m). However, reconsideration of the construction plan suggested that he cuts made were in fact not uniform and adjustments to Segment 45 and the adjacent Segment 46 (next to intake) bathymetries were investigated as discussed in a later section of this report.

Two intake elevations offer reservoir management the choice to select or mix water with different characteristics during reservoir stratification. The lower withdrawal at 343ft (104.3 m) is typically used in the model (and reality) unless specified otherwise. The Cosgrove Intake is modeled as a selective line sink in CE-QUAL-W2 within layer 33. The boundary for selective withdrawal is initially set as the top layer 2 to the bottom of layer 35. Selective withdrawal does not occur above layer 2 or below layer 35 within the model. During reservoir completely mixed conditions, the model assigns a vertical withdrawal zone from layer 2 to layer 35. As the water column become more stratified, the zone of withdrawal shrinks. (Coles and Wells, 2015).

3.2 Input Data

CE-QUAL-W2 is a deterministic model that requires temporal hydrodynamic and water quality input data for calibration. Meteorological, reservoir inflow and outflow, along with water quality data, need to be collected from various sources and processed into accepted model formats. Some data, such as meteorological, are recommended at certain temporal resolution to produce more accurate model outputs (Coles and Wells, 2015). Other inputs, such as tributary water quality, are based on data availability and are interpolated to produce daily resolutions. Most of the data used in the Wachusett model are provided by MWRA and DCR.

3.2.1 Tributary Data

The United States Geographical Survey (USGS) installed and maintains flow gauging stations in three of the nine tributaries flowing into Wachusett Reservoir. Daily mean discharge data were obtained from their website for the Stillwater and Quinapoxet Rivers, whose watersheds account for an estimated 73% of the total watershed area. One of the seven minor tributaries (Gates Brook) was recently gauged but historically, the seven minor tributary flows were approximated using Equation 1 below due to lack of gauging stations:

$$Tributary\ Flow\ \left(\frac{m^3}{s}\right) = \left(\frac{Stillwater\ Dicharge\ (\frac{m^3}{s})}{Stillwater\ watershed\ area\ (m^2)}\right) X\ (Tributary\ Watershed\ Area\ (m^2)) \quad [Equation\ 1]$$

MWRA collects Quabbin transfer discharge rate and water quality data. They also record Wachusett Reservoir outflows via the Cosgrove Intake withdrawal, Nashua River release, Wachusett Aqueduct, and withdrawals by towns. Figure 3.3 shows the percent contribution to the total inflows and outflows of the Wachusett Reservoir in 2015. The Quabbin transfer is typically the largest inflow to the reservoir, constituting approximately 38 to 60% of Wachusett Reservoir total annual inflow as discussed by Clark (2013). The largest outflow was the Cosgrove Intake withdrawal.

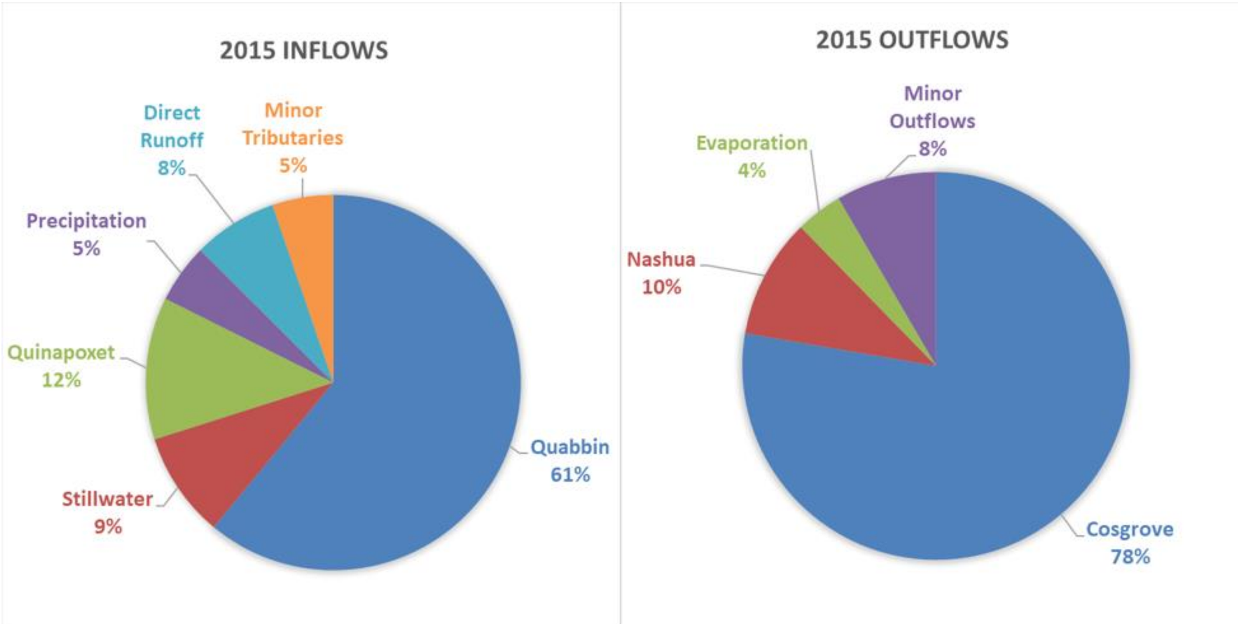

Figure 3.3 Percent Contribution of Inflows and Outflows (2015)

DCR collects biweekly grab samples from all nine tributaries flowing into the reservoir. The biweekly samples are analyzed for specific conductivity, turbidity, and water temperature. Monthly laboratory tests are conducted for UV_{254}, total phosphorous, phosphate, ammonium, nitrate, total and dissolved organic carbon.

3.2.2 Meteorological Data

Meteorological data are collected from the National Oceanic and Atmospheric Administration (NOAA) website. The closest available NOAA weather station is the Worcester Airport, approximately 10 miles southwest of Wachusett Reservoir. Temporal resolution of hourly cloud cover, wind speed, wind direction, dew point temperature and air temperature are available to be incorporated into the model. MWRA operates a weather station next to the Cosgrove Intake structure with collection of similar data. However, UMass has been advised that meteorological data collected at this station maybe affected by localized wind producing unreliable results. Hourly precipitation amounts are also collected at the Worcester Airport NOAA weather station. Weekly concentration of constituents in precipitation at a site near the Quabbin reservoir such as pH, ammonium, and sulfate are determined by the National Atmospheric Deposition Program (NADP).

3.3 Model Calibration Overview

Models for the Wachusett Reservoir are calibrated using measured hydrodynamic and water quality parameters of the actual reservoir system. The hydrodynamic water balance is calibrated based on measured, calculated and modeled water surface elevations using a water balance spreadsheet. Temperature calibration ensures that the model's total heat budget is correct, verifying that tributary inflows and meteorological data are reasonable. Specific conductivity calibration validates the transport of conservative constituents across the reservoir and verifies the ability to capture the Quabbin interflow, which is low in specific conductivity compared to bulk Wachusett Reservoir water and has a colder temperature than the Wachusett epilimnion during stratified conditions.

3.3.1 Water Balance

Figure 3.4 and Figure 3.5 show typical gauged major inflows and outflows for the Wachusett Reservoir for calendar year 2015. The two major tributaries consist of the Quinapoxet River and Stillwater River, which have a combined watershed area estimated to be 73% of the total Wachusett Reservoir basin (Tobiason, et al, 2002). Minor tributary inflows are not gauged by the United States Geological Survey (USGS); therefore, discharges are estimated using a Stillwater River based runoff ratio as discussed in section 3.2.1.

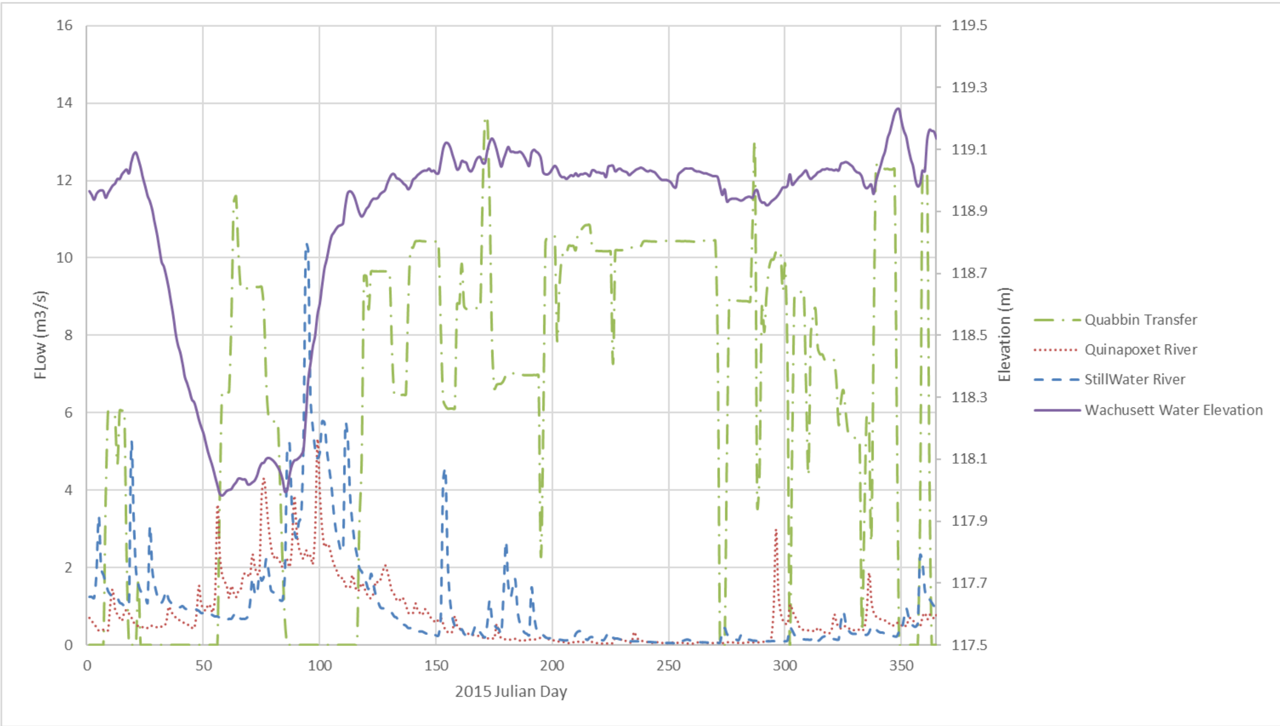

Figure 3.4 Calendar Year 2015: Major Daily Inflows into the Wachusett Reservoir.

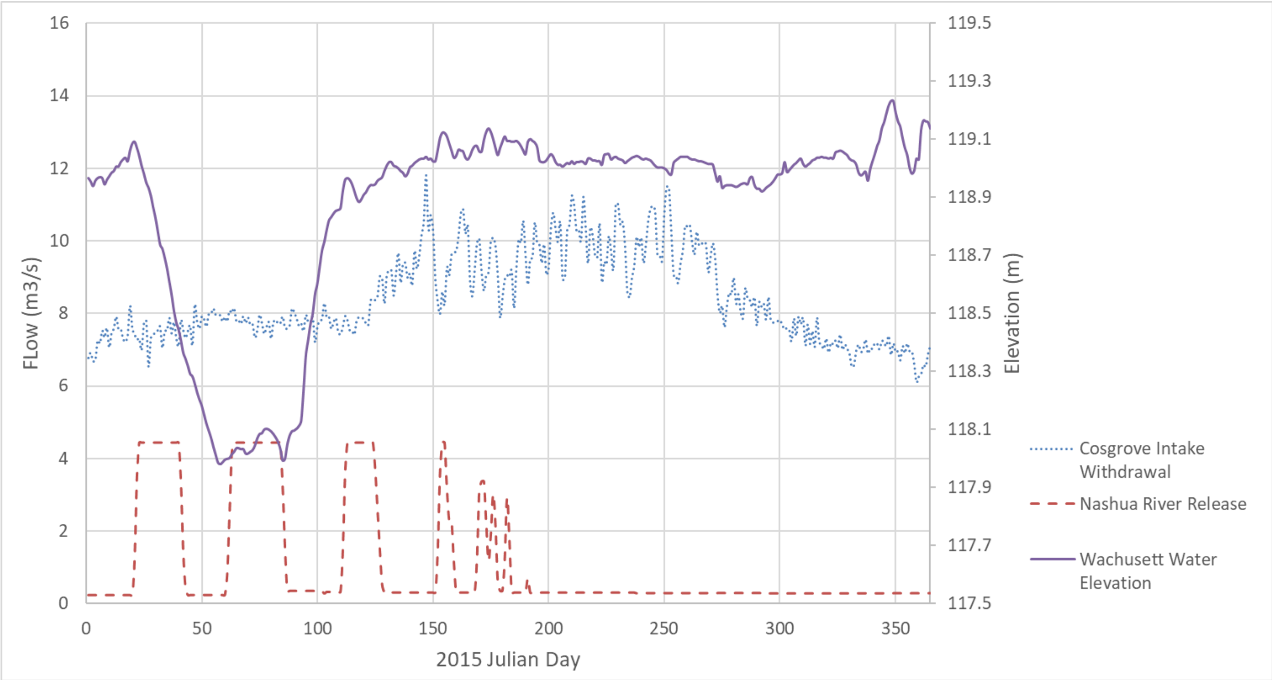

Figure 3.5 Calendar Year 2015: Major Daily Outflows of the Wachusett Reservoir.

A continuous gauging station was recently installed in the mouth of a minor tributary (Gates Brook), however the Gates Brook data have not yet been implemented into the CE-QUAL-W2 models. The Quabbin transfer is utilized to maintain Wachusett Reservoir water surface elevation and influence water quality. The Cosgrove Intake was the largest outflow for calendar year 2015 with highest demand during the summer periods from Julian Day (JD) 150 to 275

Nearly all measuring instruments come with a margin of error specified in the user's manual regarding the recorded value(s). Uncertainties in water balance data also exists due to the use of calculated evaporation rates, direct runoff and minor tributary discharges. Calibration factors are used in the water balance spreadsheet to account for the uncertainty and variability in measured data. All inflow and outflow data for Wachusett Reservoir are transferred into a water balance worksheet and multiplied by a default calibration coefficient of 1, indicating no adjustments made. MWRA measured water surface elevation is assumed 100% accurate throughout the water balance calibration process. The objective of the process is to match the calculated to the measured water surface elevations as closely as possible. Daily calculated water surface elevation (WSE) is determined by calculating the daily net change in reservoir volume based on daily reservoir inflows and outflows. Changes in volume are converted to changes in water surface elevation using a volume versus elevation hypsometric curve that is based on the reservoir bathymetry. The differences between the measured and calculated water surface elevations are minimized using the Microsoft Excel SOLVER function by adjusting the calibration factors. A calibration factor of 1.1 results in a 10% increase in a flow while a factor of 0.9 will result in a 10% reduction. Prior to a SOLVER run, constraints are established to prevent variation by 10% for most parameters and by a maximum of 30% for some calibration factors. SOLVER attempts to minimize the sum of square residuals of the measured versus calculated water surface elevations as shown in Equation 2.

$$Sum\ of\ Square\ Residuals(SSR)\ = \Sigma(Measurd\ WSE - Calculated\ WSE)^2 \qquad \text{[Equation 2]}$$

The sum of square residuals (SSR) is generated by summation over daily time steps for each calendar year and decreases as the calculated water surface elevation becomes closer to the measured elevation based on use of the calibration coefficients. The SSR value for each calendar year is used to produce a root mean squared error (RMSE) via Equation 3 below:

$$RMS = \sqrt{\frac{\text{SSR}}{Number\ of\ Days\ in\ the\ year}} \qquad \text{[Equation 3]}$$

The RMSE for measured and calculated elevations are 0.04 m in 2015 and 0.06 m in 2016. Table 3.1 shows the calibration factors Excel SOLVER used to minimize the differences between measured WSE and calculated WSE for calendar year 2015 and 2016. The calibration factors for calendar years 2015 and 2016 are relatively similar for nearly all the inflows except for the Quinapoxet River. The Quinapoxet River experienced a lower factor of 0.77 for calendar year 2015 compared to 0.99 for 2016. However, all the calibration factors are within the historical range of calibration factors used by UMass dating back to 1994.

Table 3. 1 Calibration Factors used in Water Balance

Inflows	2015	2016	Annual Averages (1994-2016)	Historical Range (1994-2016)
Direct Runoff	1.06	1.09	1.03	0.70-1.62
French Brook	1.06	1.09	1.00	0.70-1.35
Gates Brook	1.06	1.09	1.05	0.70-2.00
Malagasco Brook	1.06	1.09	1.00	0.70-1.35
Malden Brook	1.06	1.09	1.00	0.70-1.35
Muddy Brook	1.06	1.09	1.00	0.70-1.35
Nashua River	0.93	1.00	0.92	0.70-1.30
Quabbin Aqueduct	1.00	1.00	1.01	0.93-1.16
Quinapoxet River	0.77	0.99	1.11	0.72-1.30
Stillwater River	1.05	1.01	0.95	0.70-1.28
Waushacum Brook	1.06	1.09	1.02	0.70-1.65
West Boylston Brook	1.06	1.09	1.02	0.70-1.35

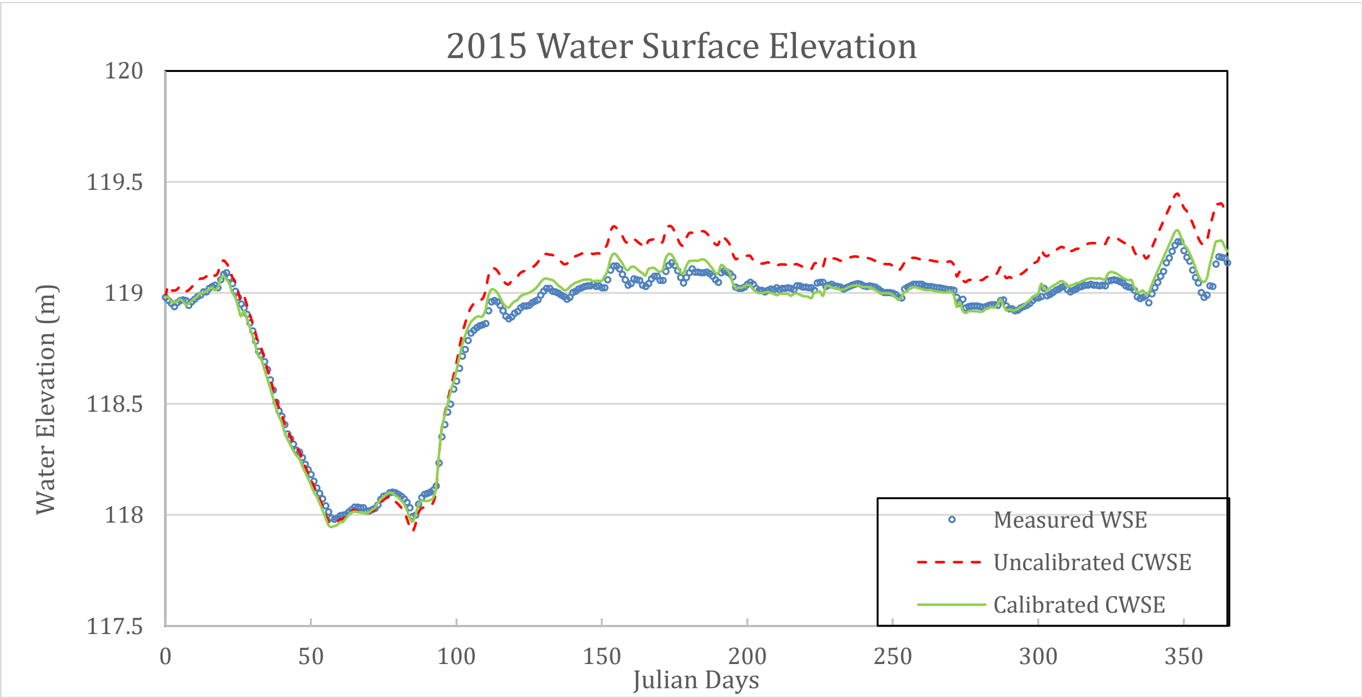

Figure 3.6 Measured, Pre-calibrated and Calibrated Calculated WSE 2015.

Figure 3.6 shows the results of post Excel SOLVER optimization on minimizing the errors between the measured and calculated water surface elevation. The uncalibrated calculated water surface elevation (CWSE) was overestimated starting on Julian Day 2 to 25 and underestimated between Julian Day 50 to 100. The calibrated CWSE rectified some of the differences to better represent the actual system.

3.3.2 Water Quality Calibration: Temperature and Specific Conductance

The MWRA installed an instrument that measures water temperature and specific conductivity at the CIT in increments of every 15-minute, year-round. Figure 3.7 illustrates the MWRA measured parameters at the CIT over the course of 2015. Reservoir temperature is low in the winter, rises during the summer, and cools as winter approaches again. Temperature values fluctuate drastically between Julian Days 125 to 160 due to stratification and wind. Sojkowski (2009) speculated that the wind direction near the intake structure will have an influence on the characteristics of water leaving via the CIT. For example, wind traveling towards the direction of the intake structure would push warmer water in the epilimnion layer down towards the intake. Wind traveling away from the intake would cause colder water in the hypolimnion layer to travel upwards and to be withdrawn by the intake. Specific conductivity is relatively constant in the first 100 Julian Days and from Julian Days 275 to 365, when the reservoir is in completely mixed conditions. The value fluctuates during the summer time as the reservoir becomes stratified and the intake withdraws water of varying characteristics.

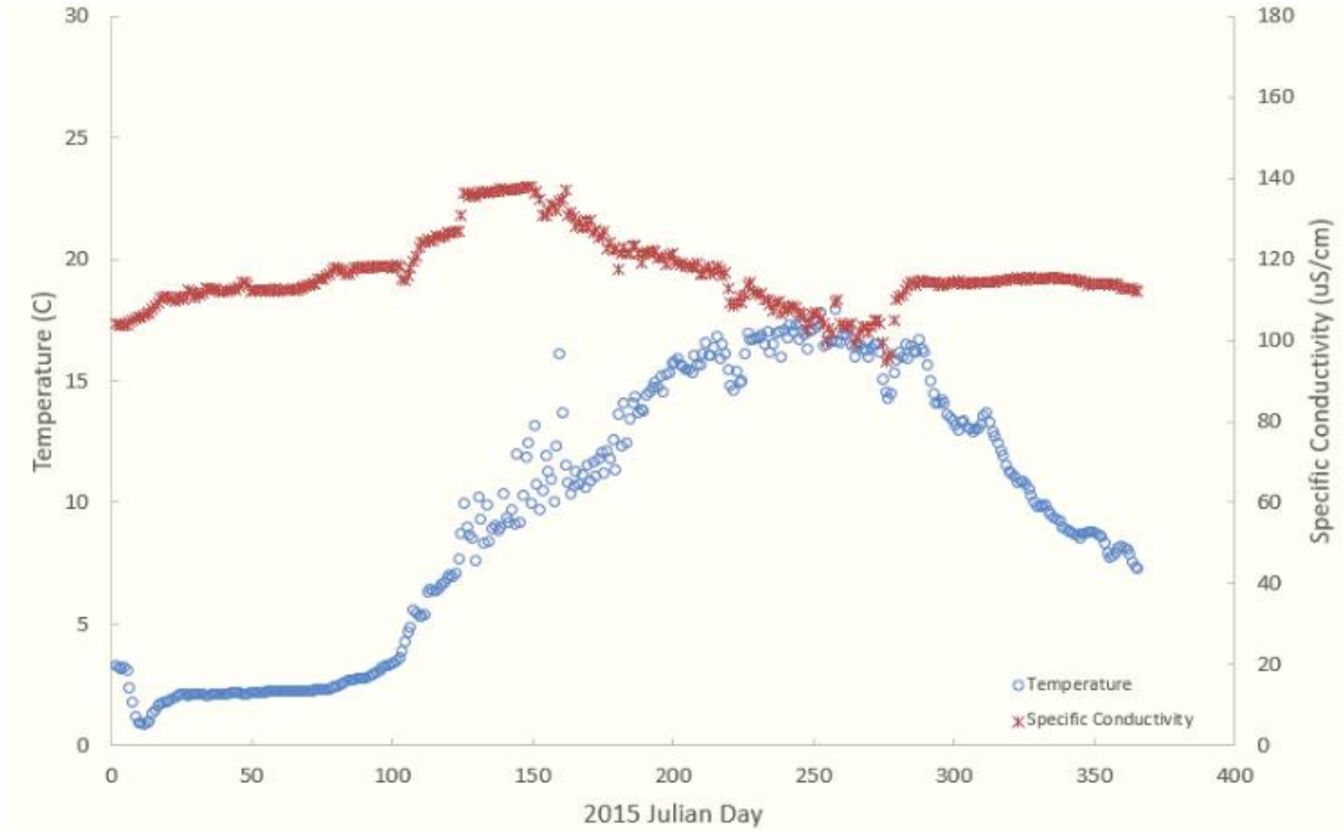

Figure 3.7 Measured Water Qualities at CIT: 2015

The DCR has been measuring water profile data at several locations within the Wachusett Reservoir dating back to at least 1998. They travel by boat to designated sites with assigned latitude and longitude coordinates and use a depth profile instruments to measure temperature, specific conductivity, dissolved oxygen (DO), and pH. Chlorophyll was added in 2011 and turbidity was added in 2015 to the parameters measured too. Some locations are sporadically measured while others, such as BN3417 in the North Basin, are frequently sampled each year and are thus used for model calibration. MWRA recently (2016) installed moored buoys that capture water profile data four times per day; one buy is stationed in the North Basin, relatively close to the DCR sampling site. The buoy is removed prior to reservoir ice formation to prevent damage to the probes. When installed, the buoy-based profiles offer greater frequency of water profile data through the year.

Profile data collected by the two agencies offer excellent opportunities for data comparison and even better CE-QUAL-W2 calibration. The high temporal resolution MWRA profile data could offer a more precise timing assessment of the Quabbin interflow arrival time.

Figures 3.8 and 3.9 show all the 2015 temperature and specific conductance profile dates when DCR made measurements at the North Basin site. Similar dates for 20016 are found in Figure A4 in the Appendix. CIT water quality data for those corresponding dates are plotted as “X”. Water characteristics at the CIT are different from DCR profiles during the summer, most likely due to a blend of water from various stratified layers entering the intake. Figure 3.8 depicts the typical reservoir temperature behavior as the water responds to changing air temperatures throughout the year. The reservoir water column transitions from completely mixed in early Spring (not shown) to thermally stratified in the Summer by JD 134. As the season changes from Summer to Fall, cooler air temperature reduces the extend of epilimnion temperature and thermal stratification. The temperature gradient in the water column completely dissipates by JD 320, showing incomplete mixing conditions.

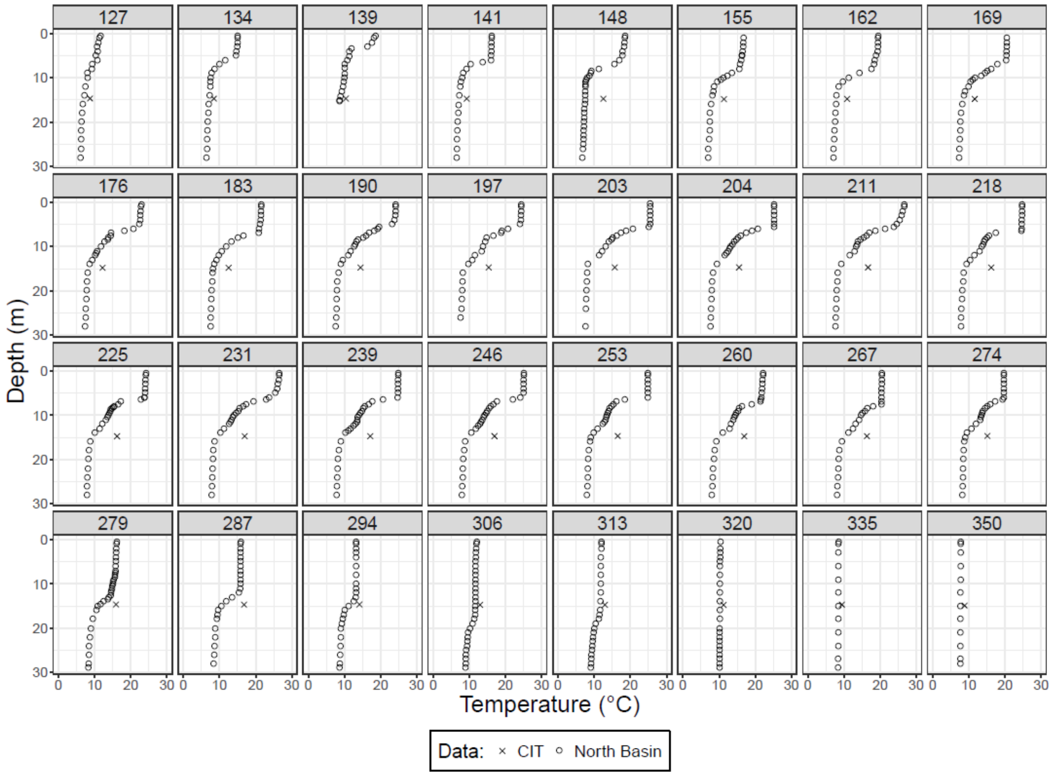

Figure 3.8 DCR Measured Temperature Profiles: 2015

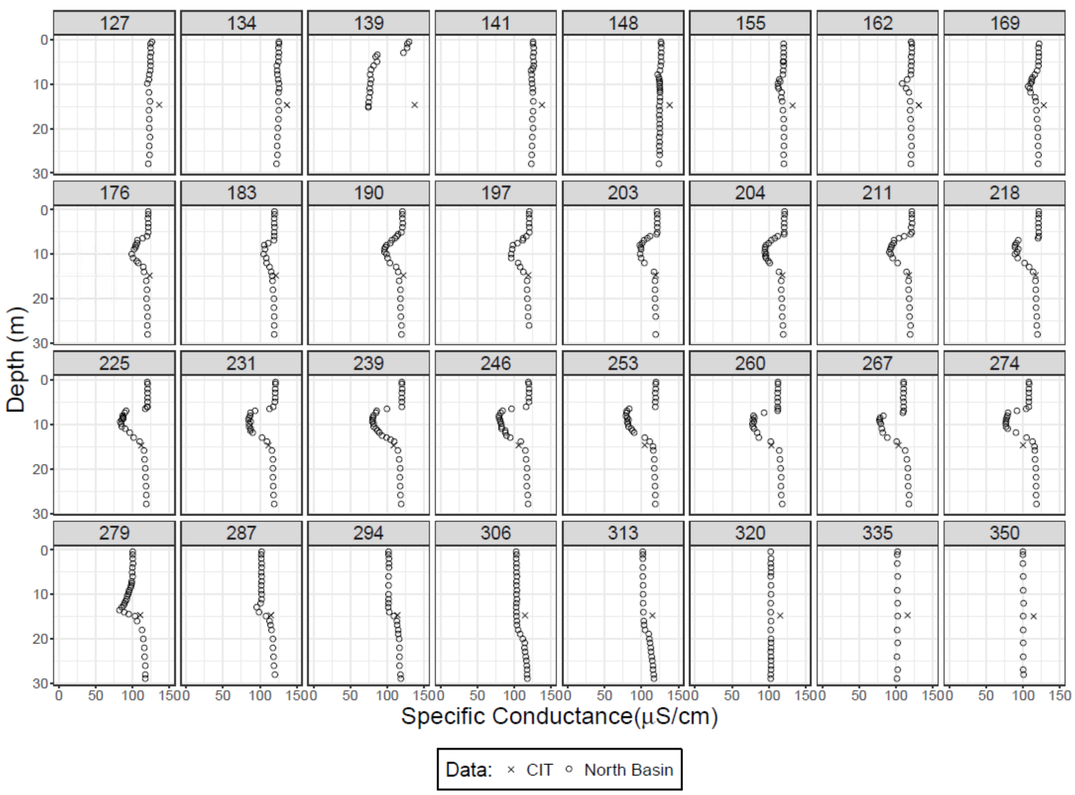

Figure 3.9 DCR Measured Specific Conductivity Profiles: 2015

The specific conductivity profiles in Figure 3.9 capture the presence of the Quabbin interflow during stratified conditions. The interflow is characterized by low specific conductivity and medium temperature, and travels between 5 to 15 meters below the reservoir water surface elevation. Uniformity within the water profile plots further supports the completely mixed condition from JD 320 and beyond. Julian Day 139 should be ignored due to incomplete measurement and erroneous data. A problem was noticed by comparing MWRA data for the CIT withdrawal and DCR measured water profile data at the North Basin. During Julian Days 320 to 350, differences in measured specific conductivity values are observed. However, both locations should have produced identical results for both water temperature and specific conductivity since the reservoir water is spatially homogenous everywhere. This prompted an investigation into the possible causes of data discrepancies.

3.3.3 Data Inconsistency

Results from an initial investigation suggested there is a long history of some inconsistencies between measured water characteristics for the Cosgrove Intake withdrawal and measured water characteristics for reservoir profiles at the North Basin. In her Master's Report, Clark (2013) noted these inconsistencies dated as far back as 2004. Figure 3.10 shows days when the North Basin temperature profile is relatively uniform with depth, implying reservoir turnover and homogeneity across the entire waterbody. Water temperature at the Cosgrove Intake for those corresponding dates are plotted as well. Temperature measurements at Cosgrove Intake matched the uniform temperature conditions at North Basin almost exactly on several occasions dating back to 2010, while maximum differences of 1 to 2 °C occurred on other days. The measured water temperature is higher at the intake than at the North Basin by an average of 1.2 °C as shown in Figure 3.10.

The differences between measured profile and Cosgrove Intake specific conductivity on the other hand are much more significant (Figure 3.11). As much as almost 15% difference in specific conductivity occurred between the two locations. Measured CIT specific conductivity is also higher than what was measured at the North Basin.

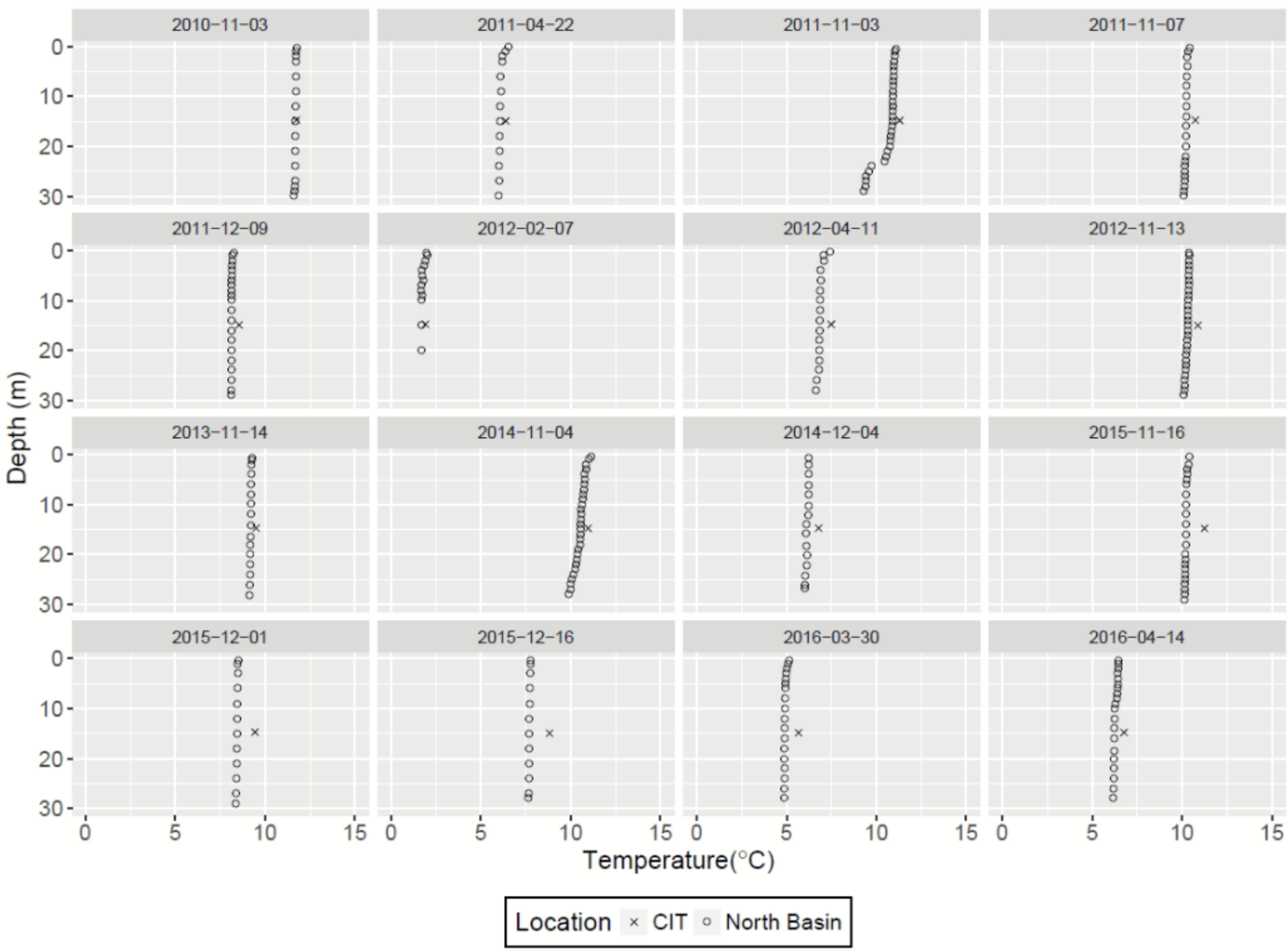

Figure 3.10 Days with Near Uniform Temperature Profiles

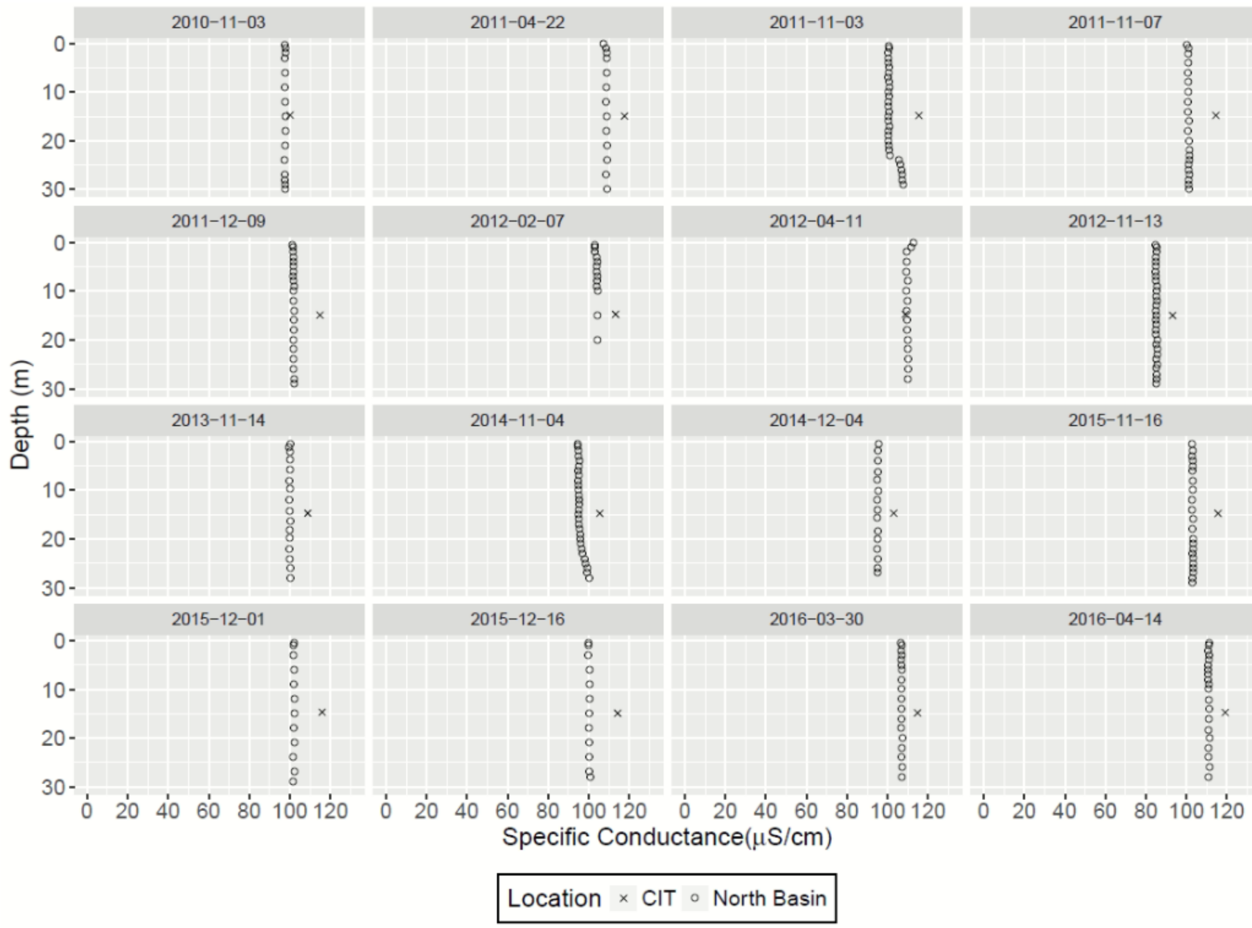

Figure 3.11 Days with Near Uniform Specific Conductivity Profiles.

The MWRA speculated that the presence of stagnant water on one side of the intake structure could have caused non-representative conditions to occur for the measurement instrument at the Cosgrove Intake therefore resulting in differences between the North Basin and CIT data. As mentioned previously, the intake has withdrawal openings at two elevations, one at 104.3 meters and the other at 110.6 meters above mean sea level. An important piece of information regarding the Cosgrove Intake was recently made known to UMass. There are withdrawal openings on both the North and South side of the intake at each of the elevations for a combined total of four openings. The temperature and specific conductivity measurements used to represent CIT water quality were recorded on the North side of the intake. Water temperature is measured every 15-

minute again at the Carroll Water Treatment Plant for treatment related reasons. Withdrawal at Cosgrove Intake is balanced between the north and south sides during normal reservoir operations.

However, there are times due to maintenance or repair when only the south side is operated for water withdrawal while the north side flow is reduced or zero. When one side of the intake is utilized over the other, discrepancies between temperature recorded at the CIT and CWTP emerged (Figure 3.12). Discrepancies occurred frequently throughout the year with drastic differences in temperature especially during the Summer. Differences of as much as 5°C between the two MWRA operated probes are observed. Variation in water temperature would cause differences in conductivity, which is temperature dependent, but specific conductivity is normalized to 25°C so it should not be affected in principle by temperature. Unfortunately, specific conductivity is not currently a measured parameter at the CWTP, therefore a comparison with the CIT measurement cannot be made. The MWRA is in the process of installing a probe at thr CWTP that measures specific conductance, thus the data will be online at the DCR Water Quality website in the future for comparison. The cause of the data discrepancy has not been identified. Another speculation is that the probes used by the two agencies are calibrated differently. Both the MWRA and DCR are currently investigating the possible causes with plans made to compare the different probes used for measurements.

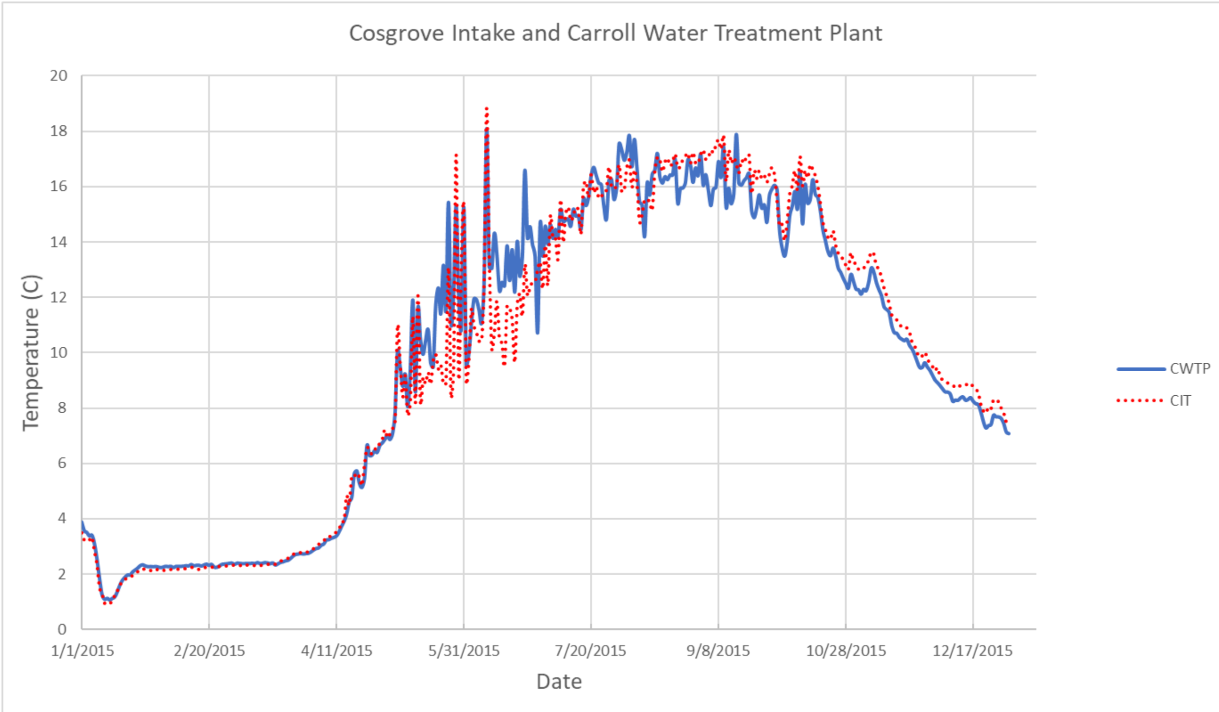

Figure 3.12 Calendar Year 2015: CIT and CWTP Measured Temperature.

The data inconsistency creates a dilemma in establishing initial reservoir conditions to calibrate the Wachusett Reservoir model. Conducting a CE-QUAL-W2 model run requires user defined reservoir initial conditions on January 1st of any modeled year. For the Wachusett Reservoir model, spatial homogeneity and uniformity across the entire reservoir in both temperature and specific conductivity are assumed. This was done because of the ease of model initialization and because the reservoir is typically not significantly stratified at that time. January 1st water quality data for any given year are only available for water withdrawn at the Cosgrove Intake, where specific conductivity and temperature are measured year-round. The UMass Wachusett Reservoir model is calibrated to match the DCR boat collected temperature and specific conductivity profile data at the North Basin. The model initial conditions, which are initially based on data for Cosgrove Intake water, are sometimes altered to best match model simulations to DCR measured water profile data.

3.3.4 Vertical Eddy Viscosity Turbulent Closure Formulation

CE-QUAL-W2 enables user to select different process dynamic equations that are appropriate for certain waterbodies (e.g. estuaries, rivers, or reservoirs). Equation 4 below shows two of the vertical shear stress algorithms used in the model; one as a function of ν_t (TKE formulation) and one as a function of A_z (W2 formulation). The equation to be used to solve for the vertical shear stress is selected by the user for the specified vertical eddy viscosity formulation (Cole and Wells, 2015)

$$\frac{\tau_{xz}}{\rho} = \nu_t \frac{\partial U}{\partial z} = A_z \frac{\partial U}{\partial z} \qquad \text{[Equation 4]}$$

ν_t and A_z are both defined as the vertical eddy viscosity (m^2/s), U is the longitudinal velocity (m/s), τ_{xz} is the shear stress acting in x-direction on z plane of the control volume (N/m^2) and ρ is the water density (kg/m^3). A_z is calculated using the W2 formulation developed by Cole and Buschak (1995) while ν_t is calculated using the turbulent kinetic energy (TKE) formulation developed by Wells (2003). The W2 formulation is usually selected for reservoirs where wind shear is dominant and includes the effects of cross-shear from wind, tributary, and branch inflows. Cole and Wells (2015) recommended use of the W2 formulation with explicit solution for waterbodies containing deep sections that could be stratified. The TKE formulation on the other hand is applicable to any general waterbody and is a typical application of the k-ε turbulence model. The TKE formulation with implicit solution removes low model time steps and enables users to run simulations with much larger time steps. Cole and Wells (2015) noted the selection of a turbulent closure formulation is difficult. Temperature profiles should be used as the deciding factor in formulation selection in the absence of current velocity data. The climate change model conducted at UMass (Jeznach 2016, Jeznach and Tobiason 2015) utilized the TKE implicit formulation. She noted that the use of the TKE formulation resulted in significantly faster model run time, especially beneficial for 100-year climate model simulation.

The TKE formulation for vertical eddy viscosity is defined by Equation 5 as follow:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \qquad \text{[Equation 5]}$$

C_μ is an empirical constant, k is the turbulent kinetic energy in m^2/s^2, ε is the turbulent dissipation in m^2/s^3. k and ε are derived and explained in greater detail in the Cole and Wells (2015) CE-QUAL-W2 user manual. ν_t is substituted into Equation 4 where the shear stress is determined. The vertical eddy viscosity used in the W2 formulation is given by Equation 6. K is the von Karman constant of 0.4, C is a constant of 1.5, l_m is the mixing length in meters, R_i is the Richardson number, τ_{wy} is the lateral cross wind shear at the surface, and $\tau_{y\ trib}$ is the shear from tributaries.

$$A_z = \mathrm{K}\left(\frac{lm^2}{2}\right)\sqrt{\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\tau_{wy}e^{-2kz} + \tau_{y\ trib}}{\rho \nu_t}\right)^2}\, e^{-CR_i} \qquad \text{[Equation 6]}$$

3.3.5 Bathymetry Adjustment

Historically, CE-QUAL-W2 simulations conducted at UMass have struggled to capture characteristics of water withdrawn at the Cosgrove Intake during periods of reservoir stratification. The selective withdrawal algorithm used in the model tended to overestimate the actual water temperature and specific conductivity at Segment 46. Cole and Wells (2015) suggested user defined bathymetry could create difficulties in temperature calibrations and should be revisited if necessary. The idea that Segments 45 and 46 bathymetries might not necessarily best represent the actual cofferdam and intake was considered.

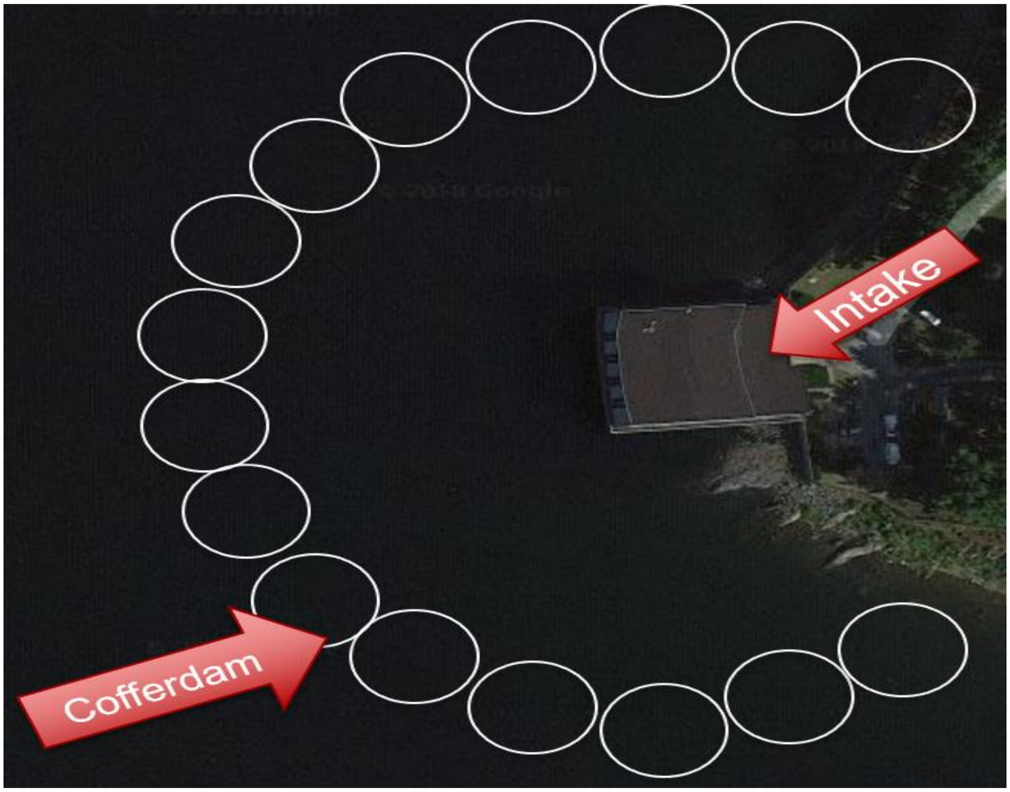

Figure 3.13 Cosgrove Intake and Cofferdam (Not to scale)

A construction plan of the Cosgrove Intake that included the final grade of an adjacent cofferdam suggested adjustments to the bathymetry file should be considered. The construction plan was not shown because of the poor scan quality however, Figure 3.13 illustrates the general layout of the Cosgrove Intake and adjacent cofferdam. Segment 45 (cut in cofferdam) should not be a constant width of 100 meters, but rather stepwise increase in width from 12.5 meters at the deepest section to 112 meters at the top. The segment length was reduced from 50 meters to 20 meters while the lowest elevation decreased from 110.7 meters to 105.7 meters above mean sea level, which increased the segment depth. Segment 45 essentially became one giant submerged multiple-step broad crested rectangular weir, positioned in front of the Cosgrove Intake. For Segment 46, a reduction in length and width from 100 meters to 50 meters and 200 meters to 120 meters, respectively, were incorporated while the lowest elevation remained unaltered at 101.2 meters above mean sea level.

3.4 Sensitivity Analyses

Sensitivity analyses are frequently conducted in computer modeling to test the robustness of a model by analyzing how independent model parameters affect dependent output variables under user specified conditions. This is a crucial step in running black-box models where users cannot access the internal algorithms to understand the logics. CE-QUAL-W2 is a white-box model with user accessible source codes separated into various files that are called upon during a model run. Sensitivity analyses for various independent inputs were investigated to compare the effects of each parameter on output results. The model parameter/coefficient under investigation was varied while everything else was held constant during sensitivity analysis. Values are selected based on a good match between the simulated and DCR measured reservoir profiles, as determined by a low RMSE value. The sensitivity analyses shown in this section are for simulations that used the W2 formulation with the old bathymetry file. Sensitivity analyses were performed for simulations that used the W2 formulation with new bathymetry and for the TKE formulation with the old and new bathymetries. The processes were the same for all the model configurations but are not shown due to redundancy.

3.4.1 Reservoir Initial Conditions: Temperature

A sensitivity analysis was performed to evaluate the effects of varying Julian Day 1 initial reservoir parameters on the modeled water temperature profiles in Segment 42 (North Basin). The Wachusett model can capture the completely mixed homogenous condition and thermal stratification periods of the reservoir shown in Figure 3.14. Drastically changing the starting initial reservoir temperature resulted in little variation of the modeled temperature profiles for the series of Julian Days plotted. Varying the initial JD 1 reservoir temperature from the 3.5°C measured at Cosgrove Intake to a lower value of 1.5°C or a higher limit of 9°C shows little impact on the temperature of reservoir water. Water temperature profiles were simulated using the W2 formulation with the historical bathymetry file (more detailed discussion later).

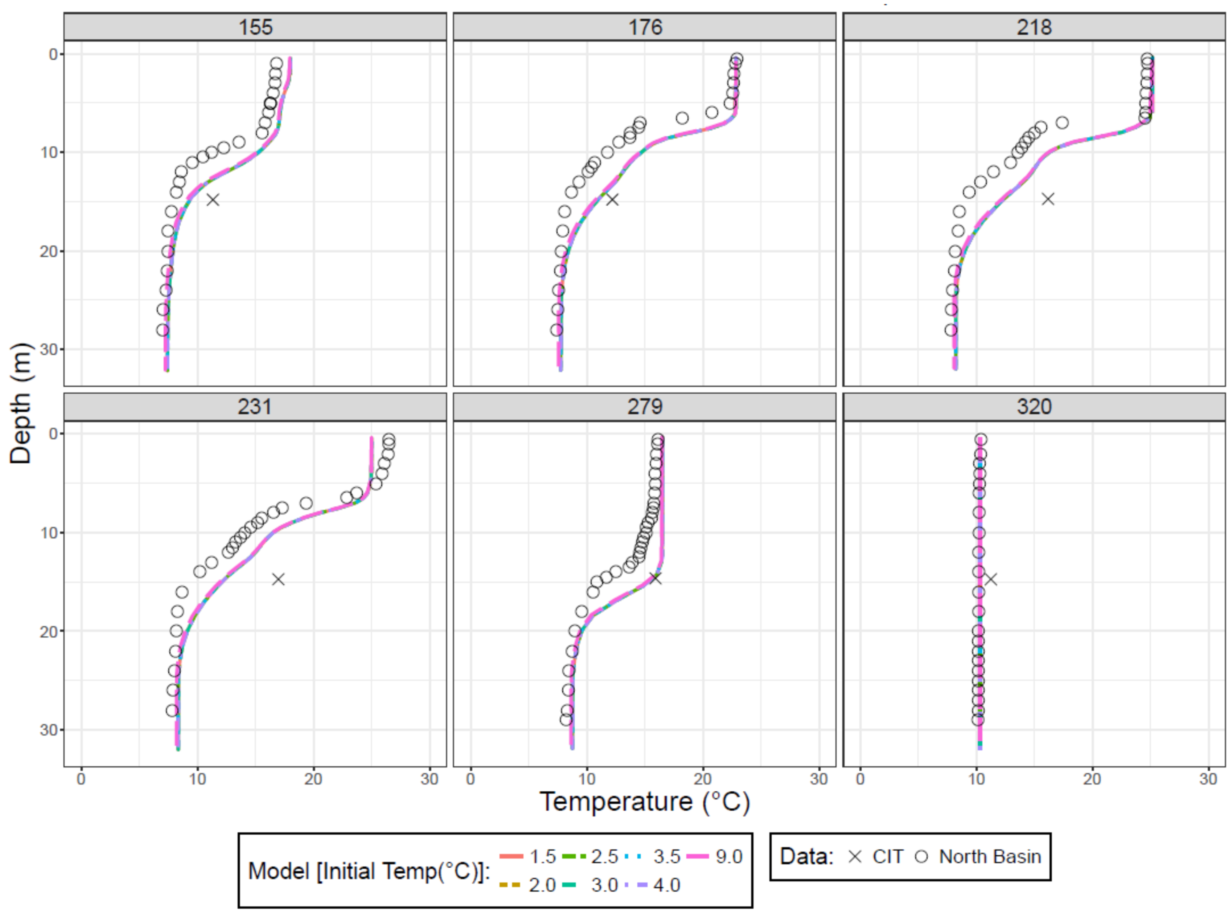

Figure 3.14 Some 2015 North Basin and Segment 42 Temperature Profiles

Water temperature at the CIT throughout calendar year 2015 was analyzed to show why starting initial reservoir temperature has minimal impact on the Figure 3.14 profiles. Figure 3.15 plots modeled temperature at the CIT with varying starting initial reservoir temperatures. Impacts of varying the modeled initial water temperature essentially vanished after JD 100 regardless of the starting condition, showing that other mechanisms dictated reservoir temperature. The driving force behind a reservoir or lake's heat budget is in fact dominated mainly by the air temperature and wind, which creates mixing, along with inflow temperature. The air-water exchange interface renders the reservoir's initial temperature condition as an insignificant factor for water temperature later in the year as evidenced in both Figure 3.14 and Figure 3.15.

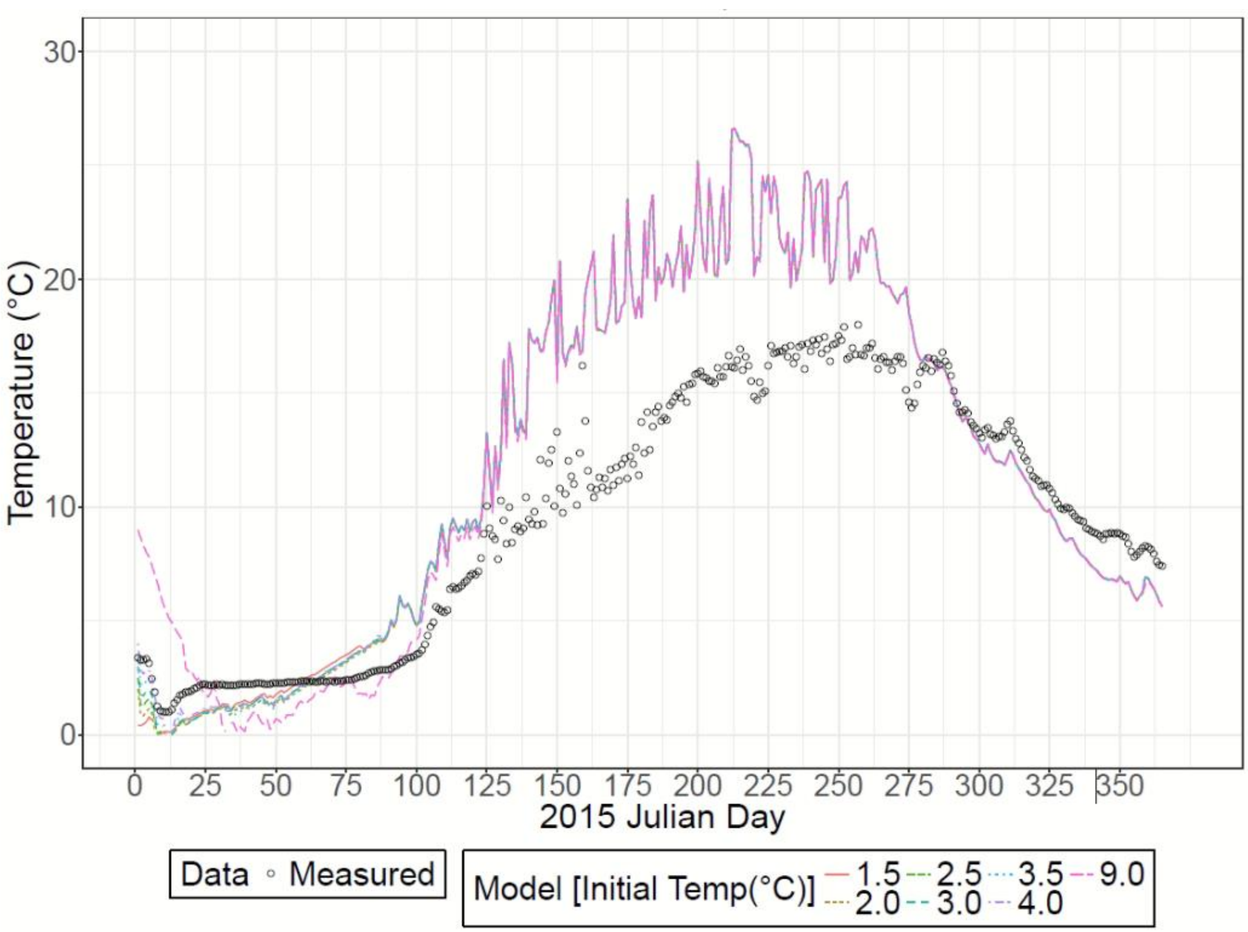

Figure 3.15 2015 Cosgrove Intake Temperature: Measured and Modeled Comparison

Water withdrawn at the actual Cosgrove Intake exhibited relatively uniform temperature between Julian Days 14 to 100 (Figure 3.15). Uniformity in withdrawn water temperature suggested ice formation occurred on the top layer of the reservoir, covering the water underneath from exposure to varying air temperature and wind. This was confirmed by Jamie Carr, an employee at DCR who verified that ice formation occurred on 1/14/2015 (JD14) and melted by 4/14/2015 (JD 104). The model struggled to simulate ice formation between Julian Days 14 to 100 as initial modeled water temperature decreased to around 0°C by Julian Day 11 and steadily increased to around 6°C by Julian Day 90. Water temperatures were overpredicted by the model by a significant margin, at some point by as much as 10°C between Julian Day 125 and 275 (Figure 3.15). The cause of model overprediction may be due to the measured data inconsistencies as mentioned in previous sections, or by inadequate model representation of the reservoir intake. The complex 3-dimensional hydrodynamics that occur at the actual cofferdam and CIT are difficult if not impossible to captured by any 2-dimensional hydrodynamic model. This challenge is one of the limitations of the CE-QUAL-W2 model that is addressed.

3.4.2 Reservoir Initial Condition: Specific Conductance

Specific conductivity (SC) is another parameter used in calibration of the Wachusett model. SC is a measurement of a water's ability to conduct an electrical current, normalized to 25°C, which is influenced by the charge and concentration of ions in the water that facilitate electrical conductance. Specific conductivity is a relatively non-reactive conservative parameter that is easy to measure and is an indirect measurement of total dissolved solids (TDS). CE-QUAL-W2 does not model specific conductivity but does simulate TDS, which is a conservative parameter.

Equation 7 developed by Tobiason et al (2002) for Wachusett Reservoir provides a ratio between TDS and SC as follows:

$$Total\ Dissolved\ Solids\ \left(\frac{mg}{L}\right) = 0.6\ X\ Specific\ Conductivity\ \left(\frac{\mu S}{cm}\right) \qquad \text{[Equation 7]}$$

The average specific conductivity on January 1st, 2015 at the Cosgrove Intake was 104 µS/cm or a total dissolved solids concentration of 62.5 mg/L based on Equation 7. As mentioned in a prior section, discrepancies between Cosgrove Intake and North Basin measured water data present a challenge in model calibration. Using the JD 1 CIT measured specific conductivity resulted in simulated model SC profiles at Segment 42 that overpredicted what the DCR measured. A sensitivity analysis shows that using an initial SC for 75 µS/cm for 2015 results in a good match of the simulated and measured values, as opposed to starting at a SC of104 µS/cm, which was measured at the intake (Figure 3.16).

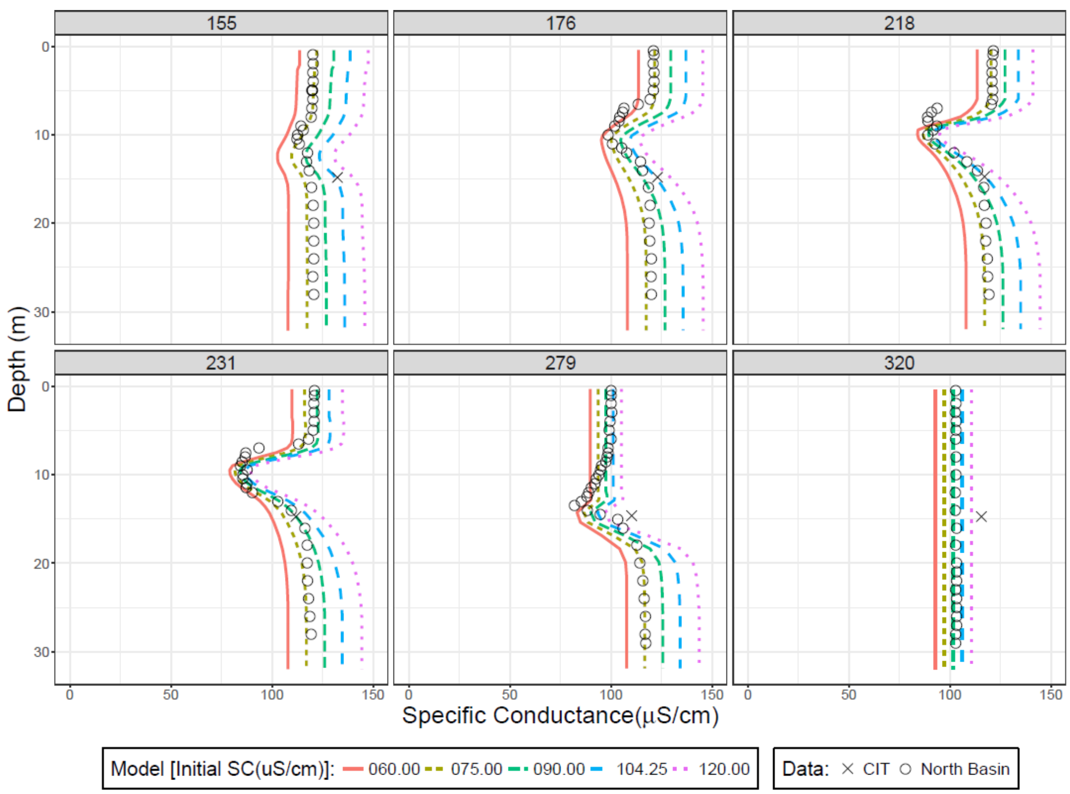

Figure 3.16 Effects of Varying Starting Initial Specific Conductivity (2015)

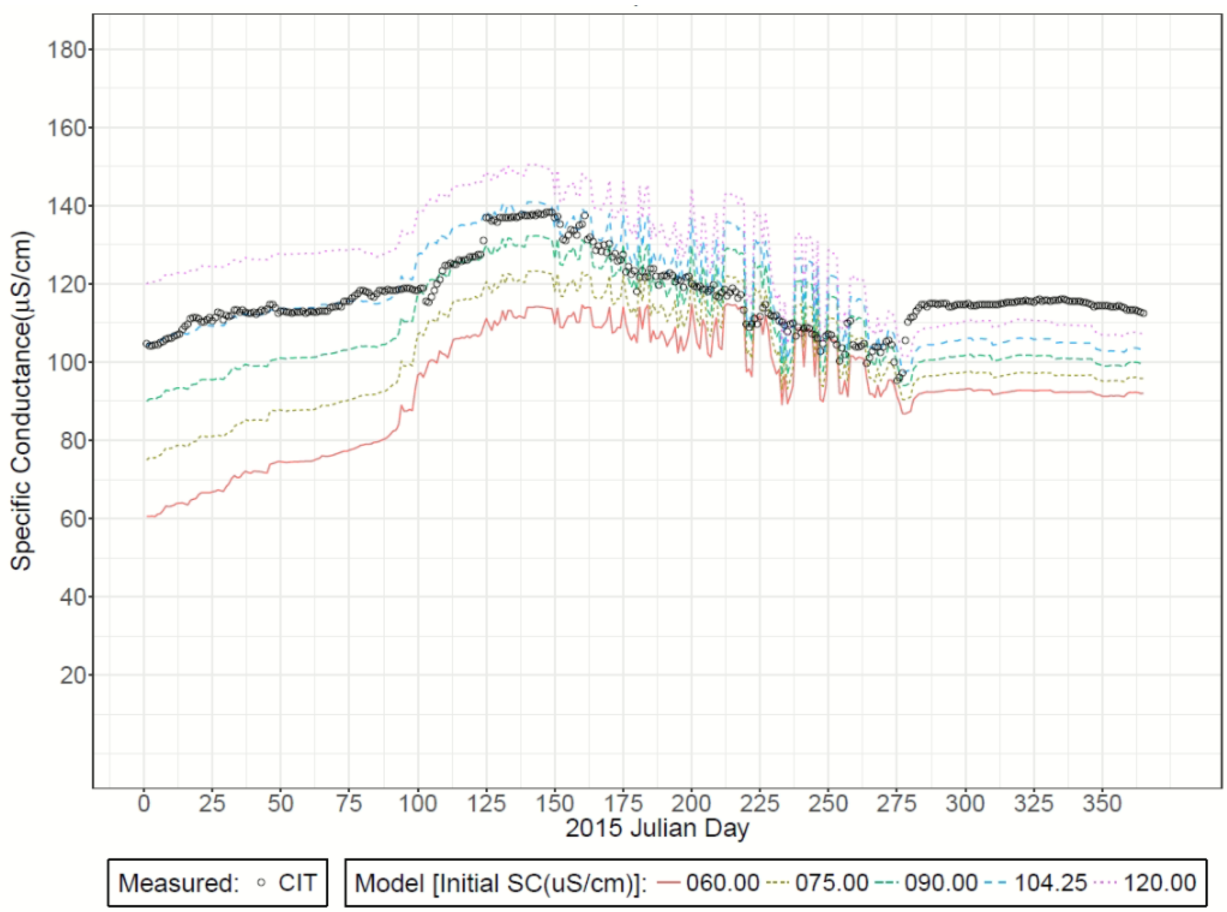

Figure 3.17 2015 Measured and Modeled Specific Conductivity at Cosgrove Intake

Figure 3.17 shows Cosgrove Intake measured SC data plotted with model data for different JD1 initial reservoir specific conductivity values. The initial value of 104 µS/cm resulted in good agreement of modeled results with the measured SC until JD 100. After JD 104, a sudden change occurred leading to a decrease for the measured SC value. This is most likely due to the complete ice melt as mentioned in a previous section. Lack of ice cover led to reservoir mixing that is driven by the wind and resulted in water of different characteristics entering the intake. The CE-QUAL-W2 selective withdrawal captured the measured water characteristics reasonably well until JD 160, when thermal stratification occurred in the reservoir. During stratification, the selective withdrawal algorithm withdraw water with higher temperature and specific conductivity compared to the measured values at the intake (Figures 3.16 and 3.17). During JD 287, relatively constant specific conductivity for the measured and modeled values suggested the reservoir was once again, completely mixed. The modeled SC using the CIT measured initial value of 104 μS/cm simulated water with lower SC than was measured at the intake for Julian Days 275 to 365.

Several speculations on what could have caused inconsistencies in modeled vs measured SC were made; some are under investigation while others are a priority for future work. One possibility is that the submerged cofferdam positioned directly in front of the intake affected the transport and mixing behavior of reservoir water. The cuts made in the cofferdam are shaped like a multiple-step broad crested rectangular weir instead of a rectangular opening that was used historically; this was discussed in Section 3.3.5. Matthews (2007) speculated that the instrument used to measure specific conductivity at the Cosgrove Intake was not calibrated to 25°C, thus resulted in higher reading than the probe used by the DCR in the North Basin. The issue of calibration looms over the topic of specific conductivity as variation in calibration procedure between the DCR and MWRA could also be a cause of the differences. The MWRA in 2016 moored a buoy that measured North Basin temperature and specific conductivity profile data four times per day; the buoy was removed prior to ice formation. Perhaps the buoy data will shed light and resolve the conductivity and temperature data conundrum between the two agencies.

3.4.3 Coefficient of Bottom Heat Exchange [CBHE]

Sediment temperature (TSED) in degrees Celsius is used in conjunction with the coefficient of bottom heat exchange (CBHE) in the CE-QUAL-W2 model. The CBHE dictates the rate of heat exchange at the sediment-water interface in the model. CE-QUAL-W2 default sediment temperature and CBHE values are 10°C and 0.3 W/m^{-2} $°C^{-1}$, respectively. Figure 3.18 shows several 2015 measured and modeled temperature profiles for different bottom heat exchange values. Adjusting the bottom heat exchange coefficient results in minimal change in the epilimnion layer except for an extreme exchange value of 3, where a reduction in surface temperature is noticeable. The simulations with the default value of 0.3 underpredicted the temperature at the very bottom of the hypolimnion layer by 1°C, while an extreme value of 3.0 overestimated the temperature by 3 °C. The sediment heat exchange value of 1 W/m^{-2} $°C^{-1}$ was selected for the 2015 model run.

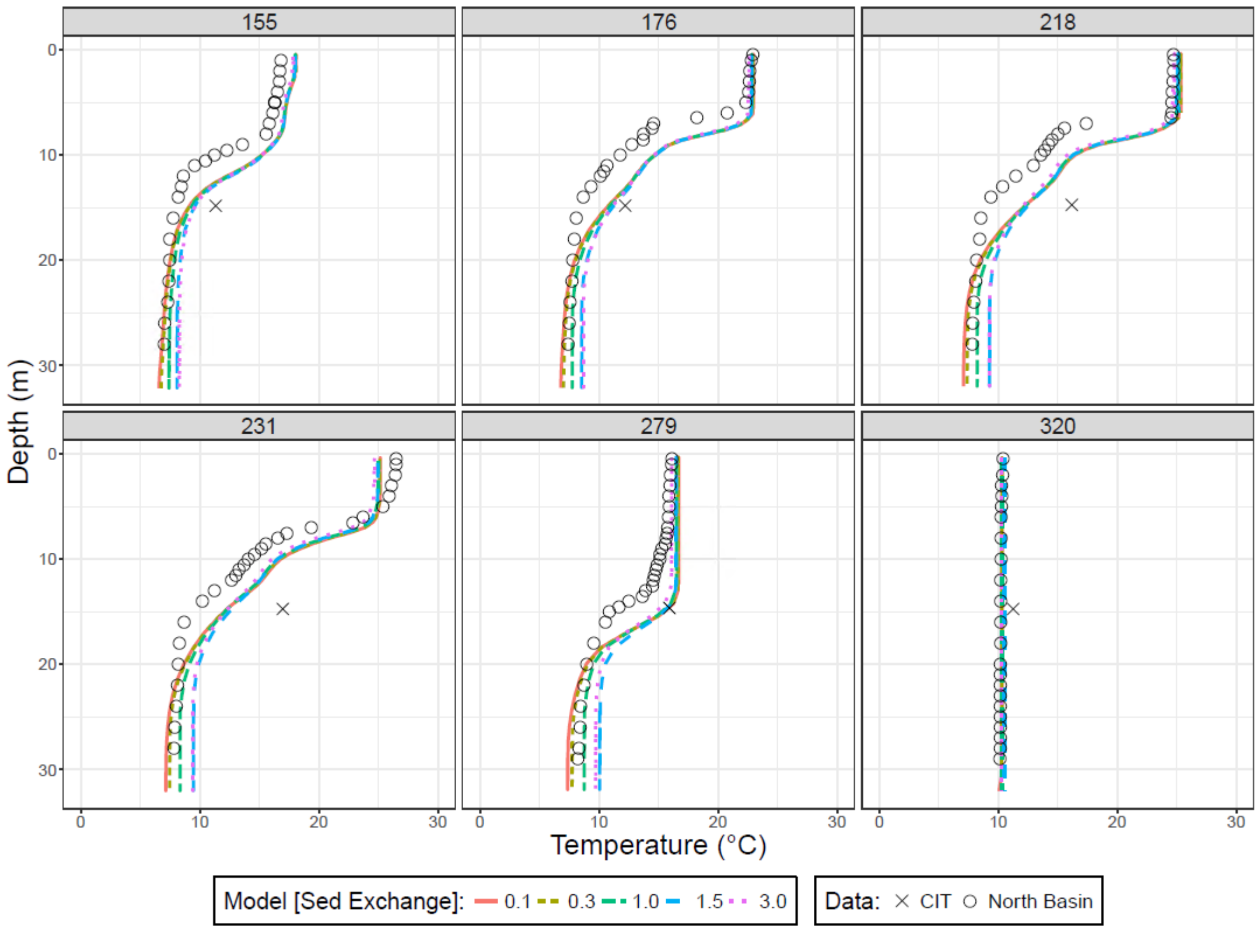

Figure 3.18 Sensitivity Analysis: CBHE (2015 W2 Old BTH)

3.4.4 Wind Sheltering Coefficient [WSC]

Constituent transport and temperature in reservoirs are driven mainly by the wind speed and air temperature. The wind sheltering coefficient (WSC) is multiplied by the wind speed to account for terrains that either reduce or magnify the impact of wind. WSC values of less than 1.0 applies a reduction while above 1.0 applies a magnification to the wind speed accounting for funneling effects; a coefficient of 1.0 represents no change to the wind speed. A WSC of 0.90 represents a 10% reduction while 1.10 represents a 10% increase in wind speed. Each segment within the model could be set at a unique WSC to account for spatial differences in topography. However, the landscape surrounding the Wachusett Reservoir is relatively uniform, thus one WSC was applied throughout the entire waterbody. The coefficient has a direct impact on reservoir hydrodynamics, which in turn affect heat and constituent transport. This makes WSC one of the most important calibration parameters, especially for reservoir temperature.

Figure 3.19 compares the effects of five different WSC on the modeled temperature profile for several days in 2015. A WSC value of 0.1 represents mountainous terrain that shield the reservoir from much of the wind's influence while 1.0 is for a completely flat field unprotected by trees or mountains. A WSC of 0.626 best captures both the epilimnion and hypolimnion layers of the measured profile and was used in model simulations. Clark (2013) used WSC of 0.625 for 2003 and 2004, 0.559 for 2005, and 0.626 for her 2006 to 2009 Wachusett Reservoir model calibrations. A notable detail is that as the WSC increases, the water profile becomes less stratified. Temperature in the epilimnion is lower while temperature for thermocline layer is higher with increasing WSC. The model shows that the temperature profile is uniform until a depth of 19 meters, while specific conductivity is essentially homogenous across the layers for a WSC value of 1.0 (Figure 3.20). The higher WSC suggests that reservoir mixing will occur even across stratified layers in the presences of strong wind. Extreme events like hurricanes or tropical storms that perpetuate strong winds could potentially induce partial or full reservoir mixing despite the existing thermal stratification. Another speculation is that strong winds will retard thermal stratification arrival time and reduce the magnitude of thermal gradient across the reservoir's water columns evidenced by the variation in WSC.

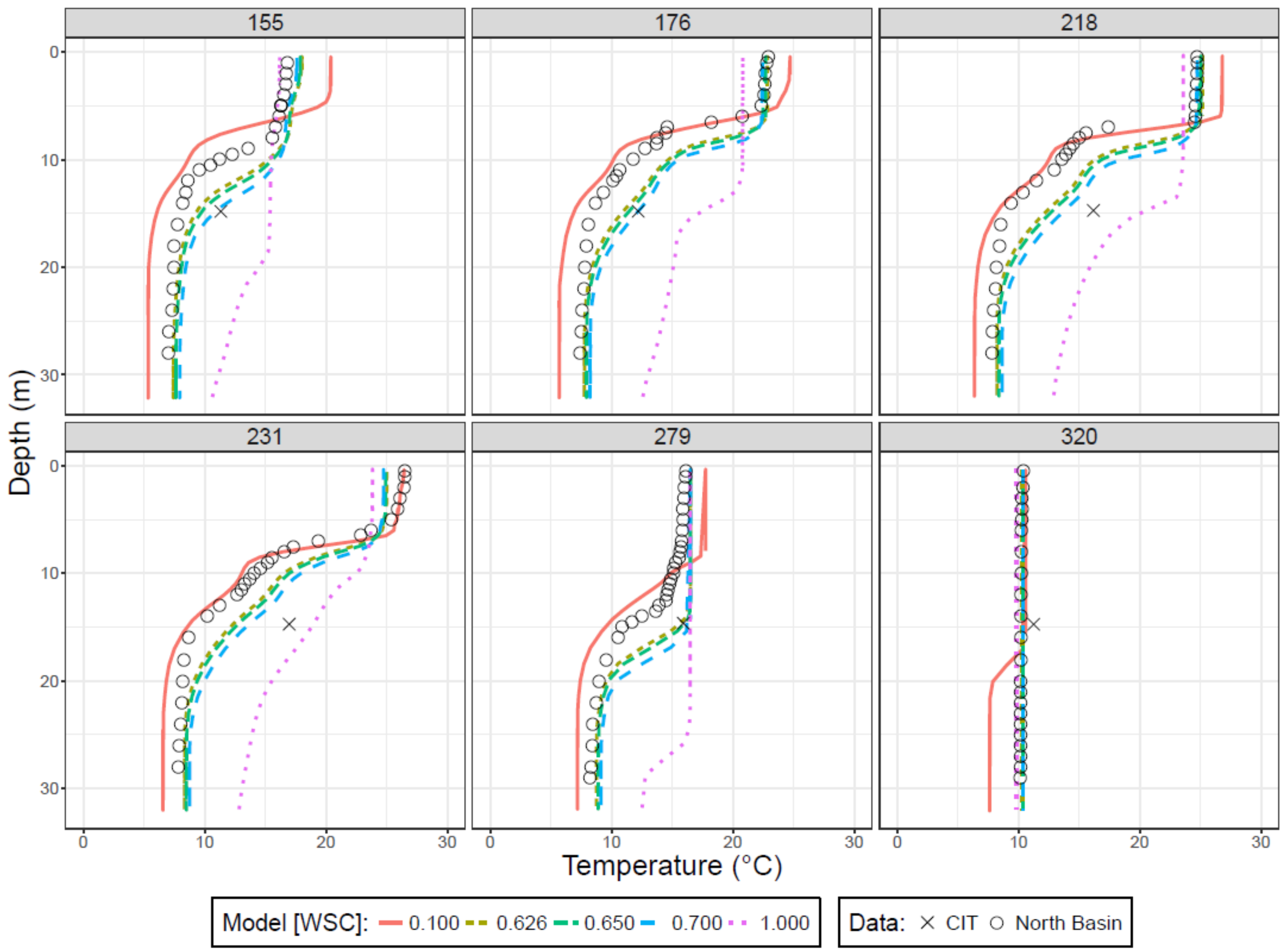

Figure 3.19 Sensitivity Analysis: WSC on Temperature (2015 W2 Old BTH)

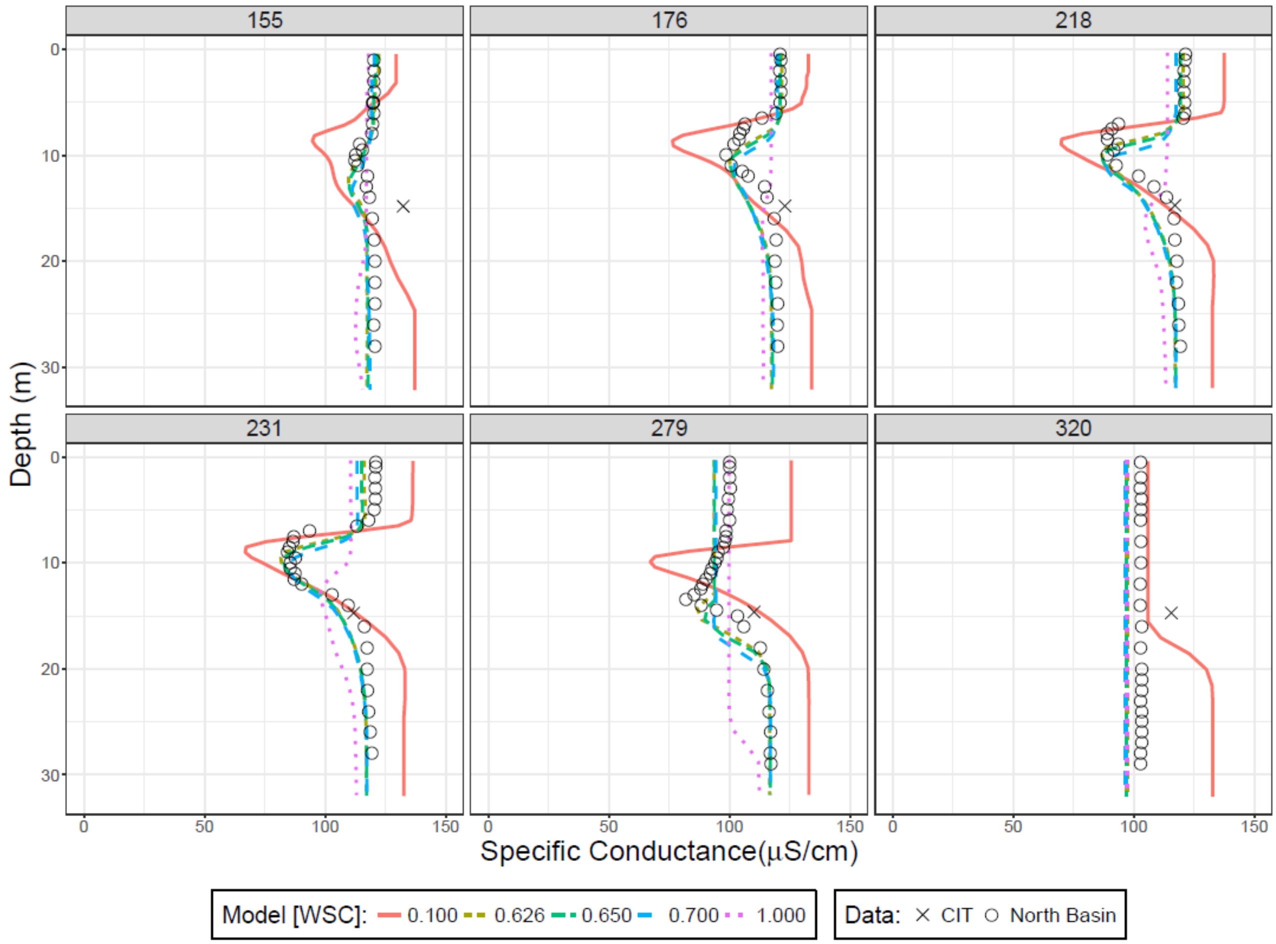

Figure 3.20 Sensivity Analysis: WSC on SC (2015 W2 Old BTH)

The effect of varying the WSC on the Cosgrove Intake water quality was also investigated. The unrealistic WSC of 0.1 applied to all segments resulted in simulated water withdrawn at segment 46 to better match measured temperature at the CIT during periods of thermal stratification (Figure 3.21). A relatively linear increase in measured temperature of water at the CIT could be observed. It is interesting to note that regardless of the WSC value, water withdrawn at the intake exhibited similar behavior in temperature starting from JD 285.

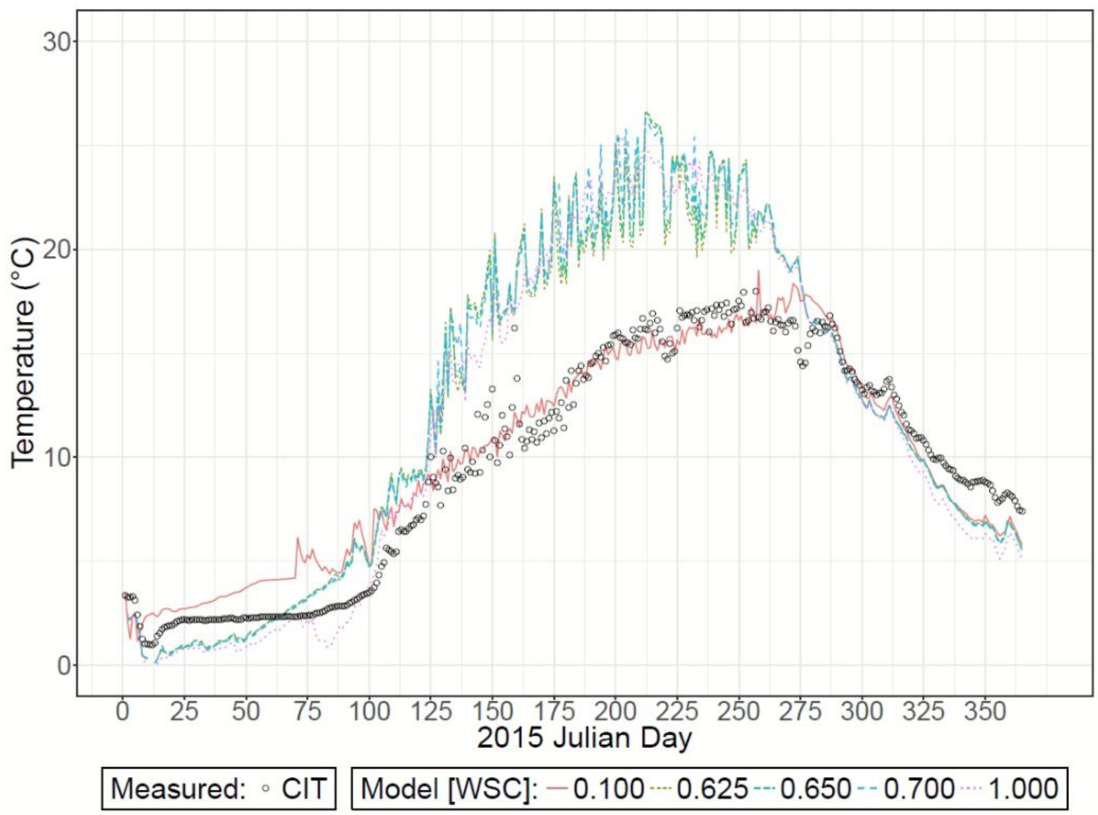

Figure 3.21 Varying WSC affects on Cosgrove Intake Temperature (2015 W2 Old BTH)

Figure 3.22 shows the SC of water withdrawn at the intake with a starting initial SC of 75 μS/cm; this value was selected as opposed to the CIT measured initial JD 1 value of 104 μS/cm because it matched the North Basin SC profiles the best. Despite an initial offset of 29 μS/cm in SC, the model simulated higher SC values during reservoir stratification for all WSC values. A WSC of 0.1 better match the offset profile, but this is unrealstic since the acutal reservoir is in a terrain that is relatively open and unshield from the wind. The cause of simulated higher specific conductivty during those periods is unclear. A speculation is that the model's selective withdrawal algorithm withdrew water from different model layers than what was occuring in the actual system during times of thermal stratifcation. More investigation in needed.

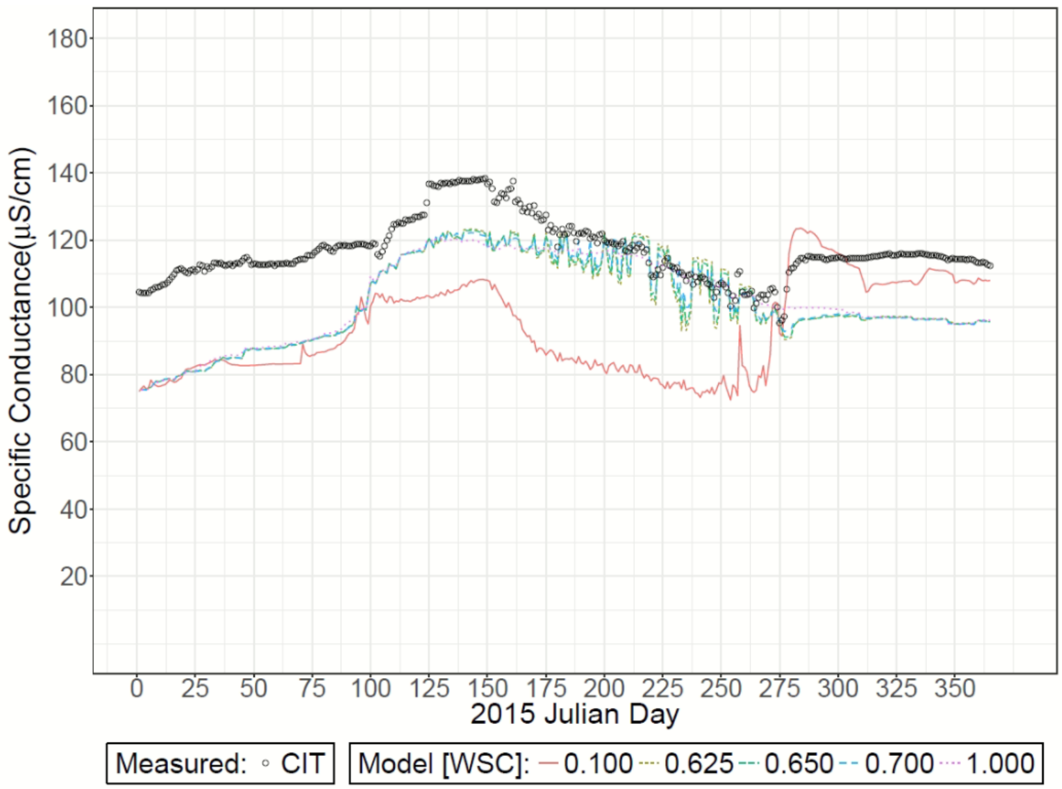

Figure 3.22 Varying WSC affects on Cosgrove Specific Conductance (2015 W2 Old BTH)

3.5 Calibrated Models

This section presents the results from four different model calibrations for calendar year 2015; 2016 was also calibrated but results are not shown here (See Appendix). The historical UMass Wachusett Reservoir model compared to suggested changes such as the shear stress formulation and the bathymetry adjustment are shown and discussed. Model calibration performance is evaluated by using the root mean squared error (RMSE), calculated with equation 8 below:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Predicted_i - Observed_i)^2}{n}} \qquad [Equation\ 8]$$

A RMSE is calculated for each model using the simulated and DCR measured temperature and specific conductivity profiles for an entire year. A lower RMSE represents a better agreement between the modeled and DCR measured profiles. Final calibration parameters used for 2015 and 2016 models are shown in Table 3.2.

Table 3. 2 Final Parameter Values used in Model Calibration.

		2015				2016			
Parameter	**Units**	**W2 Old**	**W2 New**	**TKE Old**	**TKE New**	**W2 Old**	**W2 New**	**TKE Old**	**TKE New**
Initial Temperature [T2I]	°C	3.50	3.50	3.50	3.50	7.25	7.25	7.25	7.25
Initial Specific Conductivity	µS/cm	75.00	75.00	75.00	75.00	82.50	82.50	82.50	82.50
Sediment Heat Exchange Coefficient [CBHE]	$\frac{W}{m^2 s}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sediment Temperature [TSED]	°C	10.00	10.00	10.00	10.00	11.50	11.50	13.00	13.00
Wind Shelter Coefficient [WSC]	-	0.625	0.625	0.625	0.625	0.650	0.650	0.700	0.700

3.5.1 W2 and TKE formulation

Figures 3.23 to 3.26 show calibrated W2 and TKE models using the historical Wachusett bathymetry file. Models simulated with the TKE formulation were calibrated using the same process as described in the sensitivity analyses section for the W2 formulation. DCR has sampled profile data for 32 different occasions in calendar year 2015, with the first sampling trip on JD 127 and last on JD 350. It should be noted that the last sampling day is relatively late compared to previous years and data collected on JD 139 should be omitted due to measurement error.

Simulated temperature and specific conductivity profiles showed good agreement with DCR measured profiles for both the TKE and the W2 formulations. The simulated temperature profile using the TKE formulation tended to slightly overestimate values in the epilimnion layer compared to W2. However, the TKE formulation accurately captured the thermocline gradient and hypolimnion profile while W2 overpredicted temperature by as much as 4°C in those layers (JD 148). The W2 formulation also simulated lower specific conductivity values than the TKE model and more importantly, the measured data (Figure 3.26). The simulated Quabbin interflow is spatially at deeper depth by 1 to 3 meters in models that used the W2 formulation. The hypolimnion layers of W2 simulated water profiles for Julian Days 287 to 313 also exhibited a quicker approach to completely mixed conditions when compared to the TKE formulation (Figure 3.23). The RMSE results of the W2 formulation for simulated temperature and specific conductivity are 2.71°C and 9.72 μS/cm, respectively. The TKE formulation showed lower RMSE results of 1.91 °C and 8.57 μS/cm, indicative of a model that better represents the actual Wachusett Reservoir based on the calibrated profiles.

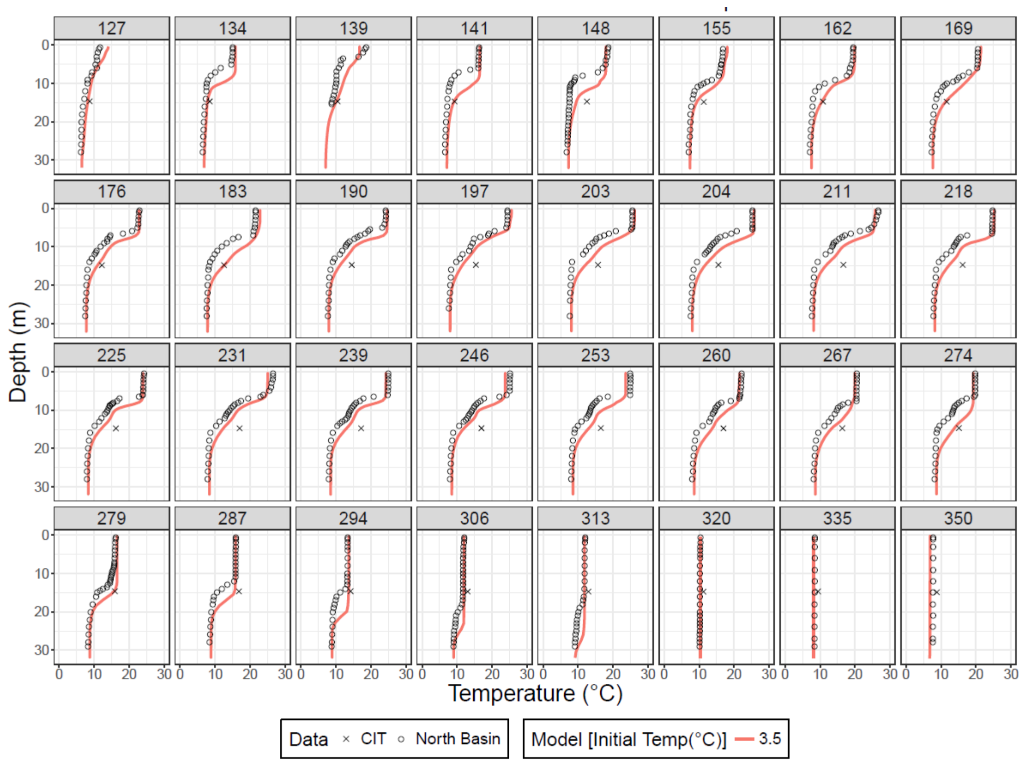

Figure 3.23 2015 Calibrated Temperature: W2 Old BTH

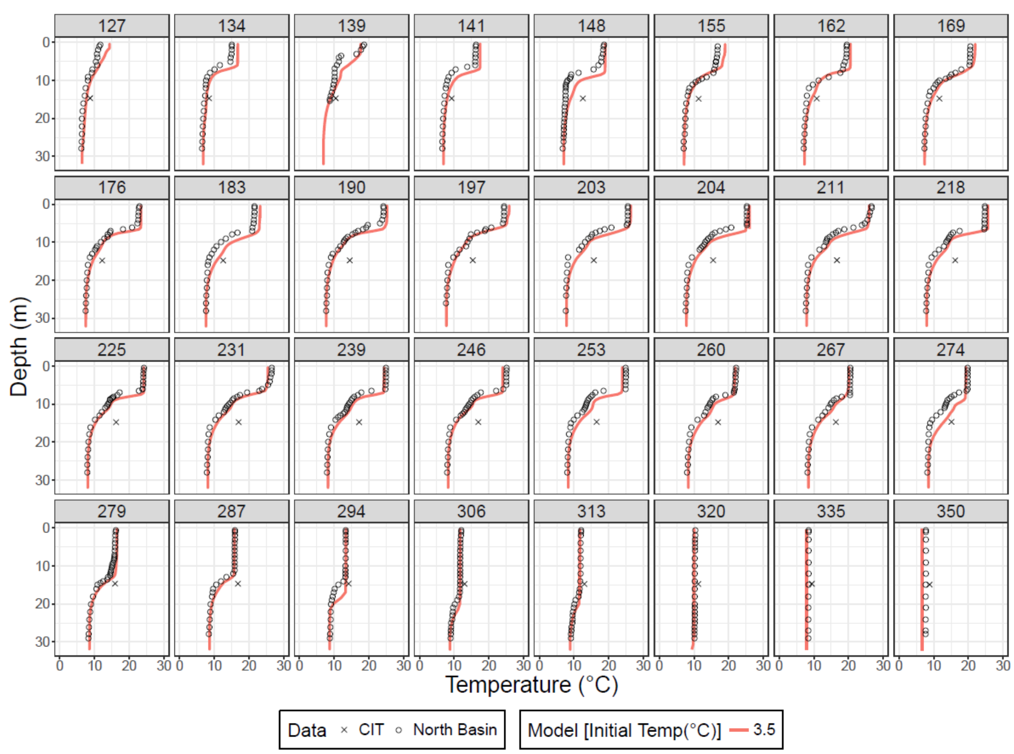

Figure 3.24 2015 Calibrated Temperature: TKE Old BTH

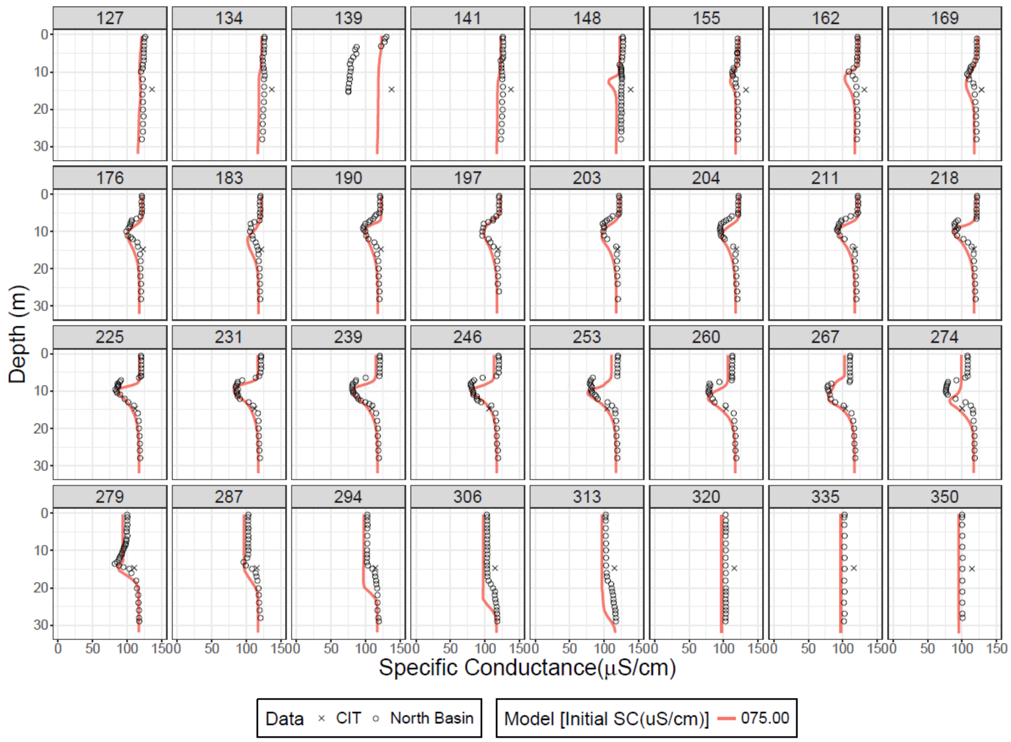

Figure 3.25 2015 Calibrated Specific Conductance: W2 Old BTH

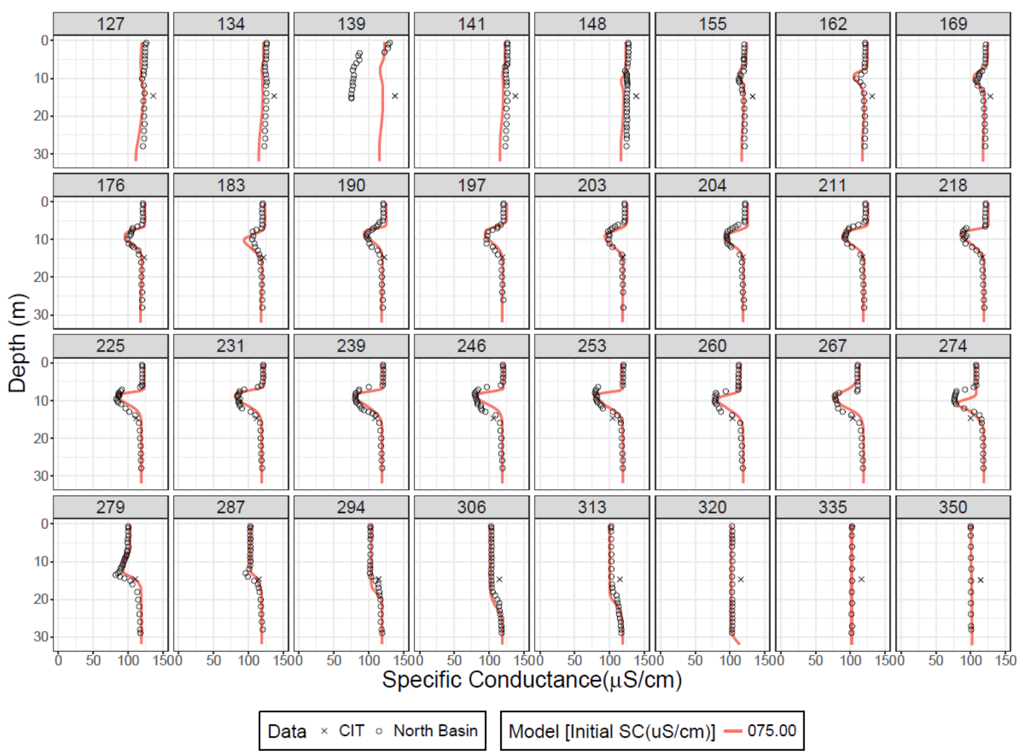

Figure 3.26 2015 Calibrated Specific Conductance: TKE Old BTH

Figures 3.27 and 3.28 show the effects of the W2 versus TKE formulation for simulated temperature and specific conductivity at the Cosgrove Intake. The model selective withdrawal algorithm more closely matched measured parameters during times of stratification when using the TKE formulation. High variability in temperature is present in models that used TKE, but the magnitude of these peaks is much lower than for the W2 formulation. Similarly, the offset in specific conductivity to match the North Basin profiles was much more prevalent during stratified periods for TKE than for W2. During the first reservoir completely mixed conditions between Julian Days 1 to 100, both models exhibited similar behavior with small variation in water parameters. However, deviation occurred during the second reservoir completely mixed period around JD 275, where the TKE formulation simulated SC is on average 20 μS/cm higher than for the W2 formulation. The TKE formulation seems to be the better of the two in accurately capturing water profiles at the North Basin and measurements taken at the Cosgrove Intake. Based on suggestion from Cole and Wells (2015), TKE should be selected and used for the Wachusett Reservoir modeling, but both models are investigated in this report.

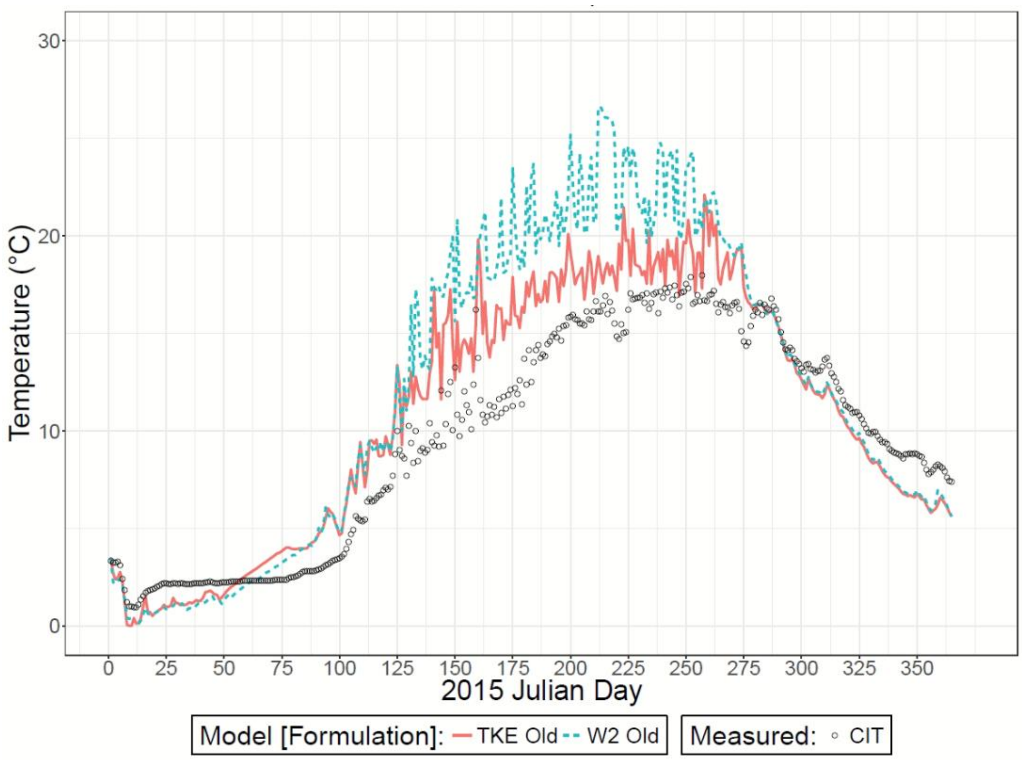

Figure 3.27 2015 Cosgrove Temperature: TKE Old BTH vs W2 Old BTH

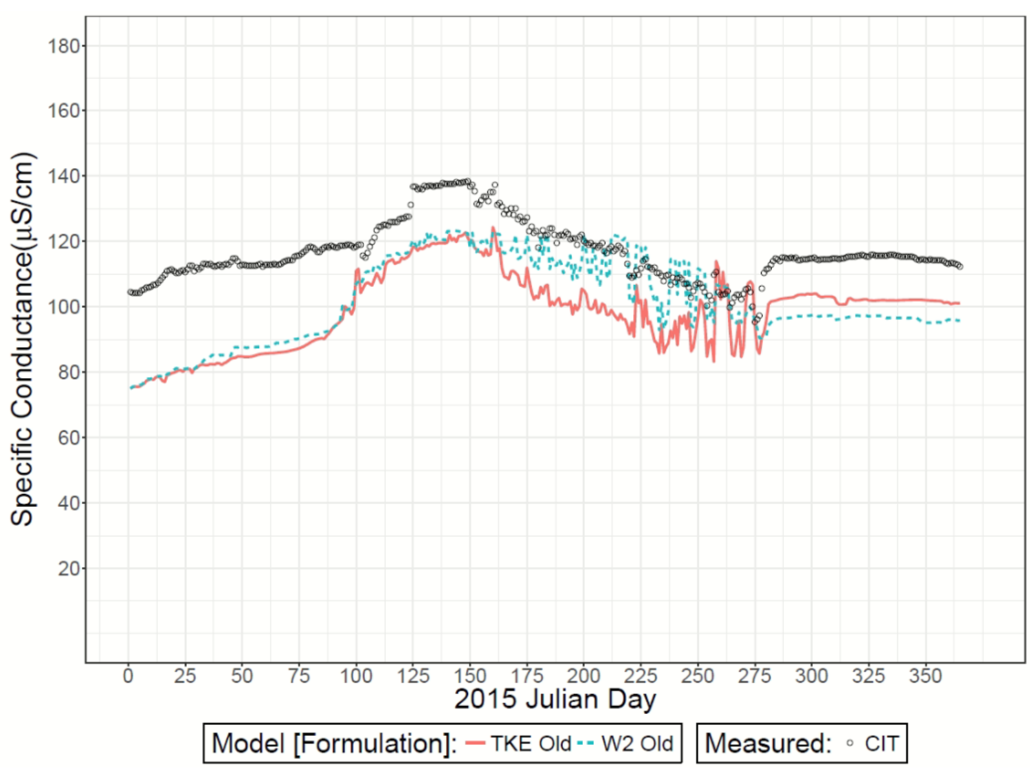

Figure 3.28 2015 Cosgrove Specific Conductance: TKE Old BTH vs W2 Old BTH

3.5.2 Model with the New Bathymetry

Adjustments to the bathymetry file were made and its effects analyzed as suggested by Cole and Wells (2015). Sensitivity analyses were performed by comparing results of model simulations using the two different Segments 45 and 46 bathymetries. The calibrated TKE with the new bathymetry file for both temperature and specific conductivity are shown in Figures 3.29 and 3.30. Simulations with the new bathymetry also produced good agreement with the DCR measured profile in the epilimnion and hypolimnion. However, the thermocline layer results diverged with model values overpredicted compare to measured data. The simulated temperature deviated by as much as 3-4 °C at a few locations within the thermocline. Modeled specific conductivity profiles also reveal a similar difficulty in simulating values in the thermocline. The simulated Quabbin interflow is shifted an average of 2 meters deeper than the recorded profile for nearly all modeled profiles that used the new bathymetry. Similar behavior was observed in simulation using the W2 formulations. The RMSE results of the W2 with new bathymetry model for the simulated temperature and specific conductivity profiles are 3.59 °C and 12 μS/cm, respectively. The TKE formulation, again exhibited lower RMSE values of 2.79 °C and 10.56 μS/cm.

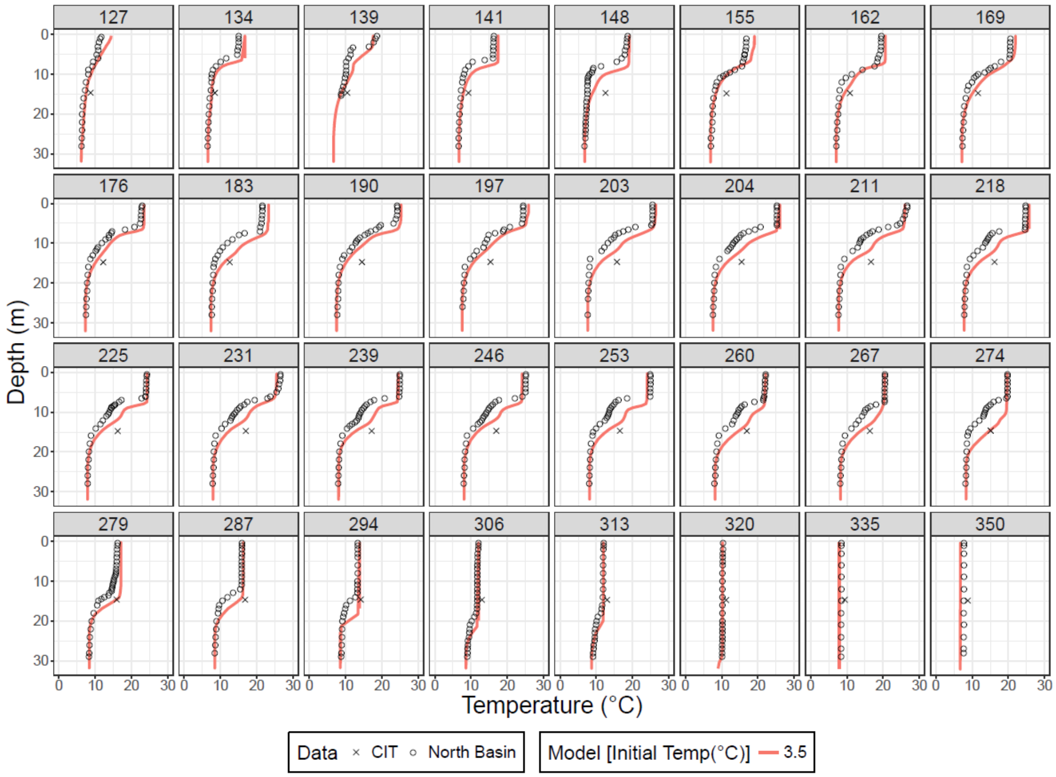

Figure 3.29 2015 Calibrated Temperature: TKE New BTH

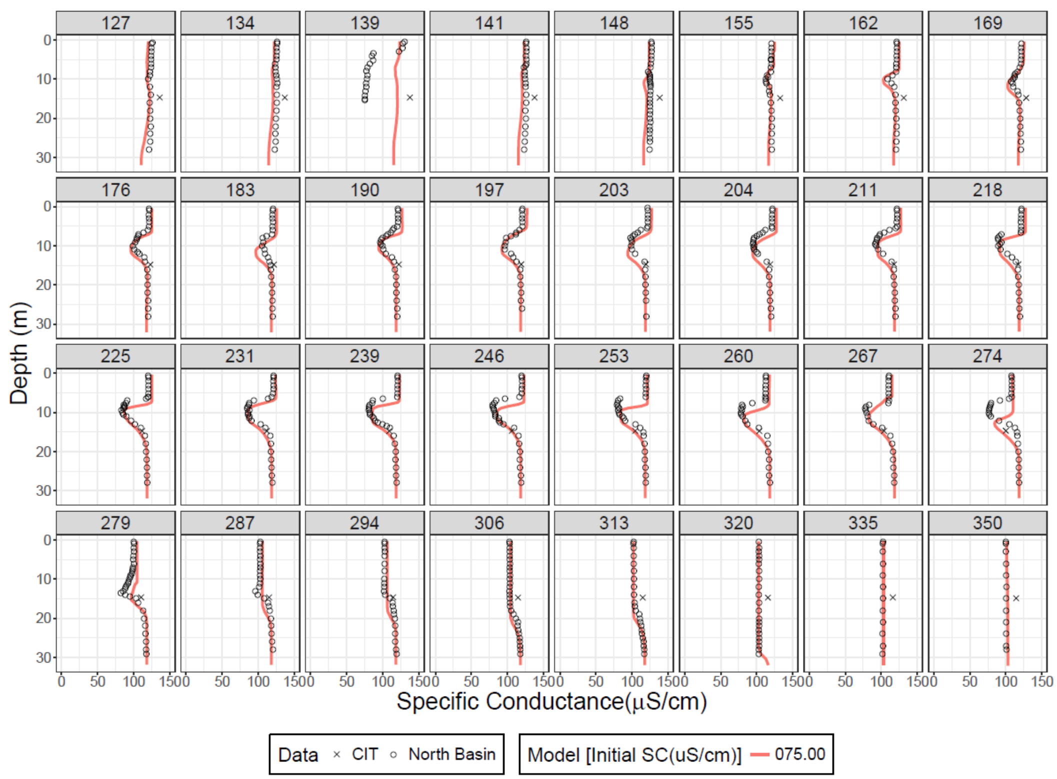

Figure 3.30 20015 Calibrated Specific Conductance: TKE New BTH

Adjustments made to the bathymetry file not only resulted in changes to the Segment 42 modeled water profiles, but also simulated water quality at the CIT. Both the W2 and TKE models showed performance enhancement with the new bathymetry in terms of capturing modeled water characteristics during stratified reservoir conditions at the CIT (Figure 3.31). Fluctuations in simulated water temperature are less drastic for the new bathymetry and more representative of the measured values. Despite the new bathymetry, the ice formation algorithm still failed to predict ice development as evidenced by the nonuniform temperature in the first 100 days. However, the simulated temperature is closer to the measured during those days.

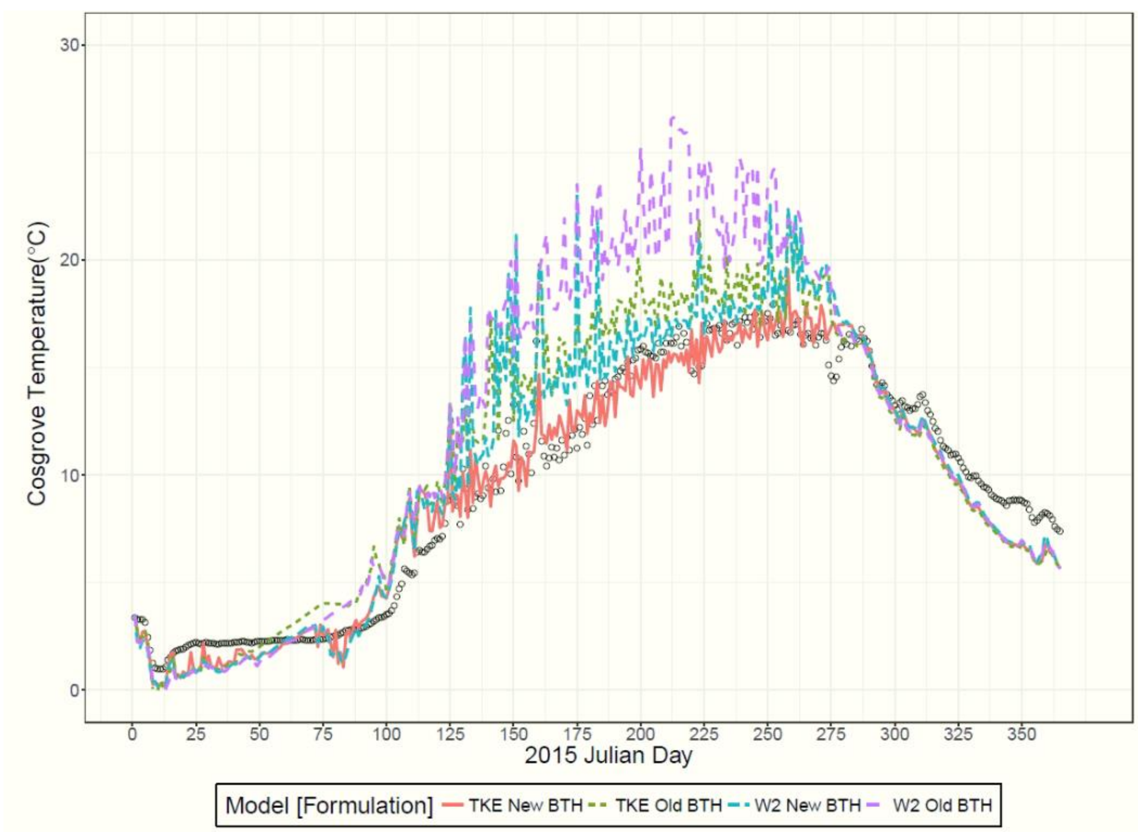

Figure 3.31 2015 Cosgrove Intake Temperature: Bathymetry Comparison

The predicted specific conductivity at the CIT is a better match to the measured values for the new bathymetry file, indicative of improved model performance at the intake (Figure 3.32). The selective withdrawal algorithm modeled water quality between JD 160 to JD 275 with a consistent offset as opposed to large variability in SC values (Figure 3.32). As previously discussed, the initial reservoir SC value was set a lower number than what was measured at the CIT to match the DCR North Basin water profiles.

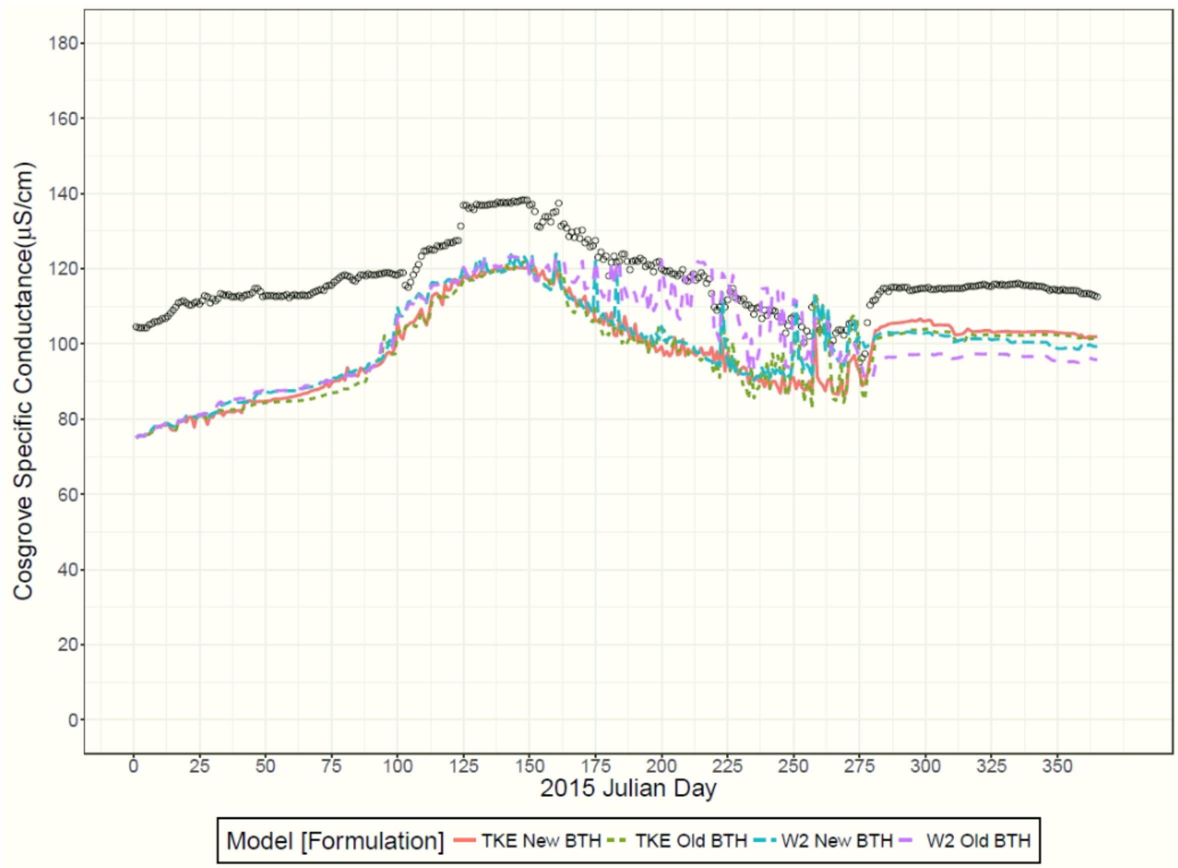

Figure 3.32 2015 Cosgrove Intake Specific Conductivity: Bathymetry Comparison

3.5.3 Discussion of Shear Stress Formulation and Bathymetry Adjustment

The TKE formulation produced model results with less standard deviation error than the W2 formulation for both the calibrated 2015 and 2016 Wachusett models. This is because the simulated temperature and specific conductivity water profiles using the TKE formulation better captured the thermocline layer, therefore resulted in lower RMSE (Figures 3.33 and 3.34). One explanation why the W2 models performed worse compared to the TKE models in simulated water temperature and specific conductivity profiles is that the W2 formulation accounted for the effects of cross shear wind. According to Cole and Wells (2015), the wind shear across the lateral axis of a segment increases the cross-shear velocity gradient and vertical mixing. Therefore, it is speculated that the vertical mixing in the water column is magnified with the incorporation of cross-shear from wind. More energy exchange occurred between the epilimnion and thermocline interface. Model water profiles simulated with the W2 formulation ultimately produced higher temperature values in the thermocline layer and slightly cooler epilimnion layer than what was measured in the Summer. The new bathymetry file resulted in better agreement of the simulated with measured water at the intake, but reduced model performance in capturing the DCR measured water profiles. Higher RMSE for both temperature and specific conductivity could be observed for models with the new bathymetry in Figures 3.33 and 3.34, regardless of the shear stress formulation.

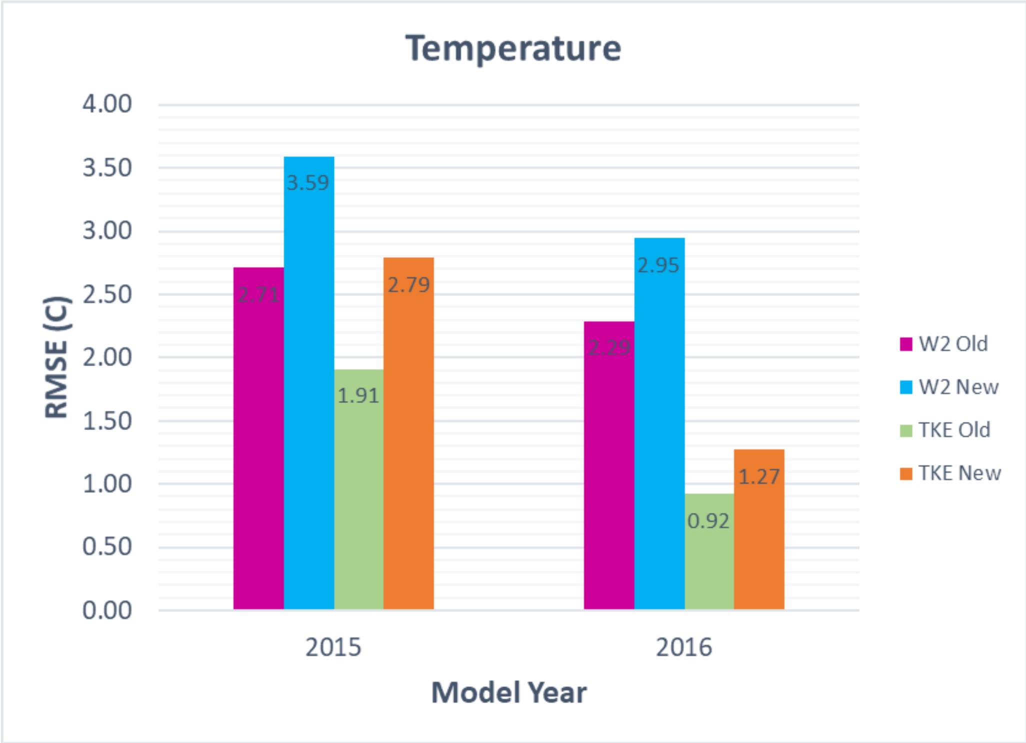

Figure 3.33 RMSE of Simulated Temperature Profiles

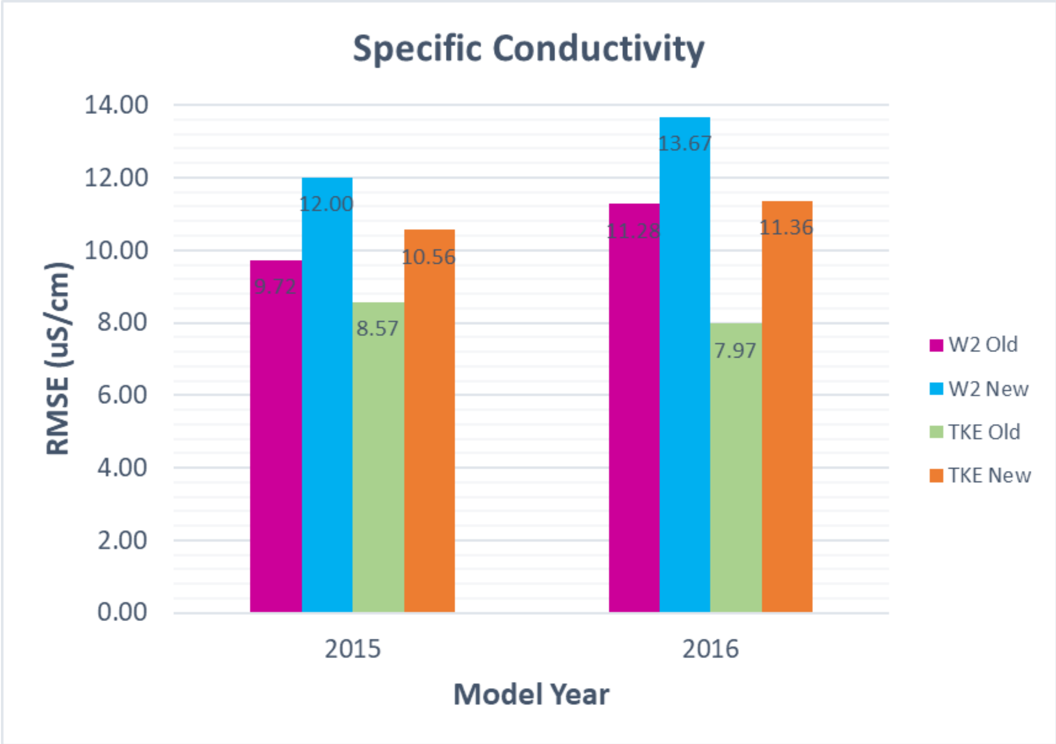

Figure 3.34. RMSE of Simulated Specific Conductivity Profiles

Figure 3.35 shows Segments 42 to 46 modeled water temperature profile with the TKE formulation and the old bathymetry file. Segments 42 to 45 exhibited similar water temperature profiles from 5 meters and below. The epilimnion water temperature is lower in Segment 42 and increases as water moves to Segment 46. Segment 46 water temperature is warmer after a depth of 8 meters compared to all the other segments. Segment 45 depth stops at 8 meters below the water surface elevation, thus most of the water that enter Segment 46 are probably from the epilimnion layer.

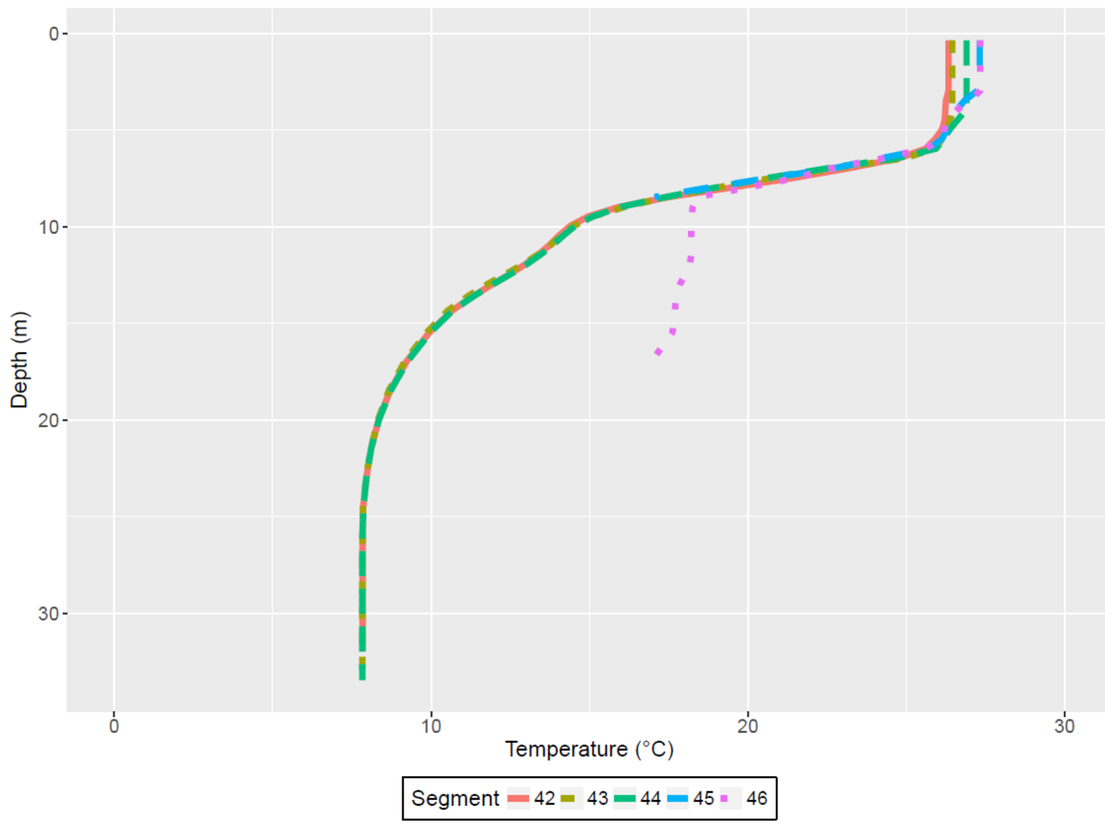

Figure 3.35 Temperature Profile of 5 Segments (2015 TKE Old BTH JD 203)

Figure 3.36 shows the water temperature profiles for those same segments but with TKE model using the new bathymetry. The adjustments made to Segments 45 and 46 resulted in noticeable changes; cooler temperature profile in segment 46 and warmer thermocline layer in Segments 42 to 45. One speculation is that the modeled velocity field was changed by the adjusted Segment 45 (cofferdam cut). Bos (1975) illustrated that water traveling over a submerged broad crested weir results in varying mixing and flow directions. The adjusted segment is 12 meters wider in the first 14 layers and 5 meters deeper, with a bottom elevation change from 110.7 meters to 105.7 meters above mean sea level. Since the Quabbin interflow traverse across the reservoir at a depth of 5 to 15 meters below the water surface elevation, its flow path could travel freely through the new Segment 45 and into Segment 46, where more of its' water is being withdrawn directly by the intake located at 104.3 m. The geometry of a multiple-step broad crested weir of the cofferdam only allowed water from the epilimnion and a majority of Quabbin interflow to pass while water from other layers are hindered by the uncut portions. Since the interflow is colder than the epilimnion layer, upward movement is unlikely due to density stratification. Upward movement from the hypolimnion layer is also unlikely with the same logic unless in response so some external force. A funneling effect created by the intake where reservoir water from mostly the epilimnion entered into the thermocline layer, therefore causing a temperature variation in that region as shown in the calibrated profiles. Maghsoodi and Sarkardeh (2012) modeled flow over submerged weirs using 3-dimensional simulations. The water velocity vector in front of a submerged broad crested rectangular weir is much higher at and above the weir height (thermocline and epilimnion). Water velocity below the weir is small and almost zero in some regions. The results from their research could potentially justify the higher modeled temperature present in the calibrated profile for 2015 simulations using the TKE formulation and the new bathymetry.

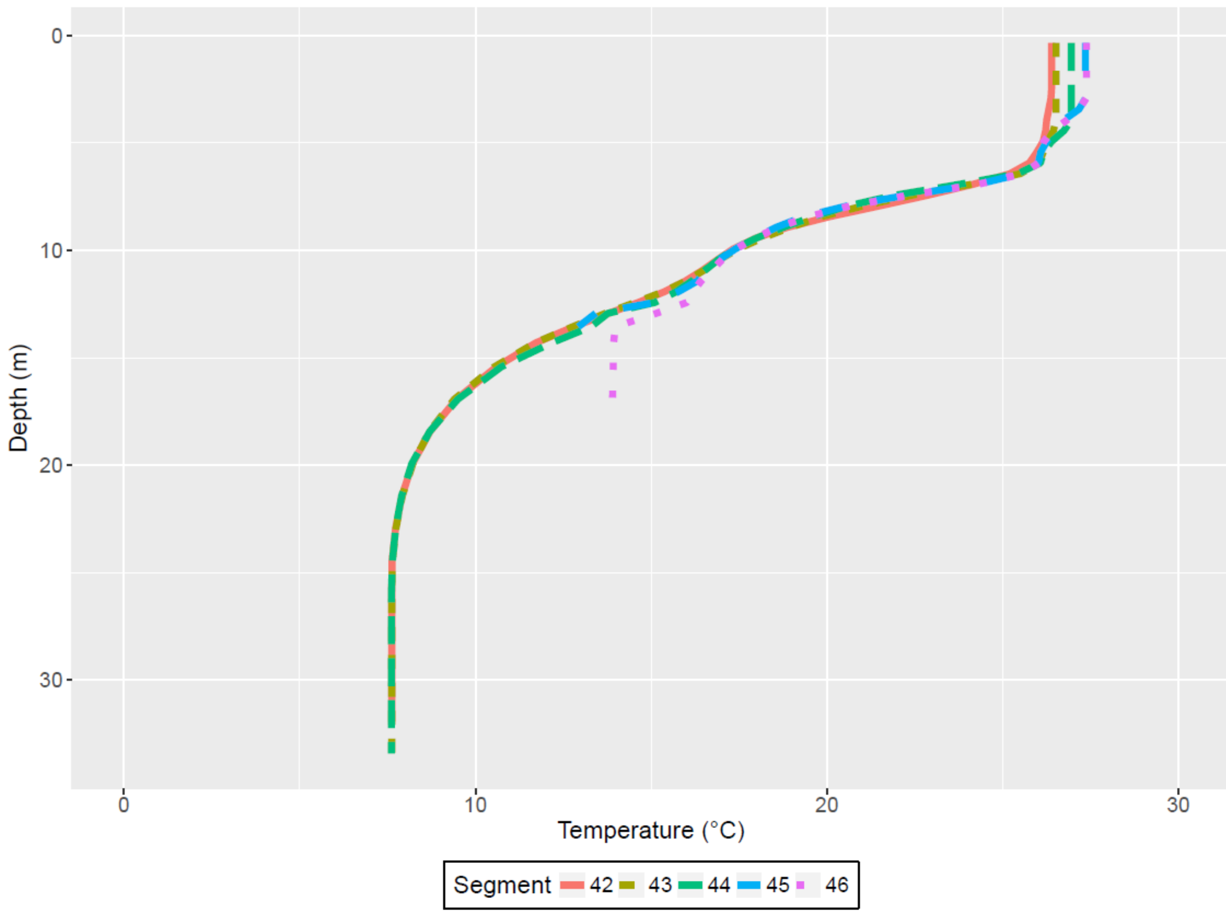

Figure 3.36 Temperature Profile of 5 Segments (2015 TKE New BTH JD 203)

Table 3.3 shows the average model run time for each of the four model types using an Intel® Core ™ i7-4770 CPU @ 3.40 GHz and running Windows 10 operating system. Cole and Wells (2015) noted that the TKE formulation is more computationally expensive compared to W2 and produced similar results in some cases. Fewer model runs can be performed simultaneously using the TKE compared to the W2 formulation was observed during sensitivity analyses and spill model runs. However, simulations that used the TKE formulation resulted in a significant reduction in model run time, 50% faster in some cases. Surprisingly, simulations with the new bathymetry file required much longer model run time for both shear stress formulations (Table 3.3). The adjustments made to Segments 45 and 46 most likely increased the complexity and/or increased the number of partial differential equations CE-QUAL-W2 most solve internally to determine the water hydrodynamics in the altered layers. This resulted in much longer model run time for both the W2 and TKE formulation.

Table 3. 3 Average CE-QUAL-W2 Model Run Time

	Average Model Run Time (Minutes)	
Models	Calendar Year 2015	Calendar Year 2016
W2 Old	15	17.5
W2 New	40	42.7
TKE Old	6.8	7.1
TKE New	26.8	23

3.6 Spill Modeling

Spill simulations were performed for model years 2015 and 2016 after model calibration for temperature and specific conductivity. UMass has historically used the W2 vertical eddy viscosity turbulent closure formulation for spill modeling. In this report, both the TKE and W2 turbulent closure formulations along with the new and old bathymetry files are used for comparison of spill contaminant behavior at the Cosgrove Intake. A constituent with non-reactive conservative properties that does not decay or volatilize was used to simulate the spill. A spill that is characterized by low flow (0.02 m^3/s), high concentration (1×10^8 mg/L), and a short duration (12 hours) was added as a tributary discharge at Segment 7 in the model. The flow entered the computational grid between Layers 2 to 22 and was distributed into the model based on density.

Temperature is a user specified parameter that behaves like density in CE-QUAL-W2 (Cole and Wells, 2015). Spill temperatures are substituted for densities in spill simulations. Three spill temperatures are used for simulation to simulate different travel locations within the reservoir water column. A cold spill will sink to the bottom of the hypolimnion, a medium spill will drift in the region of the thermocline, and a warm spill will float at the top of the epilimnion. The spill temperatures are determined from modeled water temperature profiles from Segment 42 of the selected spill dates for a given year.

Spill arrival concentration is normalized using a method developed by Stauber (2009). Equation 9 and Equation 10 are used in conjunction to determine a relative concentration of the contaminant at the Cosgrove Intake, shown below:

$$(Completely\ Mixed)\ C_o = \frac{Total\ Mass\ of\ Spill}{Full\ Reservoir\ Volume} \qquad [Equation\ 9]$$

$$Relative\ Concentration = \frac{C_{Model}}{C_o} \qquad [Equation\ 10]$$

The total mass of the spill is $8.64\text{x}10^{10}$ g and the full reservoir volume of 62 billion gallons yield a completely mixed concentration (C_o) of 368.14 mg/L. The contaminant concentrations at the CIT is divided by the C_o. A relative concentration of 1 is representative of a completely mixed reservoir in which the contaminant is uniformly mixed throughout. Spill contaminant arrival time is defined as the number of days after spill for the contaminant to first reach a relative concentration of 0.1 at the intake.

3.6.1 Spill Date Selection

Stauber (2009) discovered that contaminant arrival time and concentration at the Cosgrove Intake are influenced by wind. The spill dates selected for each calendar year are based on four consecutive days with similar wind speed and magnitude for each of the three seasons; Spring, Summer, and Fall (Table 3.4). Water temperature profile is another factor to be considered for the selection of spill dates. Spring and Fall water temperature profiles should be relatively uniform across the water column while Summer should be stratified.

Table 3. 4 2015 and 2016 Spill Day Selection

2015								
Spring			Summer			Fall		
JDAY	Wind Direction	Wind Magnitude (m/s)	JDAY	Wind Direction	Wind Magnitude (m/s)	JDAY	Wind Direction	Wind Magnitude (m/s)
116	NW	3.71	201	NW	3.89	274	NE	5.1
117	NW	5.48	202	NW	3.09	275	NE	5.93
118	SW	4.87	203	NW	5.44	276	NE	6.11
119	NW	5.05	204	NW	5.21	277	NE	4.97
Average Wind Speed		4.78	Average Wind Speed		4.41	Average Wind Speed		5.53
2016								
Spring			Summer			Fall		
JDAY	Wind Direction	Wind Magnitude (m/s)	JDAY	Wind Direction	Wind Magnitude (m/s)	JDAY	Wind Direction	Wind Magnitude (m/s)
100	NW	3.226	203	NW	4.38	272	NE	3.86
101	NW	5.76	204	WSW	5.88	273	SE	5.08
102	SW	5.94	205	NW	5.33	274	SE	4.62
103	SW	6.6	206	NW	4.92	275	NE	5.35
Average Wind Speed		5.38	Average Wind Speed		5.13	Average Wind Speed		4.73

CHAPTER 4: SPILL MODELING RESULTS

This section presents the results of Wachusett Reservoir spill simulations for calendar years 2015 and 2016. The impacts of varying vertical shear stress turbulent closure formulation, spill season, spill temperature and bathymetry adjustments on contaminant arrival time and relative concentration at Cosgrove Intake are investigated.

4.1 Seasonal Influence on Spill Concentrations

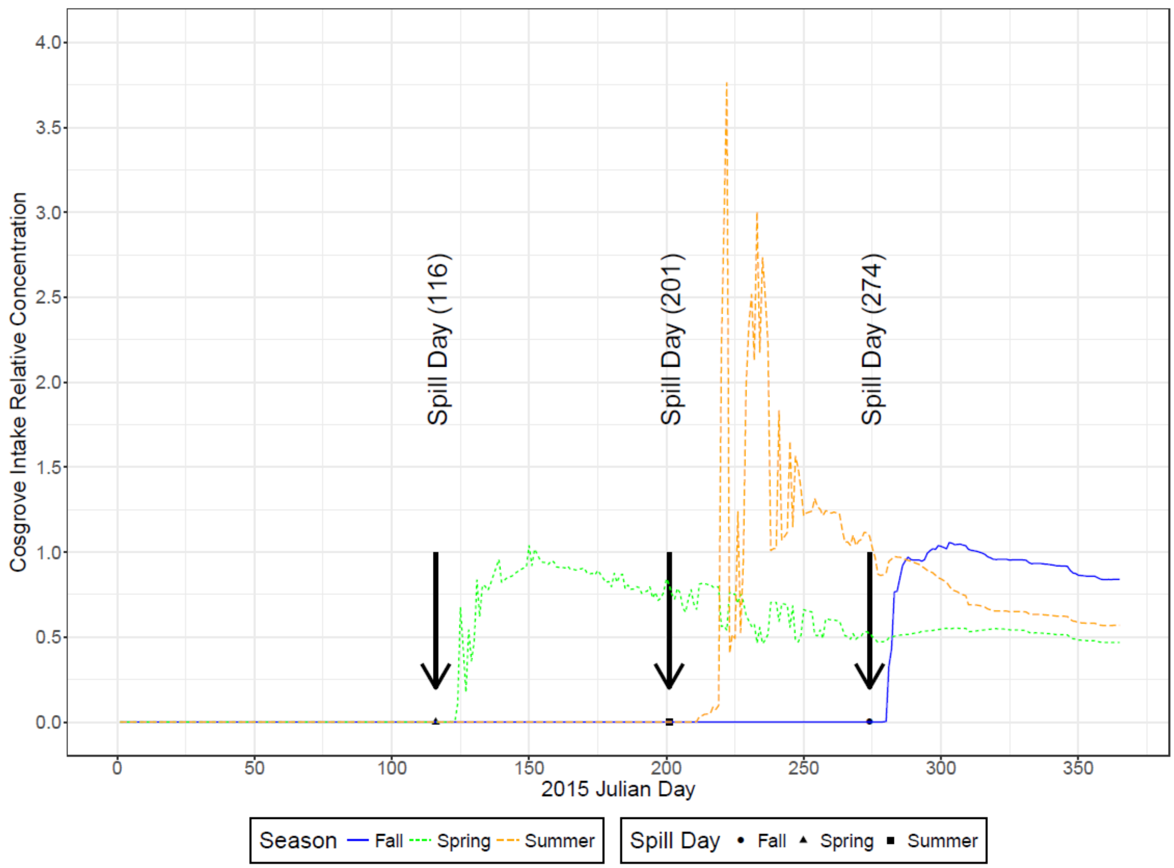

Figure 4.1 2015 Cold Spill Contaminant Relative Concentration at CIT: W2 Old BTH

Figure 4.1 shows the relative concentration at the intake for Spring, Summer, and Fall spills for cold temperature, using the W2 formulation with the old bathymetry file. Results from these simulations are similar to past UMass CE-QUAL-W2 research done by Clark (2013) and previous masters students. Season has a notable impact on the arrival concentration and arrival time of the spilled contaminant. Spring and Fall relative concentration behaved similarly due to the completely mixed condition of the reservoir during the time of spill. The relative concentration peaked at about 1.0, illustrating that the contaminant is completely mixed throughout the reservoir. A Summer spill on the other hand exhibited higher relative concentration due to stratification of the reservoir. Thermal stratification inhibited mixing across the water column resulting in higher and more variable arrival concentration at the intake.

4.1.1 Spring

During the Spring, the Wachusett Reservoir is under completely mixed conditions, experiences higher precipitation amounts, and higher discharges from tributaries due to snow melt. Concentration at the intake is independent of spill temperature during the Spring due to reservoir turnover that induces mixing across the reservoir water column. Regardless of the spill temperature, constituents are mixed throughout the water column resulting in similar arrival time and concentration magnitude at the Cosgrove Intake as shown in Figure 4.2.

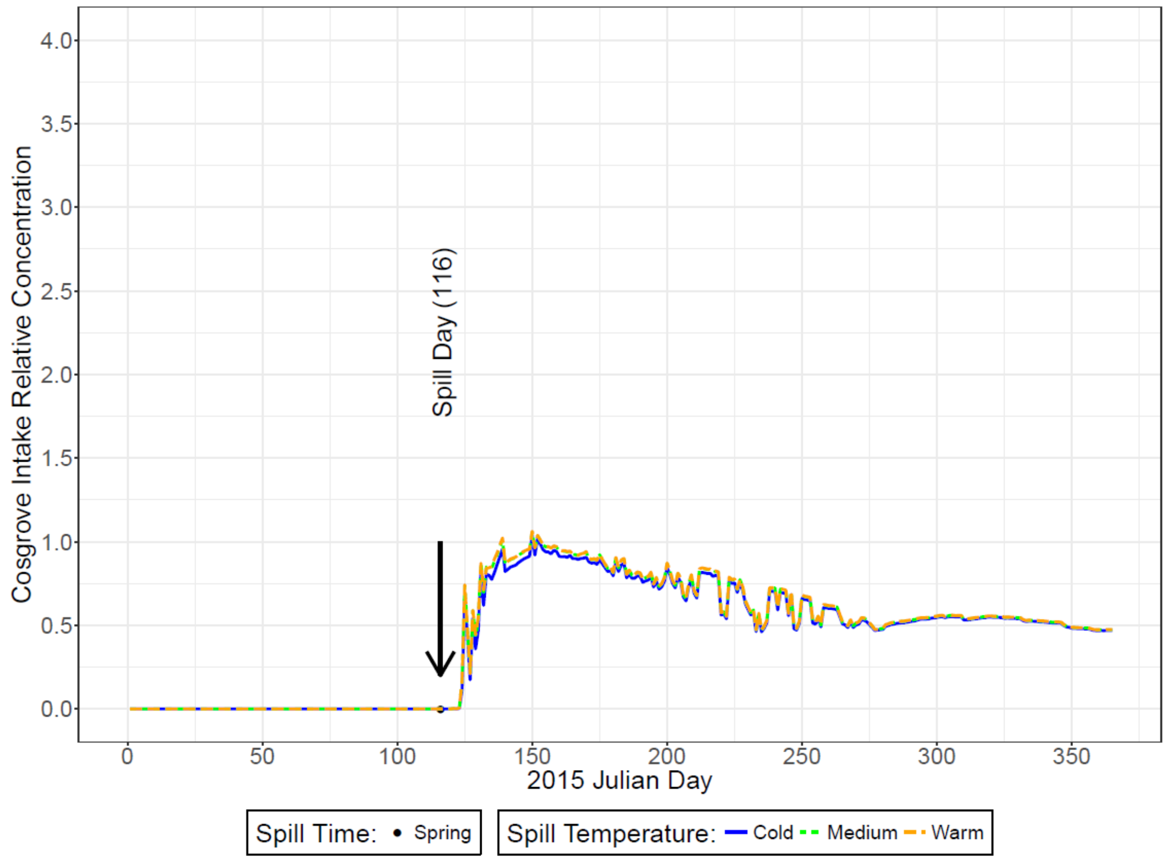

Figure 4.2 Relative Concentration at Cosgrove Intake: 2015 Spring Spill W2 Old BTH

The behavior of the contaminant in a Spring spill is similar to that of a delayed non-ideal continuous flow stirred tank reactor response to a pulse input. Since the spill duration is relatively short compared to length of a calendar year, the spill is almost like an injection of a pulse load as opposed to a step load. A few days elapsed before a measurable response could be seen at the intake. The concentration peaked at a relative concentration of about 1, and then slowly become diluted over time. Figure 4.2 reinforced the notion of a completely mixed reservoir as all three spill temperatures exhibited similar relative concentration identical throughout the entire calendar year with arrival time to the intake of about 7.5 days. Higher variability in the CIT contaminant concentration is observed between Julian Day 200 and 275, the period of stratification of the reservoir.

2016 Spring contaminant spills also exhibited similar behavior in magnitude of contaminant concentration and arrival time at the intake. 2015 and 2016 Spring contaminant cold spill results are compared in Figure 4.3. In 2015, a low tracer concentration is observed at the intake 3.5 days after the spill, with significantly higher concentration arriving 7.5 days post spill. The simulated 2016 spill contaminant on the other hand first arrived at the intake in just 1.5 days, slightly faster than in the previous year likely due to the higher average wind speed (Table 3.4). Despite a faster arrival time, contaminants for both years at the intake peaked at a similar relative concentration of 1.

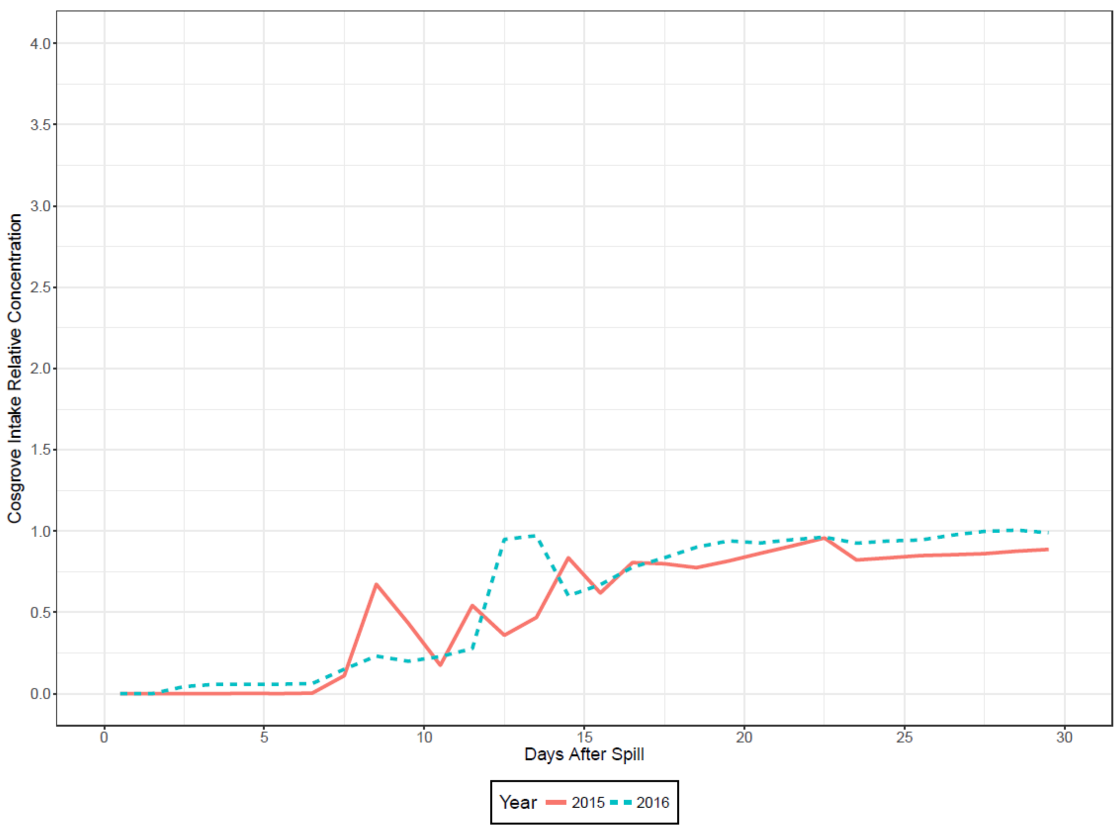

Figure 4.3 Days After Spring Cold Spill: W2 Old BTH

4.1.2 Summer

The Wachusett Reservoir experiences lower tributary inflows, warmer air temperatures and thermal stratification of the water column during Summer seasons. Withdrawal at the intake is typically higher in the Summer to meet the increased water demand from the metropolitan Boston area. The Quabbin transfer is utilized to compensate for the reduction in tributary inflows and to improve reservoir water quality due to the lower UV_{254} of the Quabbin water.

Thermal stratification and operation of the Quabbin transfer create complex hydrodynamics of the reservoir with noticeable impacts on the Summer spill. The 2015 and 2016 Summer spills exhibited distinct temporal differences in contaminant arrival time and concentration between the warm versus cold and medium spill temperature (Figures 4.4 and 4.5). Cold and medium spills are characterized by extreme variability in CIT contaminant concentration during periods of reservoir stratification. Little relative concentration variation is observed between the cold and medium temperatures, an indication that complete mixing occurred in the lower region of the thermocline and hypolimnion layer. Meanwhile, warm spills for both years exhibited faster arrival time and lower variability in CIT concentration. The thermocline and the Quabbin transfer functioned as a barrier that prevented mixing between the epilimnion and everywhere else. Wind dictates mixing behavior in the epilimnion layer where the warm spill travels. The cold and medium spills are dominated by the hydrodynamics of the reservoir as they travel at and below the thermocline. Differences in concentration vanished, becoming indistinguishable after Julian Day 275 during fall turnover, as the reservoir completely mix throughout the water column once again.

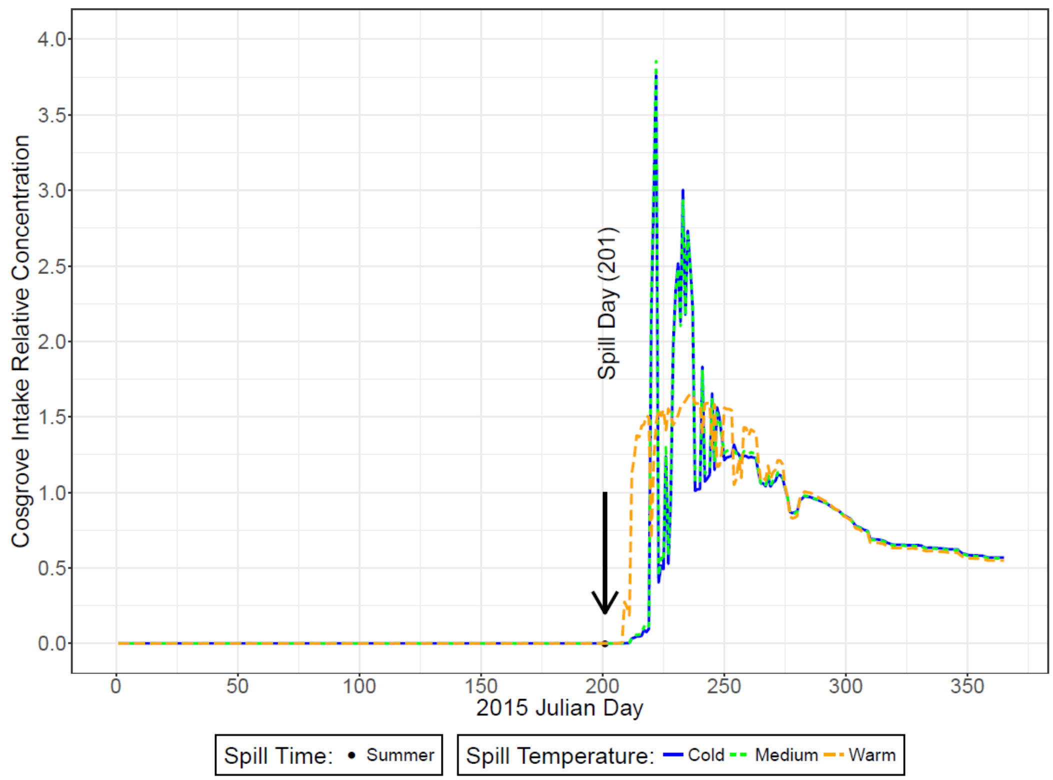

Figure 4.4 Relative Concentration at Cosgrove Intake: 2015 Summer Spill W2 Old BTH

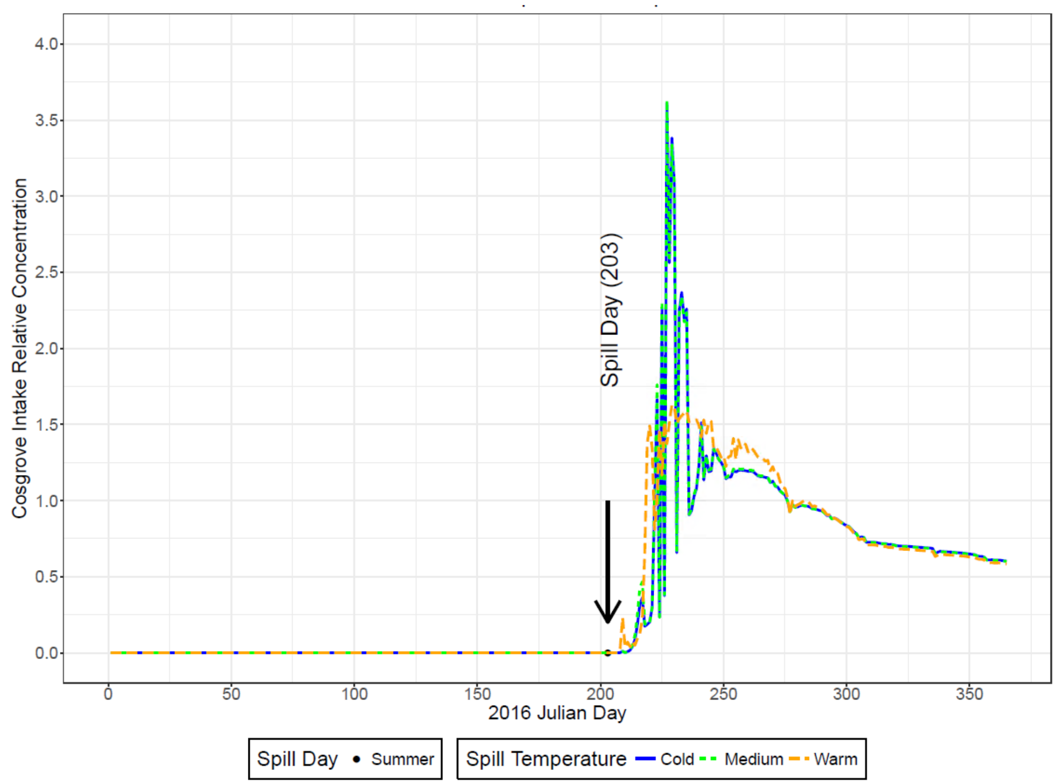

Figure 4.5 Relative Concentration at Cosgrove Intake: 2016 Summer Spill W2 Old BTH

Contaminant concentration at the CIT appeared almost identical for both 2015 and 2016 Summer spill scenarios. In 2015, the warm spill contaminant arrival time at the intake was 7.5 days, while for both cold and medium spill, the contaminant arrival times were 18.5 and 15.5 days respectively (Figures 4.6 and 4.7). 2016 experienced shorter arrival time of 5.5 days, 10.5 days and 11.5 days for warm, medium, and cold spill respectively. The shorter arrival times are most likely caused by the slightly higher magnitude in the 2016 Summer wind speed compared to 2015.

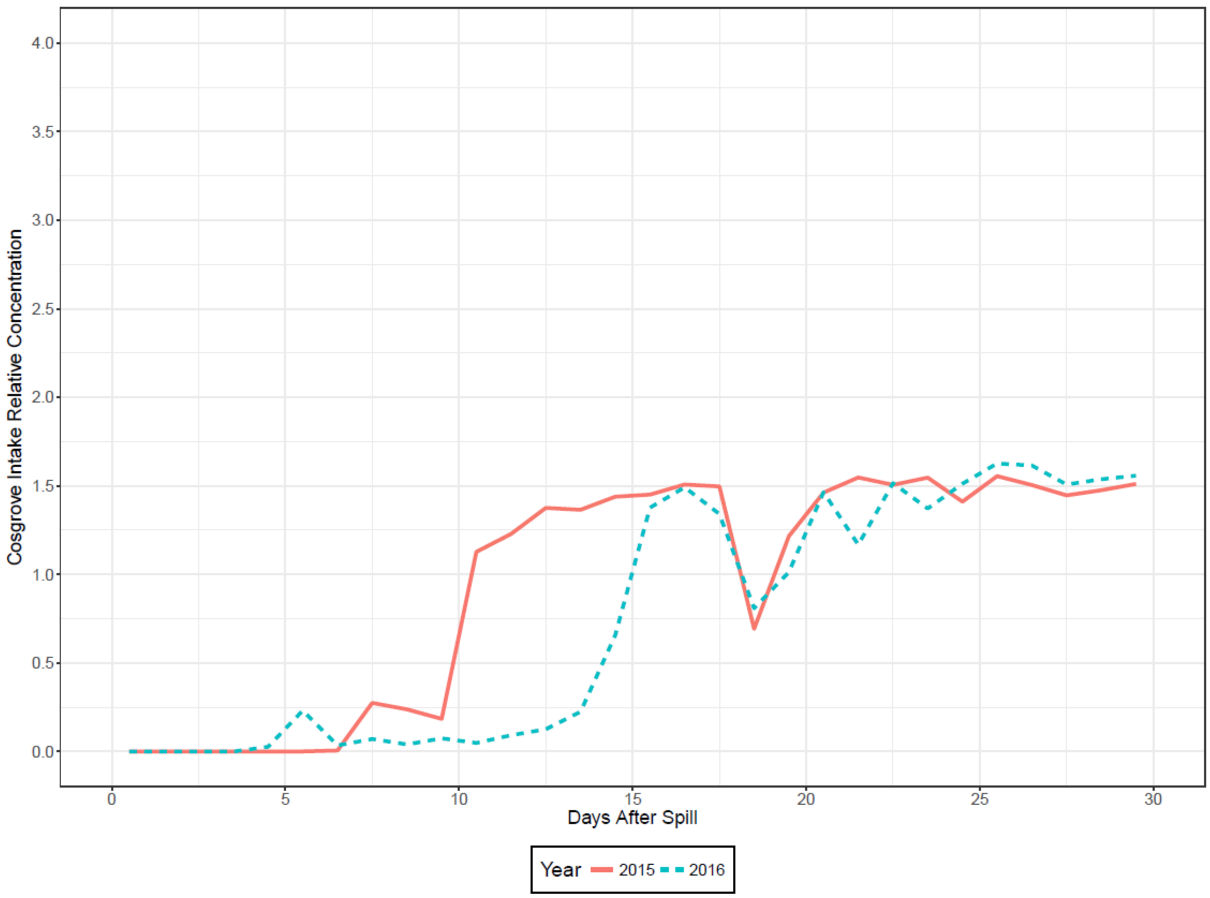

Figure 4.6 2015 and 2016 Summer Warm Spill: W2 Old BTH

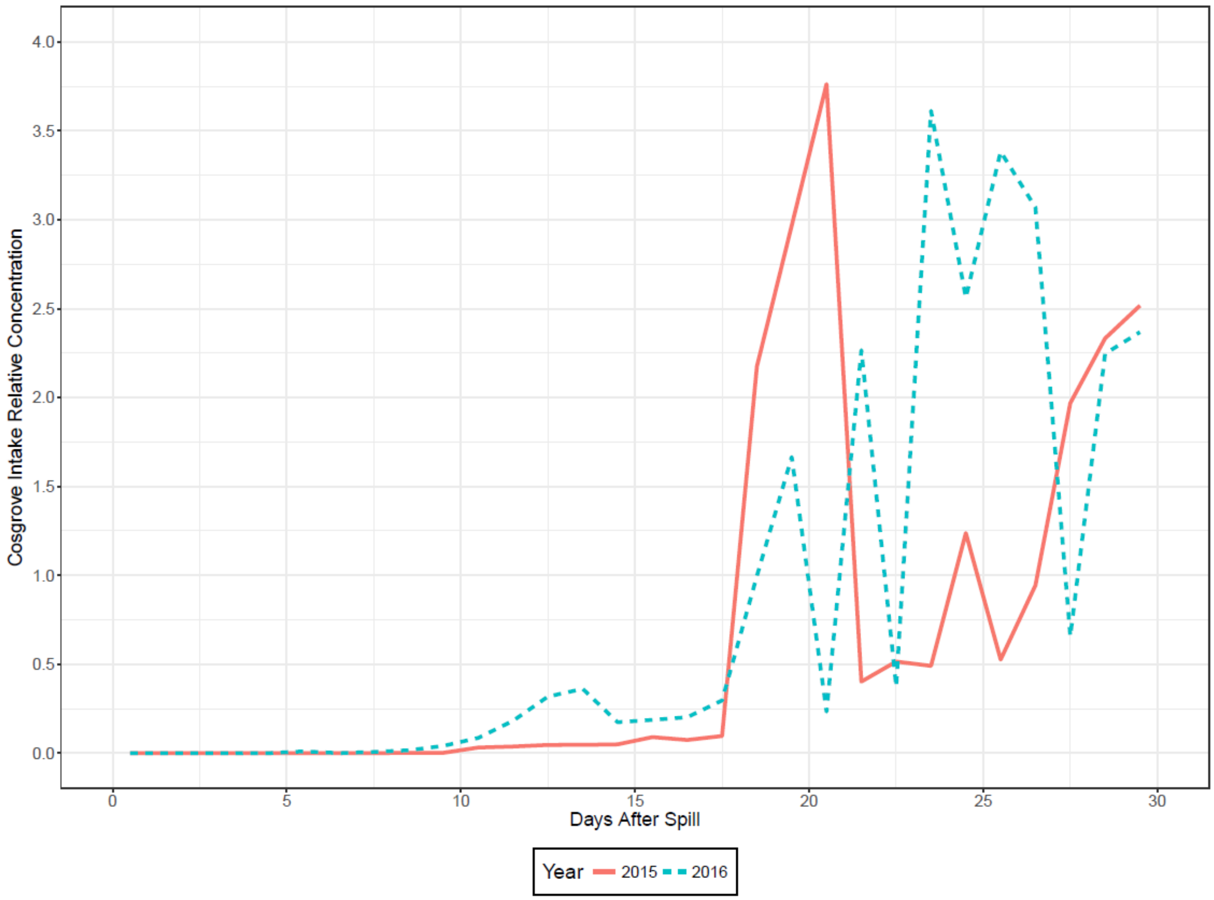

Figure 4.7 2015 and 2016 Summer Cold Spill: W2 Old BTH

4.1.3 Fall

Fall spill behavior is similar to Spring due to the Fall reservoir turnover. The water column once again becomes completely mixed, resulting in little spill temperature related variation in the arrival time and behavior of the contaminant at the intake. The warm spill scenario required a slightly longer time to reach a maximum relative concentration compared to cold and medium spills scenarios in 2015 (Figure 4.8). The warm spill behavior is different from the other two most likely because the water column is not fully in a completely mixed condition; the epilimnion layer is slightly warmer than the lower layers. Contaminant arrival time at the intake was around 6.5 days post spill regardless of the spill temperature.

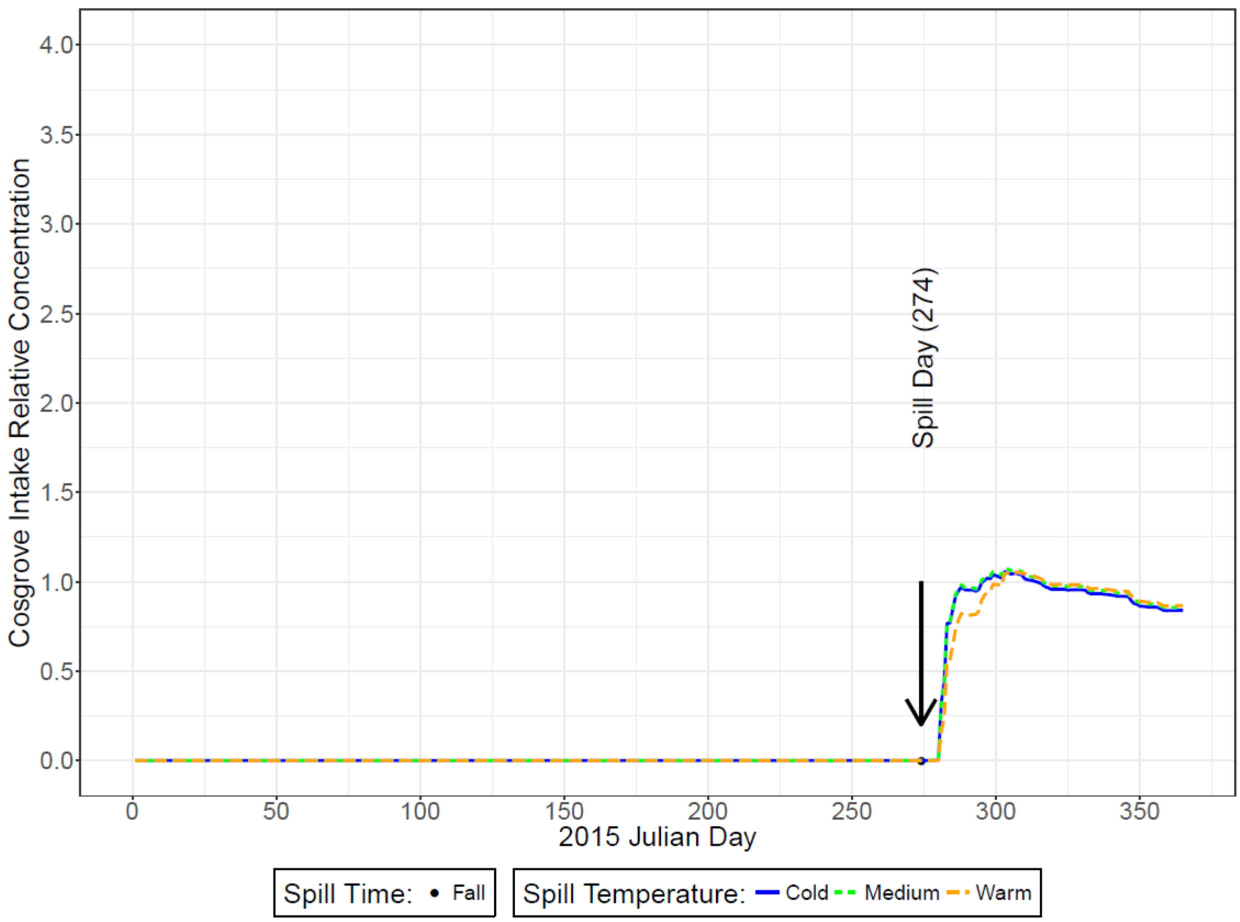

Figure 4.8 Relative Concentration at Cosgrove Intake: 2015 Fall Spill: W2 Old BTH

4.2 Varying Shear Stress Formulation and Bathymetry

Spill arrival time and concentration at the Cosgrove Intake were compared for the two shear stress formulations and two bathymetry files. The combinations resulted in four different model types: W2 with the old bathymetry, W2 with the new bathymetry, TKE with the old bathymetry and TKE with the new bathymetry. Although UMass has historically used the W2 old bathymetry file, TKE old better matched the DCR measured temperature and specific conductivity water profiles, which potentially indicate a more accurate depiction of the reservoir system. All four model types were investigated for calendar years 2015 and 2016 to provide reservoir management a wider range of potential outcomes of a spill. Only 2015 spill scenarios are discussed in this section.

4.2.1 Turbulent Kinetic Energy Formulation Comparison

Wachusett Reservoir model calibration in this report showed that the type of shear stress formulation used has an impact on the modeled temperature and specific conductivity profiles. The impact of the type of formulation used on the contaminant arrival time and concentration at the intake was evaluated. Figure 4.9 presents the results of varying the shear stress formulation. Spill simulation with the TKE formulation exhibited a steady rise to a peak concentration as opposed to sudden increase for the Spring cold spill with the W2 formulation. Results from spill simulations for the TKE formulation were also characterized by a higher maximum relative concentration of 1.5 compared to 1.0 for the W2 model and longer arrival time of 11.5 days compared to 7.5 days for W2. All three temperature spills in the Spring exhibited the same behavior regardless of the model type due to the completely mixed nature of the reservoir at the time, thus only one temperature was shown in Figure 4.9.

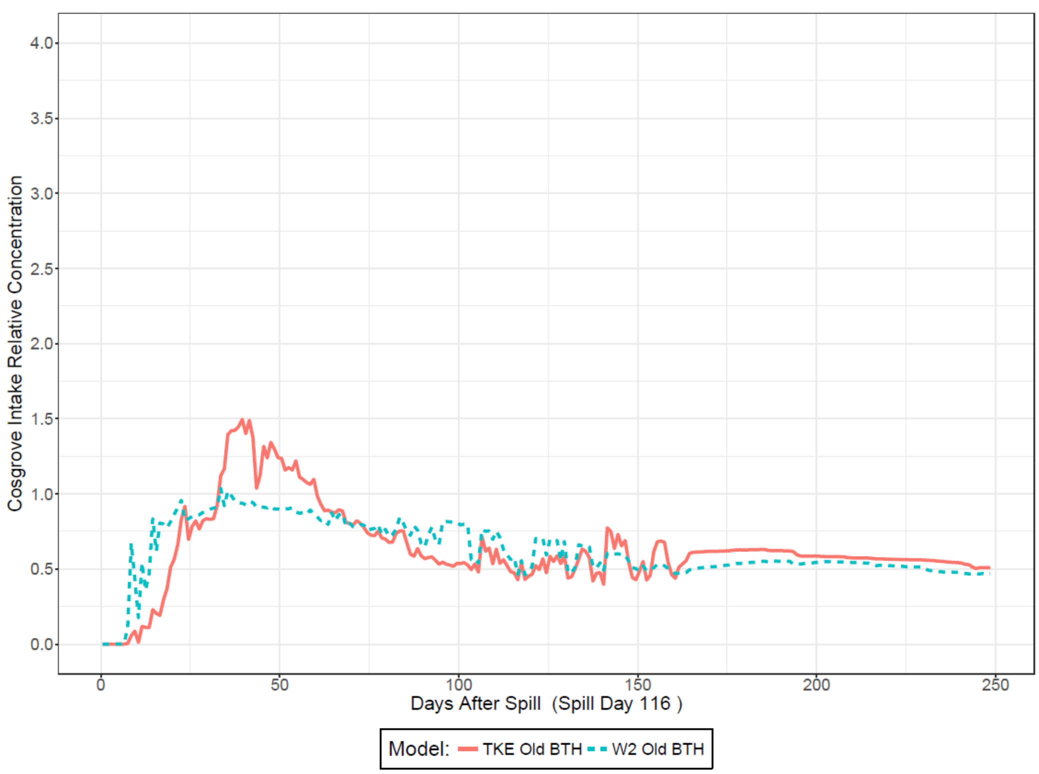

Figure 4.9 TKE vs W2 Comparison: 2015 Spring Cold Spill

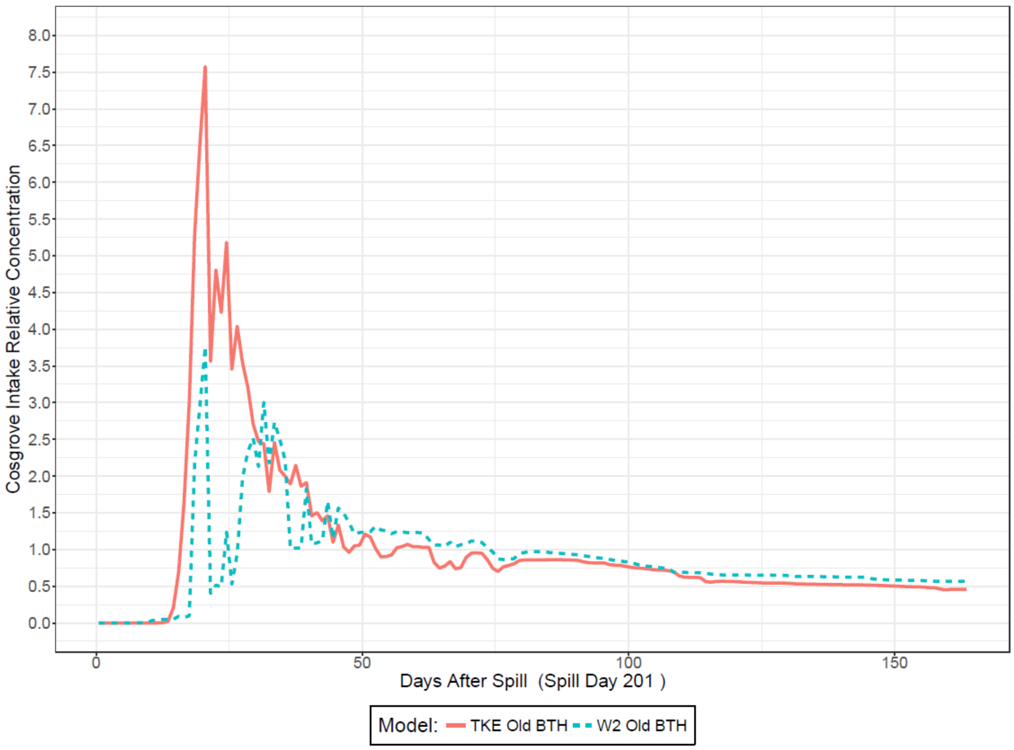

Figure 4.10 TKE vs W2 Comparison: 2015 Summer Cold Spill

Previously in this report, it was concluded that the Summer season has complex reservoir hydrodynamic behavior that affected the transport of a constituent across the reservoir. Varying the spill temperature revealed that Summer cold and medium spill have nearly identical characteristics in terms of the contaminant arrival time and relative concentration; only the Summer cold spill is shown in Figure 4.10. The TKE model simulations indicated significantly higher maximum relative concentration at the intake during the Summer with a value of 7.6 compared to 3.7 for W2. It is interesting to note that unlike the Spring cold spill, the TKE model simulated less time required to reach maximum relative concentration at the intake than for W2 during the Summer. Both stimulations however, exhibited similar behavior 40 days post spill. The Summer warm spill for the TKE formulation and for W2 also showed higher arrival concentration and variability due to thermal stratification (Figure 4.11).

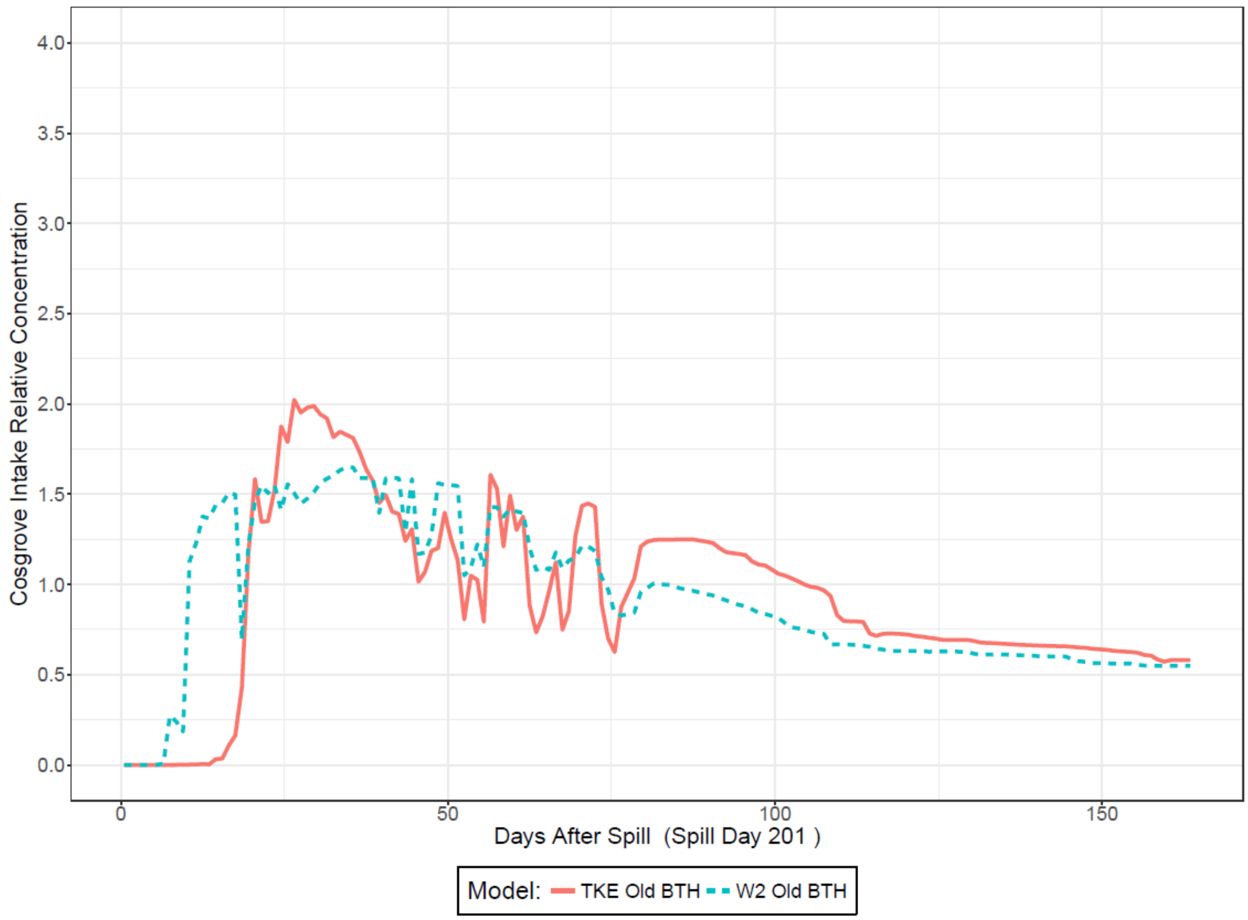

Figure 4.11 TKE vs W2 Comparison: 2015 Summer Warm Spill

4.2.2 Impact of Bathymetry Adjustment on Contaminant Behavior

As previously discussed in an early section of this report, the new bathymetry file resulted in better agreement of modeled and measured water temperature and specific conductivity at the Cosgrove Intake, especially during periods of stratification (Figures 3.30 and 3.31). Simulations with the new bathymetry withdrew water in the model that is more representative of what is actually leaving the Cosgrove Intake, based on CIT water quality data.

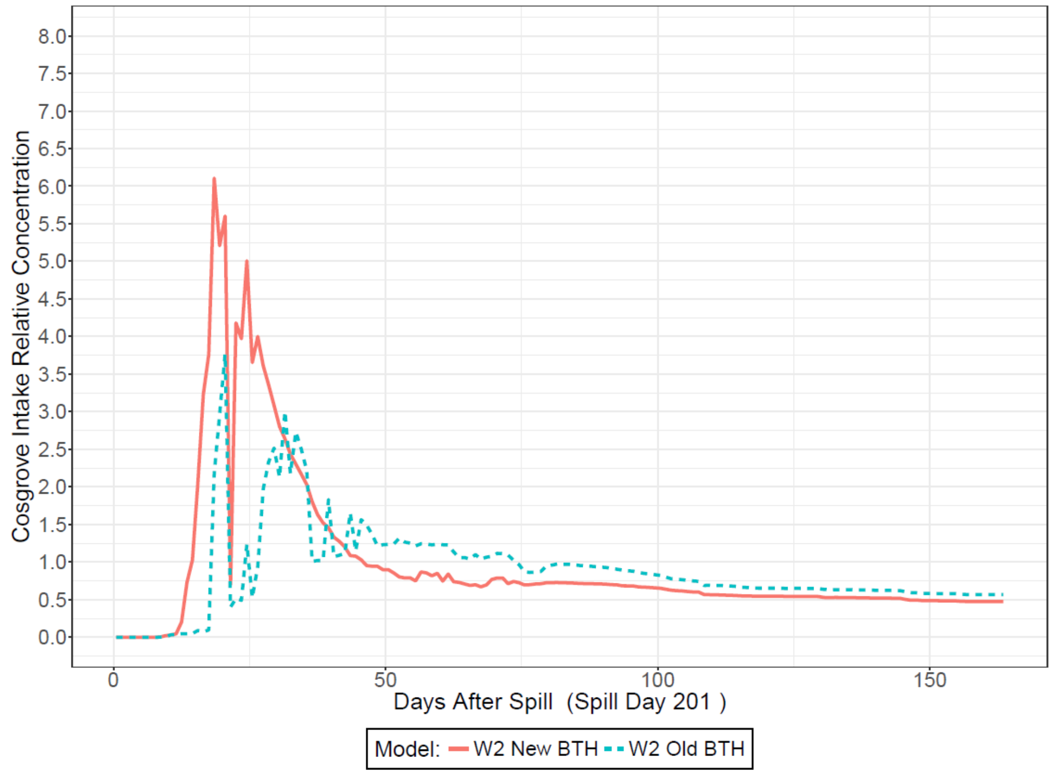

Figure 4.12 Old vs New Bathymetry Comparison: 2015 Summer Cold Spill

An initial comparison between the old and new bathymetry files is shown Figure 4.12. The results showed significantly different contaminant arrival times and concentrations at the intake. The W2 formulation with the new bathymetry simulated a higher maximum relative concentration that quickly tapered off compared to results from the spills simulated with the old bathymetry. The conclusion that bathymetry file adjustment affected the transport of contaminant spill in the reservoir is verified and further investigated for the TKE formulation as well. Figures 4.13 to 4.16 present results from the bathymetry adjustment investigation. As speculated, the contaminant arrival time and concentration are both influenced by the changes in Segments 45 and 46. Simulations using the TKE formulation with the new bathymetry consistently exhibited the longest time to reach a maximum relative concentration at the intake, regardless of the season. The maximum relative concentration is also lower than results for the TKE with old bathymetry models. Interestingly, simulations using the TKE formulation with the new bathymetry (except for Summer warm spill) yielded lower peak relative concentrations compared to the old bathymetry. The W2 formulation simulated results different from the TKE formulation; higher peak relative concentration and slightly faster contaminant arrival time at the intake occurred with the new bathymetry (except for Summer warm spill). One speculation of why the Summer warm spill does not fall under these two generalizations is the presence of thermal stratification. Thermal stratification inhibited mixing between the epilimnion layer with the remaining water column where the warm spill travels. The wind is the predominate driving force of movement in in the epilimnion while other hydrodynamics dominate the lower water column. Stauber (2009) noted that wind has a significant influence on a warm spill that is traveling on top of the water column.

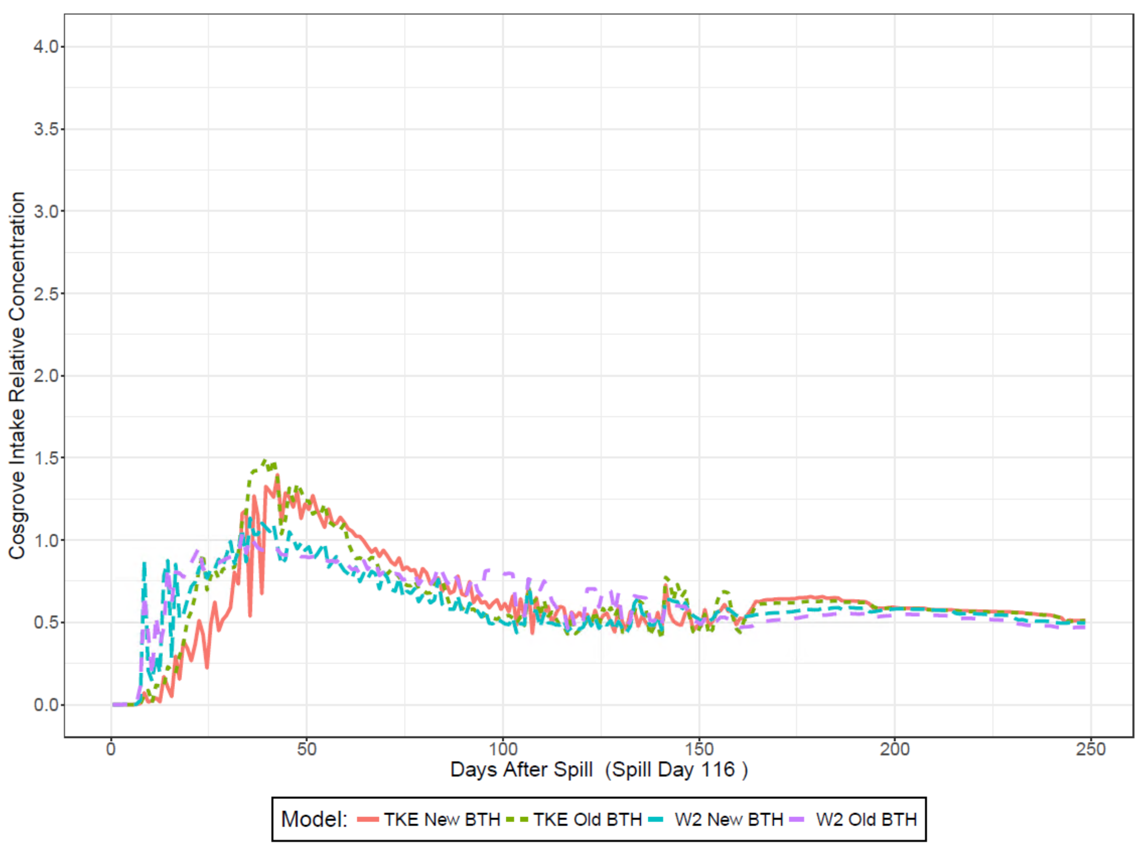

Figure 4.13 Old vs New Bathymetry Comparison: 2015 Spring Cold Spill

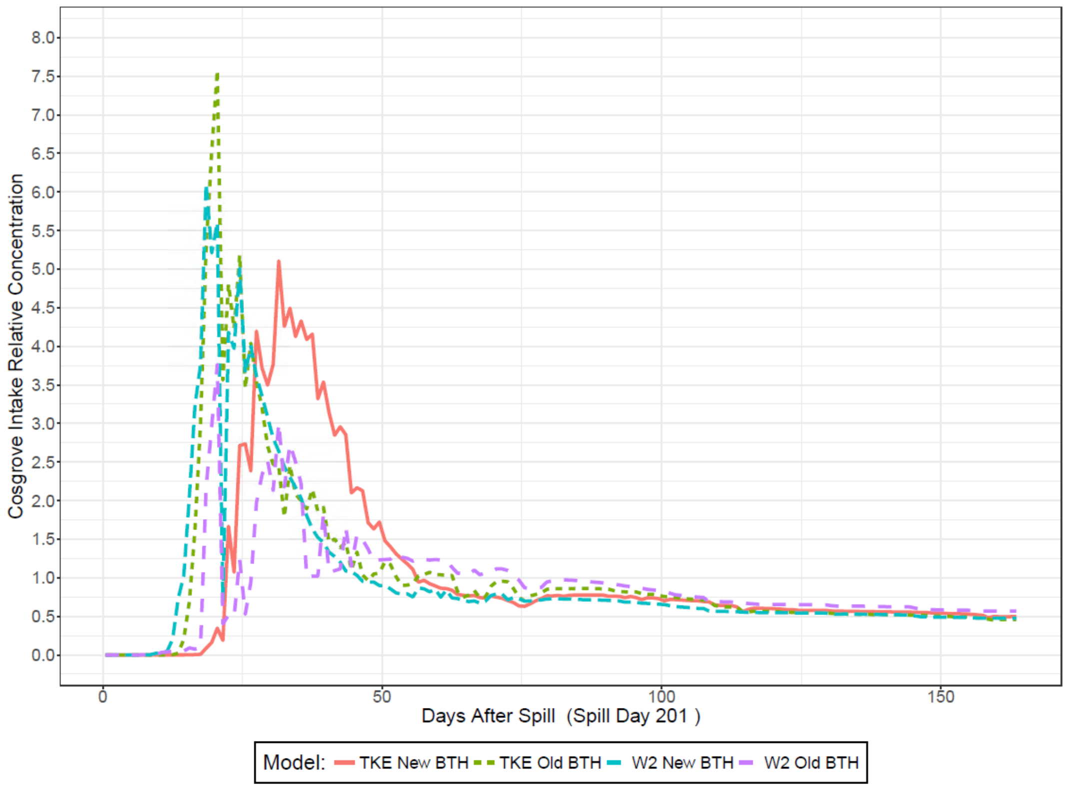

Figure 4.14 Old vs New Bathymetry Comparison: 2015 Summer Cold Spill

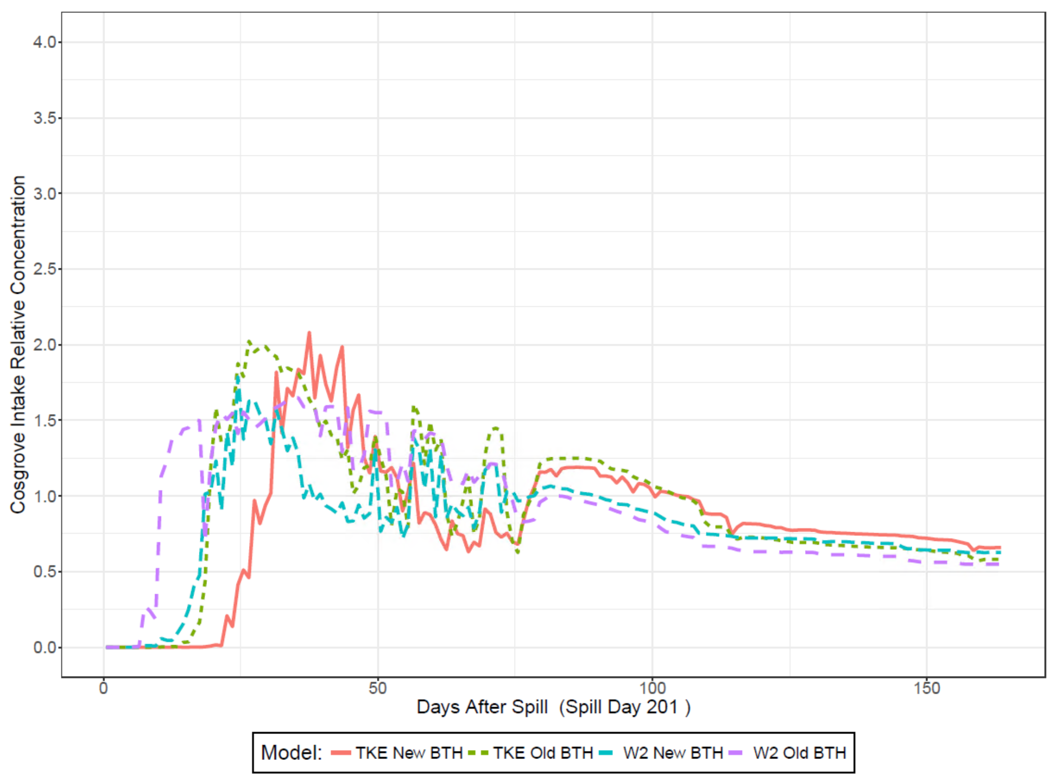

Figure 4.15 Old vs New Bathymetry Comparison: 2015 Summer Warm Spill

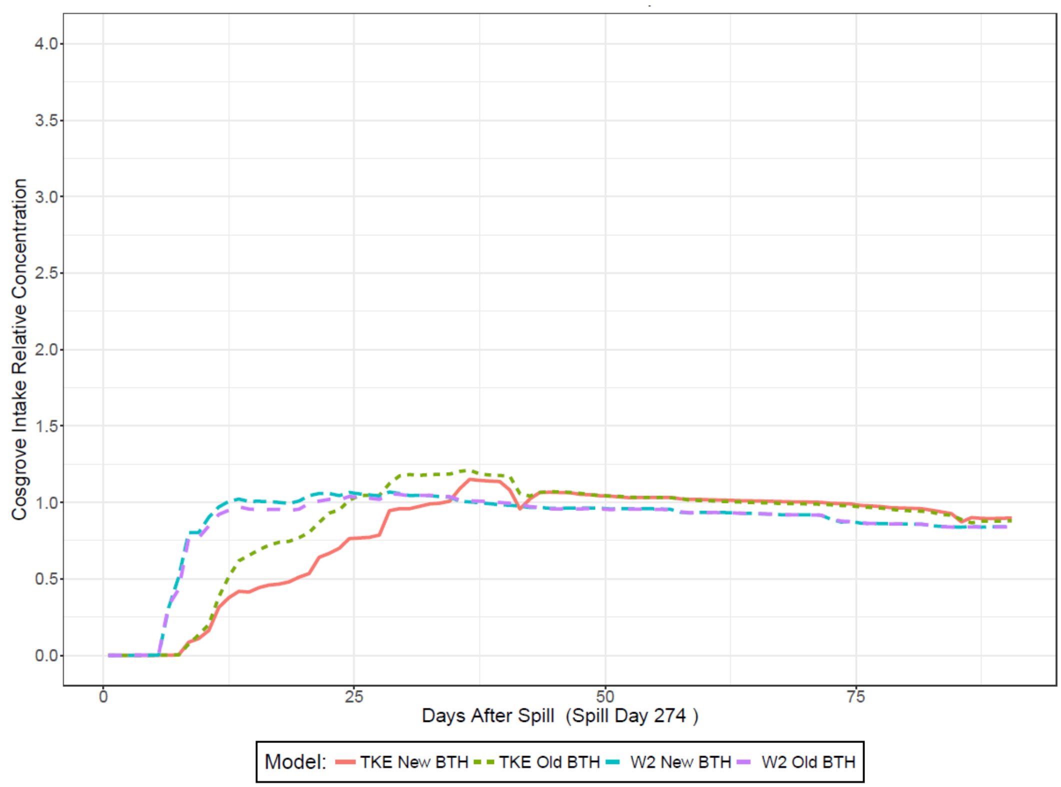

Figure 4.16 Old vs New Bathymetry Comparison: 2015 Fall Cold Spill

Tables 4.1 and 4.2 present average results for the 2015 and 2016 contaminant spill simulations. Simulations with the TKE formulation exhibited a longer contaminant arrival time and higher maximum relative concentration at the intake for nearly all spill scenarios. The bathymetry adjustment showed little effects on Spring and Fall spills. However, significant differences in contaminant arrival time and maximum relative concentration at the intake could be observed for Summer spills.

Contaminant arrival time at the intake using the historical W2 formulation with the old bathymetry file are within the ranges reported by Clark (2013); her 2003-2009 modeled contaminant arrival time ranged from 2 to 7 days, 5 to 15 days, and 4 to 11 days for Spring, Summer, and Fall spills, respectively. The maximum relative concentration at the CIT are also within the ranges of 1.0 to

2.9 and 0.8 to 1.5 for Spring and Fall spills, respectively. Summer maximum relative concentrations are slightly higher, by 0.55 when compared to her 2003 to 2009 spill modeling results. Differences are most likely caused by different meteorological conditions, such as higher maximum wind speed during time of spill.

Table 4. 1 2015 and 2016 Averaged Arrival Time of Spill Contaminant at CIT

Formulation	Average Arrivial Time (Days)								
	Spring			Summer			Fall		
	Cold	Medium	Warm	Cold	Medium	Warm	Cold	Medium	Warm
W2 Old	7.5	7.5	7.5	15	13	6.5	8	8	8
W2 New	7.5	7.5	7.5	12	12	14	7.5	7.5	8
TKE Old	10.5	10	10	15	15	17	14.5	14.5	15.5
TKE New	10.5	10.5	10.5	21.5	21	25.5	15	14.5	16.5

Table 4. 2 2015 and 2016 Averaged Maximum Relative Concentration of Spill Contaminant at CIT

Formulation	Average Maximum Relative Concentration (C_{model}/C_o)								
	Spring			Summer			Fall		
	Cold	Medium	Warm	Cold	Medium	Warm	Cold	Medium	Warm
W2 Old	1.03	1.03	1.04	3.57	3.75	1.64	1.15	1.16	1.15
W2 New	1.09	1.10	1.11	5.50	5.48	2.26	1.15	1.16	1.14
TKE Old	1.27	1.27	1.28	7.64	7.15	2.45	1.17	1.17	1.13
TKE New	1.24	1.27	1.25	5.16	4.84	2.62	1.09	1.10	1.10

CHAPTER 5: SUMMARY AND CONCLUSION

5.1. Summary

2015 and 2016 CE-QUAL-W2 Version 4.0 models of the Wachusett Reservoir were successfully developed. Parameters in a water balance were optimized to minimize the differences between calculated and measured water surface elevations through EXCEL SOLVER. Four different models were developed for each year to investigate vertical shear stress formulation and bathymetry adjustment effects on the reservoir heat budget and transport of a conservative constituent. Sensitivity analyses were performed by varying one model parameter at a time. All four models were calibrated individually to produce a low RMSE that better match the simulated Segment 42 temperature and specific conductivity profiles with the DCR measured profiles in the North Basin for both years.

The calibrated models were used to simulate contaminant spill scenarios into the Wachusett Reservoir that occurred near the Beaman Street Bridge on Route 140. Consistent vehicle traffic across the Beaman Street Bridge and a railroad that travels parallel to the reservoir's shore are risk factors that designate this location as highly susceptible to an oil truck or train accident. A conservative, nonreactive tracer was used in contaminant spill simulations. Spill scenarios included varying spill temperature and spill season for each of the four models. This was performed to investigate the impact of density and seasonal trends on spill contaminant behavior at Cosgrove Intake.

5.2 Conclusion

Spill scenarios using 2015 and 2016 Wachusett Reservoir models were simulated to analyze the effects of spill temperature (density) and seasonality on contaminant concentration at the Cosgrove Intake. The results from this report concluded that Spring spills appear at the intake in shortest amount of time all three seasons for all model types with average arrival time for the entire season of 7.5 to 10.5 days. The Fall spills have the second fastest travel time with average arrival time between 7.7 to 15.3 days. The Summer spills required the longest period of time before reaching the intake and were much more variable, ranging from 11.5 to 22.7 days. Spring and Fall spills share similar maximum relative concentration regardless of the spill temperature due to reservoir turnover that induced mixing across the layers. Summer spills exhibited the highest variability in arrival time and concentration due to thermal stratification of the reservoir at this time of the year.

The type of vertical shear stress formulation used in a model run results in variation of contaminant behavior at the Cosgrove Intake (Figure 5.1). The W2 formulation simulated a faster average arrival time at the Cosgrove Intake of 7.5 to 14 days, while the TKE formulation results showed a longer period of 10 to 25.5 days. When the reservoir is completely mixed during the Spring and Fall, the peak maximum relative concentration is lower for models simulated with the TKE formulation. However, the opposite is true when the reservoir is stratified in the Summer as lower peak maximum relative concentration can be observed for a spill simulated using the W2 formulation (Figure 5.2).

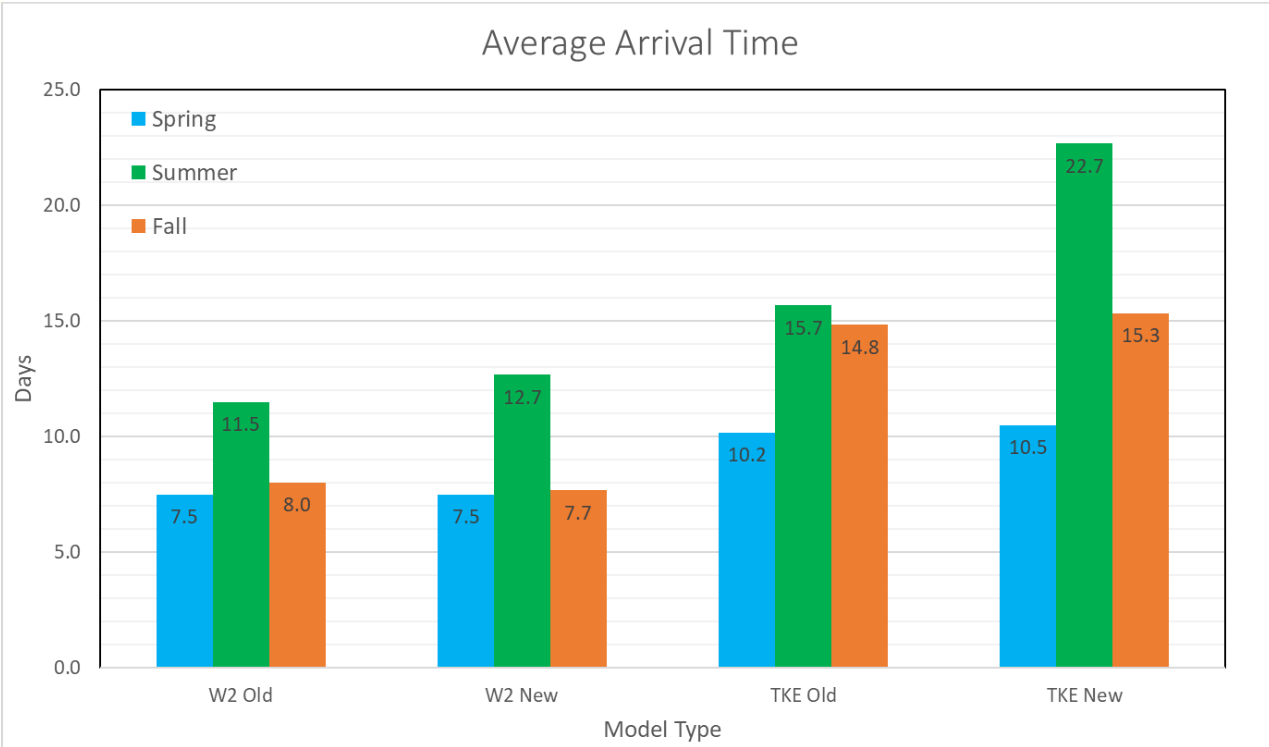

Figure 5.1 Average Arrival Time Spilled Contaminant at Cosgrove Intake.

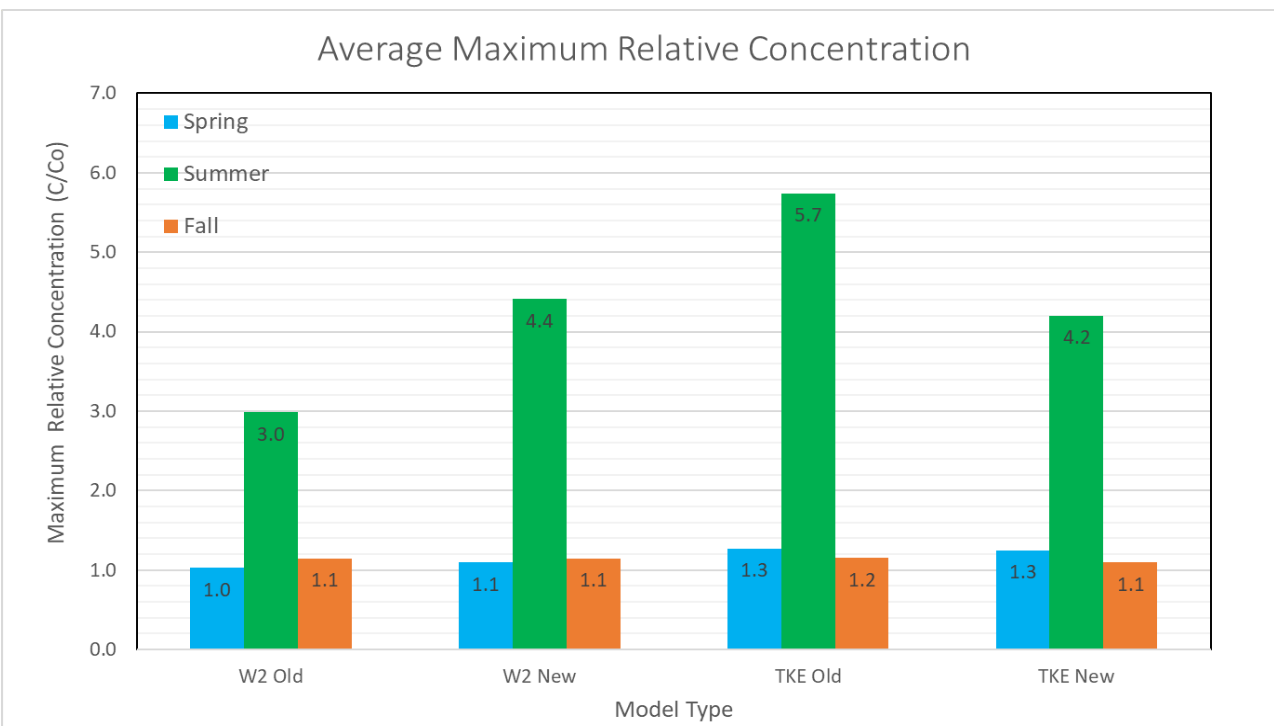

Figure 5.2 Average Maximum Relative Concentration of Spilled Contaminant at CIT

During the Spring and Fall when the reservoir is completely mixed, contaminant arrival times are similar between model runs regardless of bathymetry adjustments. In the Summer when thermal stratification occurs, the contaminant for both warm and medium spills required slightly longer time to arrive at the intake as compared to the old bathymetry file. This could be due to the fact that the adjusted bathymetry facilitated increased flow from the thermocline and hypolimnion layer while reducing flow from the epilimnion. Spring and Fall spills shared similar maximum relative concentration regardless of shear stress formulation used or bathymetry adjustment. A significant difference in arrival concentration and arrival time can be observed for the results of simulations with two different bathymetry files for Summer spills. The W2 formulation with the new bathymetry experienced an increase while TKE saw a reduction in the maximum arrival concentration of contaminant. The cause of this is unclear and requires further investigation into the TKE and W2 vertical shear stress formulations.

5.3 Recommendations and Future Work

Future work should include a comprehensive investigation to resolve the underlying problem that caused the data inconsistency between the MWRA CIT and DCR North Basin measured temperature and specific conductivity during times of reservoir turnover. The validity of the CIT and cofferdam construction plan should be verified. Data from the recently installed discharge gauge at the mouth of Gates Brook should be incorporated as opposed to the continued use of estimated flow values based on the Stillwater River Ratio. The measured and estimated discharges could then be compared, and adjustments made accordingly to the other Stillwater ratio estimated tributary discharges. Optimization could be performed simultaneously on all the user defined model parameters to achieve the lowest possible RMSE between measured and modeled constituent profiles, instead of single parameter at a time calibration.

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APPENDIX

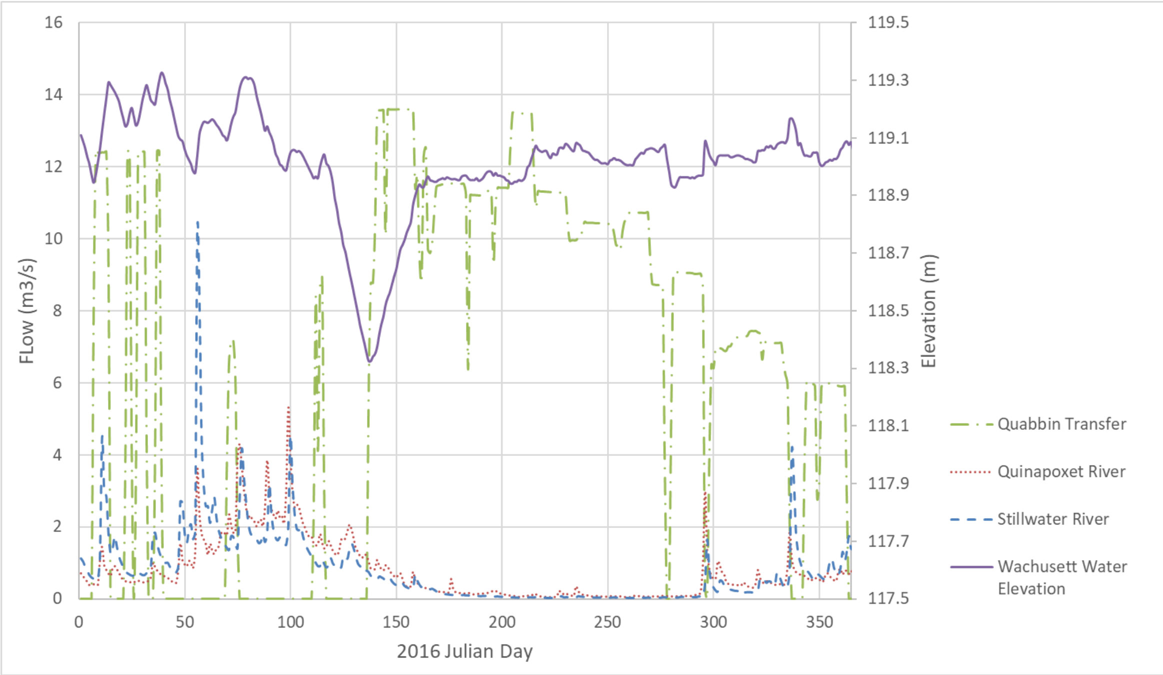

Figure A.1 Calendar Year 2016: Major Inflows

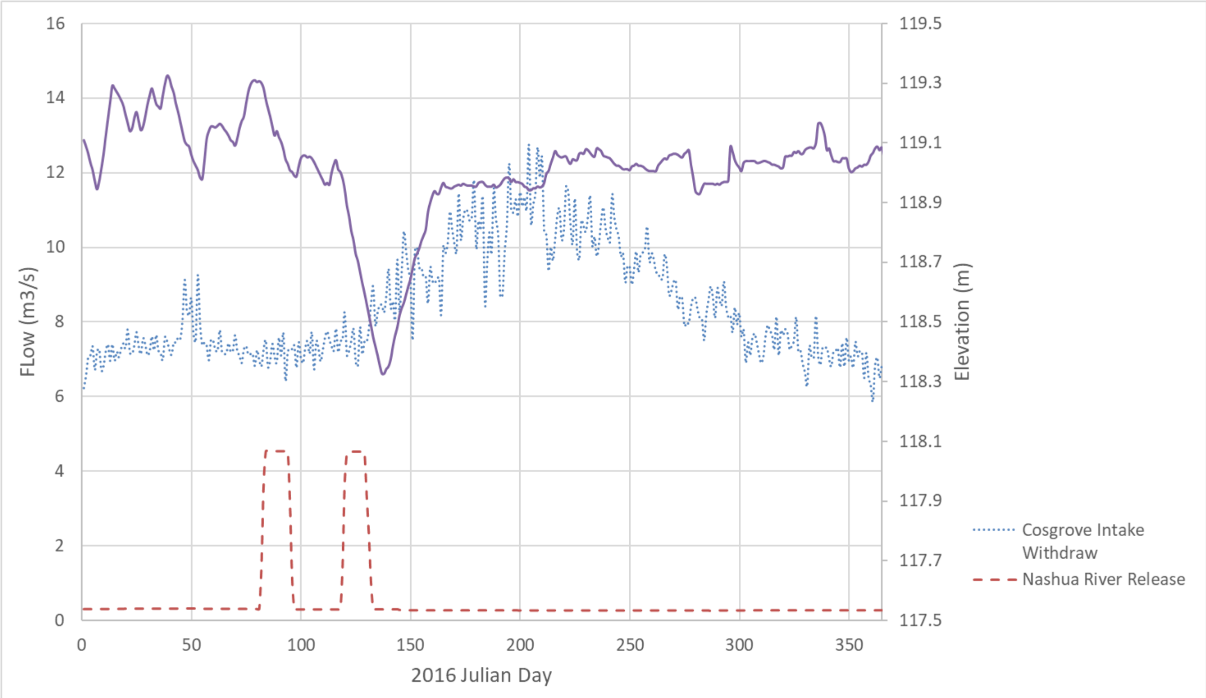

Figure A.2 Calendar Year 2016: Major Daily Outflows of the Wachusett Reservoir.

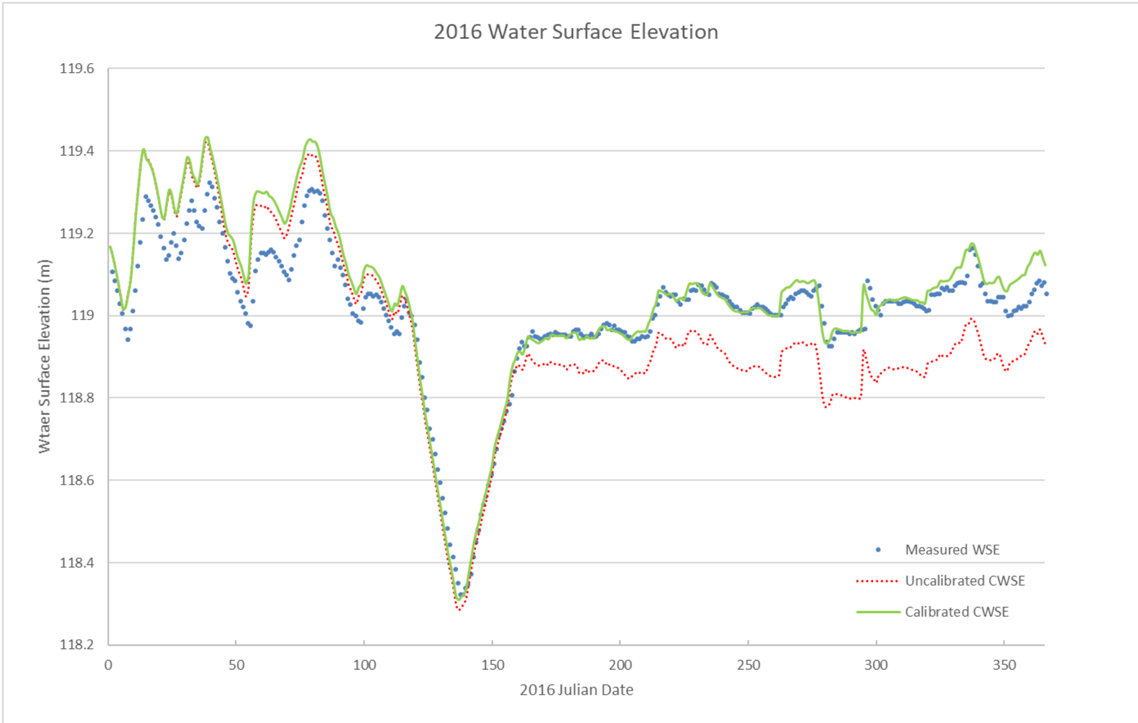

Figure A.3 Measured, Pre-calibrated and Calibrated WSE, 2016.

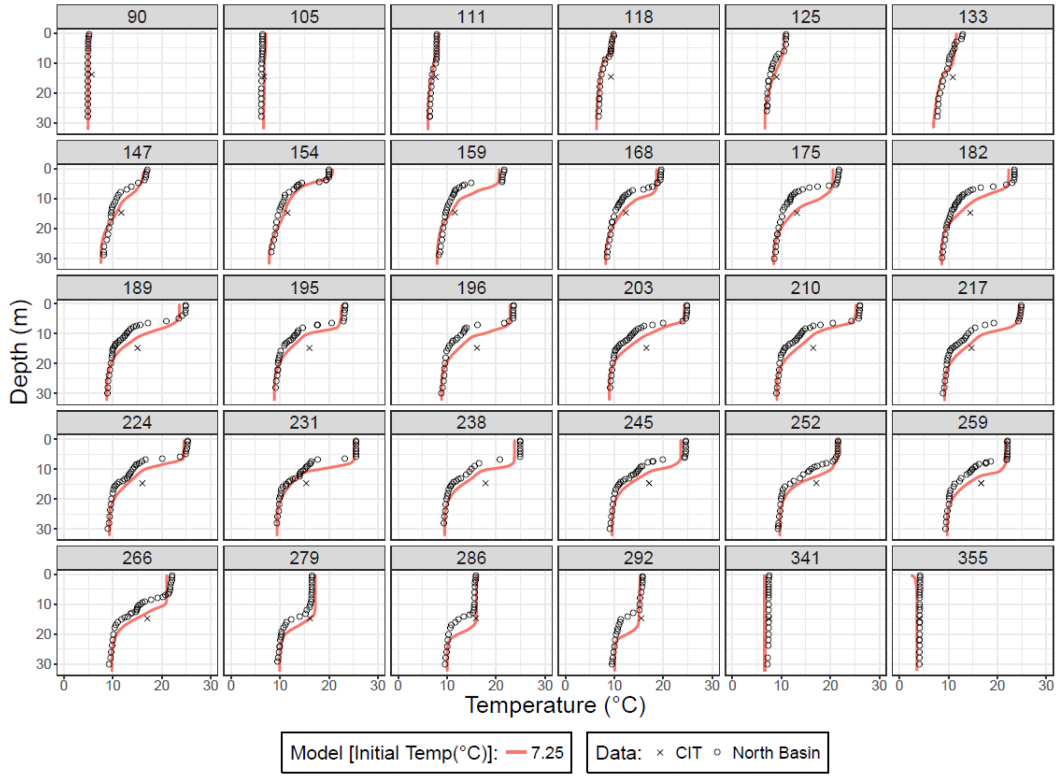

Figure A.4 2016 Calibrated Temperature: W2 Old BTH

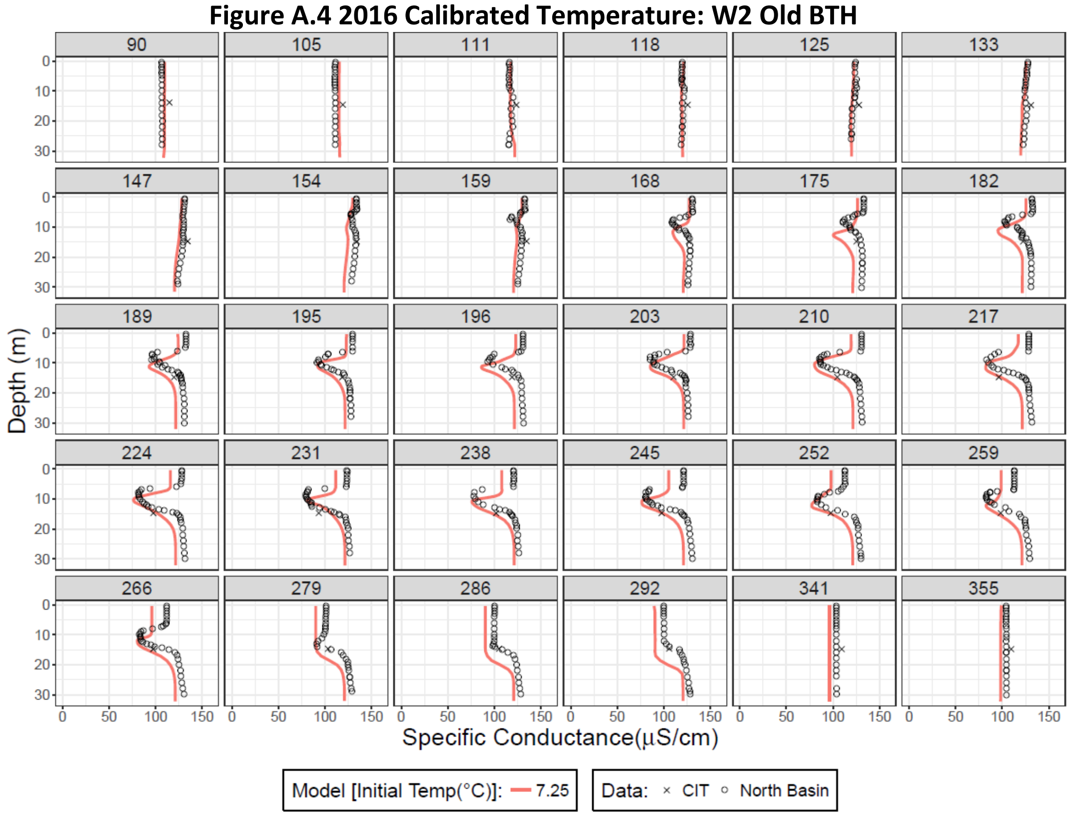

Figure A.5 2016 Calibrated Specific Conductance: W2 Old BTH

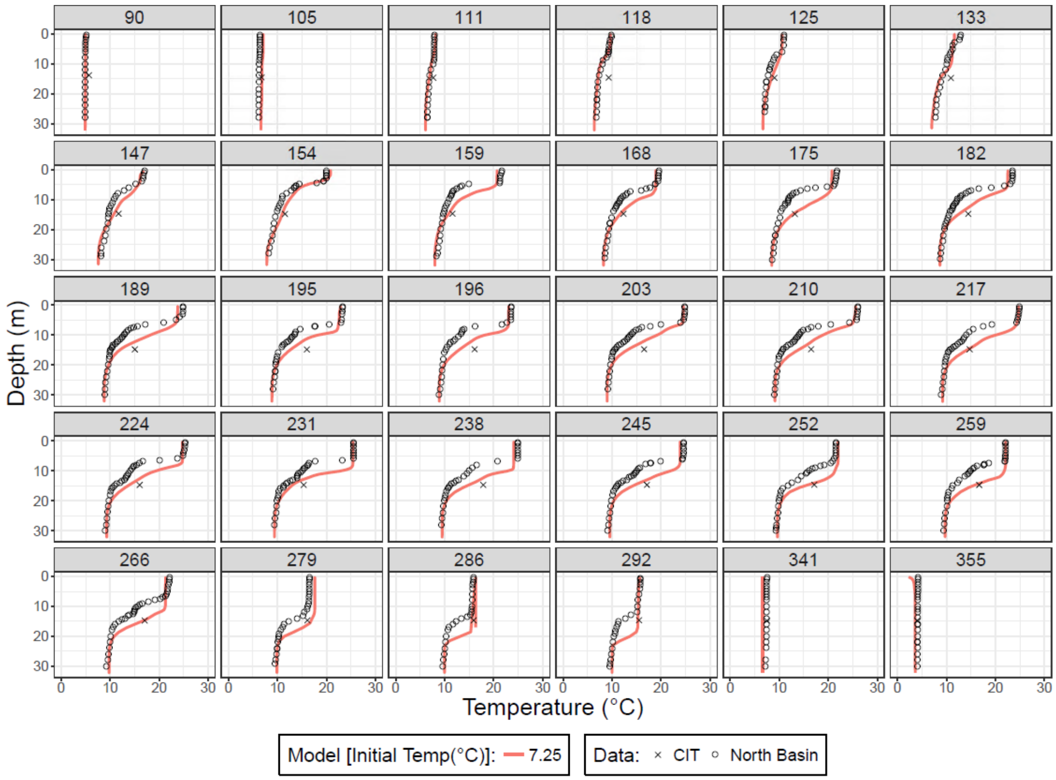

Figure A.6 2016 Calibrated Temperature: W2 New BTH

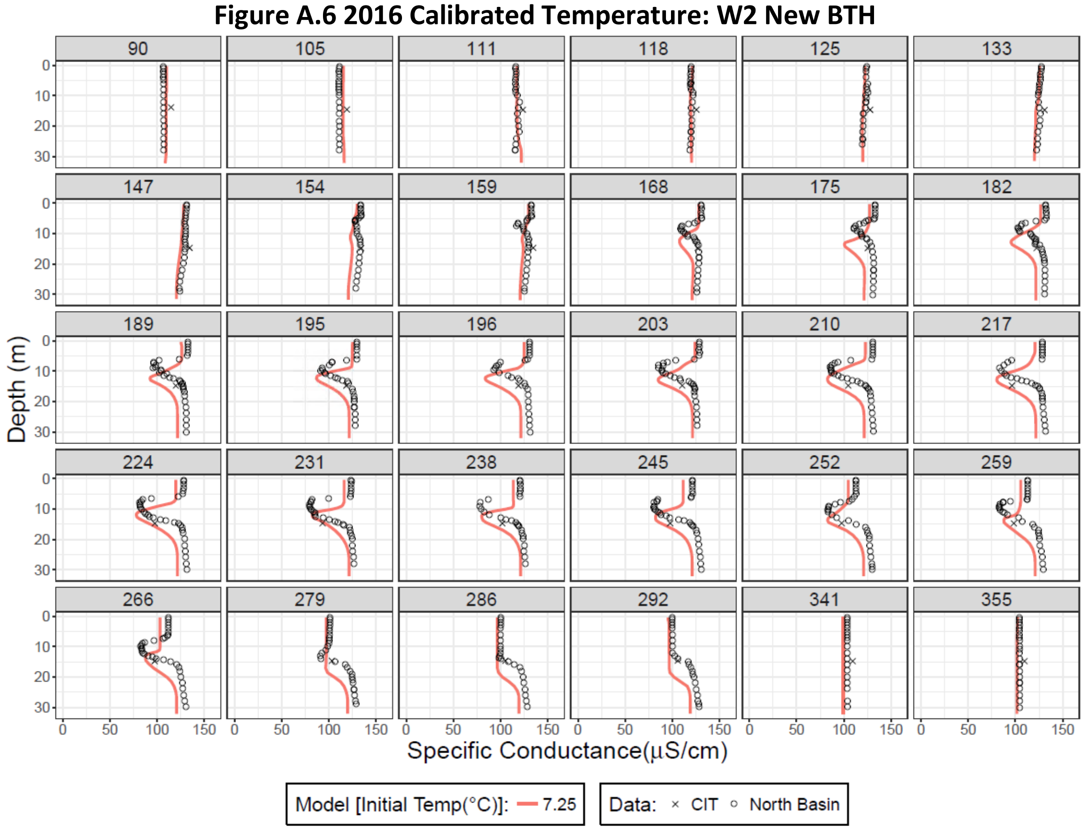

Figure A.7 2016 Calibrated Specific Conductance: W2 New BTH

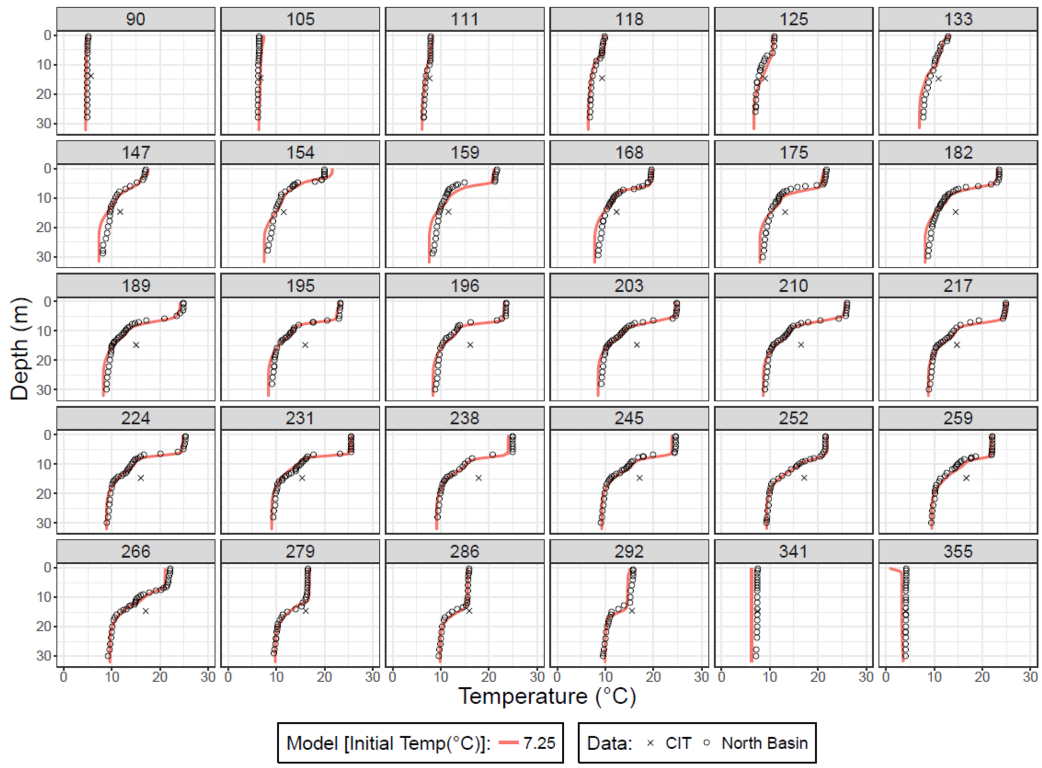

Figure A.8 2016 Calibrated Temperature: TKE Old BTH

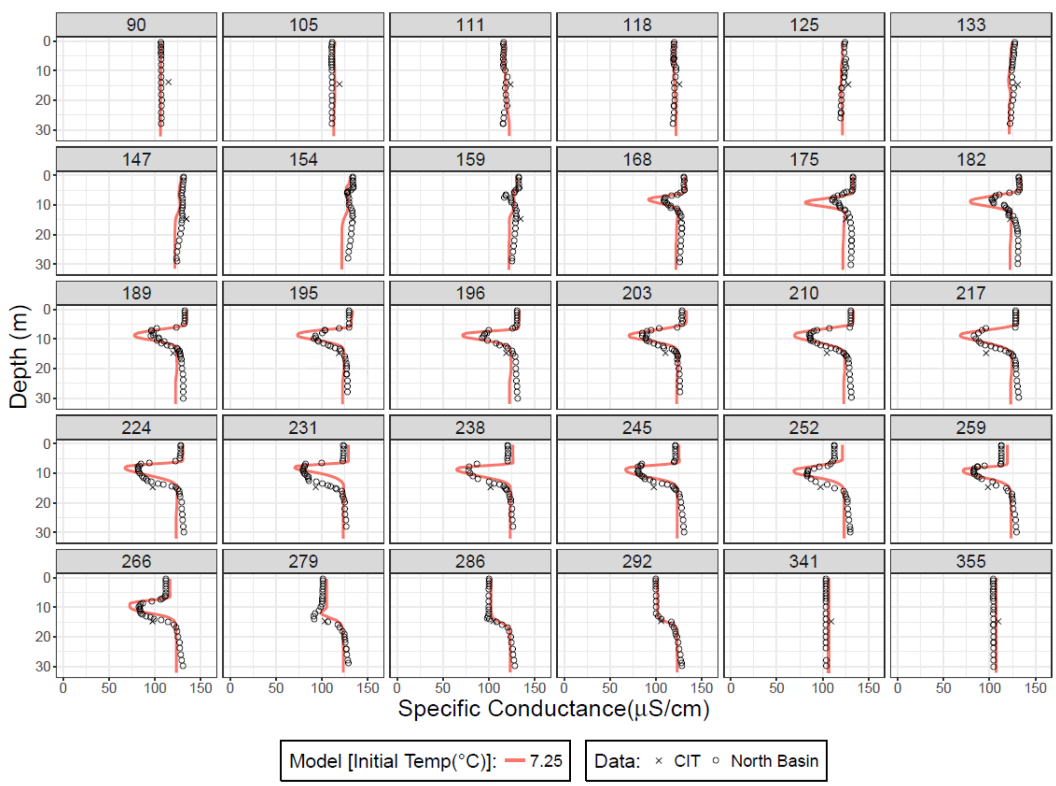

Figure A.9 2016 Calibrated Specific Conductance: TKE Old BTH

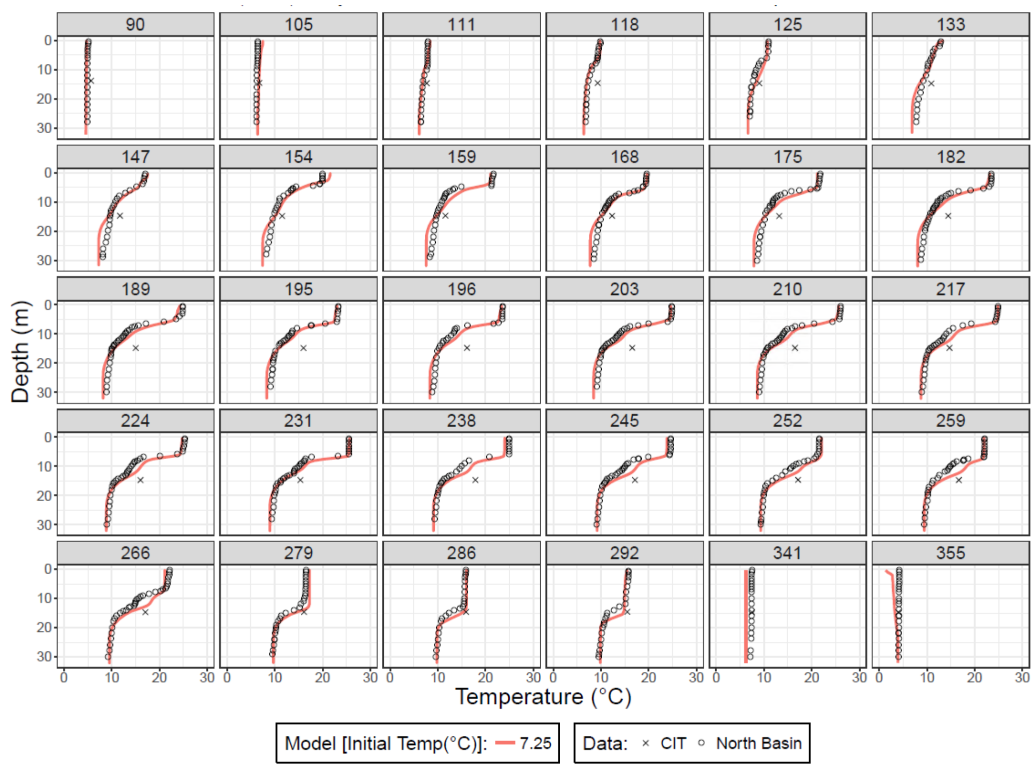

Figure A. 10 2016 Calibrated Specific Conductance: TKE New BTH

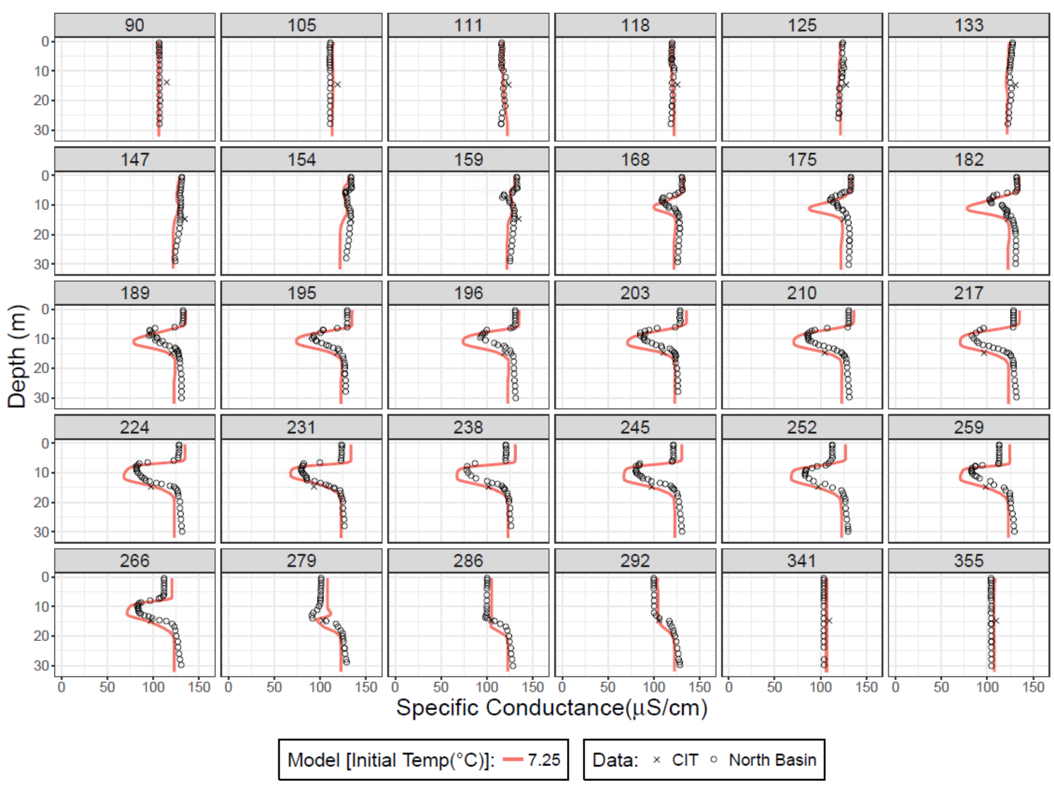

Figure A. 11 2016 Calibrated Specific Conductance: TKE New BTH