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Hydrodynamic Modeling of the Green Bay of Lake Michigan Using the Environmental Fluid Dynamics Code

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HYDRODYNAMIC MODELING OF THE GREEN BAY OF LAKE MICHIGAN USING THE ENVIRONMENTAL FLUID DYNAMICS CODE

by

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ABSTRACT

HYDRODYNAMIC MODELING OF THE GREEN BAY OF LAKE MICHIGAN USING THE ENVIRONMENTAL FLUID DYNAMICS CODE

by

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The University of Wisconsin-Milwaukee, 2015
Under the Supervision of Professor Hector Bravo

In this project we created a hydrodynamic model of the Lower Green Bay of Lake Michigan in Wisconsin, United States using the Visual Environmental Fluid Dynamics Code (EFDC). The model includes four tributary rivers to Lower Green Bay as well as the open boundary flow conditions at Chambers Island. This case study is used to: 1) compare the results obtained with a previous study of Lower Green Bay to validate the creation of the model 2) examine the hydrodynamics of the bay, and 3) create a framework for future studies at Lower Green Bay. The Geographic Information used to build the Grid was obtained from the NOAA web site. Meteorological and flow information was obtained from the National Weather Service and USGS web sites, respectively. It was necessary to create a new model grid as a platform for future studies of Lower Green Bay, and the Visual EFDC 1.2 code was a useful tool in the development of the grid. However, some limitations in the code made the creation of the grid a challenge. In this project, we summarize the process used to overcome challenges in creating a correct grid, and analyze the hydrodynamic results of the model simulation for the period between June and October 2011. Overall, we conclude that the model reproduces field data reasonably well, and a correct modeling framework for hydrodynamic modeling of Lower Green Bay was created.

To

my parents,

my husband,

my sister

and Richard.

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Professor Hector Bravo for his support with this project as well as my career development. Besides my advisor I would like to thank the members of my thesis committee Professor Qian Liao and Professor ChangShan Wu for their insights and interest in this project. I will also like to thank Dr. Sajad Hamidi for sharing his knowledge with me, and Kim M. Weckerly Research Specialist for her help in the initial project set up.

CHAPTER 1

INTRODUCTION

1.1. Location, site description: Green Bay

Green Bay is located between the Door Peninsula in northeastern Wisconsin and the southern edge of Michigan's Upper Peninsula (Figure 1). The area of Green Bay is about 525 square miles (Doyle B. et al., n.d.) and the mean depth is about 10 meters in the shallow areas (south) increasing gradually to a depth of 36 meters at Chambers Island. The Green Bay watershed contains almost half of the water that drains into the Lake Michigan, with the Fox River as the principal fluvial system (Klump et al. 1997) and the Peshtigo, Menominee and Oconto Rivers as tributaries. (14901)

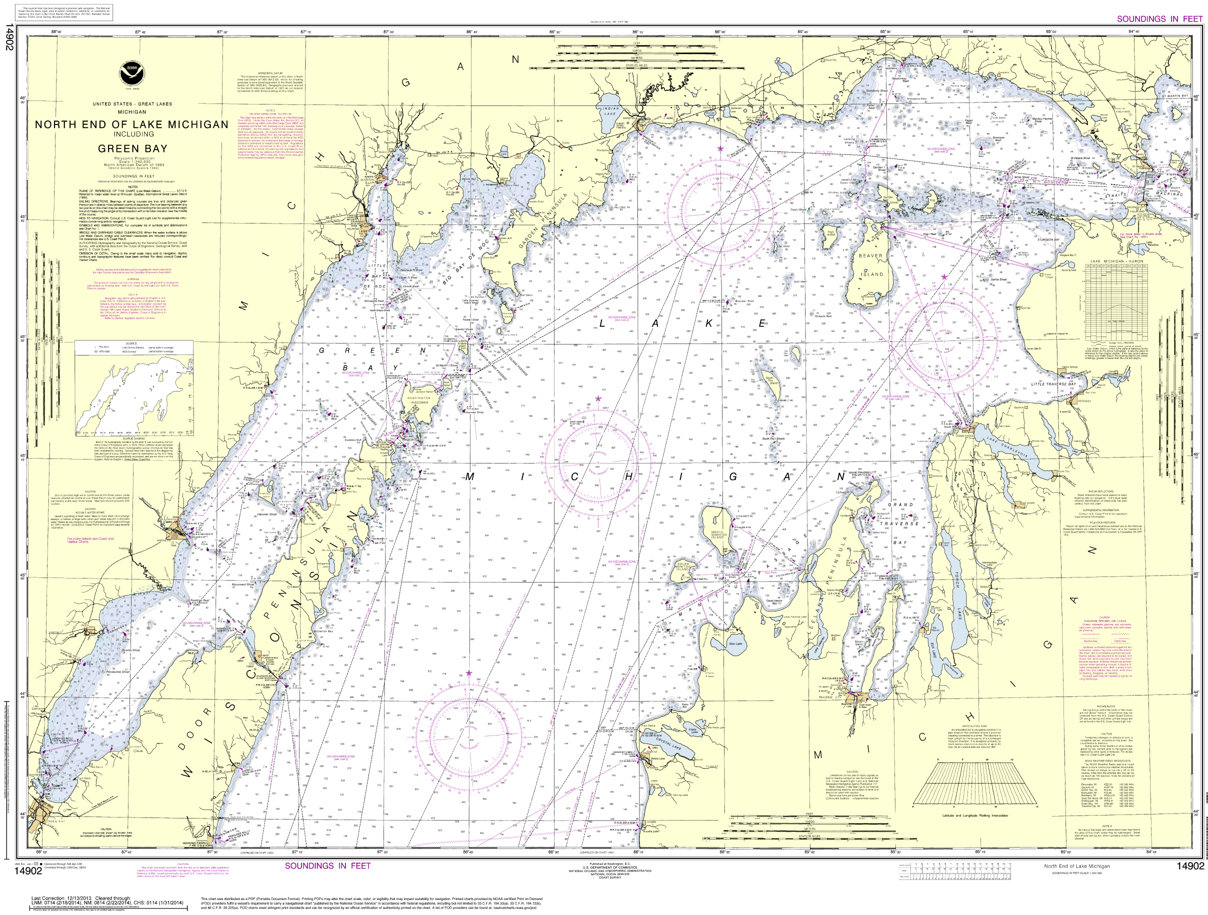

Figure 1 Location of Green Bay (Survey, n.d.)

The Green Bay area has been the subject of various studies because of its known contamination problems caused by industrial development, particularly paper mills and urbanization. Consequently, it is important to develop a hydrodynamic model to provide a framework for current and future studies in this zone.

It is important to highlight that the Lower Fox River in Green Bay is one of the most contaminated rivers that generates demanding stressors for the bay ecosystem and therefore for Lake Michigan as a whole.

1.2. Purpose

The main goal of this project was to develop a hydrodynamic model for Lower Green Bay by using Visual EFDC 1.2 (Environmental Fluid Dynamics Code) developed by Tetra Tech, Inc. This model is the first step for the subsequent study of transport of contaminated sediments, excess of nutrients and re-suspension in Lower Green Bay. Sediment and sediment transport are very important in the vicinity of rivers and has a large environmental impact on the Green Bay system. Contaminated Sediments affect water quality putting at risk small animals and biota in the bay.

The model took into account the four Green Bay main tributaries: Fox, Menominee, Peshtigo and Oconto Rivers as well as the effects of circulation and stratification in the whole Lake Michigan.

The model was validated against field measurements of currents and temperature obtained during 2011, and its results were also compared with previous computational models.
This project is organized as follows. In Chapter 2, the existing approaches and uses of hydrodynamic codes in different water systems are discussed. In Chapter 3, the governing equations are briefly explained. In Chapter 4 the model development is presented. In Chapter 5, an overview of the obtained results is given. In Chapter 6, a comparison of the results obtained from the model against the observed values at Lower Green Bay is elaborated. Finally, in Chapter 7, the conclusions and further works are summarized.

CHAPTER 2

This chapter reviews previous studies related to numerical modeling of hydrodynamics in a water system. The focus is primarily on existing projects related to this case study and the analysis of the results obtained.

2.1 Modeling Framework in water systems

The intricate nature of the hydrodynamic processes in water systems requires use of numerical modeling. This approach is a powerful tool, providing us with a description of circulation, temperature variations and stratification processes that can affect the transport of pollutants and water quality within a basin.

Hydrodynamic models use the topography of the modeled domain, tributaries as inflow conditions, meteorological data, and boundary conditions in order to simulate circulation, water levels, velocity, and temperatures. In a basin, the hydrodynamic simulator should be capable of modeling and performing all the physical processes such as wind forcing, buoyancy, mass transport and turbulent transport of momentum.

Several hydrodynamic models have been developed. Some of the applications of these models are explained below to provide an overview of the different options that are available.

The CH3D-z (Kim 2007) is a hydrodynamic model most frequently used to analyze water quality by linking this model with the CE-QUAL-ICM water simulator; CE-QUAL-ICM was used to develop an eutrophication study for Chesapeake Bay. The CH3D model provides a grid to identify cells and flow faces. This model allows the user to choose a different number of layers below each surface cell in the grid. In order to develop this model, some assumptions are considered: 1) the hydrostatic pressure distribution describes the vertical fluid pressure distribution. 2) Boussinesq approximation is valid. 3) The eddy viscosity approach describes the correct mixing in the flow (Raymond S. Chapman and Billy H. Johnson, S. Rao Vemulakonda 1996).

The MIKE 3 (DHI 2013) is a hydrodynamic model that has been developed for oceanographic, coastal and estuarine environments. The Danish Hydraulic Institute markets this package and includes various modules for different applications. Using the finite volume method, this hydrodynamic model performs the spatial discretization of the governing equations. The Mike 11 modeling system was applied in order to create a detailed hydrodynamic model for Lowe Rideau River System. The developed model was able to simulate the hydrodynamics of the river with a high degree of accuracy and is now used for various watershed management purposes (Ahmed 2010).

The Princeton Ocean Model (POM) has been applied to many water systems around the world and has been used to model estuarine, coastal and oceanic bodies of water. The model is able to solve the equations for estuarine velocity, temperature and salinity conditions. In February 2000, this model was applied to St. Andrew Bay to obtain the circulation patterns and the estimates of fresh water inflows (Blumberg and Kim 2000).

In Lake Michigan, POM was applied for the periods 1982-1983 and 1994-1995 to study the variability of circulation and thermal structure in the lake (Beletsky and Schwab 2001). The model was able to reproduce the thermal structure features in the Lake and define the circulation patterns. However, the model tended to predict a more diffusive thermocline than what was observed.

The EFDC model is an open source code in the public domain maintained by Tetra Tech Inc. that includes the hydrodynamic, sedimentation and water quality modules that are necessary to obtain a deep understanding of various environmental and fluid processes. This code is currently being supported by the U.S. Environmental Protection Agency and it solves the three-dimensional equations of motion necessary to assess different environmental problems related to fluid flows. For more details regarding how the code solves the governing equations, the user’s manual guide developed by Tetra Tech, Inc. is available to the public and provides a detailed explanation of the equations and assumptions for each scenario (Tetra Tech 2007)

CHAPTER 3

This chapter explains the numerical model that was applied to Lower Green Bay and gives a brief explanation of the governing equations in the hydrodynamic code.

THREE DIMENSIONAL HYDRODYNAMIC MODEL

In order to expand the modeling framework for Lower Green Bay, an efficient numerical model capable of simulating the flow process in all three dimensions was required. The Environmental Fluid Dynamics Code (EFDC) is a public domain, open source, surface water modeling system, originally developed by Dr. John M. Hamrick that offers modules fully integrated in a single source code implementation. EFDC has been applied to over 100 water systems (Tetra Tech 2007) and is being currently supported by the U.S Environmental Protection Agency (EPA). For this reason, this model was selected for this project.

"EFDC code solves the three dimensional primitive variable vertically hydrostatic equations of motion for turbulent flow in a coordinate system which is curvilinear and orthogonal in the horizontal plane and stretched to flow bottom topography and free surface displacement in the vertical direction which is aligned with the gravitational vector" (Tetra Tech 2007). EFDC includes four major modules: 1) a hydrodynamic model, 2) a sediment transport model, 3) a water quality model and 4) a toxics model. In this project the hydrodynamic module is used to obtain the desired results.

The governing equations and physical processes used in the development of the EFDC model are similar to those used by the Princeton Ocean Model developed for coastal ocean applications by Blumberg and Mellor (Beletsky and Schwab 2001).

3.1. Governing Equations:

In the EFDC model, a time variable mapping is required to accommodate the x and y coordinates in a curvilinear and orthogonal way. By doing this mapping, it is possible to obtain a realistic representation of the horizontal boundaries in the vertical direction. The mapping is (Tetra Tech 2007):

$$z = (z^* + h)/(\zeta + h)$$

Eq. 1

Where:

z^*: Original vertical coordinates

h: Vertical coordinates of the bottom topography

ζ: Vertical coordinates of the free surface

The transport equations for salinity and temperature are obtained transforming the vertically hydrostatic boundary layer form of the turbulent equations of motion and utilizing Boussinesq approximation for variations in density.

$$\delta_t(mHu) + \delta_x\big(m_yHuu\big) + \delta_y(m_xHvu) + \delta_z(mwu) - \big(mf + v\delta_x m_y - u\delta_y m_x\big)Hv$$
$$= -m_yH\delta_x(g\zeta + p) - m_y(\delta_x h - z\delta_x H)\delta_z p + \delta_z(mH^{-1}A_v\delta_z u) + Q_u$$

Eq. 2

$$\delta_t(mHv) + \delta_x\big(m_yHuv\big) + \delta_y(m_xHvv) + \delta_z(mwv) + \big(mf + v\delta_x m_y - u\delta_y m_x\big)Hu$$
$$= -m_xH\delta_y(g\zeta + p) - m_x\big(\delta_y h - z\delta_y H\big)\delta_z p + \delta_z(mH^{-1}A_v\delta_z v) + Q_v$$

Eq. 3

These are the momentum equations where:

u and v: horizontal velocity components in the dimensionless curvilinear orthogonal coordinates x and y

m_x *and* m_y : Square roots of the diagonal components of the metric tensor ($m = m_x m_y$ Jacobian of the metric tensor determinant)

f= Coriolis parameter

A_v= Eddy Viscosity (vertical turbulent)

Q_u and Q_v= Momentum source-sink terms

$H = h + \zeta$ Is the total depth, where $w^* = 0$

The density ρ is a function of temperature (T), and salinity (S). The buoyancy is defined here as follows:

$$\delta_z p = -gH(\rho - \rho_0)\rho_0^{-1} = -gHb$$

Eq. 4

Where:

$\delta_z p$=Excess hydrostatic pressure

ρ= Density (depends on temperature T and salinity of water S)

b = Buoyancy

The continuity equation is defined by:

$$\delta_t(m\zeta) + \delta_x(m_y Hu) + \delta_y(m_x Hv) + \delta_z(mw) = 0$$

Eq. 5

And has been integrated over the interval (0,1) with respect to z to obtain the depth integrated continuity equation

$$\delta_t(m\zeta) + \delta_x\left(m_y H \int_0^1 u\, dz\right) + \delta_y\left(m_x H \int_0^1 v dz\right) = 0$$

Eq. 6

The boundary conditions considered for (6): $w = 0\ at\ Z = (0,1)$

$$\rho = \rho(p, S, T)$$

Eq. 7

The transport equations for Salinity and Temperature are:

$$\delta_t(mHS) + \delta_x(m_y HuS) + \delta_y(m_x HvS) + \delta_z(mwS) = \delta_z(H^{-1} A_b \delta_z S) + Q_s$$

Eq. 8

$$\delta_t(mHT) + \delta_x(m_y HuT) + \delta_y(m_x HvT) + \delta_z(mwT) = \delta_z(H^{-1} A_b \delta_z T) + Q_T$$

Eq. 9

Where:

Q_s and Q_T: Are the source and sink terms that include subgrid scale horizontal diffusion and thermal source and sinks.

A_b : Vertical turbulent diffusivity

The vertical velocity in the dimensionless vertical coordinate z is expressed as w and is related to w^*(physical velocity) by:

$$w = w^* - z\left(\delta_t\zeta + u m_x^{-1}\delta_x\zeta + v m_y^{-1}\delta_y\zeta\right) + (1 - z)(u m_x^{-1}\delta_x h + v m_y^{-1}\delta_y h)$$

Eq. 10

With equations 2-9 a closed system for the vertical turbulent viscosity and diffusivity is provided with the source and sink terms specified.

To provide the vertical turbulent viscosity and diffusivity, it is necessary to define the second moment turbulence closure model that was developed by Mellor and Yamada in 1892 and modified by Galperin in 1988 (Tetra Tech 2007).

$$A_v = \phi_v q l = 0.4\left(1 + 36R_q\right)^{-1}\left(1 + 6R_q\right)^{-1}(1 + 8R_q)ql$$

Eq. 11

$$A_b = \phi_b q l = 0.4\left(1 + 36R_q\right)^{-1}ql$$

Eq. 12

$$R_q = \frac{gH\delta_z b l^2}{q^2 H^2}$$

Where:

A_v: Vertical turbulent viscosity

R_q: Richardson number

l: Turbulent length scale

q: Turbulent intensity

ϕ_b *and* ϕ_v: Stability functions (accounts for vertical mixing in unstable and stable stratified environments, respectively)

The turbulence length scale and intensity are defined by the transport equations:

$$\delta_t(mHq^2) + \delta_x\left(m_yHuq^2\right) + \delta_y(m_xHvq^2) + \delta_z(mwq^2)$$
$$= \delta_z(mH^{-1}A_q\delta_zq^2) + Q_q + 2mH^{-1}A_v((\delta_z u)^2 + (\delta_z v)^2) + 2mgA_b\delta_z b - 2mH(B_1 l)^{-1}q^3$$

Eq. 13

$$\delta_t(mHq^2l) + \delta_x\left(m_yHuq^2l\right) + \delta_y(m_xHvq^2l) + \delta_z(mwq^2l) = \delta_z(mH^{-1}A_q\delta_zq^2l) +$$
$$Q_l + mH^{-1}E_1lA_v((\delta_z u)^2+(\delta_z v)^2) + mgE_1E_3lA_b\delta_z b - mH(B_1)^{-1}q^3(1 + E_2(\varkappa L)^{-2}l^2)$$

Eq. 14

$$L^{-1} = H^{-1}(z^{-1} + (1-z)^{-1})$$

Eq. 15

Where:

B_1, E_1, E_3: Empirical constants

Q_q, Q_l: Additional source-sink terms

A_q: Vertical diffusivity= A_v

For more information regarding the numerical solution techniques for the equations of motion, EFDC code provides a users manual guide with all the information needed for a deeper understanding.

CHAPTER 4

This chapter explains the development of the computational model of Lower Green Bay and gives a brief explanation of the different input files that are necessary to run the model and obtain the results desired for analysis. In order to develop a correct simulation, this model included data of atmospheric pressure, air temperature, solar radiation, and other meteorological variables provided by the National Oceanic and Atmospheric Administration - NOAA (NOAA 2011b) and the National Weather Service, as well as a bathymetric map of the lake prepared using the raster files obtained in NOAA's web site with a 3 arc second resolution (NOAA 2011a). Data on tributary flows was obtained from the United States Geological Survey (USGS) web site (USGS 2011), and wind speed and direction near the centroid of Lower Green Bay was obtained from the whole-lake model of Lake Michigan .

EFDC APPLIED TO LOWER GREEN BAY

4.1. Bathymetric Survey Data

The bathymetric data for Lake Michigan used in this study was obtained from a NOAA project that surveyed the Great Lakes' lake bottom. The NOAA National Geophysical Data Center's Marine Geology and Geophysics Division (NGDC/MGG) carried out the project in collaboration with the NOAA Great Lakes Environmental Research Laboratory (GLERL) (NOAA 2011a).

NGDC's GEODAS-NG (GEOphysical DAta System-Next Generation) desktop software tools offered in NOAA web page can be used to download the grid of the bathymetric data (WCS Grid Extraction Tool)

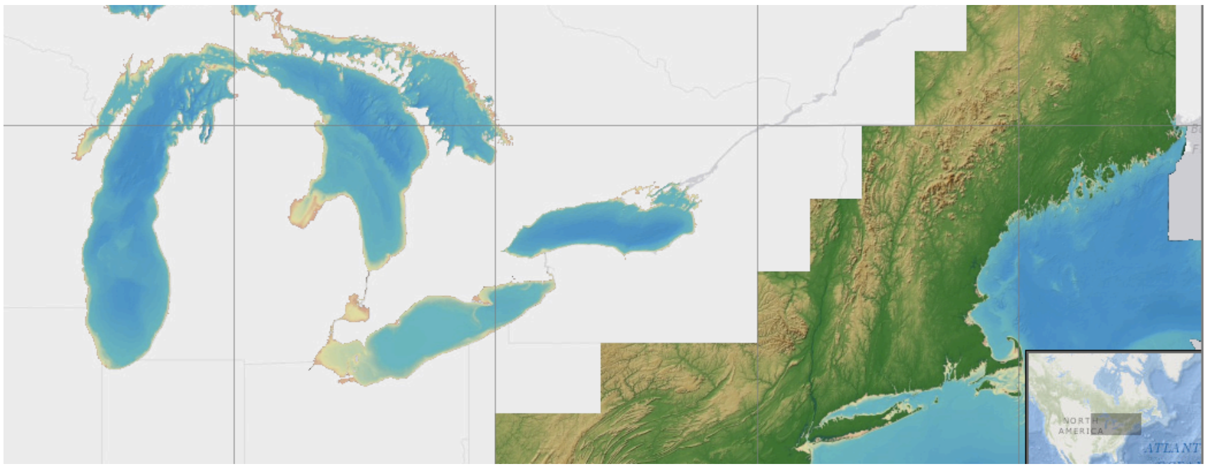

Figure 2: Bathymetry of Lake Michigan(NOAA 2011a)

Using the WCS Grid Extraction Tool, the bathymetry of the Lower Green Bay of Lake Michigan was obtained at a resolution of 3 arc seconds. The file that contained Lake Michigan's bathymetry was in NetCDF format. For this reason, the ArcGIS software was used as a tool for the conversion of the file to a dot shape file that uses NAD 1983 zone 16N as the coordinate system.

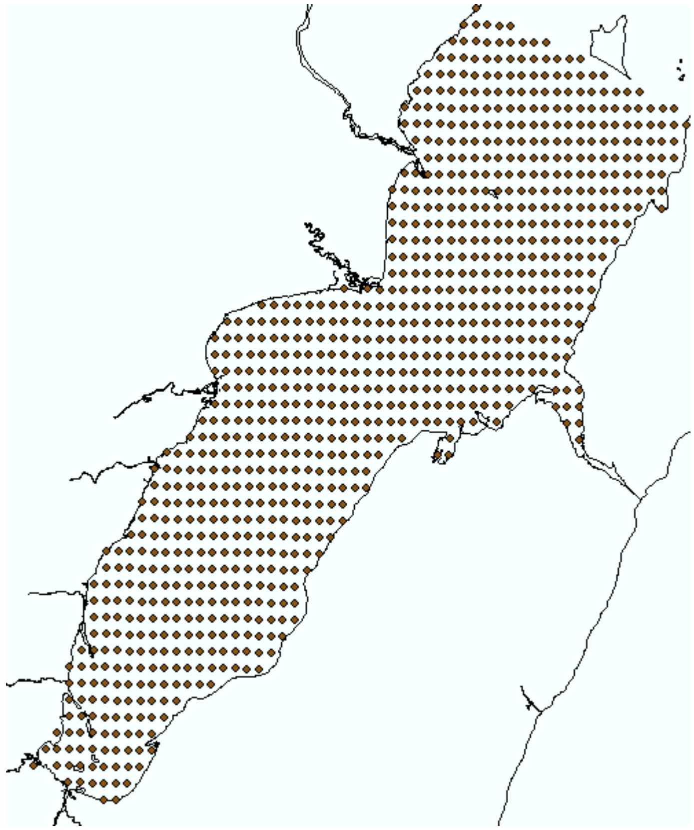

Figure 3: Interior Points at Green Bay

In the bathymetry, the depth values are gradually increasing from 1 m to about 36 meters at the Chambers Island zone. Given that range of depths, some stratification can be expected to occur in the values of temperature and circulation during the analysis of Lower Green Bay.

4.2. Grid Generation

To develop the orthogonal grid for Lower Green Bay, first the horizontal and vertical model domains where defined. This model domain extends from the Lower Fox River to Chambers Island, and it considers four tributaries including the Fox River.

To obtain a uniform grid, Visual EFDC code includes an option that allows for the automatic selection of IJ values throughout the grid. In this option, the number of cells in each direction and the rotation angle for the model were selected. The number of cells assigned to Lower Green Bay was 53 on the x-axis (across the bay) and 123 on y-axis (along the bay). The rotation angle was 60 degrees from the east in the counter clockwise direction.

The interior points (bathymetry) that identify the water depth of Lower Green Bay were imported to the grid and a special file was created for this purpose. It is important to mention that bathymetry data files are usually very large, and such files can produce out-of-memory errors and a general poor performance of EFDC. For this reason, the bathymetry data imported to this project was carefully processed to cover only the intended area of study.

In our first attempt to build the orthogonal Grid, we generated 4962 cells. However, the model could not manage the size of this arrangement, as it exceeded the maximum dimension allowed by the software (Appendix 1.2). Therefore, a new grid was generated with a smaller number of cells.

The newly generated grid consisted of 2750 cells. The report shown below is a summary obtained from EFDC that explains the characteristics of the newly generated grid in detail.

General Information

Date/Time Created:	11/16/2015 5:13:20 PM
Map Projection:	NAD_1983_UTM_Zone_16N
Conversion Factor (units/m):	1
Maximum Grid Column (IC):	43
Maximum Grid Row (JC):	127
Number of Grid Cells:	2750
Number of Barriers:	0

Cell Statistics

Parameter	Number of Cells	Minimum Value	Maximum Value	Mean Value
Dx	2750	458.09	1068.50	803.36
Dy	2750	442.57	1028.70	776.79
Aspect Ratio (Dx/Dy)	2750	1.02	1.05	1.03
Elevation	2750	-35.72	-0.95	-12.27
Roughness	2750	0.01	0.01	0.01
Vegetation	2750	0.00	0.00	0.00

Figure 4: Summary Report

The next illustration shows the Lower Green Bay grid.

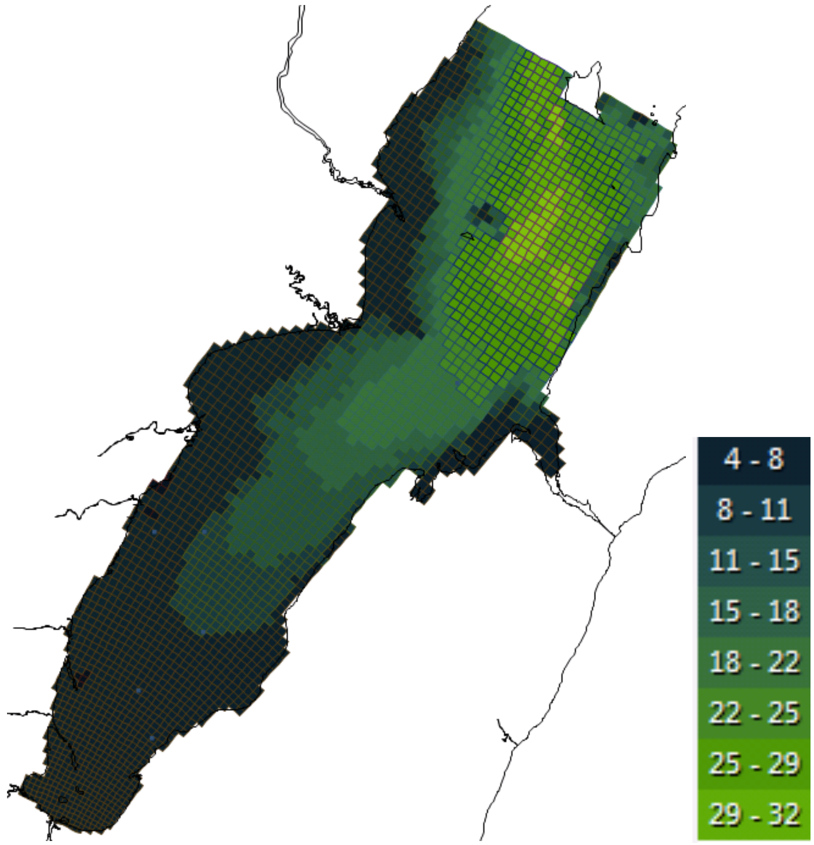

Figure 5: Bathymetry and Grid of Lower Green Bay Depth (m)

4.3. Volumetric Source/Sink locations and Concentration Series

Boundary conditions have to be specified in order to simulate the hydrodynamic processes in Lower Green Bay using EFDC. The values of flow rate sources are uniformly distributed in the vertical direction for the tributary rivers, while the sources/sinks values at the Chambers Island open lake boundary vary in the vertical direction. The locations of the tributary sources and the sources/sinks at Chambers Island in the grid are shown in in Figure 6 and in Appendix 1.1.

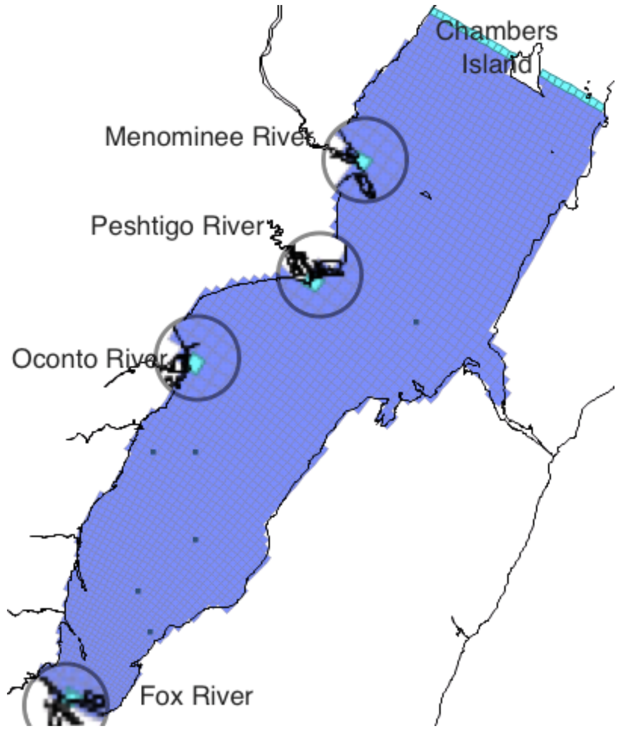

Figure 6: Tributaries at Lower Green Bay

4.4. Auxiliary files

EFDC requires several input files, described below, in order to simulate the hydrodynamics of Lower Green Bay.

4.4.1. Aser.inp

This input file specifies the meteorological data used to run the simulation. The data used in this study was obtained from NOAA National Climatic Data Center (NCDC) and NOAA

GLERL for the period of Jun - Oct 2011 (NOAA 2011b). It is important to mention that we used the Matlab language to interpolate the data and complete the gaps found in some readings (missing data). The atmospheric pressure, dry air temperature, wet bulb temperature, solar short wave radiation, and cloud cover data are shown in Figures 7-11.

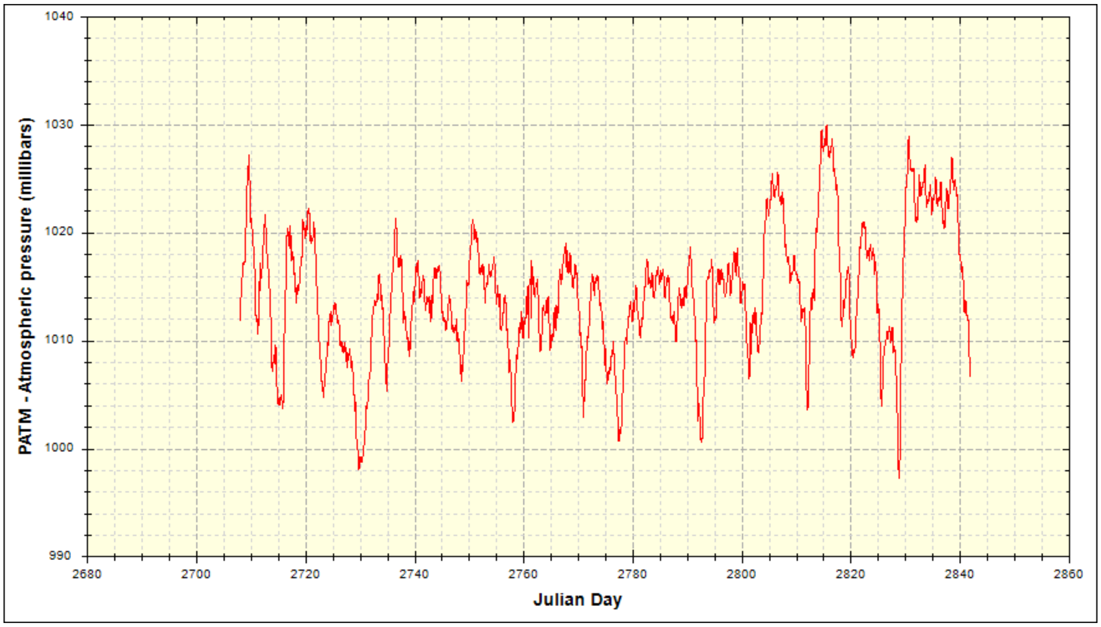

Figure 7 Atmospheric Pressure in Lower Green Bay (January 1st 2011 = Julian Day 2557. Data shown for Julian Day 2708 to 2841 means June 1st to October 12th)

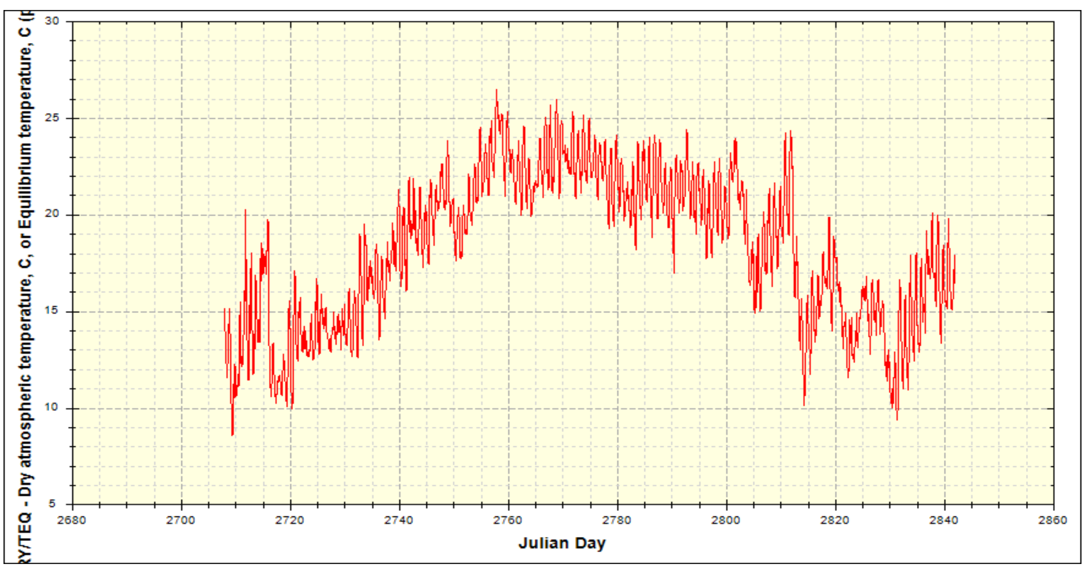

Figure 8: Dry Air Temperature in Lower Green Bay

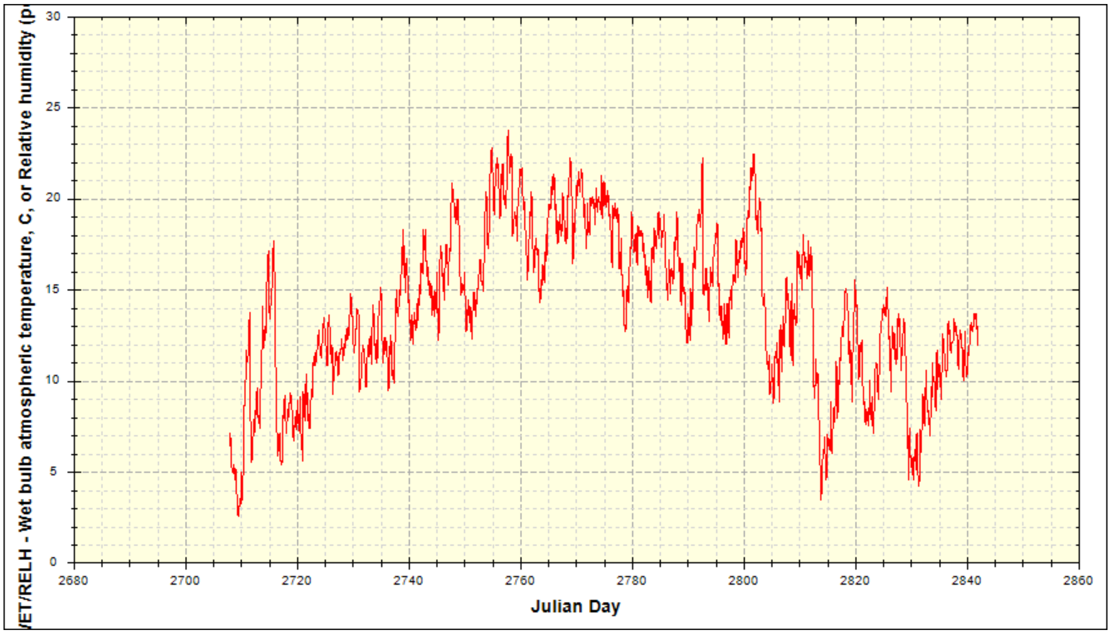

Figure 9: Wet Bulb Temperature in Lower Green Bay

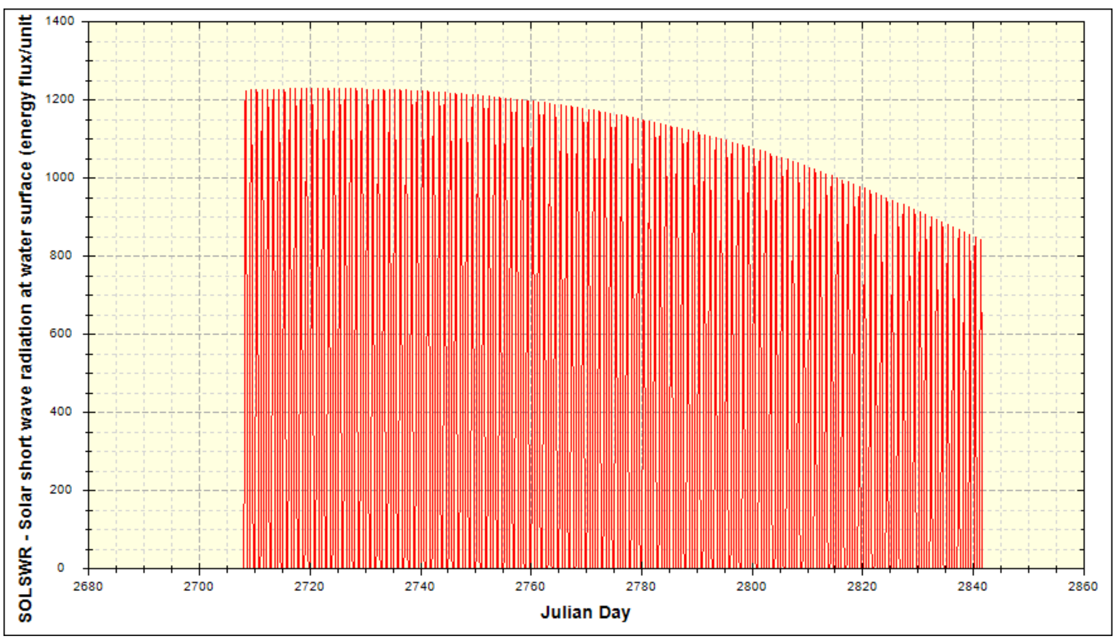

Figure 10: Solar Short wave radiation in Lower Green Bay (W/m²)

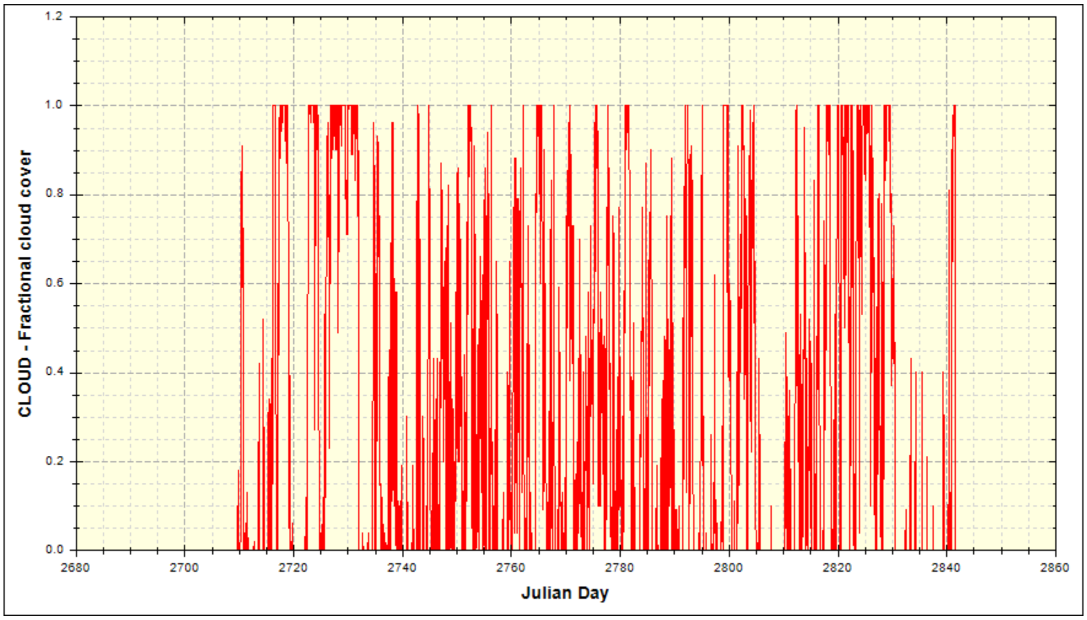

Figure 11: Cloud Cover in Lower Green Bay

4.4.2. Qser.inp

Source and sink flow boundary conditions were defined to drive the flow in the model,. The data used to build this input file was obtained from the United States Geological Survey (USGS 2011). Hourly data was interpolated and carefully reviewed for consistency at each station:

- Fox River (at Oil Tank Depot)
- Peshtigo River (at Peshtigo)
- Menomonee River (Near McAllister)
- Oconto River (Near Oconto)

The inflow data, shown in Figures 12-15, was uniformly distributed in 10 vertical layers (depth intervals).

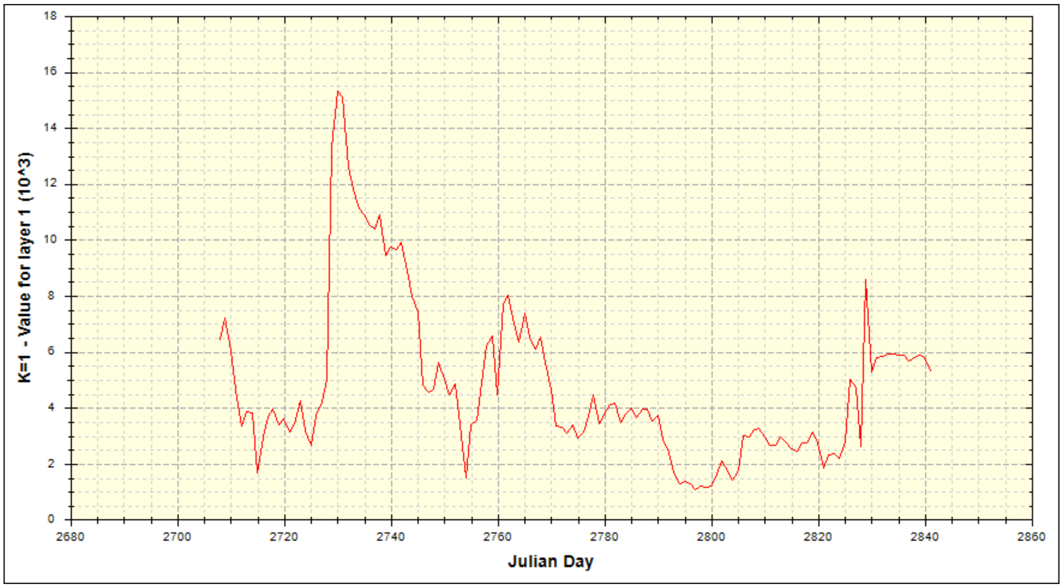

Figure 12: Flow in Fox River (ft3/s) (January 1st 2011 = Julian Day 2557. Data shown for Julian Day 2708 to 2841 means June 1st to October 12th)

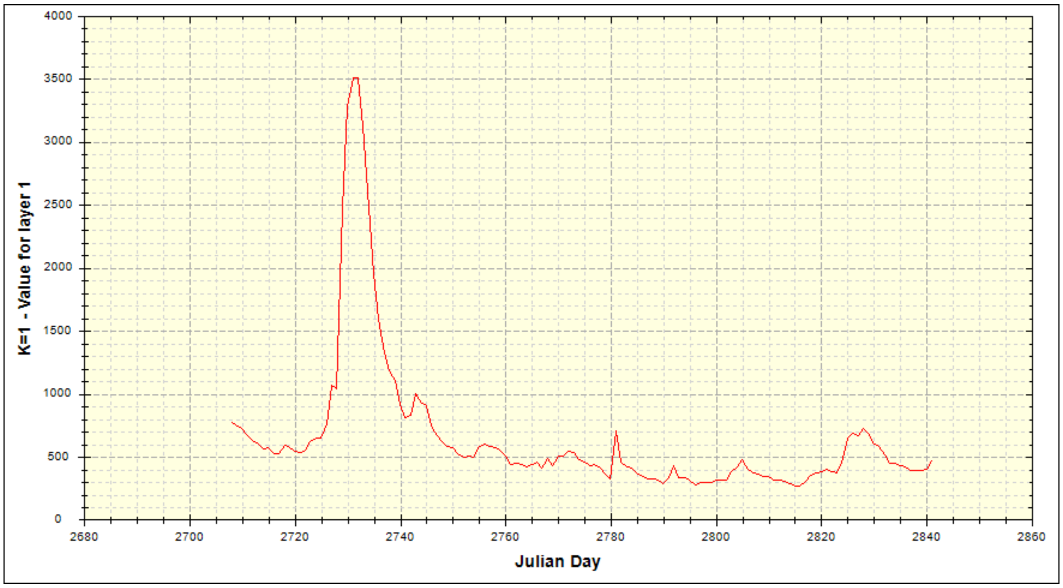

Figure 13: Flow in Oconto River (ft3/s)

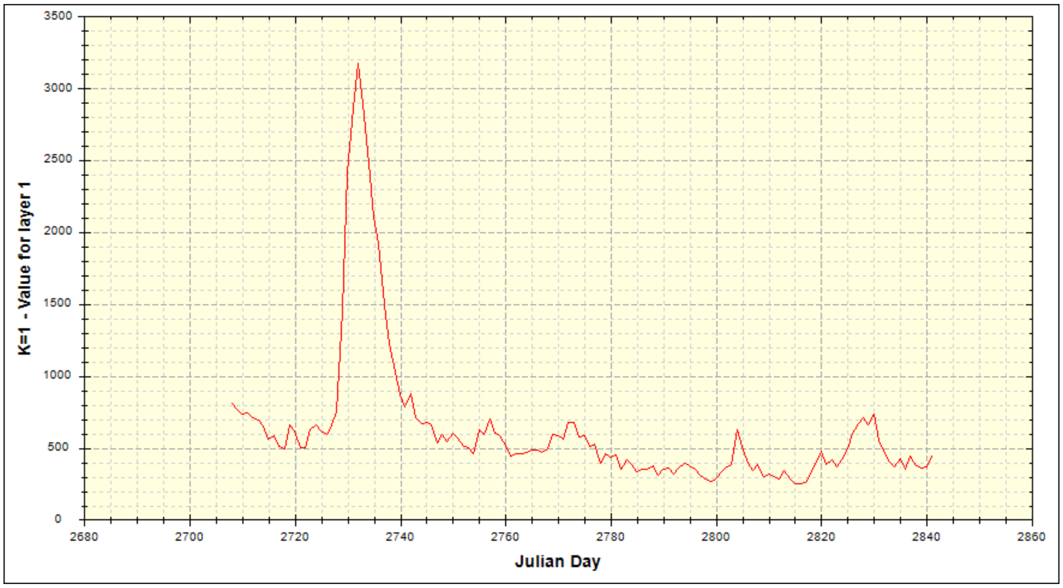

Figure 14: Flow in Peshtigo River (ft3/s)

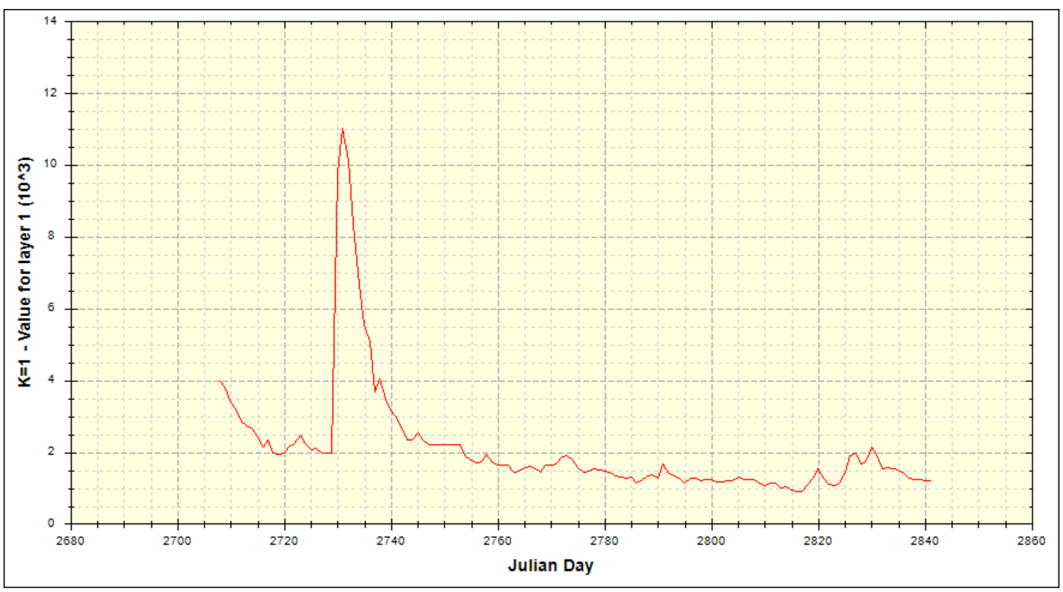

Figure 15: Flow in Menominee River (ft3/m)

For the open boundary between Lower Green Bay and Upper Green Bay at Chambers Island, the velocity component and water temperatures were assigned from the NOAA

Great Lakes Costal Forecasting System (GLCFS) whole-lake model. The NOAA GLCFS simulates the whole Lake Michigan without tributary flows, because they are negligible at the whole-lake scale. Combining GLCFS flows at Chambers Island with USGS-measured tributary flows results in excess inflows to Lower Green Bay. The flows at the Chambers Island open boundary were therefore adjusted to match the water level measurements obtained from the nearby data station Menominee, MI - Station ID: 9087088. The measured water levels are available at the data inventory NOAA tides and currents web site (NOAA 2011c).

The flow values were distributed over the 22 open boundary cells at Chambers Island in 10 vertical layers to mimic the flow distribution calculated by the GLCFS. Figures 16 and 17 show the flows for Chambers Island cell 16 (just west of the island) and layer 1 (top one of ten layers).

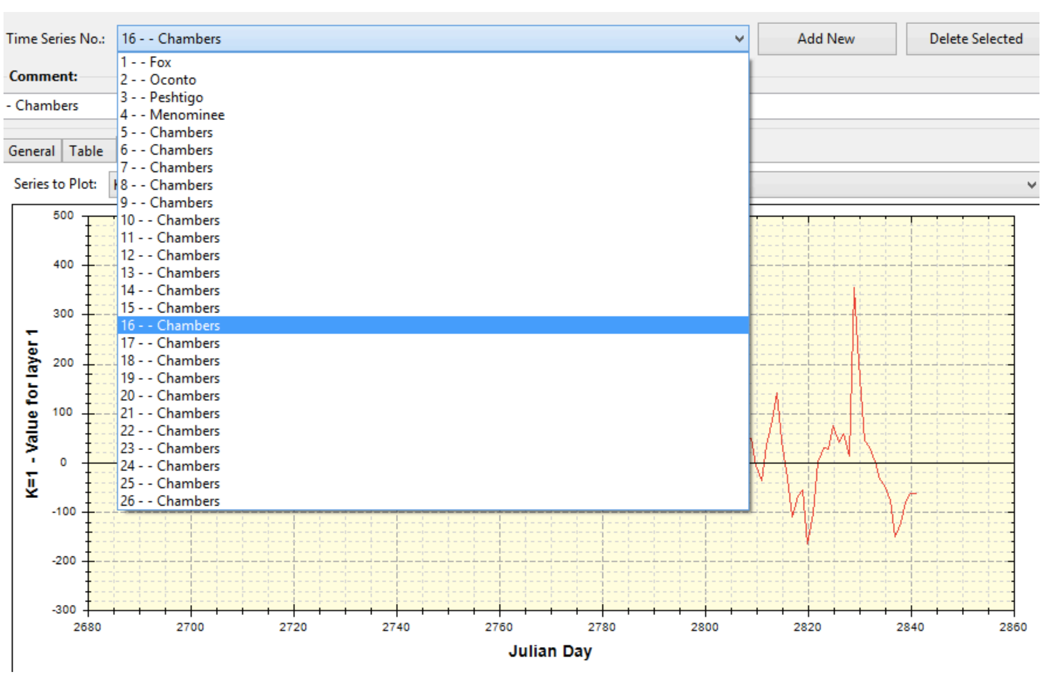

Figure 16: Selection of flow values for different cells at Chamber Island open boundary (m3/s)

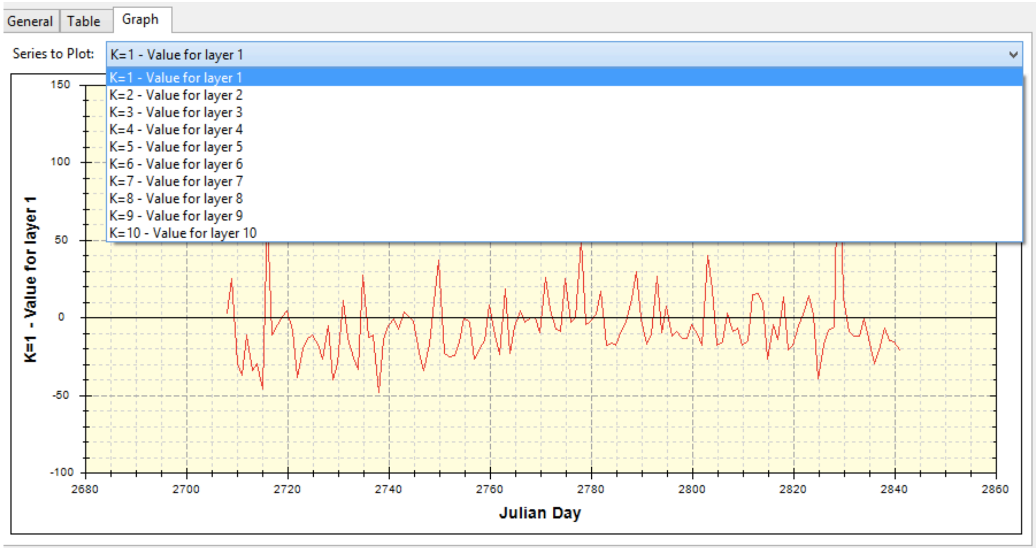

Figure 17: Selection of flow for different Layers at Chambers Island (m3/s)

4.4.3. Tser.inp

To obtain the temperature data needed for this input file, we followed a similar procedure that was explained previously for the open boundary flows. The tributary temperature data (shown in Figures 18-21) was obtained from the USGS at the same stations described in the flow section (USGS 2011). The temperature was assumed to be uniformly distributed in the vertical direction at the four river tributaries. At the Chambers Island open boundary the temperature distribution in the vertical direction and across the bay was obtained from the GLCFS whole-lake model. Figure 22 shows the temperature versus time for cell 8 (center of west passage) and layer 1 (top layer).

Figure 18: Fox River Temperature (°C); Temperature values were assumed to be uniformly distributed in the vertical direction for all the tributaries

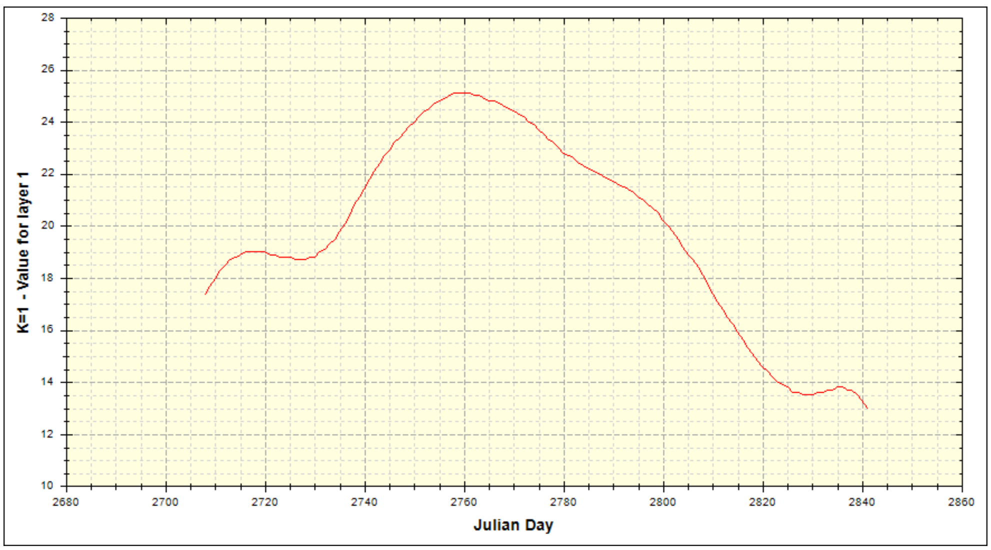

Figure 19: Oconto River Temperature (°C)

Figure 20: Peshtigo River Temperature (°C)

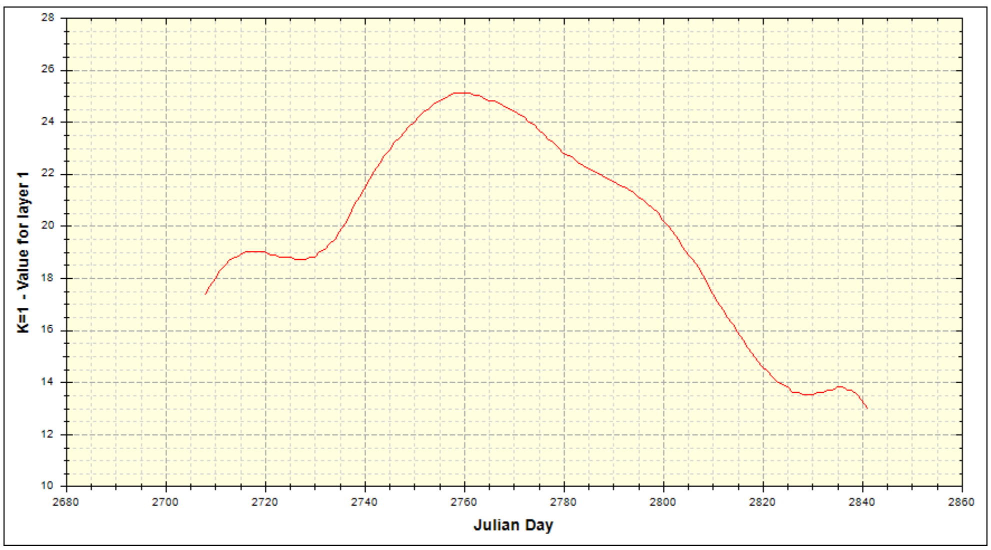

Figure 21: Menominee River Temperature (°C)

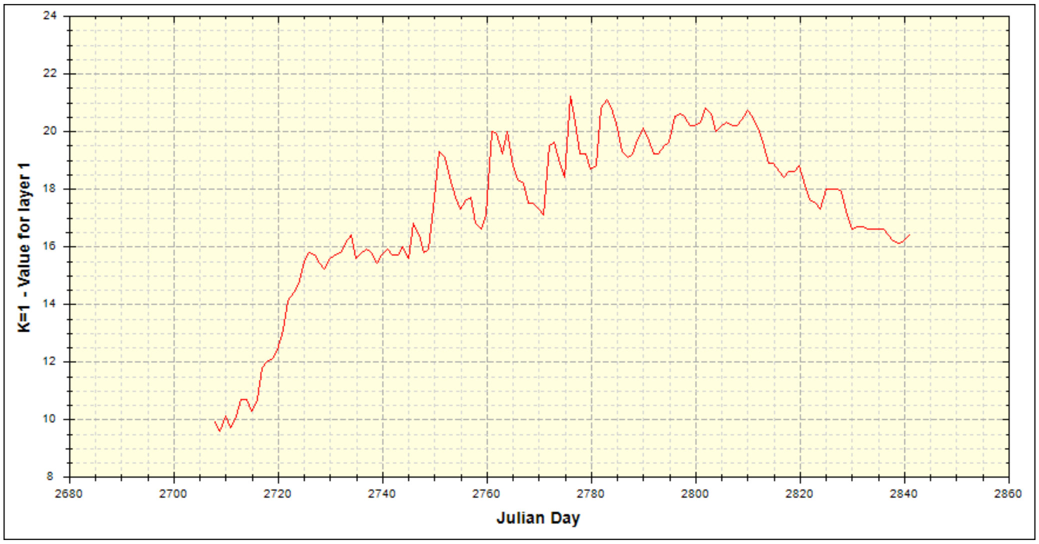

Figure 22: Chambers Island: cell I=8 J=125 layer#1 Temperature (°C)

For Chambers Island we defined 22 cells and 10 vertical layers.

4.4.4. Wser.inp

Strong winds and frequent storms are major drivers of the hydrodynamics of Lower Green Bay. Due to the orientation of Lake Michigan, the northern winds generate the largest waves in the southern region of the Lake (Lou et al. 2000). Hamidi et al. (2015) showed that monthly-averaged winds vary from year to year, showing for example that the wind speed at the meteorological station in Green Bay in August 1989 was significantly larger than that measured in August 2011. They focused on those two years existing 1989 and 2011 field data were instrumental in their model validation. The wind interactions between the open region of Lake Michigan and the northern bay are also important driving

forces to take into account when circulation is analyzed. Figures 23 and 24 show the 2011 wind speed and direction used in the EFDC model.

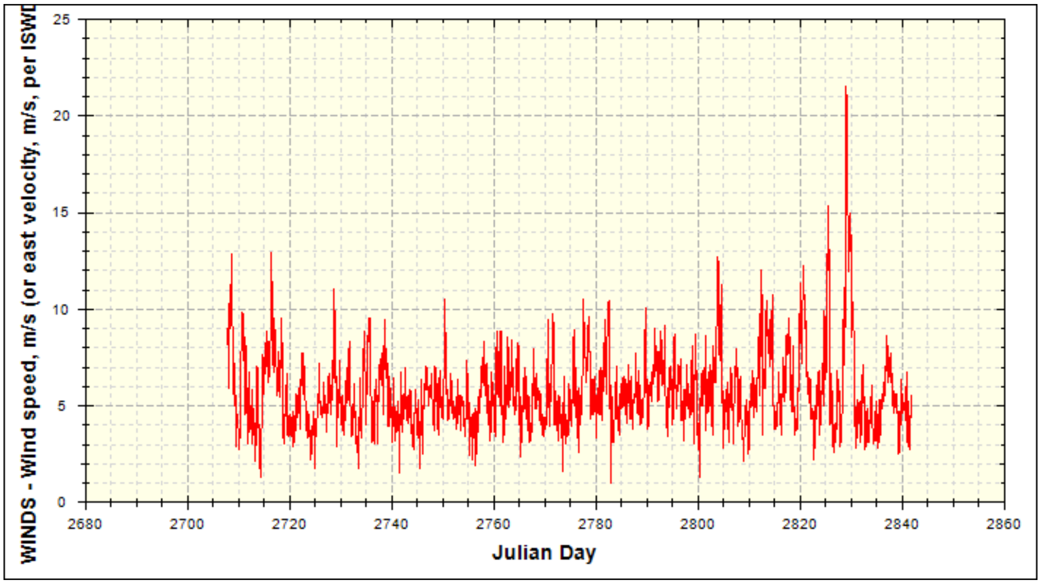

Figure 23: Wind Speed

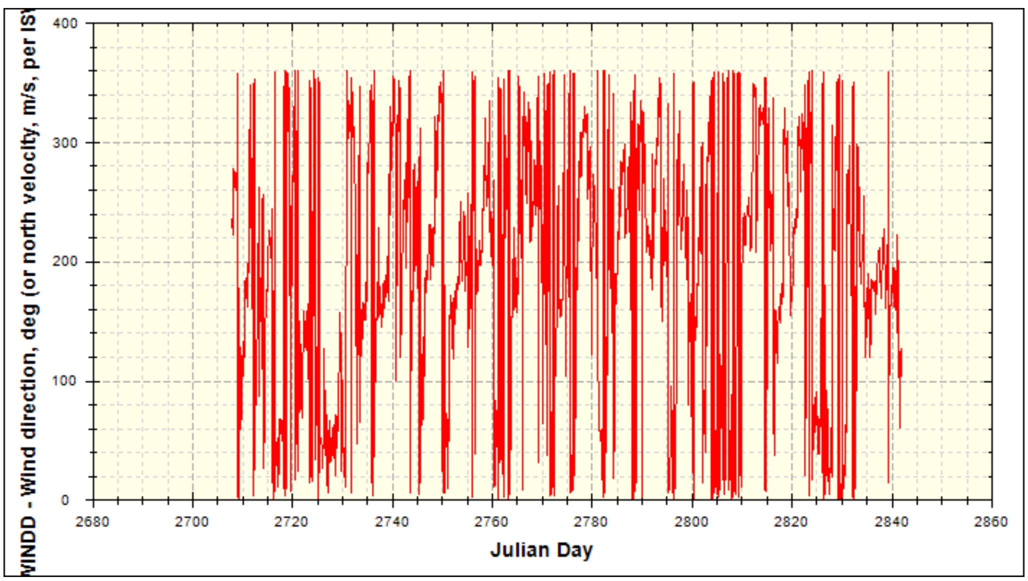

Figure 24: Wind Direction

4.4.5. Pser.inp

This input file specifies the surface elevation time series at the open boundary at Chambers Island. Figure 25 shows daily-averaged water surface values obtained from the nearby data station Menominee, MI - Station ID: 9087088.

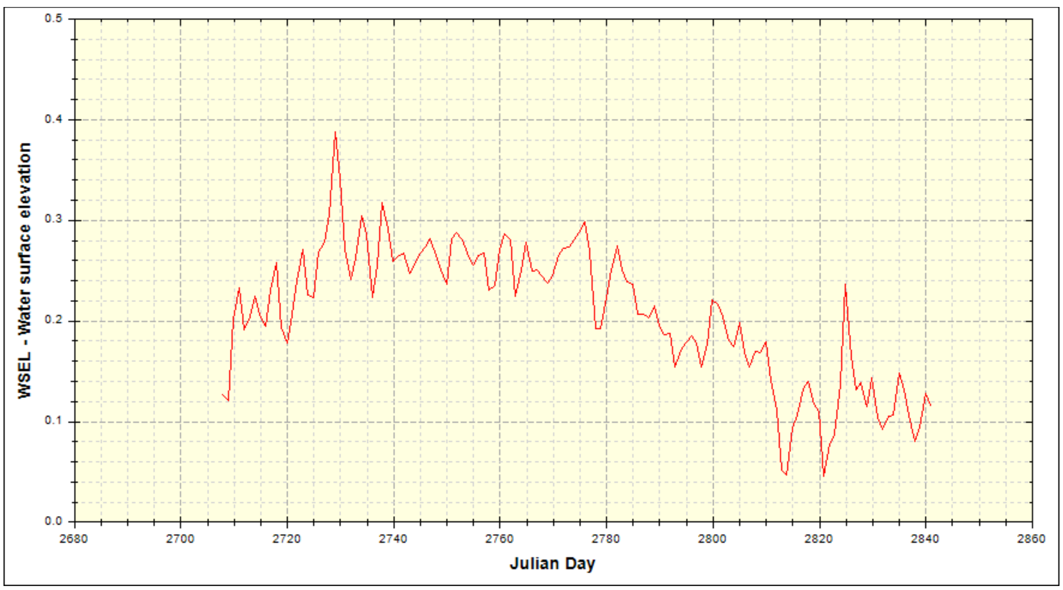

Figure 25: Water Surface Elevation

4.4.6. Running EFDC Hydrodynamic Model

Finally, with all the parameters correctly defined and input files in the required format the model was executed obtaining the binary file with all the required data. The results are explained in the next chapter.

CHAPTER 5

This chapter shows the model results for circulation and thermal regime in Lower Green Bay and compares the model results with the actual measurements obtained from stations located in the bay (measured field data). This analysis serves as an important validation step for the computational model.

RESULTS FROM THE MODEL

To evaluate the results from the model, we compared calculated (model) and measured current and temperature data at the measurement stations shown in Table 1 and Figure 26.

Station	Northing	Easting	Latitude	Longitude	Depth (m)	Data
1	4938885.195	430955.2401	44.611	-87.883	4.99	Current
9	4949952.166	435035.0655	44.706	-87.821	9.74	Temp
18	4958838.755	435124.594	44.794	-87.821	9.76	Current
19	4968885.925	430485.8634	44.794	-87.883	5.00	Current
31	4975300.913	459755.2834	44.928	-87.508	24.93	Temp
Entrance Light EL	4944465.029	428635.6728	44.653	-87.901	5.91	Temp/DO

Table 1: Stations at Lower Green Bay

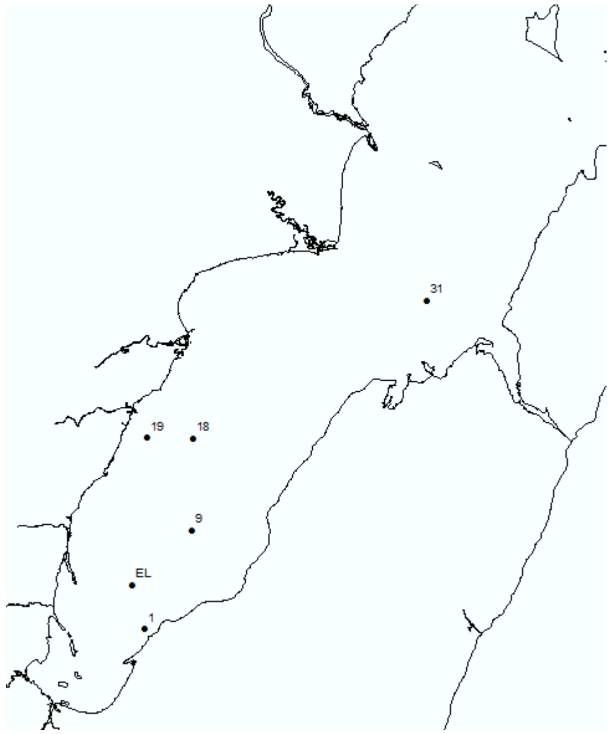

Figure 26: Measurement Stations in Lower Green Bay during summer 2011

The available 2011 field measurements include measured currents at stations 1, 18 and 19 , and water temperature measurements at Station 31. Currents were measured with a sampling interval of 30 minutes and temperatures were measured with a sampling interval of 2 minutes (Hamidi et al. 2015).

In each station we analyzed data at different instrument deployments and compared the modeled values with the measured data to validate the model. It is important to highlight that the EFDC software has a limitation in the size of the input data that it can accept. Because of that limitation, source/sink flows and temperature values at the open boundaries were given as daily values. The use of boundary values that filter out time

scales smaller that a day can limit the accuracy in the comparison with measured currents and temperature, and should be further explored in futures uses of this model.

5.1. Temperature

Station 31 was used to verify the resulting temperature values from the EFDC model. We created a program in Matlab in order to compare the values of temperatures and check the accuracy of our model.

The pronounced annual thermal cycle of Lower Green Bay is one of the more challenging situations for modeling. This is secondary to the wide range of thermal variations present in the Lake, having a completely mixed pattern in winter and a stratified pattern in summer(Beletsky and Schwab 2001).

The results obtained from the EFDC model shows that surface and near bottom temperatures are predicted quite well, having a reasonable variation of temperature when compared with the measured data (Figures 27-29). For this project we analyzed the period of June to September of 2011, where we were able to observe the thermal stratification (vertical distribution) of the temperature. Figure 27 shows the vertical temperature profile versus time at Station 31. Figure 28 shows individual time series of temperature measured at different depths and calculated at different model layers. We initialized the simulation with a temperature of 2 Celsius, to simplify the initial conditions in this model. The

temperature adjusted to more realistic values within a week or so, as shown later in figure 28.

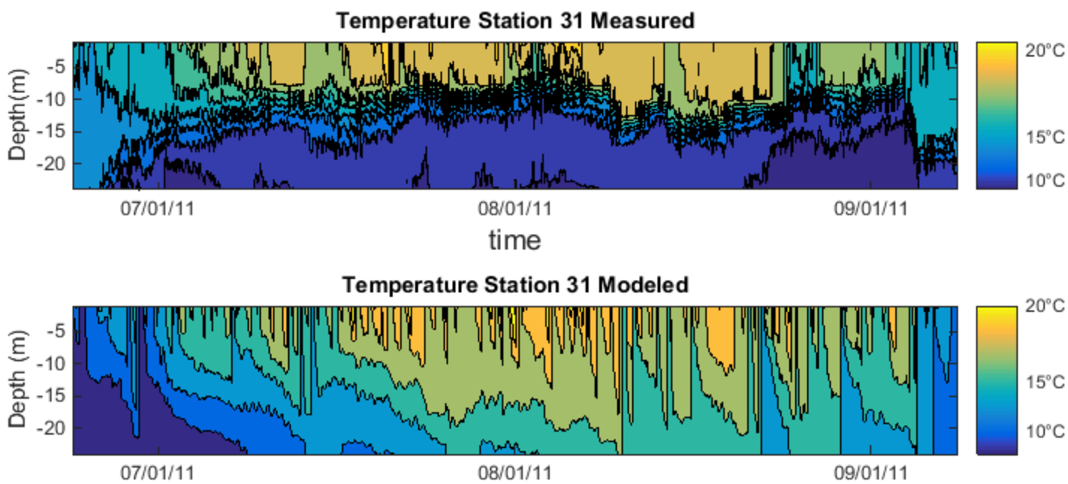

Figure 27: Temperature Contour Modeled and Measured at Station 31

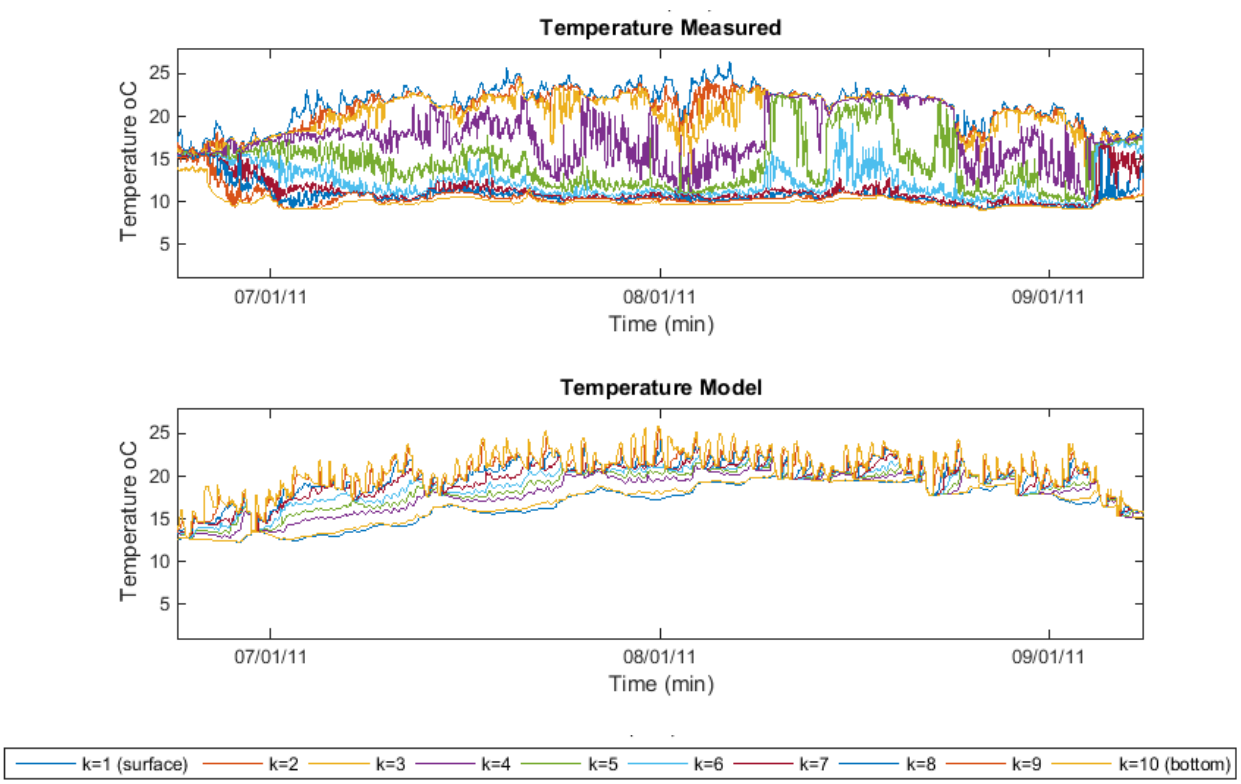

Figure 28: Temperatures Modeled and Measured at station 31

In summary, the model was able to capture reasonably well the steepness of the thermocline observed in the measured data, with a warmer behavior of modeled temperature. To obtain further insight we calculated the temperature root mean square error as a function of depth, for the June-September 2011 period, as shown in Figure 29.

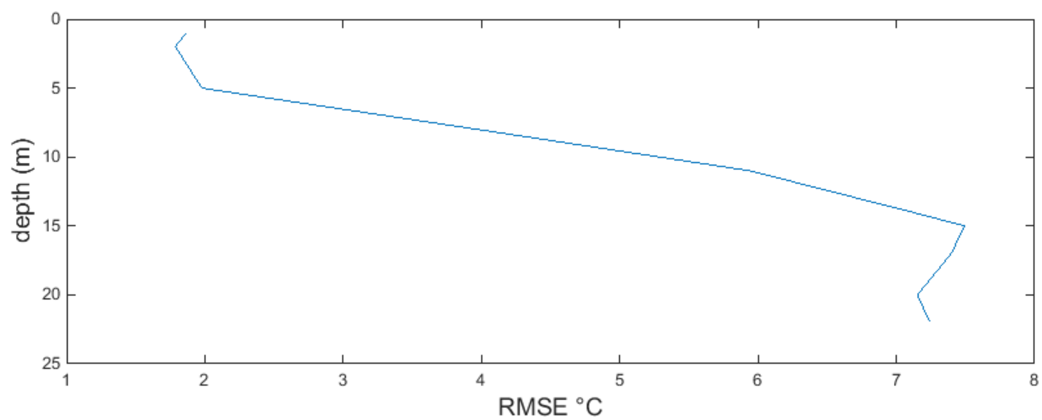

Figure 29: RMS at Station 31 (June-September)

The RMSE graph (Figure 29) compares modeled and measured data. Discrepancies between measurements and model results are larger at 15 m depth. The differences are possibly due to the turbulence model. Further work may be necessary to improve that aspect of the simulation.

5.2. Water Velocities

The hydrodynamic model results were tested against the measurements obtained in 2011; in this section we present the analysis of currents at Station 18 which is located at a depth of 9.8 meters and Station 19 located at 5 m depth. Figures 30 and 31 show the north and

east components, respectively, of the depth-averaged, measured and calculated velocity, at Station 18 for three deployments (July 21-August 12, August 16-September 7, and September 8-October 5, 2011.

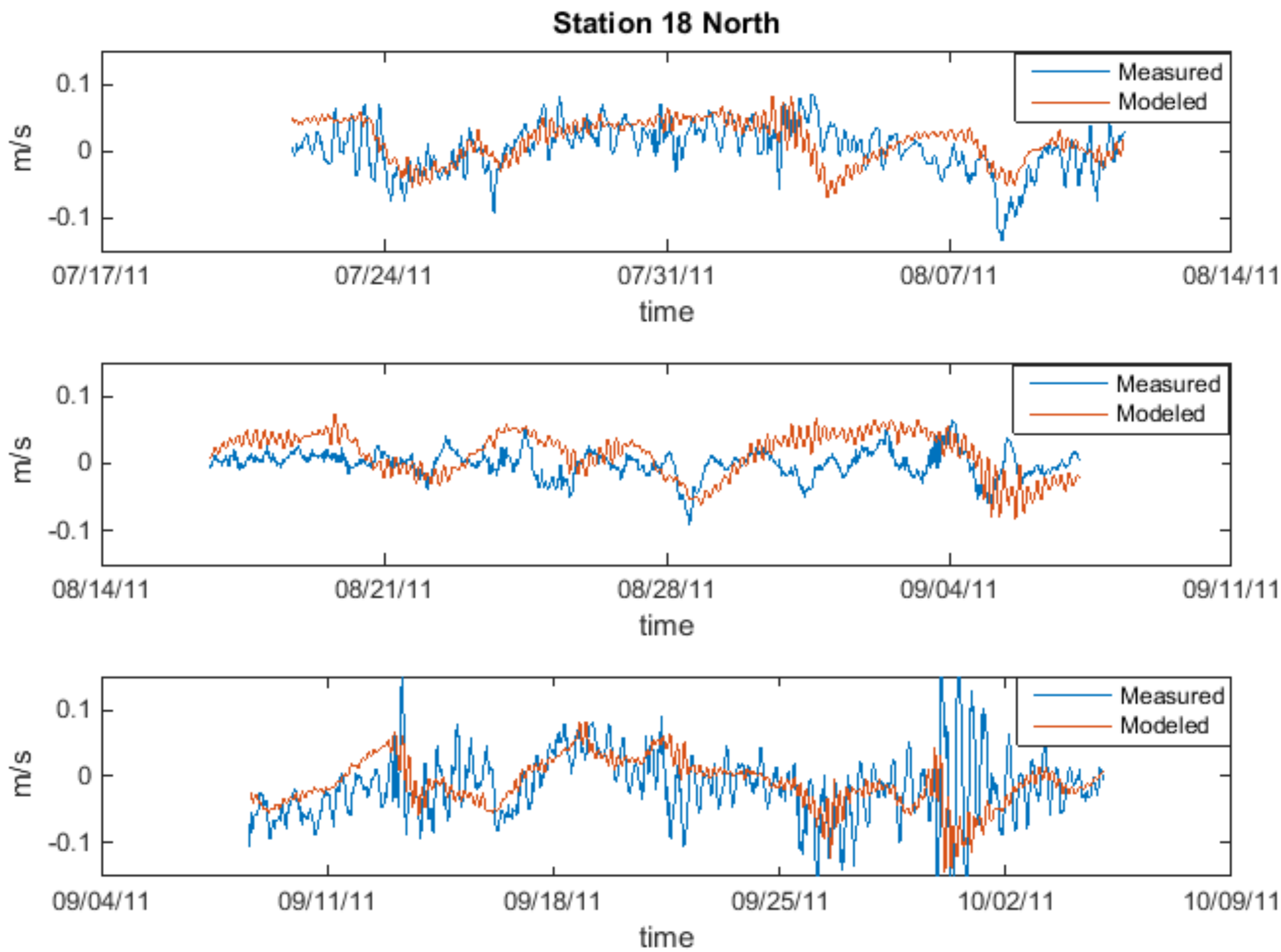

Figure 30: Station 18 North Velocities (Modeled and Measured)

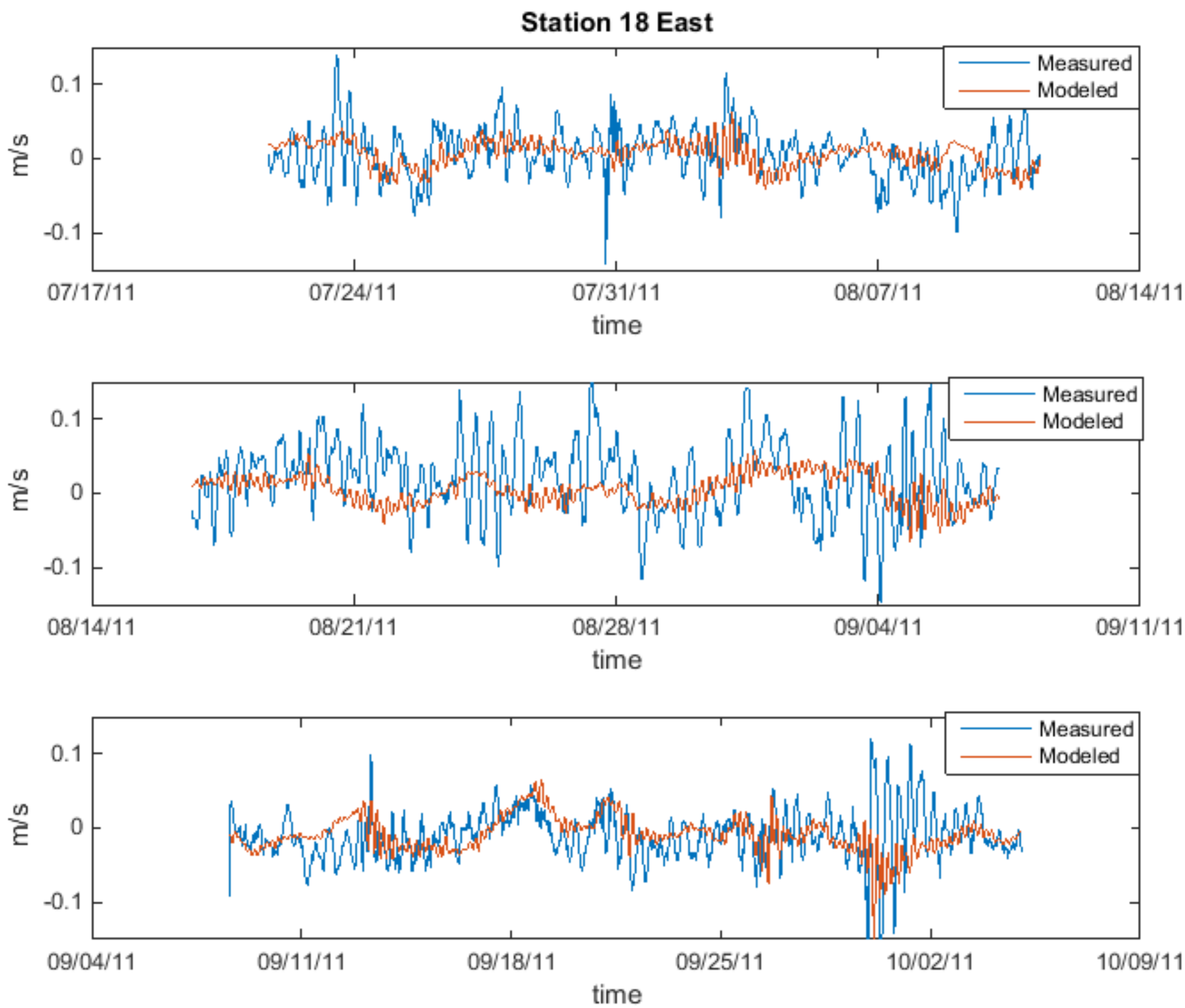

Figure 31 Station 18 East Velocities (Modeled and Measured)

Figures 32 and 33 show the north and east components, respectively, of the depth-averaged, measured and calculated velocity, at Station 19 for three deployments (July 21-August 12, August 16-September 7, and September 8-October 5, 2011.

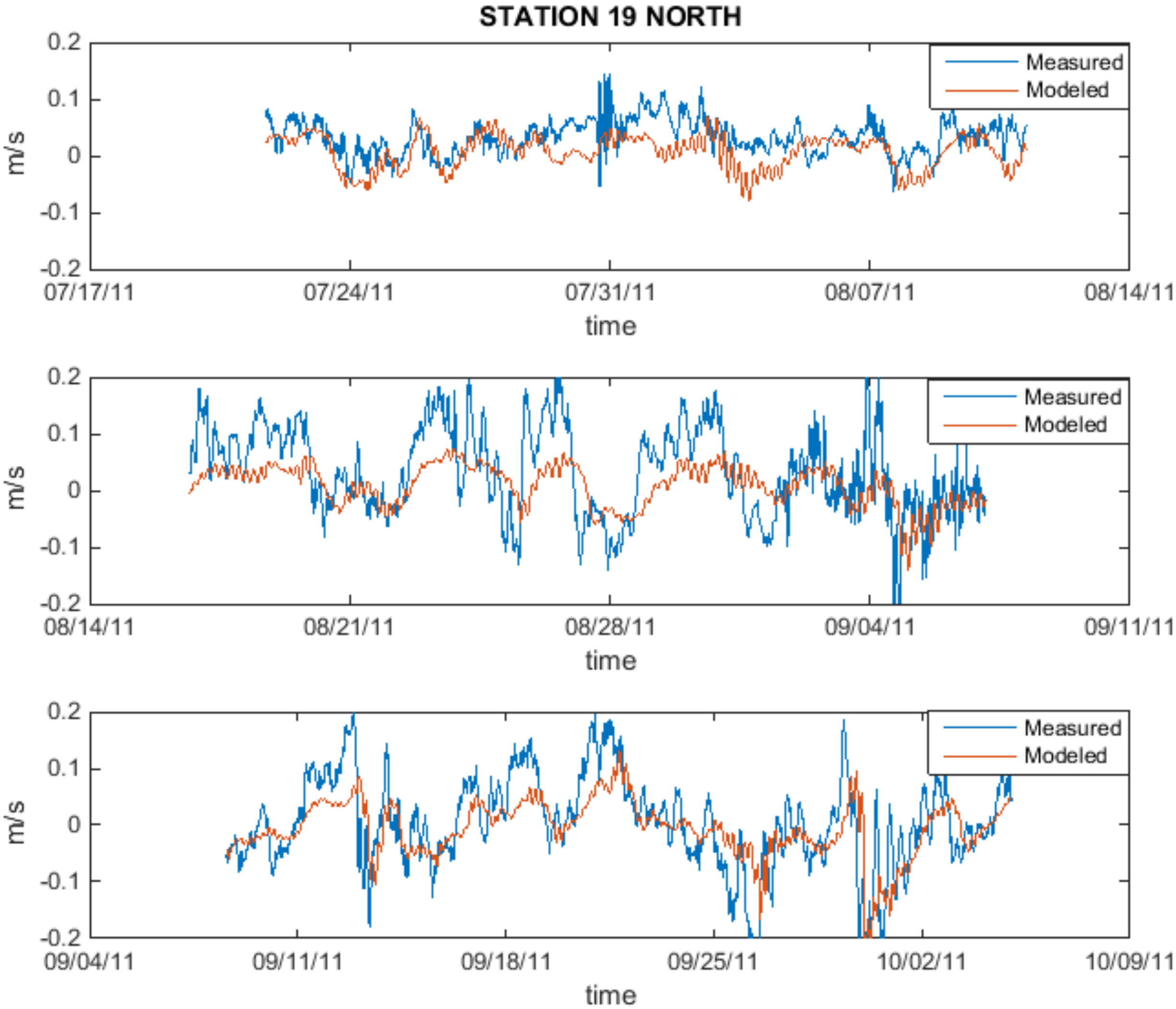

Figure 32 Velocities Station 19 North

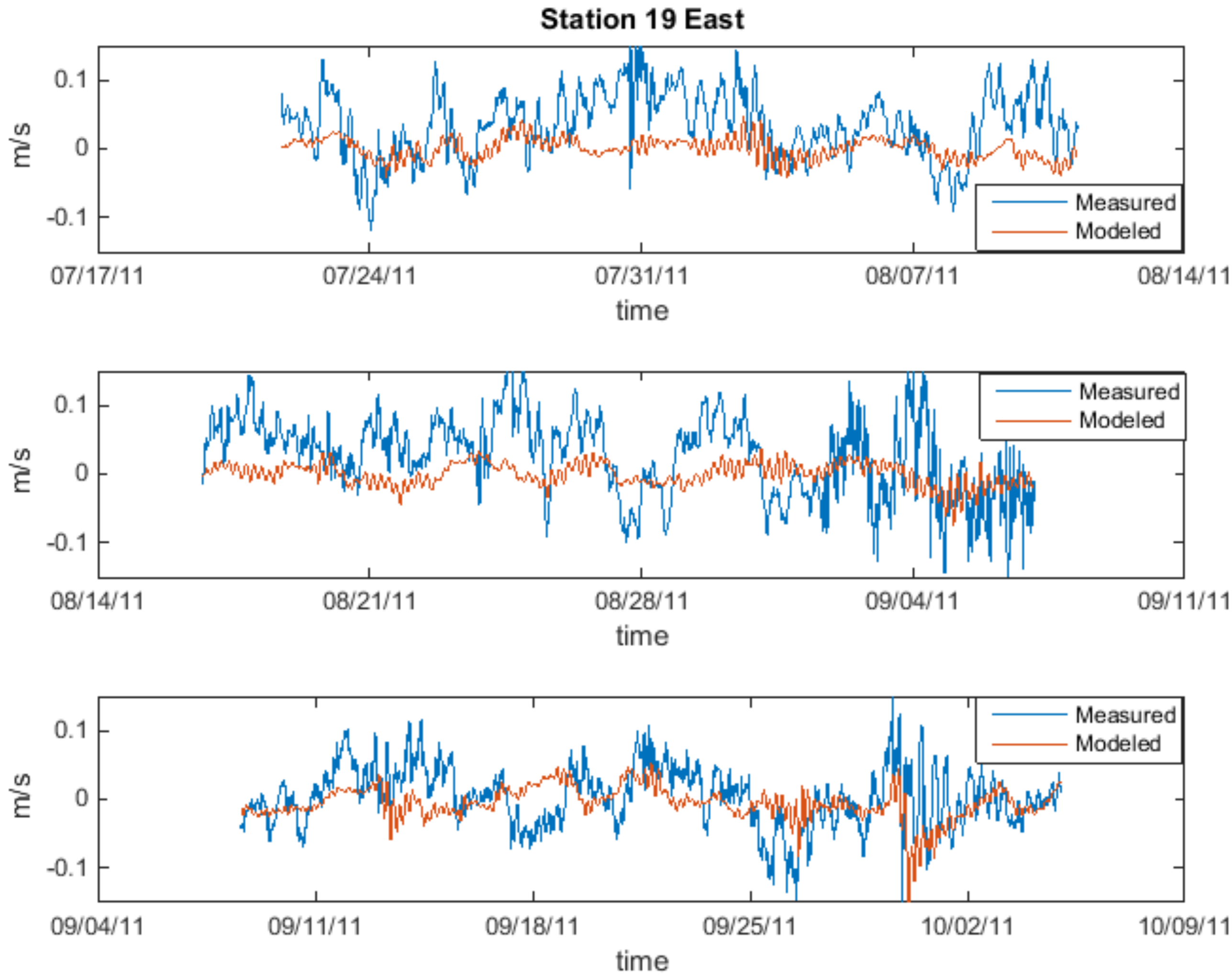

Figure 33 Velocities Station 19 East

The results presented in Figures 30-33 show a reasonably good agreement in magnitude and timing between the actual observations and modeled data. However, the modeled velocities show less variability when compared to the measured data.

The circulation at Lower Green Bay is frequently changing directions forming cyclonic and anticyclonic gyres depending on the month of the year and the topography of each location,

making the modeling of currents a challenging task. During the period analyzed herein, the average current speed was around 7 cm/s with a maximum speed reaching 10 cm/s.

To better understand the differences between the modeled and observed velocities, the root mean square error (RMSE) and normalized root mean square error (NRMSE) values were obtained for each deployment at Stations 18 and 19 (Table 2 and Table 3 respectively).

Station 18 (2011)				
Month	NORTH		EAST	
	RMSE(m/s)	NRMSE	RMSE(m/s)	NRMSE
July-August	0.036	1.01	0.036	1.05
August-September	0.036	1.70	0.053	1.08
September-October	0.053	1.01	0.039	1.12

Table 2: RMSE and NRMSE values Station 19

Station 19 (2011)				
Month	NORTH		EAST	
	RMSE(m/s)	NRMSE	RMSE(m/s)	NRMSE
July-August	0.042	1.35	0.057	1.17
August-September	0.070	0.89	0.062	1.06
September-October	0.063	0.75	0.046	1.06

Table 3: RMSE and NRMSE values Station 19

The RMSE values demonstrate that the model predicts currents with magnitudes similar to the measured values. The figures that compare measured and calculated currents present a reasonably good agreement in terms of timing and that is reflected in the values of NRMSE. Further work on the forcing mechanisms would be necessary to improve model predictions.

5.3. Wind Forcing

Wind forcing is a crucial driver of circulation and temperature stratification in Lower Green Bay. Discrepancies between measured and calculated circulation velocities and temperatures could be a result of variation in wind speed and direction, cloud cover and short wave radiation (Beletsky and Schwab 2001).

In order to analyze the correct direction and influence of wind in the model, we also performed a comparison of the wind used to run our model against the observed wind at the Straubel Airport Station (NOAA 2011b). The forcing winds used in the model were the winds at the centroid of Lower Green Bay, obtained from the GLCFS whole-lake model. The GLCFS winds, in turn, are calculated from measurements at stations around Lake Michigan, as described by Beletsky and Schwab (2001). The winds were interpolated from meteorological data using the nearest neighbor technique (using a smoothing radius), with height adjustments, overland/overlake adjustment and smoothing; this ensures a correct distribution of the data over the grid.

As wind direction plays a key role in the simulation, wind roses were created to facilitate the evaluation of the overall wind bearing, allowing us to compare the modeled data to the actual recorded data in Straubel Airport Station. By comparing this data from the months of June and August of 2011 with the data that we used to run our model, we were able to ensure that the wind direction in our model was set correctly. In the wind roses we can observe that for both months, the wind direction generally matches the observed data (Figure 34).

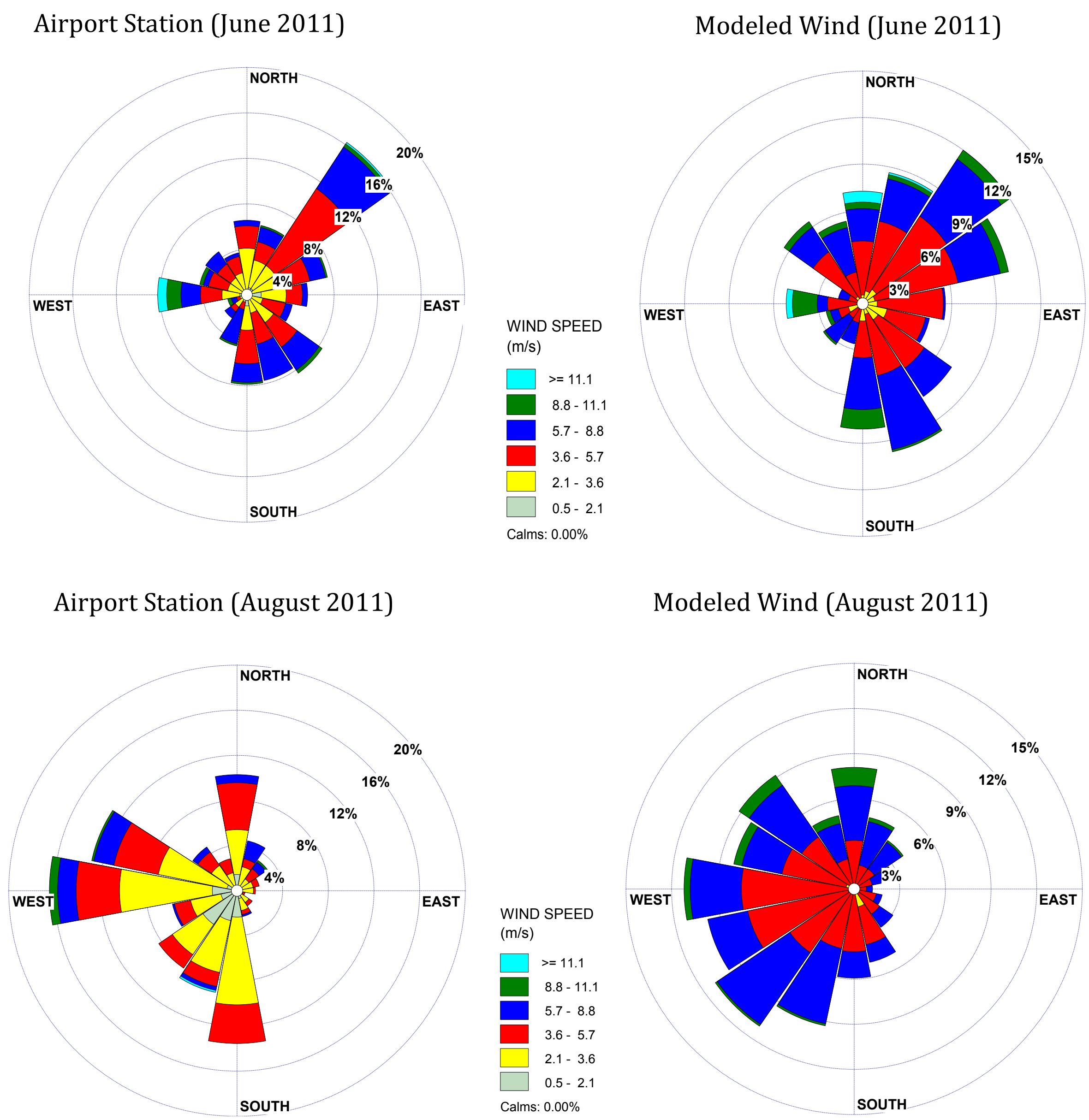

Figure 34 Observed and Modeled winds in Lower Green Bay

5.4. Circulation

Examining circulation patterns in Lower Green Bay by obtaining the velocity vectors during the onset of stratification one can observe that in late June- early July, 2011 the near bottom currents (Figure 35) are directed into the bay while surface currents (Figure 36) are directed out to the bay. The two-layer circulation contributes to the observed decrease in bottom temperatures during that period. Two anticyclonic gyres can be observed in the near bottom velocity vectors figure. One is located near to Chambers Island while the other gyre can be seen in the middle of Lower Green Bay. This flow pattern coincides with the description of circulation patterns showed in previous studies of the area (Hamidi et al. 2015) where the authors described two anticlockwise gyres inside the mouth of the bay and north of Chambers Island during the months of July and August.

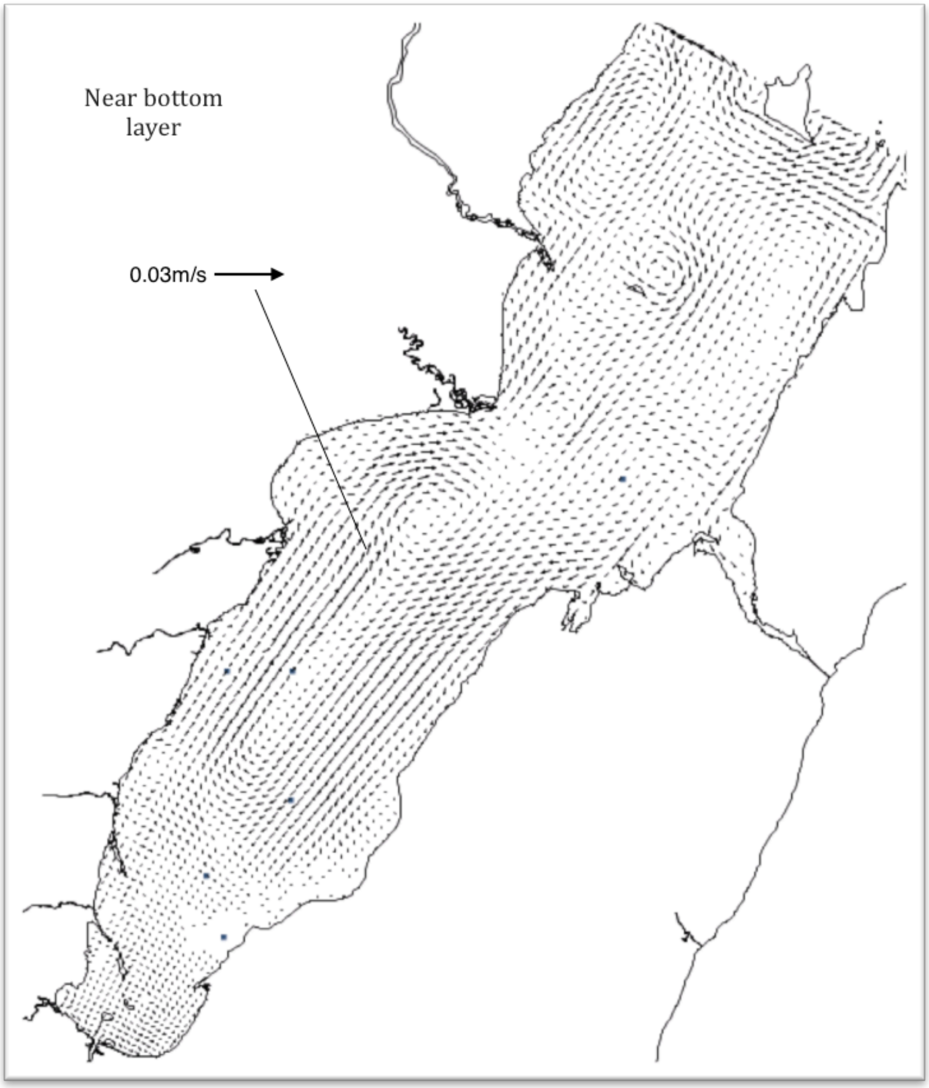

Figure 35 Calculated averaged currents from June 29th to July 5th of 2011 at near bottom at Lower Green Bay

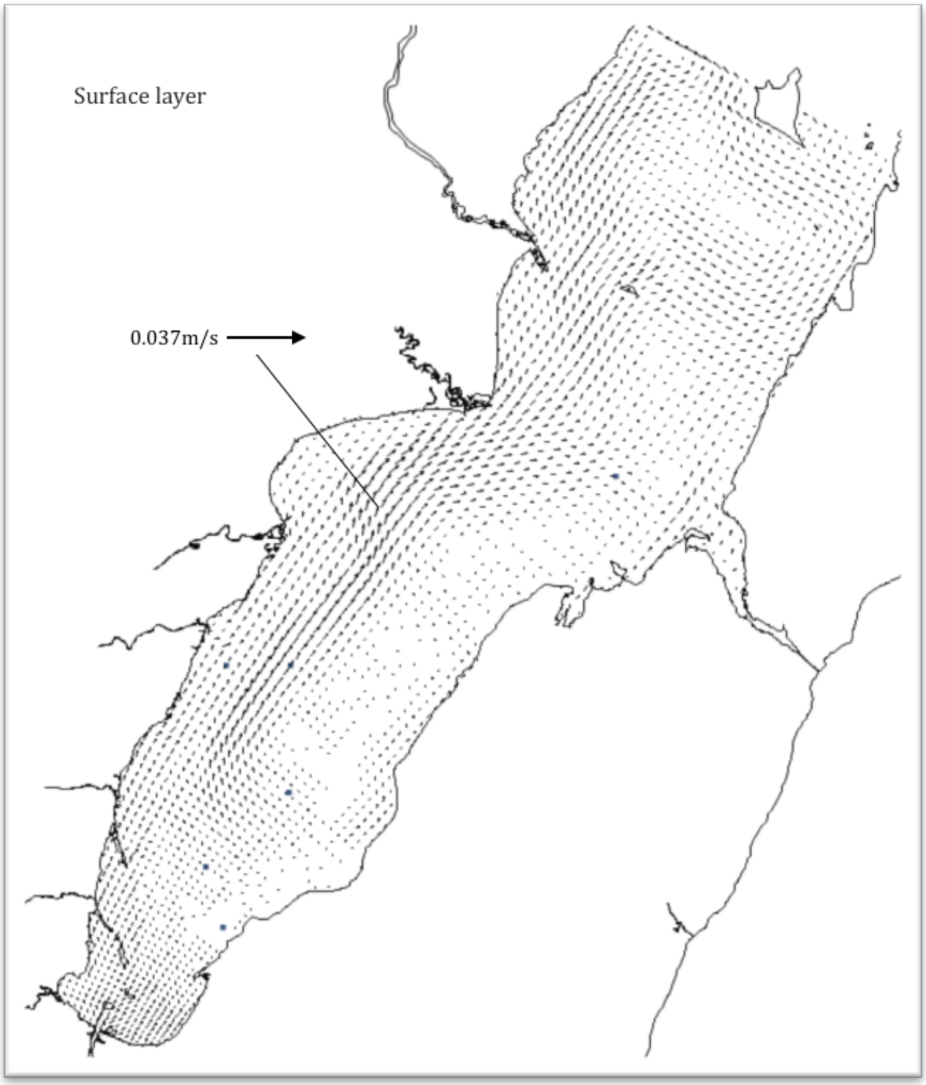

Figure 36 Calculated averaged currents from June 29th to July 5th of 2011 at Surface at Lower Green Bay

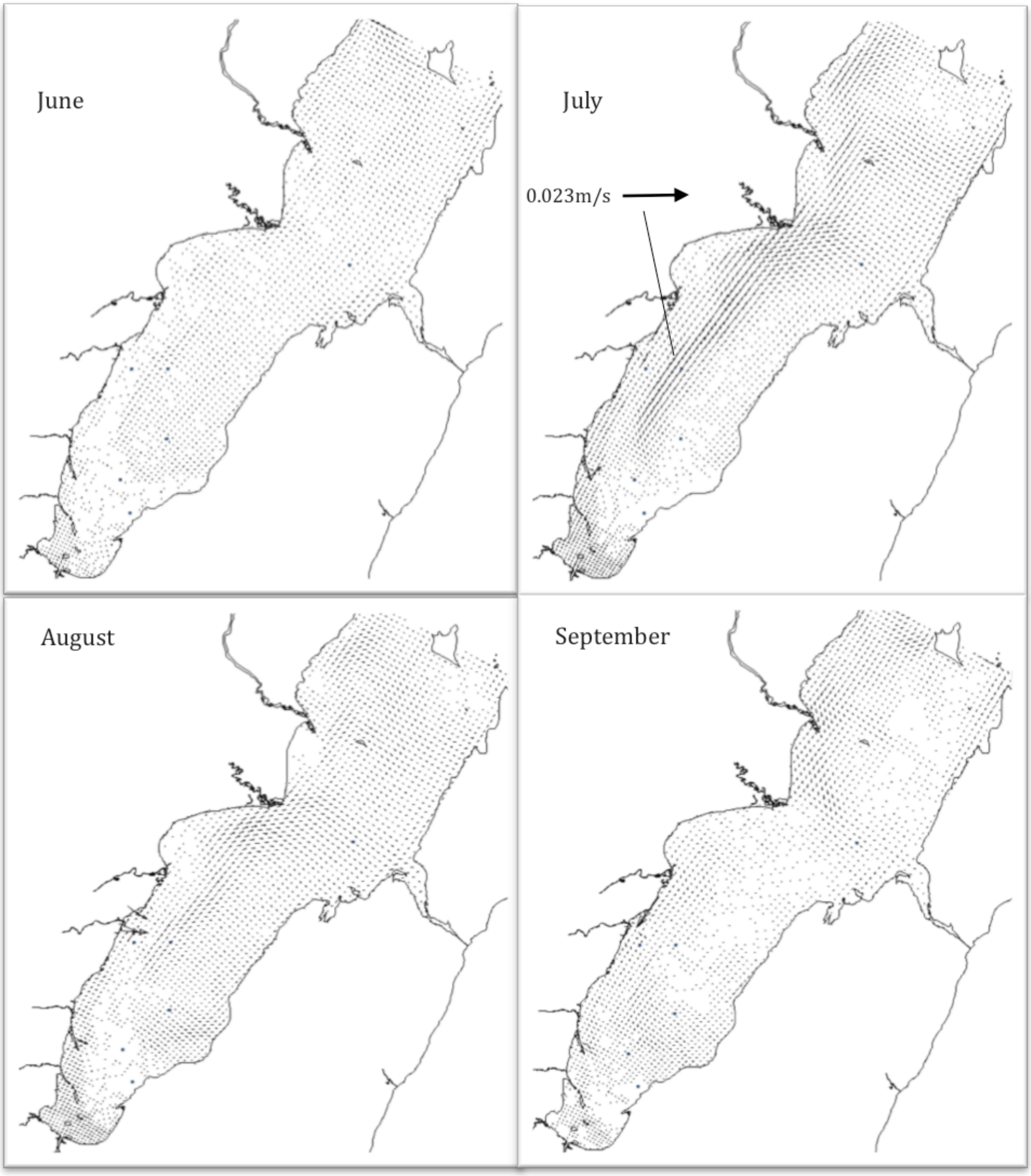

Figure 37 Monthly averaged circulation for the June-September 2011 period.

Figure 37 shows the calculated depth-averaged, monthly averaged currents for the June to September 2011 period. The circulation patterns look similar to 5-year averages described by Hamidi et al. (2015).

CHAPTER 6

This chapter explains the conclusions and improved understanding gained from the project as well as the future modeling work required in Lower Green Bay.

CONCLUSIONS

A hydrodynamic model that simulates temperatures and circulation in for Lower Green Bay was created using Visual EFDC software.

This thesis sets the stage for the subsequent study of transport of sediments and contaminants in Lower Green Bay. Those future studies can proceed with confidence because the EFDC model simulates with good accuracy the circulation and thermal regime in the bay.

The model was verified and run for the June to October 2011 period. Comparison of the observed data with the model showed that the model was able to capture reasonably well the observed circulation patterns and thermal stratification. The calculated depth-averaged, monthly averaged circulation patterns from June to October of 2011 are similar to those shown by Hamidi et al. (2015), showing that circulation is stronger during the September-October months, because of stronger winds. The temperature profiles at

Station 31 were analyzed, showing a reasonably good representation of the thermal stratification in Lower Green Bay during the study period.

Circulation patterns along Lower Green Bay have a wide variability depending on the month of the year and topography of the region. For this reason, the description of currents based on single-year measurements can give an inaccurate representation of circulation in the bay. This study brings a good approach to describe the patterns in Lower Green Bay, taking into account wind forcing and atmospheric conditions. A hydrodynamic model validated against measurements can be used to analyze circulation and thermal regime and their widely varying driving meteorological conditions.

The model was developed taking into account the effects of circulation and stratification in the whole lake Michigan through the open boundary conditions at the Chambers Island boundary, and the four main tributaries to Lower Green Bay. The model reproduced the observed two-layer summer circulation that contributes to the onset of stratification. In late June- early July 2011 the near bottom currents bring colder water into the bay while surface currents transport warmer water out of the bay.

The open boundary flows and temperature at the Chambers Island model boundary were obtained from the whole-lake model of Lake Michigan (Princeton Ocean Model), and the open boundary flows at the Chambers Island boundary were adjusted to match the water levels measured by NOAA (NOAA 2011c) . A deep understanding of the interactions

between the tributary watersheds, Green Bay, and Lake Michigan is needed in order to determine the different variables affecting the results of this model.

Wind direction and magnitude at Lower Green Bay were studied by comparing the interpolated data used for the model against the observed data collected at Straubel Airport station. That comparison showed good agreement, a reassuring finding because of the influence and importance of wind forcing on both circulation and thermal regime.

Further studies at Green Bay are required in order to improve model predictions. Additional information used for this model is shown in Appendix one.

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APPENDIX 1

1.1 Location of the tributaries in the Lower Green Bay model grid

I	J	DESCRIPTION
20	8	FOX RIVER
9	68	OCONTO RIVER
15	86	PESHTIGO RIVER
11	102	MENOMINEE RIVER
8	125	CHAMBERS 1 OF 22
9	125	CHAMBERS 2 OF 22
10	125	CHAMBERS 3 OF 22
11	125	CHAMBERS 4 OF 22
12	125	CHAMBERS 5 OF 22
13	125	CHAMBERS 6 OF 22
14	125	CHAMBERS 7 OF 22
15	125	CHAMBERS 8 OF 22
16	125	CHAMBERS 9 OF 22
17	125	CHAMBERS 10 OF 22
18	125	CHAMBERS 11 OF 22
19	125	CHAMBERS 12 OF 22
20	125	CHAMBERS 13 OF 22
25	125	CHAMBERS 14 OF 22
26	125	CHAMBERS 15 OF 22
27	125	CHAMBERS 16 OF 22
28	125	CHAMBERS 17 OF 22
29	125	CHAMBERS 18 OF 22
30	125	CHAMBERS 19 OF 22
31	125	CHAMBERS 20 OF 22
32	125	CHAMBERS 21 OF 22
33	125	CHAMBERS 22 OF 22

Table 4 Location of the tributaries at Lower Green Bay Grid

1.2 Limitation of the EFDC Software

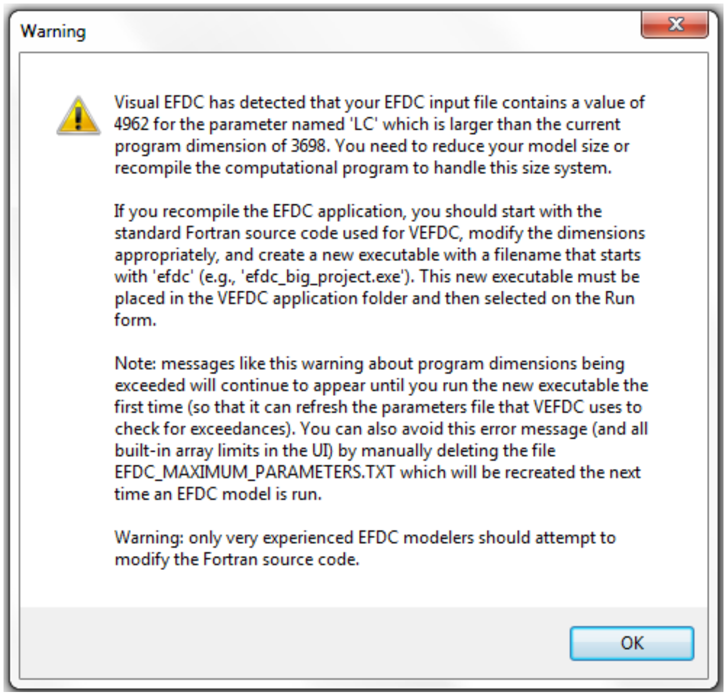

Figure 38 Limitation of EFDC Software