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DEVELOPING THREE DIMENSIONAL HYDRODYNAMIC MODEL FOR LAKE ST. CLAIR

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1 INTRODUCTION

Lake St. Clair is part of the channel connecting Lake Huron and Lake Erie. This channel serves as a recreational waterway, source of drinking water for Detroit and surrounding cities, as well as a shipping channel to Lakes Huron, Michigan, and Superior. There are several public beaches on Lake St. Clair and the microbial water quality at these beaches is constantly changing due to numerous environmental factors. The prediction of microbial contamination levels is required in order to manage beach access and to minimize the economic losses associated with unnecessary or prolonged beach closures. Hydrodynamic models will be valuable tools to be used for particle and/or source tracking analysis that identify specific areas or tributaries that contribute to increased microbial contamination. Current one and two dimensional steady state hydrodynamic models developed by Environment and Climate Change Canada are able to provide depth averaged general water circulation patterns in the lake (Holtschlag and Koschik, 2002a). Schwab et al. (1981) developed the first hydrodynamic model based on the 2D-unsteady finite-difference schemes to describe circulation patterns and effect of wind direction in Lake St. Clair. Later, in 1985 steady state current patterns of Lake St. Clair were studied for the first time using 3D-finite element models and wind forcing direction was considered to be uniform (Ibrahim and McCorquodale 1985). Until recently, several one-, two- or three-dimensional models were developed but were not able to take into account the temporal variation of forcing data through the lake in combination with considering variable flows. In order to better track the sources of microbial contamination or to develop the capability of predicting the level of microbial contamination at the beaches in real time, it is expected that a model with the capability to predict the unsteady hydrodynamics in 3D space and time will be necessary. Proposed models have been applied extensively to study lake processes and for biogeochemical and management studies in the Great Lakes (e.g. Valipour et al., 2016; Zhao et al. 2012; Rao et al., 2009; Leon et al, 2011; Bocaniov et al., 2014).

2 MATERIAL AND METHOD

2.1 Study Area and Data Collection:

Lake St. Clair forms part of the binational boundary water between Canada and the United States is part of the Great Lakes Basin (Figure 1). It has an area of 430 mi^2. Its main inlet, the St. Clair River, which has a drainage area of about 222,400 mi^2, delivers water to Lake St. Clair at a rate of about 185,000 ft^3/s from Lake Huron (Holtschlag et al., 2008). Lesser amounts of water are received from the Thames, and Sydenham Rivers in Ontario, Canada and Clinton River in Michigan, United States. The Detroit River with a discharge rate of about 186,000 ft^3/s is the only natural outlet from Lake St. Clair. Evaporation and withdrawals for water supply are associated with water loss from this body. Figure 1 shows the bathymetry, location of the buoys and all the main tributaries considered in the modeling.

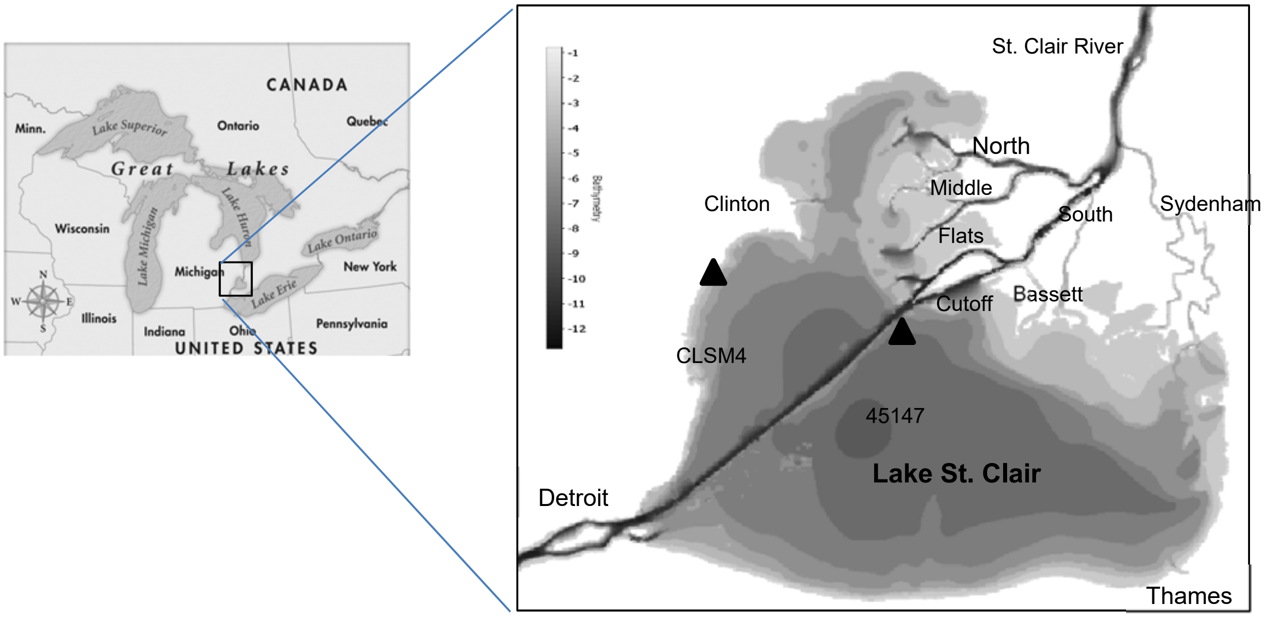

Figure 1: Map of Lake St. Clair and its bathymetry. Symbols show the locations of the mornings. Bathymetric contours are in meters. All tributaries are labeled on the map.

In the current study, a 3D unsteady numerical model of Lake St. Clair was set up over a four-month period (June-September) of 2010 using the ELCOM hydrodynamic modelling framework and validated against measured observations. The bathymetry file used was obtained from NOAA/Great Lakes Environmental Research Laboratory data and the depths are referenced to a generic datum of 176.784 meters (580 feet). Flow and temperature data of the four major river loads to the lake (Thames, Sydenham, St. Clair, and Clinton Rivers) and the only outflow (Detroit River) were also obtained using the nearest station's information. Necessary interpolation was done for missing data. Meteorological forcing data sets consisting of wind direction, wind speed, air temperature, humidity, atmospheric pressure, short and long-wave radiation, and rainfall were obtained from the nearest stations and moored surface buoys. Data was QA/QC checked by Environment and Climate Change Canada (ECCC) and the NOAA National Data Buoy Center.

2.2 Model Description:

ELCOM solves hydrostatic Reynolds-averaged Navier–Stokes equations, based on a semi-implicit scheme which is adapted from a three-dimensional model known as TRIM approach, for heat and momentum transfer on a Cartesian Arakawa C-grid with a fixed Z-coordinate finite difference mesh (Hodges et al., 2000). It uses the scalar transport equations to simulate spatial and temporal variations of mass, temperature and salinity distributions (Hodges and Dallimore, 2006). To resolve Lake St. Clair geometric data, a structured, uniform 200m grid is created for the hydrodynamic model consisting of 31,228 square cells. An existing 3D hydrodynamic model (Leon et al, 2011; Oveisy et al. 2014) was extended to simulate flow patterns on Lake St. Clair focused more on nearshore region such as public beach areas like Sandpoint beach in the South-West of the lake. Unsteady simulation was used to identify current patterns near the beaches for variable wind conditions which likely are associated with microbial fluctuation in nearshore regions.

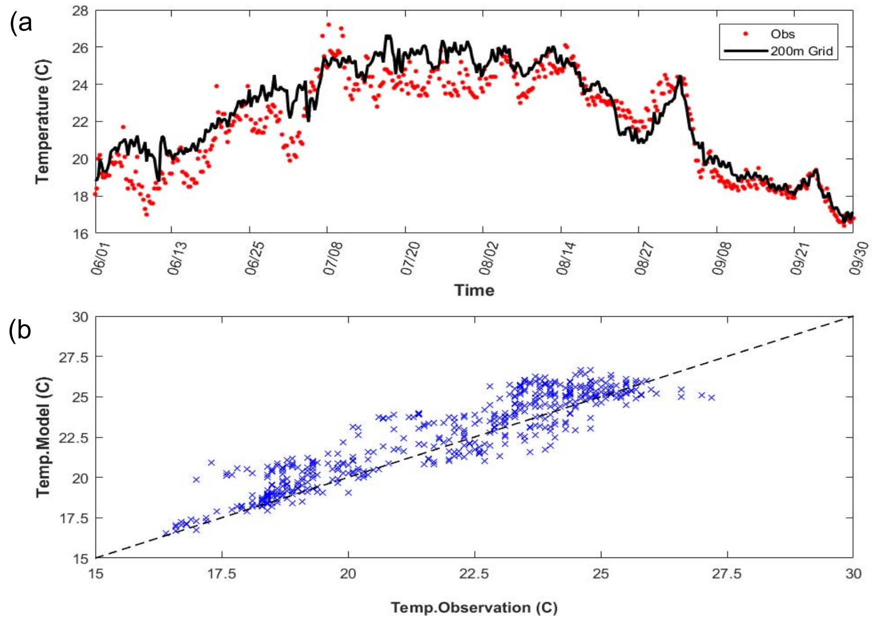

Figure 2: Observed vs. Model Temperature (a) Time series illustration (b) Comparison of model and observed data.

3 RESULTS AND DISCUSSION

Model outputs were used to better understand the circulation and temperature profiles in Lake St. Clair. The vertical distribution of temperature revealed little to no stratification in the water column, which is expected in a shallow lake such as Lake St. Clair. Modelled temperature was compared with buoy recorded water temperature which is illustrated in Figure 2. As can be seen in the time series (Fig. 1a), the model is able to predict both small- and large-scale fluctuations in water temperature for the observed period, especially during rapid weather change in late August and early September. Model predicted temperature values were in good agreement with the observed data (Fig.1b) with Root Mean Square Error RMSE and Mean Absolute Error MAE values of 1.1 ℃ and 0.9 ℃ respectively. Current patterns in Lake St. Clair are dominated by the wind conditions (Schwab et al. 1989) which affect water temperature by changing heat transfer coefficients as well. In addition, water temperature could potentially have been influenced by the variation in flow distribution in the St. Clair River's branches. Discharge distribution is similar to previous studies (North=34.79%, Middle=20.09%, Flats=17.25%, St. Clair Cutoff=24.7%, Bassett=3.15%; (Schwab et al., 1989; Holtschalag and Koschik, 2002b)

4 CONCLUSION

ELCOM was successfully set up for Lake St. Clair over a four-month period (June-September) of 2010 in order to provide better understanding of current patterns and water temperature to help in further analysis of microbial source tracking. For the first time, 200m uniform grid size allow for all tributaries and lake areas to be represented with high resolution. Observed water temperature comparison with model data correctly predicted different fluctuations during the modeling period. Simulations for the study period show the mean error between observed and simulated water temperature to be around 1 ℃ which is less that 5% of the mean water temperature for that time period. In addition to the water temperature, flow through the delta channels also simulated in good agreement with previous work.

References

Bocaniov, S.A.; Smith, R.E.H.; Spillman, C.M.; Hipsey, M.R.; Leon, L.F. 2014. The nearshore shunt and the decline of the phytoplankton spring bloom in the Laurentian Great Lakes: insights from a three-dimensional lake model. *Hydrobiologia* **731**: 151

Hodges, B.R. and Dallimore, C. 2006. Estuary, Lake and Coastal Ocean Model: ELCOM v2.2 Science Manual. Centre for Water Research Report, University of Western Australia.

Hodges, B.R.; Imberger, J.; Saggio, A.; Winters, K.B. 2000. Modeling basin-scale internal waves in a stratified lake. *Limnol. Oceanogr*. **7**.

Holtschlag, D. J.; Shively, D. A.; Whitman, R. L.; Haack, S. K.; Fogarty, L. R. 2008. Environmental Factors and Flow Paths Related to Escherichia coli Concentrations at Two Beaches on Lake St. Clair, Michigan. *Scientific Investigations Report Series* 2008-5028, 2002–2005.

Holtschlag, D. J., and Koschik, J. A. 2002a. A two-dimensional hydro- dynamic model of the St. Clair-Detroit River waterway in the Great Lakes Basin. *Water-Resources Investigations Rep*. No. 01-4236, USGS, Lansing, Michigan.

Holtschlag, D. J., & Koschik, J. A. 2002b. Flow distribution in selected branches of St. Clair and Detroit rivers. *Journal of Great Lakes Research,* **28**(3): 379–395.

Leon, L.F.; Smith, R.E.H.; Hipsey, M.R.; Bocaniov, S.A.; Higgins, S.N.; Hecky, R.E.; Antenucci, J.P.; Imberger, J.A.; Guildford, S.J. 2011. Application of a 3D hydrodynamic–biological model for seasonal and spatial dynamics ofwater quality and phytoplankton in Lake Erie. *J. Great Lakes Res*. **37**: 41–53.

Oveisy, A., Rao, Y. R., Leon, L. F., & Bocaniov, S. A. 2014. 3D winter modeling and the effects of ice cover on hydrodynamics, thermal structure and water quality in Lake Erie. *Journal of Great Lakes Research*, **40**(S3): 19–28

Rao, Y.R., Marvin, C.H., Zhao, J., 2009. Application of a numerical model for circulation, temperature, and pollutant distribution in Hamilton Harbour. *J. Great Lakes Res*. **35**: 61–73.

Schwab, D.J., Clites, A.H., Murthy, C.R., Sandall, J.E., Meadows, L.A., and Meadows, G.A. 1989. The effect of wind on transport and circulation in Lake St. Clair: *Journal of Geophysical Research*, v. 94, no. C4, April, p. 4947–4958.

Valipour, R.; León, L. F.; Depew, D.; Dove, A.; Rao, Y. R. 2016. High-resolution modeling for development of nearshore ecosystem objectives in eastern Lake Erie. *Journal of Great Lakes Research*, **42**(6): 1241–1251.

Zhao, J., Rao, Y. R., and Wassenaar, L. I. 2012. Numerical modeling of hydrodynamics and tracer dispersion during ice-free period in Lake Winnipeg. *Journal of Great Lakes Research*, **38**(3), 147–157.