Lake Erie Hypoxia Simulations with ELCOM-CAEDYM

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Abstract: This paper presents the simulation of the dissolved oxygen (DO) dynamics in the central basin of Lake Erie using a three-dimensional hydrodynamic model (ELCOM) coupled with an aquatic ecological model (CAEDYM). The objective was to simulate the recurrent hypoxic conditions that occur in the shallow hypolimnion of the central basin of the lake after the onset of stratification. In early spring, oxygen concentrations are relatively high, but by late summer, large areas in the central basin of Lake Erie are effectively hypoxic (<2 mg l^{-1}). This numerical modeling study successfully reproduced horizontal variability and vertical decay of dissolved oxygen during 1994. The magnitude of oxygen depletion has been observed to vary inter-annually depending on water temperature and the thickness of the hypolimnion, which will be investigated further with ELCOM-CAEDYM simulations for other years.

Keywords: 3D Hydrodynamic Lake Model; Water Quality Model; Hypoxia Lake Erie

1. INTRODUCTION

Physical mechanisms drive the dynamics in large lakes and can be decisive influences on processes that determine water quality, fisheries success and amenity value, see Harris [1986]. A good example is the problem of hypoxia in the hypolimnion of the central basin of Lake Erie.

Billions of dollars have been spent on control of nutrient loading to Lake Erie in U.S. and Canada, being the elimination of hypolimnetic hypoxia (generally defined as oxygen concentrations less than 2 mg l^{-1}) an important goal. There has been success in meeting a variety of water quality targets, notably chlorophyll and phosphorus, for the offshore lake waters, Charlton et al. [1999], but hypolimnetic hypoxia has persisted and may actually have worsened in recent years as shown by Charlton and Milne [2004].

In the central basin of Lake Erie, oxygen depletion in the hypolimnion typically decreases to a range of 2-4mgO_2 l^{-1}. Inter-annual variation is heavily influenced by the effect of water temperature and thermocline depth on the hypolimnion thickness as shown by Lam et al. [1987]. A thin hypolimnion (2-6m) results in strong O_2 depletion, strong inter-annual variation in late summer O_2 concentrations, and a heavy dependence on the sediment oxygen demand.

Essentially, if the sediment oxygen demand (SOD) dominates consumption in the hypolimnion during the stratified season then the thermocline depth, and consequently the hypolimnion depth, will define the initial mass of oxygen for consumption by SOD. A year with a thicker hypolimnion (i.e. higher thermocline) will not attain the degree of hypoxia as a year with a thinner hypolimnion (lower thermocline).

This can be modified by how strong a thermocline barrier is to downward mixing of oxygen. All these factors (except SOD) are directly dependent on the hydrodynamics of the lake. Therefore late season oxygen minimum will be under physical control. Inter-annual variability in the depth of the thermocline, and hence relative volume of the thin hypolimnion, is a major driver in late summer oxygen conditions.

The variation of hypolimnetic oxygen depletion among smaller lakes has been predicted from measurements of the epilimnetic productivity, hypolimnion thickness and temperature (e.g. Cornett 1989), and such studies all confirm that lakes with thin hypolimnia are prone to hypoxia even at low nutrient levels. Charlton [1987] concluded that even a 50% productivity decrease would still leave Lake Erie with a problem and Lam et al. [1987] estimated that hypoxia would persist for many years even if nutrient loading targets were fully met. These findings point to the importance of climatic influences, though it is also possible that undetected changes in nutrient loading or in biological processes in the lake have contributed to the hypoxia problem in recent years.

There is no clear evidence of a systematic increase of phosphorus (P) load in recent years, although there are always uncertainties in the estimates (D. Dolan, pers. comm.). Biological conditions in the lake certainly changed with the arrival of the dreissenid mussels in the late 1980's, see Mills et al. [1999]. The expansion of the dreissenids was associated with increased water clarity, diminished phytoplankton abundance, and increased organic enrichment of the benthic habitat in many areas (Vanderploeg et al. [2002], Hecky et al. [2004]) and may have altered the sediment oxygen demand and the potential for photosynthesis as described in Smith et al. [2005].

Individual mussel retains P while it is living but releases most of that retained P when it dies. Increasing populations of mussels (more births than deaths) will also retain P. However at the population reaches steady state then it is primarily a processor of P not a significant net retainer. The maturation of the new, dresissena-dominated, benthic community in more recent years may have resulted in release of phosphorus, according to Charlton and Milne [2004], and altered pathways of organic matter transport to the hypolimnion (Hecky et al. [2004]). As Hecky et al. [2004] explain, mussels may increase bioavailability of P by passing formerly tightly mineral bound P (iron oxides) by providing a reducing environment in their guts as well as in surrounding environment that becomes enriched in organic matter by accumulation of feces and pseudofeces.

Even if loading does not change, the internal processing of P by mussels will increase the bioavailability of P. However in terms of hypoxia the important effect of mussels may be in the repackaging of organic matter into larger particles that may increase the loading to the hypolimnia, where smaller organic particles (phytoplankton) are more likely to be decomposed.

Assessing these and other changes in processes that affect oxygen cycling and hypolimnetic depletion requires a realistic modelling framework that can capture all relevant processes but also account for the hydrodynamic influences. This preliminary application to simulate the DO dynamics, in particular the hypoxia phenomena in the hypolimninetic waters in the central basin of Lake Erie, builds on previous hydrodynamic modeling in the lake with ELCOM, as shown in Leon et al. [2005]. Application to Lake Erie requires choices for many parameters, some of which (i.e. SOD) are major sources of uncertainty in the modelling and prediction of oxygen dynamics.

The purpose of the present study is to assess the ability of the model to reproduce the dynamics of oxygen and related biogeochemical variables in Lake Erie, and to generate the first truly three dimensional representation of the oxygen cycle in the lake. The strategy is to use a largely generic parameterization but with modifications to reflect the particularities of Erie's ecosystem. Lake Erie is an advantageous subject in this regard because of the relative wealth of existing data on its biota and biogeochemical processes.

2. ELCOM-CAEDYM IN LAKE ERIE

The ELCOM-CAEDYM simulation, described by Romero et al. [2004], couples a 3D hydrodynamic model with a realistic 3D ecological model and provides a new tool for numerical investigations of the water quality in Lake Erie.

ELCOM, described by Hodges et al. [2000], is the 3D hydrodynamic model that drives the water quality model. As described in the scientific documentation, Hipsey et al. [2005], CAEDYM is a robust aquatic ecological model designed, since its inception, to be coupled to hydrodynamic models such as ELCOM.

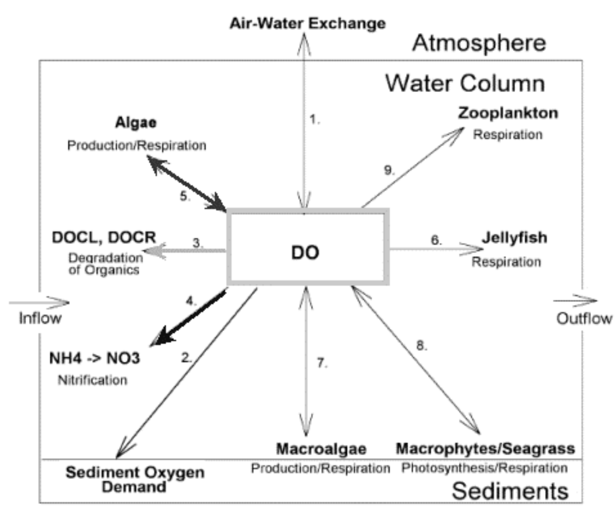

Figure 1. CAEDYM dissolved oxygen dynamics

Each time step ELCOM transfers to CAEDYM temperature/salinity to simulate fate dependencies, and horizontal velocities to simulate re-suspension from the sediments. CAEDYM passes back to

ELCOM dynamically simulated light extinction coefficients (based on suspended material) and the fate of all state variables. All the hydrodynamic transport is performed by ELCOM.

One of the features of CAEDYM is its flexible ecological configuration that can be tailored for specific applications, although definition of major element cycling and at least of one algal group is compulsory. CAEDYM includes comprehensive process representations of carbon (C), nutrients (N and P), silica (Si), oxygen cycles, several size classes of inorganic suspended solids (SS), and phytoplankton dynamics. Related to the DO issue, Figure 1 shows the schematic for the oxygen dynamics as conceptualized in CAEDYM.

2.1 Model Setup

Even for the simplest setup of CAEDYM, it is compulsory to model ortho-phosphate (PO4), nitrate (NO3), ammonia (NH4), and silica (SiO2). It is optional to model pH and dissolved inorganic carbon (DIC) state variables. In order to simplify the initial modeling effort and reduce the computational cost of including these optional state variables, we did not simulate them at this time, but they can be readily included in later applications. CAEDYM can model multiple phytoplankton and zooplankton groups. However, it is simpler and often more robust to keep the number of phytoplankton limited to several of the dominant assemblages. In Lake Erie, we decided to simulate four generic groups (cyanobacteria, chlorophytes, cryptophytes and diatoms).
Zooplankton dynamics greatly complicate the modeling process, so in this first instance it was decided not to include them in the present simulation. Again, f required, these can be taken into account in later applications.

Additionally, inflow nutrient concentrations and initial conditions of state variables throughout the lake are required as inputs to the ecological model. Spatial variations of the state variable over the lake were set up for the initial conditions to emulate observations at the start of the simulation. Figure 2 shows a map of Lake Erie with all its tributaries and the sampling sites used to setup the initial conditions.

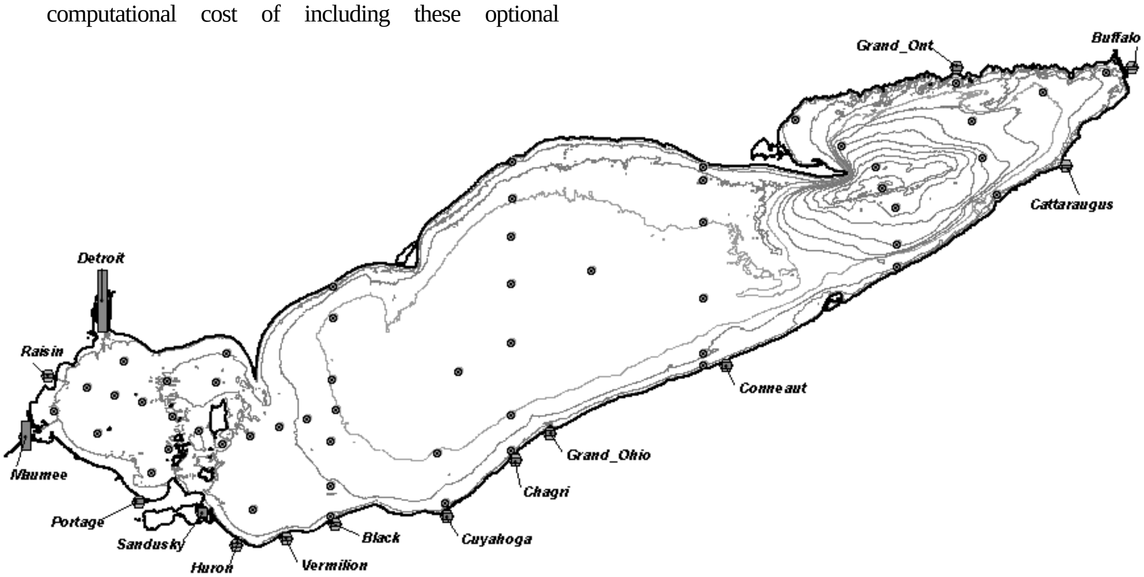

Figure 2. Map of Lake Erie showing the relative magnitude of phosphorus load from the main rivers. It also displays the sampling stations in 1994 used to define the initial conditions and validate the model output.

The year selected for the simulation was 1994 (for ELCOM validation work i.e. vertical temperature structure and current meter data, refer to the URL: http://sciborg.uwaterloo.ca/~lfleonvi/eriemodel/1994_page.html). The simulation was run for 135 days from early May through mid September.

Several sources of information were used as model inputs. Dolan [2005] provided daily loading data for the main tributaries. The 'Star Database', housed by the NWRI (National Water Research Institute), had in-lake sampling data for the period of simulation.

For values not available in the database, historical data for early spring was used as initial conditions, making sure such values were within the range reported elsewhere: Charlton et al. [1999], Smith et al. [1999], Makarewicz et al. [2000], Charlton and Milne [2004].

Table 1 presents a summary of the concentrations for each basin that were translated into the spatially variable initial conditions on this simulation.

Table 1. Average values of chemical parameters (post-invasion years 1989-1993) in early spring.

Parameter	Unit	West	Central	East
TP	µgP l^{-1}	20.3	10.7	10.3
SRP	µgP l^{-1}	2.8	2.8	4.6
NO3	mgN l^{-1}	0.8	0.28	0.28
TKN	mgN l^{-1}	0.18	0.16	0.14
NH3	µgN l^{-1}	34.9	6.6	4.3
Silicate	mg l^{-1}	1.4	0.4	0.7
Chla	µg l^{-1}	4.1	3.8	1.3

2.2 Simulation Results

Model outputs for surface levels of DO, as well as vertical averages and bottom distributions were recorded periodically to properly identify the zones of hypoxia. Figure 3 shows a snapshot of the DO spatial distributions across Lake Erie during mid summer. The simulations captured the development of hypoxia in the bottom waters of the central basin.

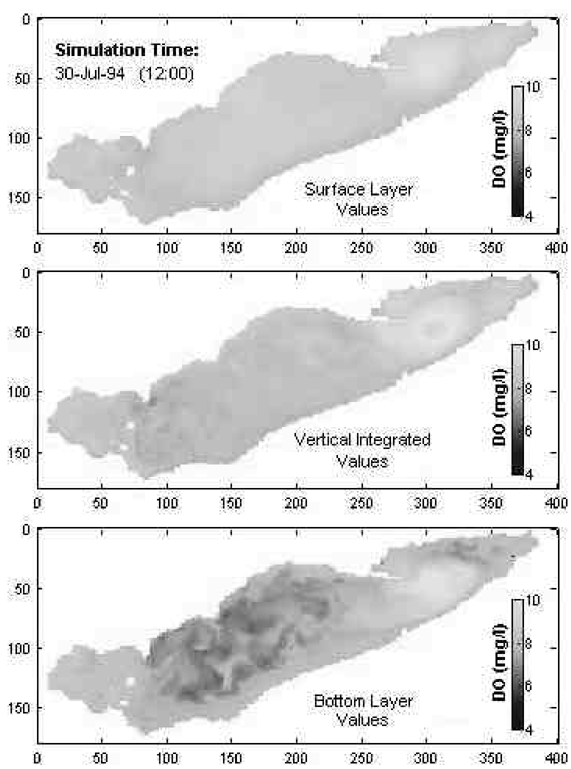

Figure 3. Surface, vertical averages and bottom distributions for DO. Snapshot for Jul. 30, 1994

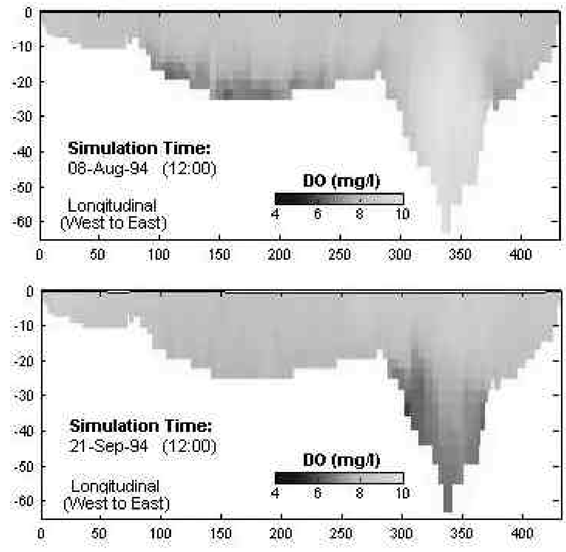

Figure 4. DO along a transect across Lake Erie on Aug. 6 and Sep. 21 of 1994

Figure 4 present two snapshots of simulated DO transects across the lake (longitudinal cross section). It shows, in early August, the decay and zone of lower oxygen in the central basin, while in the east basin, concentrations were above 8mg l^{-1}.

By the end of September, the DO in bottom waters of the central basin had increased (ca. 8 mg l^{-1}) and the east basin had now lower concentrations in the hypolimnion. The figures show the dynamics of DO, decreasing towards hypoxia conditions, and there is evidence that 1994 was not a year where hypoxia was strong enough.

2.3 Comparison

Simulated vertical profiles of DO were extracted that corresponded to the same location, date, and time as observations. Comparisons of simulated and observed profiles of DO at different sites in the west, central and east basins were encouraging, (Figure 5). After 80 days of simulation on July 28th, at three representative sites in the three basins the simulation replicated observed DO profiles. Low concentrations near the bottom of the central basin and high levels in the deep east basin were simulated in agreement to the observations.

The numerical results agreed well with the observations at various buoy locations, providing confidence that the model is reproducing the water temperatures, thermal stratification, and oxygen dynamics of Lake Erie. Additional comparisons of the model for 2002 are presented in the URL: http://sciborg.uwaterloo.ca/~lfleonvi/eriemodel/2002_page_elcd.html).

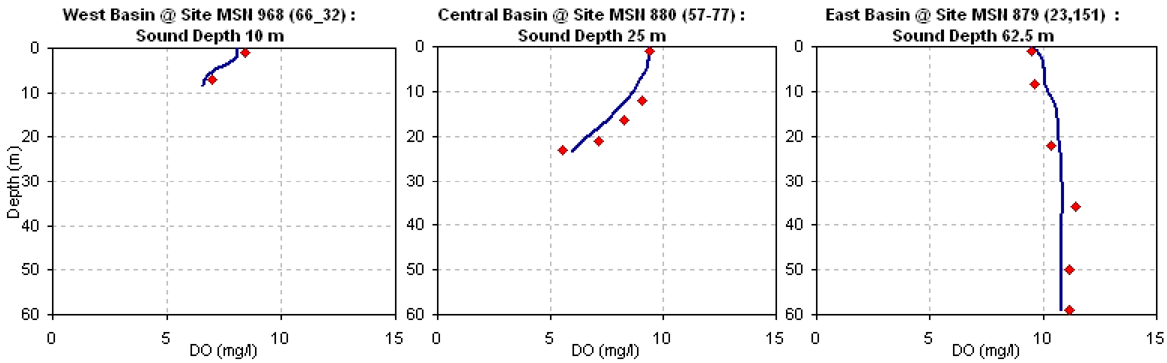

Figure 5. Comparison of measured versus calculated dissolved oxygen profiles for selected sites in the west, central and east basin of Lake Erie for the 1994 simulation after 80 days of simulation on July 28th

3. CONCLUSIONS

ELCOM-CAEDYM, a 3D hydrodynamic model coupled to a water quality model, was successfully applied to Lake Erie to simulate DO dynamics in the central basin of the lake.

The simulated patterns of DO were consistent with the measured spatial and temporal distributions throughout this lake. In early spring, oxygen concentrations were relatively high, but by late summer large areas in the central basin of the lake were nearly hypoxic. The results are encouraging and current work is in progress, to simulate a greater range of conditions to further investigate observed oxygen. In particular, the inference that hypoxia in the central basin of Lake Erie is regulated by inter-annual variations in water temperature and depends on the thickness of the hypolimnion will be quantified in a numerical framework.

In this preliminary study, the model validation focused on the accuracy of the simulations to reproduce vertical DO profiles in different regions of Lake Erie. Spatial distributions of DO were reproduced well in the simulations and provide confidence for further investigations of the areal extent of oxygen depletion and the causal mechanisms for inter-annual variations of these low DO regions in the central basin of Lake Erie.

4. ACKNOWLEDGMENTS

We acknowledge the data contribution for this analysis from several sources. Paul Hamblin from NWRI provided meteorological and thermistor chain data for 1994. Detroit River inflow data were obtained from the National Oceanic and Atmospheric Administration (NOAA). The Unites States Geologic Survey (USGS) provided Niagara River outflow data, near Buffalo. Dave Dolan, from the University of Wisconsin, provided daily inflow load data for 1994.

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