MISG Final Narrative Report, Award Number R/CGLH-7

Section A. Summary

- **Title Page**

a) Project Title:
Cladophora, mussels and the nearshore phosphorus shunt in Lake Michigan

b) Completion Date: 06/30/2021

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e) Abstract:

Stimulated by discharges of phosphorus, the filamentous green alga *Cladophora* has fouled the beaches of the Great Lakes for more than 80 years. Phosphorus control measures implemented in the 1970s and 80s reduced the frequency of algal blooms but, more recently, increased water clarity related to the filtering activities of invasive mussels has expanded the area of colonization by *Cladophora* and led to a resurgence in nuisance growth. Management of the phosphorus-*Cladophora* dynamic represents one member of the Dual Challenge, a dynamic that positions implementation of more stringent phosphorus loading objectives (to control *Cladophora* in the nearshore) in conflict with a foreseen need to mitigate oligotrophication in the offshore (to sustain a healthy fishery). While it is clear that mussels capture, transform and excrete phosphorus in a bioavailable form, the ability for phosphorus-poor offshore waters to support *Cladophora* growth in the absence of local sources in the nearshore is not fully understood. We apply a biophysical model simulating soluble reactive (SRP) and particulate (PP) phosphorus, mussel biokinetics and cross margin mass transport of phosphorus in addressing the Dual Challenge. Under present conditions, offshore phosphorus forcing would not support SRP levels in the nearshore sufficient to cause nuisance conditions and thus would not reduce the efficacy of more stringent management of local phosphorus loads. We have also performed scenario simulations to establish limits for increases in offshore phosphorus levels that would favor food web-fisheries conditions, but would not hinder efforts to reduce nuisance algal growth in the nearshore.

f) Key words: *Cladophora*; phosphorus; dreissenid mussels; cross margin transport; Great Lakes; oligotrophication; Dual Challenge

- **Executive Summary**

This study characterizes the role of cross-margin transport of offshore P reserves and P recycling by dreissenid mussels in stimulating nuisance growth of *Cladophora* in the Lake Michigan nearshore in the absence of local sources of P enrichment. The study site at Good Harbor Bay is located within Sleeping Bear Dunes National Lakeshore where high densities of *Cladophora* biomass have been reported in the apparent absence of a local source of P.

Our work draws on the capabilities of a biophysical model consisting of linked biogeochemical (mussel filtration with processing of PP and excretion of SRP) and hydrodynamic (cross-margin and near-bottom transport of PP and SRP) components. Model inputs and coefficients are established from the literature, from monitoring datasets and through hydrodynamic modeling. The biophysical model is run for paired values of PP in the offshore and mussel biomass density in the nearshore, simulating SRP concentrations in the nearshore colonized by *Cladophora*. Simulation results indicate that nearshore waters, forced solely by offshore PP and SRP contributions, would be P-limited and consistent with the objective of limiting nuisance growth of *Cladophora*.

Model application is then extended to three additional sites: Big Bay De Noc, MI, the nearshore at Milwaukee, WI, and a segment of the southeast coastline, MI. The result for these sites agrees with that for Good Harbor Bay, i.e., offshore-forcing by open lake PP and SRP would not be sufficient to support nuisance growth of *Cladophora*. Finally, we demonstrate application of the model in establishing offshore levels of PP and SRP that would support the offshore food web (fishery) without engendering nuisance growth of *Cladophora* in the nearshore.

In summary, we find that:

1. In the absence of local sources of phosphorus, rates of *Cladophora* growth and biomass accrual are controlled by cross-margin transport of the nutrient from offshore to nearshore waters. The development of *Cladophora* beds and attendant beach accumulation will vary as a function of open-lake SRP and PP concentrations, i.e., the system's trophic status.

2. At present, offshore P forcing would not result in SRP levels in the Lake Michigan nearshore sufficient to cause nuisance conditions. We posit that observations of accumulating algal debris in waters adjoining Good Harbor Bay (e.g., Sleeping Bear Dunes National Lakeshore) reflects not cross-margin transport, but rather habitat expansion due to water column clearing by mussels.

3. A margin exists between contemporary P levels in the nearshore and those required to maintain an absence of nuisance growth that could be exploited to support a healthy fishery in the offshore.

4. Effective management of *Cladophora* blooms in Lake Michigan should occur through management of P loading at local scales while ensuring lake wide P concentrations do not increase above those identified here to eliminate nuisance growth.

Section B. Accomplishments

Introduction

Nuisance growth of the filamentous green alga *Cladophora* has plagued the nearshore waters of the Great Lakes for over 80 years (Kuczynski et al., 2016), depositing mats of rotting algal biomass that foul beaches and harbor microbes responsible for bird kills (avian botulism; Lafrancois et al., 2011). The frequency of reports of nuisance growth declined in the 1980s in response to phosphorus (P) management and then worsened significantly with the proliferation of invasive mussels (Kuczysnski et al., 2016). Acting upon heightened stakeholder sensitivity and a rekindling of scientific attention (Auer et al., 2010), the Agreement Review Committee (ARC 2006) concluded that the Great Lakes Water Quality Agreement had not adequately addressed eutrophication in the nearshore. The resulting GLWQ Protocol of 2012 directs attention to the nearshore, calling for maintenance of levels of algal biomass below those constituting a nuisance condition.

Phosphorus is the nutrient limiting *Cladophora* growth (Kuczynski et al., 2016), with the alga taking up the nutrient only in its soluble reactive form (soluble reactive phosphorus-SRP; ~orthophosphate, PO_4). The open waters of Lakes Huron, Michigan and Ontario are presently oligotrophic and lack SRP at levels that stimulate nuisance growth. Scientists surveying the Lake Ontario nearshore recently concluded that it is not open-lake SRP concentrations, but rather inputs from local watersheds that are the underlying driver for site-to-site variability in *Cladophora* biomass (Higgins et al., 2012). However, high densities of *Cladophora* biomass have been documented in northern Lake Michigan (e.g., North and South Manitou Islands and nearshore waters at Sleeping Bear National Lakeshore; Bootsma, unpublished; Bootsma et al., 2015). These sites are remote from any local P source, suggesting that *Cladophora* growth may rely on supplies from open lake waters (Bootsma et al., 2015). Therefore, the cross-margin transport between offshore and nearshore waters may play a critical role in ecosystem function. At issue here is the possibility that phosphorus supply to the nearshore through cross-margin transport may continue to support nuisance growth of Cladophora even following control of local phosphorus sources.

The conflicting nature of managing these offshore and nearshore water quality issues, *connected by cross-margin water transport*, also lies at the heart of what has been termed the Dual Challenge (Hecky and DePinto 2020). Here, attention is focused on two issues, *Cladophora* in the nearshore and the food web in the offshore, as endmembers for phosphorus management scenarios. The phosphorus concentration required to eliminate nuisance *Cladophora* is the nearshore endmember and that supporting a healthy fishery is the offshore endmember. In this work, we apply the biophysical phosphorus-mussel model in establishing the nearshore endmember SRP concentration.

Our objective, stated as a guiding question, is thus, "*Would ambient nearshore SRP concentrations, determined solely by cross-margin transport of offshore SRP and PP (the latter subsequently mineralized, in part, to SRP in the nearshore by mussels) be sufficient to support nuisance growth of Cladophora?"* Beyond addressing the efficacy concern (cross-margin transport), attainment of this objective would provide an upper bound for SRP and PP in the offshore required to protect nearshore waters from *Cladophora* proliferation. That upper bound would offer guidance for future work seeking to balance eutrophication potential in the nearshore and oligotrophication in the offshore, the consequences concern of the Dual Challenge. We seek to achieve our objectives by linking a hydrodynamic model simulating cross-margin transport and a biokinetic model simulating the ecophysiology of dreissenid P recycling.

Project Narrative

Method

The study site for this research is Good Harbor Bay (Lake Michigan), part of the Sleeping Bear Dunes National Lakeshore (Figure 1). The site is particularly appropriate for our study as it was the location for research on mussels and bottom boundary layer phosphorus (Dayton et al., 2014), has been reported to host high densities of *Cladophora* biomass (Bootsma et al., 2015) and is a component of the USGS Great Lakes *Cladophora* survey (Przybyla-Kelly et al., 2020). Additionally, no significant local sources of phosphorus have been identified at Good Harbor Bay and thus it may be assumed that *Cladophora* growth there is supported by mussel recycling of particulate phosphorus delivered from offshore waters.

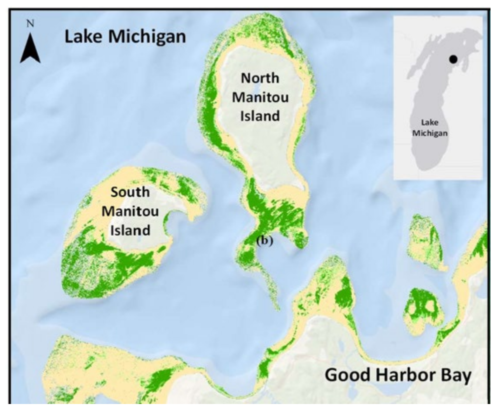

Figure 1. Good Harbor Bay study site: (a) geography and distribution of colonized (Cladophora; green) and uncolonized (sand; tan) substrate; courtesy of Michigan Tech Research Institute

Our biophysical modeling approach draws upon the capabilities of linked hydrodynamic and biokinetic models with the former simulating mass transport of water and P components (PP and SRP) across the nearshore-offshore boundary and the latter simulating mussel filtration of PP and attendant P recycling (Figure 2). In this process-oriented study, the biokinetic model is applied to a nearshore control volume, assuming horizontal and vertical homogeneity in PP and SRP and in mussel distribution and density. This approach is appropriate for our objective to explore mussel mediation of nearshore ambient SRP levels supported only by offshore PP reserves, and eases the computational burden so that we may focus on process-based (biokinetic) features and more rigorously characterize model sensitivity and uncertainty. We note that concentrations of $SRP_{nearshore}$ predicted for low concentrations of $PP_{offshore}$ ($\leq$0.5 mgP·m^{-3}·d^{-1}) in combination with low rates of cross margin transport ($\leq 2\text{x}10^{8}$ m^{3}·d^{-1}) and/or high biomass densities (most commonly $\geq$45,000 mgAFDW^{-1}·m^{-2}) represent non-equilibrium (starvation) conditions. While calculated rates are applicable in the time frame of our simulation, the occurrence of starvation conditions would lead to mussel mortality and establishment of a new equilibrium condition over a longer time frame (see Li et al., 2021). The governing equations for the nearshore P-mussel model are described as

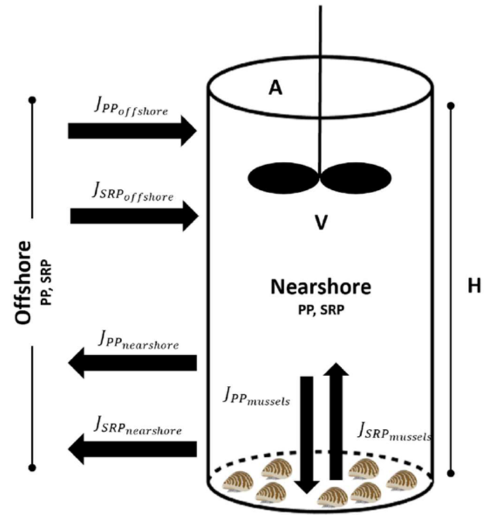

Figure 2. Conceptual diagram of the model framework used to simulate the mussel-phosphorus dynamic. Arrows represent the mass flux of PP and SRP (mgP·d^{-1}) across the nearshore-offshore and sediment-water boundaries. Implicit here are the roles of the two.

$$\frac{dPP_{nearshore}}{dt} = \frac{Q\cdot(PP_{offshore} - PP_{nearshore})}{V} - \frac{F_{vol}\cdot B\cdot PP_{nearshore}}{H} \tag{1}$$

$$\frac{dSRP_{nearshore}}{dt} = \frac{Q\cdot(SRP_{offshore} - SRP_{nearshore})}{V} + f\cdot\frac{F_{vol}\cdot B\cdot PP_{nearshore}}{H} \tag{2}$$

In this form, solution for the PP and SRP mass balances requires, 1) parameterization of the biokinetic coefficients F_{vol} (mussel-specific volumetric filtration rate (m^{3}·mgAFDW·d^{-1}))and f (the PP to SRP conversion efficiency); 2) specification of mussel biomass density (B); 3) specification of offshore PP and SRP concentrations; 4) specification of control volume physical characteristics of water depth (H) and water volume (V); 5) and determination of the rate of cross boundary flow (Q).

Here we adopt a value for F_{vol} = 4.75x10^{-4} m^{3}·mgAFDW^{-1}·d^{-1} as a representative rate for use in the biokinetic model. This rate is the median value for ranges of F_{vol} reported by Diggins et al. (2001), Vanderploeg et al. (2010) and Xia et al. (2021) (Figure 3). The upper (6.46x10^{-4} m^{3}·mgAFDW^{-1}·d^{-1}) and lower (3.04x10^{-4} m^{3}·mgAFDW^{-1}·d^{-1}) quartiles of these ranges are utilized in sensitivity analysis.

Based on calculations made using results from Bootsma (2009) and Mosely and Bootsma (2015), we carry forward $f = 0.29$ as the representative conversion efficiency for application to shallow water habitats co-inhabited by mussels and *Cladophora*. This representative value is comparable to estimates of f applied in other modeling studies focusing on the quagga mussel in Lake Michigan (Shen et al., 2020, $f = 0.35$ and Rowe et al., 2017, $f = 0.30$). We apply conversion efficiencies of $f = 0.2$, 0.3, 0.4 and 0.5 in performing sensitivity analyses.

We carry forward a mussel density of 1,796 individuals·m^{-2} calculated as the simple average of the measurements from Dayton et al., 2014; LimnoTech, 2020; Przybyla-Kelly et al., 2020. In biokinetic applications, this representative value is expressed as a mussel biomass density of 15,266 mgAFDW·m^{-2} (ash-free dry weight). The conversion is performed based on the representative mussel density and length-weight metrics developed specifically for Good Harbor Bay by LimnoTech (2020): a mean shell length of 15 mm, a ratio of shell-free dry weight to shell length of 0.67 (LimnoTech, 2020) and a ratio of ash-free dry weight to shell free dry weight of 0.85 (Nalepa et al., 1993; Glyshaw et al., 2015).

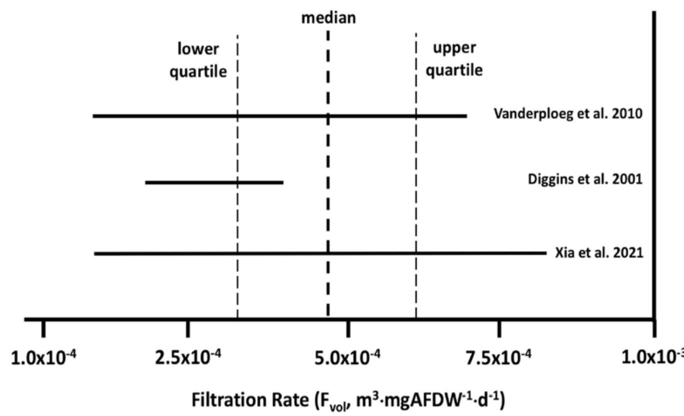

Figure 3. Ranges in quagga mussel filtration rates (F_{vol}, m^3·mgAFDW^{-1}·d^{-1}; horizontal lines) reported in three studies compared with the median rate for data pooled from those studies (F_{vol} = 4.75x10^{-4} m^3·mgAFDW^{-1}·d^{-1}; vertical bold dashed line) and taken as the representative value for this research. The vertical dashed lines are the lower and upper quartiles for those data, used in sensitivity analysis.

For phosphorus, , we refer to monitoring performed by the U.S. EPA Great Lakes Water Quality Survey available through the GLENDA database. These surveys have been performed in Spring (late-March to early-May) and Summer (late-July to mid-September) from 1983-2018 (excepting 1994). We selected 11 stations on Lake Michigan having a maximum depth of ≥90 m and a monitoring record of 30 or more years. We limited further analysis to the Spring Surface quadrant as that sampling aligns well temporally with the alga's growing season, capturing SRP levels during the period of active *Cladophora* growth and prior to SRP drawdown by phytoplankton. Finally, differences in the Spring Surface

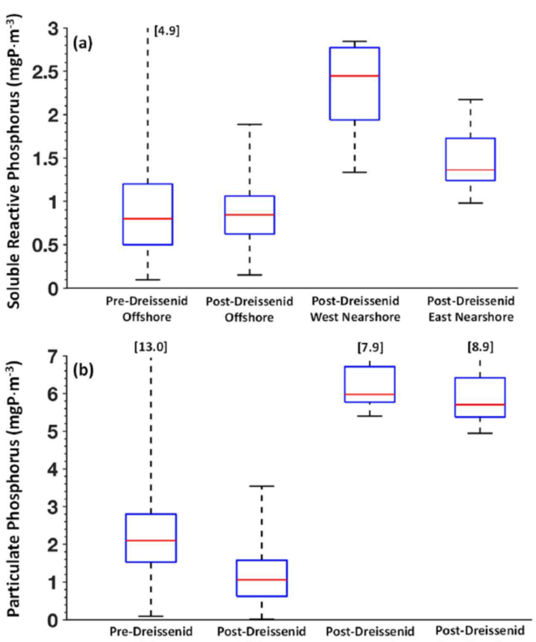

Figure 4. Box and whisker plots for: (a) soluble reactive phosphorus and (b) particulate phosphorus with the median (red line), lower quartile (blue box, bottom), upper quartile (blue box, top), maximum and minimum for offshore waters and nearshore waters.

subset were examined in a long-term context, i.e., prior to (Pre-Dreissenid Period, 1983-1992) and following (Post-Dreissenid Period, 2009-2018) colonization of Lake Michigan by dreissenid mussels. Striking changes in PP were reported from the Pre- to Post Dreissenid periods (Figure 4). PP dropped 50% from 2.10 to 1.05 mgP·m^{-3}; SRP levels modestly (5%) from 0.80 to 0.84 mgP·m^{-3}.

As a basis for comparison to offshore conditions, we also examined monitoring results for TP, SRP and PP obtained during a survey of the Lake Michigan nearshore performed from 9-15 September 2010 by Yurista et al. (2015; Anne Cotter, U.S. EPA MED, personal communication). Samples were collected at depths <20 m at 15 stations along a ~1000 km track encircling Lake Michigan. We separated the nearshore data set into east and west components, recognizing the potential impact of different levels of landscape activity. It is evident from this analysis that SRP concentrations (the source immediately available to *Cladophora*) are markedly higher in the nearshore than the offshore and higher along the west coast than the east (Figure 4).

Due to the complexity of the flow pattern (Figure 5a), it is not sufficient to estimate cross-boundary transport from one or several ADCP (Acoustic Doppler Current Profiler) observations of water velocity. It is more effective to calculate cross-boundary transport using a hydrodynamic model and test model performance using ADCP measurements. The Finite Volume Community Ocean Model (FVCOM) is applied here to determine cross-boundary transport. The particular version of the tool used here is the Lake Michigan-Huron FVCOM model which supports the NOAA Lake Michigan-Huron Operational Forecast System (LMHOFS). FVCOM was applied in calculating the mean daily cross-margin flow at Good Harbor Bay for the April-August period of 2016, 2017 and 2018; these were then averaged to provide a representative cross-margin flow for the study system (Q = 2.1x10^{8} m^{3}·d^{-1}). Good Harbor Bay includes shallow nearshore water and shoal environments having light conditions favorable for *Cladophora* growth (0-10 m; Kuczynski et al., 2016). Thus, in our biophysical model, we utilize the water volume and transport as calculated for the mean depth of 21 m normalized to a depth of 10 m. Finally, we calculate cross-margin flow for 2018 at several other nearshore and embayment locations**.**

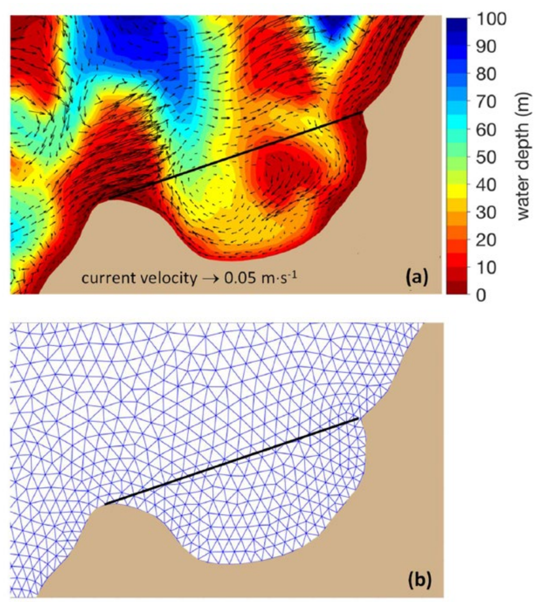

Figure 5. Physical conditions at Good Harbor Bay: (a) bathymetry and monthly average flow patterns (arrows) for July 2018 and (b) FVCOM model grid. Black line in both panels defines the study system boundary.

The modeling objective is to calculate concentrations of $PP_{nearshore}$ and $SRP_{nearshore}$ corresponding to a matrix of $PP_{offshore}$ concentrations and mussel biomass densities (B) for specified values of $SRP_{offshore}$ and cross-boundary flow (Q). Model calculations also require input of two biokinetic coefficients: F_{vol}, the mussel-specific filtration rate, and *f*, the coefficient for efficiency of mussel conversion of PP to SRP. Representative values and ranges for F_{vol}, *f* and B have been identified from the literature, for Q from FVCOM simulations, and for PP and SRP in the nearshore and offshore from the U.S. EPA database. Inputs and coefficients supporting numerical experiments are summarized in Table 1.

Table 1. Coefficients and model inputs used in simulations: (a) median concentrations and ranges for soluble reactive and particulate phosphorus the offshore waters of Lake Michigan as applied in sensitivity analyses and management simulations for the Post-Dreissenid Period, (b) model inputs and coefficients representative of conditions in Good Harbor Bay for the Post-Dreissenid Period, (c) median concentrations for soluble reactive and particulate phosphorus in the offshore waters of Lake Michigan for the Pre-Dreissenid Period and (d) median concentrations for soluble reactive and particulate phosphorus in the east side and west side nearshore waters of Lake Michigan for the Post-Dreissenid Period.

Model Input or Coefficient	Value	Range
a. Model inputs and coefficients for Good Harbor Bay, Post-Dreissenid Period		
Mussel biomass density (B, $mgAFDW \cdot m^{-2}$)	15,266	0 - 50,000
Mussel filtration rate ($F_{vol,}$ $x10^{-4}$ $m^3 \cdot mgAFDW^{-1} \cdot d^{-1}$)	4.75	3.04, 4.75, 6.46
Mussel PP to SRP conversion efficiency (*f*, d'less)	0.29	0.2, 0.3, 0.4, 0.5
Rate of cross-margin flow (Q, $x10^8$ $m^3 \cdot d^{-1}$)	2.1	0.25, 1.0, 2.0,4.0, 6.0
b. Phosphorus levels for the Lake Michigan offshore, Post–Dreissenid Period		
SRP in the offshore, $SRP_{offshore}$, $mgP \cdot m^{-3}$	0.84	0.50, 0.75, 1.00, 1.25, 1.50
PP in the offshore, $PP_{offshore}$, $mgP \cdot m^{-3}$	1.05	0 - 7
c. Phosphorus levels for the Lake Michigan offshore, Pre-Dreissenid Period		
SRP in offshore waters ($SRP_{offshore}$, $mgP \cdot m^{-3}$)	0.80	
PP in offshore waters, ($PP_{offshore}$, $mgP \cdot m^{-3}$)	2.10	
d. Phosphorus levels for the Lake Michigan nearshore, Post-Dreissenid Period		
SRP at nearshore east stations, $SRP_{nearshore}$, $mgP \cdot m^{-3}$	1.45	
SRP at nearshore west stations, $SRP_{nearshore}$, $mgP \cdot m^{-3}$	2.34	
PP at nearshore east stations, $PP_{nearshore}$, $mgP \cdot m^{-3}$	5.70	
PP at nearshore west stations, $PP_{nearshore}$, $mgP \cdot m^{-3}$	6.12	

Results and Discussion

The primary focus of our work is to characterize the potential for offshore reserves of SRP and PP, delivered to the nearshore through cross-margin transport, to maintain nearshore SRP concentrations at levels sufficient to support nuisance growth of *Cladophora* in the absence of local sources of the nutrient. Here we adopt an SRP concentration of 1.25 $mgP \cdot m^{-3}$, mid-range in the region of P limitation, as the criterion for avoidance of nuisance growth of *Cladophora*. We note that there is uncertainty with respect to the value identified for the adopted criterion (interpretation of the *Cladophora* biomass – SRP curve), input of the offshore SRP and PP concentrations (spatiotemporal variation, limit of detection) and the biophysical model (variability in biokinetic coefficients). These uncertainties are of lesser concern below the adopted criterion, as any position there is expected to avoid nuisance growth. Above the adopted criterion, however, uncertainties become more important as efforts to supplement phosphorus nutrition in offshore waters drives nearshore SRP concentrations toward those supporting nuisance conditions. In the result and discussion, we display the adopted criterion as a solid black line overlain on the SRP map at a concentration of 1.25 mgP·m^{-3}.

Management Analysis for Good Harbor Bay

The biophysical model is first applied to examine management considerations relating to offshore forcing of nuisance growth of *Cladophora* at Good Harbor Bay. They are then examined through sensitivity analyses and identified as representative values for Good Harbor Bay (Table 1). The biophysical model generates a two-dimensional map of $SRP_{nearshore}$ for ranges of $SRP_{offshore}$ and mussel biomass density (Figure 6). The location of the Good Harbor Bay environment on the $SRP_{nearshore}$ map is then identified for the Post-Dreissenid Periods based on $SRP_{offshore}$, $PP_{offshore}$ and mussel biomass density for the respective time intervals (Table 1). This positioning is then evaluated with respect to the adopted criterion for elimination of nuisance growth of *Cladophora* (SRP of 1.25 mgP·m^{-3}) and placed in a management context by comparing conditions forced solely by offshore SRP and PP reserves with those forced locally. Simulation results for the Post-Dreissenid Period indicates that nearshore waters, forced solely by offshore PP and SRP levels, would be P-limited and essentially consistent with the objective of the SRP adopted criterion for limiting nuisance *Cladophora* growth (Figure 6).

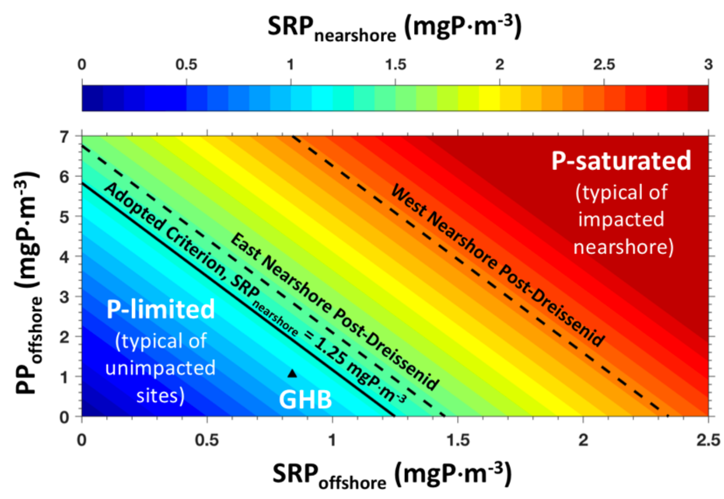

Figure 6. A two-dimensional map of model-predicted $SRP_{nearshore}$ concentrations, with the adopted $SRP_{nearshore}$ criterion for eliminating nuisance growth of Cladophora (solid line) dividing the map into P-limited (below the line) and P-saturated (above the line) regions. Map positions corresponding to sole open lake forcing of $SRP_{nearshore}$ by offshore sources are identified for the Post-Dreissenid (triangle) Periods. As a point of reference, SRP concentrations measured for the east and west nearshore in the Post-Dreissenid Period (Table 1) are positioned on the $SRP_{nearshore}$ map.

The two-dimensional map of $SRP_{nearshore}$, presented previously as Figure 6, serves well in illustrating several points relating to offshore forcing and the Dual Challenge.

However, its application as a more general purpose tool is limited as it accommodates only the intrinsic representative values for mussel biokinetics (F_{vol} and *f*) selected here and the site-specific conditions of cross-margin transport (Q) and mussel biomass density (B) for Good Harbor Bay. To provide a more broadly applicable and user-friendly tool, we have developed algorithms for determination of conditions satisfying the adopted criterion for combinations of inputs and coefficients for other sites.

A term α, the biophysical coefficient is introduced and defined mathematically as,

$$\alpha = \frac{F_{vol} \cdot B}{H} \cdot \tau \quad (3)$$

where τ is the water residence time (days) in an embayment or coastal segment. The R.H.S of equation (3) can be rewritten as,

$$\alpha = \frac{F_{vol} \cdot B}{H} / \left(\frac{1}{\tau}\right) \quad (4)$$

which reflects the complementary or competitive role of biological ($F_{vol} \cdot B/H$) and physical ($1/\tau$) processes in determining the value of α. For example, a site with high mussel biomass densities and low flushing rate (extended residence time) would reflect a case where biophysical processes act in a complementary fashion to increase the value of α and thus the potential for nuisance growth of *Cladophora*. On the other hand, a site with high mussel biomass densities but a high flushing rate (limited residence time) provides an example of competition between biophysical processes resulting in a lower value of α and a lower potential for nuisance growth.

In this derivation, α is embedded in a parenthetical term referred to as the biophysical influence factor, $IF = \left(1 - \frac{1}{1+\alpha}\right) \cdot 100\%$, quantifying the percentage of the $PP_{offshore}$ delivered to the nearshore by cross-margin transport converted to SRP. Substituting α to the governing equations of the nearshore P-mussel model (Equations 1 and 2), a steady state solution for $SRP_{nearshore}$ can be developed as,

$$SRP_{nearshore} = SRP_{offshore} + IF \cdot f \cdot PP_{offshore} \quad (5)$$

Mathematically, α could range from 0 to positive infinity (∞^+) and the influence factor (*IF*) would vary between 0 and 100% (Figure 7). For, $\alpha \rightarrow 0$, the influence factor → 0 and $SRP_{nearshore}$ would → $SRP_{offshore}$, its lower limit. At the other extreme, ∞^+, the influence factor → 1 and $SRP_{nearshore} \rightarrow SRP_{offshore} + f \cdot PP_{offshore}$, its upper limit. The model-calculated concentration of $SRP_{nearshore}$ would lie between these extremes, with its position depending on the value of *IF* as mediated by α, i.e., local biophysical conditions (Equation 3). The significance of this solution lies in the fact that, for any given set of boundary conditions (the open lake properties $SRP_{offshore}$ and $PP_{offshore}$), intrinsic processes of mussels (*f* and F_{vol}) and site specific values of B, H and τ, concentrations of $SRP_{nearshore}$ can be estimated at any location.

The nonlinear nature of the α, *IF* relationship Figure 7a) is such that *IF* increases rapidly with α when α is small (e.g., α = [0, 2.4] corresponds to *IF* = [0, 70%]) and less rapidly as α increases further, with the value of *IF* increasing less rapidly and asymptotically approaching a value of 1 (e.g., $\alpha = [4, \infty^+]$ corresponds to *IF* = [80%, 100%]). This suggests that value of IF may be insensitive to changes in τ and B for values of α>2 and certainly insensitive for α>5 (Figure 7b). This is illustrated for Good Harbor Bay by examining the *IF* response to variation in τ about its representative value (4.47±2 days). The resulting change in *IF* (68%-81%) is only 13% because Good Harbor Bay (filled black dot in Figure 7b) lies in the insensitive region. Similarly, the response for a change in B about it representative value (15,266±5,000) mgAFDW $\cdot$ m^{-2} would result in only a change of 12% (69%-81%), again because Good Harbor Bay lies in the insensitive region (filled black dot in Figure 7b).

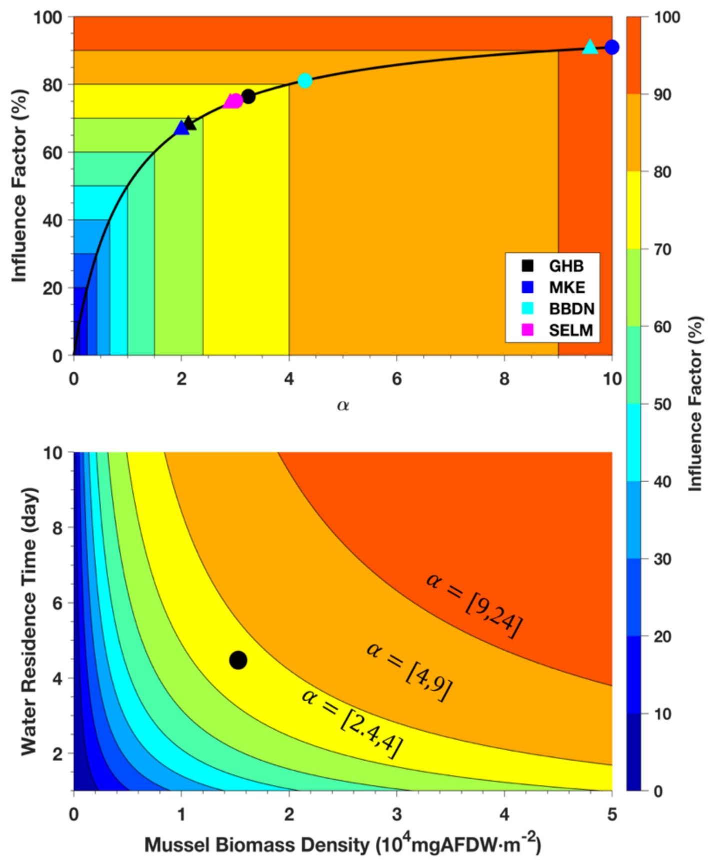

Figure 7. Model simulation of the relationship between (a) the coefficient α and the biophysical influence factor IF as developed in Equations 4 and 5; (b) between α and IF and their biological (mussel biomass density) and physical (water residence time) forcing conditions. Model inputs and coefficients for this simulation are those for Good Harbor Bay (Tables 1 and Table 2). Colored areas in both panels demarcate ranges in IF having different slopes ($\Delta IF/\Delta\alpha$, the black line) and thus different sensitivity to changes in biophysical forcing. In (a), dots represent values of α calculated for contemporary conditions of mussel biomass density (intersite variability) and triangles represent future conditions, i.e. the average of biomass density for the three sites largely unimpacted by local sources (BBDN, GHB and SELM). The black dot in (b) represents the position of GHB within the region insensitive to variability in biophysical conditions.

Next, we extend the application of the model to three additional sites on Lake Michigan, yielding a total of four study locations: two embayments (Good Harbor Bay, MI, GHB, and Big Bay De Noc, MI, BBDN) and two near-linear coastal segments (the nearshore at Milwaukee, WI, MKE and a segment of the southeast coastline, MI, SELM). The coefficients α is calculated using Equation 4 and site-specific values for H (depth, influencing water column dilution of mussel SRP excretion), B (mussel biomass density, influencing PP processing capacity) and τ (residence time, influencing flushing of the nearshore).

Simulation results are presented for each location (filled circles in Figure 7a) applying site-specific values of H and τ (invariant in time) and values of B representing contemporary levels of food supply (i.e., prior to any local P source remediation). All of the stations fall within the insensitive region of the α - *IF* plot, yielding IF values ranging from 70% to 100% (yellow, orange and red) and indicating that variability in B would have only a small impact on the impact factor.

We note, however, that α is defined for equilibrium conditions, i.e., that mussel biomass densities are in equilibrium with the contemporary mussel food supply. Changes in nearshore conditions, such as reductions in point source effluent P levels, would alter mussel food source concentrations, lead to an increase in mussel mortality and result in a new equilibrium condition with different values for α and *IF*. We test this consideration by running the model at a level of B (10,069 mgAFDW·m^{-2}) calculated as the simple average for densities measured at sites apparently unimpacted by local inputs (GHB, SELM and BBDN). The results indicate that all four locations (Figure 7a, triangles) would remain within the *IF*-insensitive region for levels of B characteristic of locations unimpacted by local sources. There is a small incursion into the transition region for GHB and MKE, but the magnitude of this effect is with the tolerances of the regional definitions. We conclude from these simulations that model inputs of B may be equally well represented by biomass densities at local source-driven sites or those estimated for unimpacted sites.

Having addressed the issue of intersite variability in biophysical factors, we turn to the management implications of our findings with respect to offshore forcing of *Cladophora* growth in the absence of local sources and to a management approach for meeting the objectives of the nearshore endmember of the Dual Challenge. First, we examine model-predicted concentrations of $SRP_{nearshore}$ at the four sites identified previously. The simulation takes the form of a 2-D map of $SRP_{nearshore}$

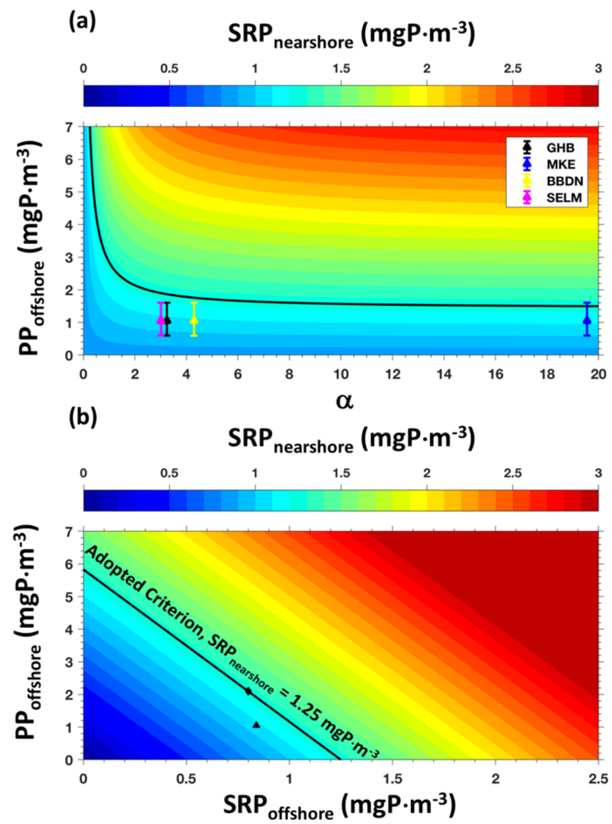

Figure 8. Management derived from this analysis: (a) sensitivity to variation in biophysical forcing conditions at four locations on Lake Michigan: Big Bay de Noc, MI (BBDN), Good Harbor Bay, MI (GHB), a southeast coastal segment, MI (SELM) and the Milwaukee, WI nearshore (MKE); (b) nearshore SRP levels at Good Harbor Bay for Pre- (diamond) and Post-Dreissenid (triangle) conditions, illustrating a management approach where a return to Pre- SRP concentrations in the nearshore could offer nutrient supplementation to the offshore without stimulating nuisance growth of Cladophora in the nearshore.

(Figure 8a) with the biokinetic coefficients F_{vol} and *f* as in Table 1a and site-specific inputs (H, τ and B) as in Table 2. $SRP_{nearshore}$ is simulated for the Post-Dreissenid $SRP_{offshore}$ (0.84 mgP·m^{-3}; Table 1b) and for $PP_{offshore}$ as its median value (1.05 mgP·m^{-3}, Table 1b; triangles in Figure 8a) and the lower and upper quartiles (0.6 and 1.6 mgP·m^{-3}, Figure 4; lower and upper bars in Figure 8a). The black line represents the adopted criterion for elimination of nuisance growth of *Cladophora* ($SRP_{nearshore}$ ≤1.25 mgP·m^{-3}).

The results of these simulations, colored triangles (the median) with the upper and lower quartiles as bars, affirm the finding presented above that variability in biophysical conditions (as reflected in α) will not influence the magnitude of $SRP_{nearshore}$ (Figure 8a). Thus, simulations using Equations 1 and 2 or the simplified form presented as Equation 5 and drawing on inputs developed for Good Harbor Bay and the offshore waters of Lake Michigan (Tables 1 and 2), will yield credible results for all sites on Lake Michigan (and potentially across the Great Lakes). Of particular importance is the key finding that concentrations of $SRP_{nearshore}$ remain below the adopted standard for all cases, indicating that none of the sites would be expected to experience nuisance conditions of *Cladophora* growth solely through offshore forcing.

The finding that, absent local sources, the Lake Michigan nearshore would not support nuisance growth solely through offshore forcing suggests that there is a margin available for use in supplementing offshore nutrient conditions to benefit the food web. To explore this concept, and in the spirit of Figure 6, we utilize a map of model-calculated $SRP_{nearshore}$ concentrations corresponding to sole source forcing by offshore reserves of SRP and PP. We then place Pre- and Post-Dreissenid $SRP_{nearshore}$ concentrations on that map a two dimensional plot based on concentrations of $SRP_{offshore}$ and $PP_{offshore}$ (Figure 8b). The outcome is twofold. First, we find that $SRP_{nearshore}$ levels remained at or below the adopted threshold for nuisance *Cladophora* growth in both the Pre- and Post-Dreissenid periods. Second, the difference in $SRP_{nearshore}$ between the Pre- (2.10 mgP·m^{-3}) and Post- (1.05 mgP·m^{-3}) Dreissenid periods, ~1 mgP·m^{-3}) may reflect the change in tropic state engendering food web disruption and thus the margin available to supplement offshore phosphorus reserves with engendering nuisance *Cladophora* growth in the nearshore.

Table 2. Coefficients and inputs used to calculate the value of α for four selected regions on Lake Michigan

Site on Lake Michigan	H (m)	τ (days)	B contemporary ($mgAFDW\cdot m^{-2}$)	α contemporary (dimensionless)	B no local P sources ($mgAFDW\cdot m^{-2}$)	α no local P sources (dimensionless)
Good Harbor Bay	10	4.47	15266 Dayton et al., 2014; LimnoTech, 2020; Przybyla-Kelly et al., 2020	3.24	10069	2.13
Milwaukee, WI nearshore region	13.03	5.44	98560 Bootsma et al., 2012	19.55	10069	2.00
Big Bay De Noc	7.63	15.3	4510 Nalepa et al., 2014	4.29	10069	9.59
Southeast nearshore region	12.29	7.48	10431 Nalepa et al., 2014	3.01	10069	2.91

Research/Management Implications

The research results presented here have sought to address questions relating to the efficacy and consequences of implementing a higher level of phosphorus removal for point source discharges. In the management implications, we return to our initial point. Offshore levels of SRP and PP mediate rates of *Cladophora* growth and biomass accrual in the absence of local sources. And, while colonization of solid substrate by *Cladophora* is almost ubiquitous across the nearshore waters of Lakes Michigan, Huron, and Ontario, the occurrence of nuisance conditions is not. This observation and the results of our offshore forcing analysis in Lake Michigan resonate with the conclusion of Higgins et al. (2012) that, in Lake Ontario, there was little evidence that P from metabolic waste products of dreissenid mussels was sufficient to produce severe *Cladophora* blooms in the absence of localized P enrichment. The association of severe blooms of the alga with local P sources has been demonstrated for Lake Michigan (e.g., Bravo et al., 2019) and evidenced in the regional effect of local P sources, with higher SRP and PP concentrations along the west shore of the lake than along the east shore (data of Yurista et al., 2015); a result ascribed to differences in landscape activity. We thus support the recommendation made by

Higgins et al. (2012) that effective management of *Cladophora* blooms should occur through management of P loading at local scales while ensuring lake wide P concentrations do not increase.

Potential Applications, Benefits and Impacts

In conclusion, we have used a biophysical model and an adopted criterion for nearshore SRP to support identification of combinations of SRP and PP in offshore waters that would meet the objective of the nearshore endmember, i.e., elimination of nuisance growth of *Cladophora*. We have also provided a first cut estimate for an allowable level of SRP and PP offshore which could serve in achieving the offshore endmember objective (a healthy fishery) without sacrificing the nearshore endmember objective (nuisance algae growth). While the Dual Challenge may seem to represent an insurmountable obstacle, we have taken the first step by establishing the nearshore endmember. Future work with phosphorus-mussel-food web dynamics will necessarily focus on the offshore endmember. It will then be necessary to perform engineering analysis to identify discharge strategies, in time and place, for meeting the final endmember concentrations.

Section C. Outputs

Journal Publications:

- Zhou, X., Auer, M. T., **Xue*, P**. (2021), "Open Lake Phosphorus Forcing of *Cladophora* Growth: Modeling the Dual Challenge in Great Lakes Trophic State Management." *Water* (under review)
- Feng, X., Ma, G., Su, S., Huang, C., Boswell, M., **Xue, P.** (2020), "A multi-layer perceptron approach for accelerated wave forecasting in Lake Michigan", *Ocean Engineering, 211, 107526*
- Zhou, X., Ma, G. Auer, M. T., **Xue*, P**. (2021), "Impact of Turbulent Mixing on the Disruption of SRP Concentration Bottom Boundary Layer in the Context of Nuisance Algae Growth*", In Prep.*

Presentations:

- *<u>Zhou, X</u>., **Xue, P**., Auer, M. T. Offshore P-forcing of Cladophora growth in the Lake Michigan nearshore: a 1D modeling approach (2020). International Association for Great Lakes Research (IAGLR), June 9–11, 2020 (poster).
- **Zhou, X.,** (2019). "*Cladophora*, mussels and the nearshore phosphorus shunt in Lake Michigan," Atmospheric Program, Michigan Technological University, Houghton, MI. Apr 06, 2019 (oral).
- **Zhou, X.,** (2019). "*Cladophora*-mussels-phosphorus dynamics in Lake Michigan," Department of Civil, Environmental, and Geospatial Engineering, Michigan Technological University, Houghton, MI. Dec 09, 2019 (oral).
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Graduate students supported by this grant

- Xing Zhou, PhD student (2017-present), Department of Civil, Environmental, and

Geospatial Engineering, (SG Supported PhD Grad Student)

- Miraj Kayastha, MS (2019-2021), Department of Civil, Environmental, and Geospatial Engineering, (hourly)
- Chenfu Huang, PhD (2014-2021), Department of Civil, Environmental, and Geospatial Engineering, (hourly)

Related Projects

- "Understanding and Forecasting Potential Recruitment of Lake Michigan Fishes" United States Geological Survey (USGS), period covered: 03/25/2021-3/24/2023. $416,000 (funded), led by *USGS Great Lakes Science Center:* Cooperator/Partner(s): Purdue University; Michigan Tech; NOAA/GLERL;

- "Addressing the Dual Challenge in Lake Huron: Balancing Phosphorus and Primary Production in Nearshore and Offshore Waters", Michigan Sea Grant, Period cover: 02/01/2022-01/31/2024; $200,000 (pending), led by Michigan Tech, Cooperator/Partner(s): NOAA/GLERL, University of Michigan/CIGLR.

Student Awards

- Zhou X.: Great Lakes Research Center Student Research Grant, Michigan Technological University (2020)
- Kayastha M.: Great Lakes Research Center Student Research Grant, Michigan Technological University (2020)
- Huang C.: Graduate Student Government Grant, Michigan Technological University (2019)

Section D. Data Management Plan Form: Completion Phase (attached PDF form)

Section E. References

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