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ASSESSING THE SPATIAL AND TEMPORAL VARIABILITY OF THE DETROIT
RIVER AND HARMFUL ALGAL BLOOMS IN WESTERN LAKE ERIE

By

Angela W. Yu

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Geology

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

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This thesis has been approved in partial fulfillment of the requirements for the Degree of
MASTER OF SCIENCE in Geology.

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Acknowledgements

This research was primarily funded through Michigan Sea Grant's Graduate Student Research Fellowship and Michigan Space Grant Graduate Fellowship, with additional research support through NSF/NIH grants. Additional support for conference participation was provided by the Department of Geological and Mining Engineering and Sciences, MTU Graduate Student Government, and the Great Lakes Research Center.

Many, many thanks to my advisor, Colleen Mouw, for your continual support, guidance, and advice. I am forever grateful for all the skills I have learned from you over the years. While this journey may have not resulted in the goal we originally set out for, I feel more prepared for the professional world than I did when we started. Thank you to John Gierke for your patience as I explained my research, navigated the paperwork, and letting me randomly pop/barge into your office. I cannot adequately put into words how grateful I am for your support and advice as I finished up this journey. Thank you to Tim Moore for your support, ideas, positive attitude, and development of the water types this research relied upon. Thank you to Gary Fahrenstiel and Tom Johengen who provided early research support. While the research shifted a bit, your contributions and advice were immensely valuable. Thank you to Audrey Ciochetto for the coding, statistical, and everything else support. I am much more confident working in a lab because of you. Thank you to the Department of Geological and Mining Engineering and Sciences, particularly Brittany Buschell, Carol Asiala, and Kelly McLean. I would be completely lost and not graduating without your behind the scenes support.

To all the friends I have made during my many years at Michigan Tech, thank you. Many of you have come into my life and have offered lots of support, kindness, and laughter. I would list you all, but it would extend past a page! Major props to MTU Counseling Services, Keweenaw Running Group, and coffee. Graduate school would have been even more crazy without these!

Brian, thank you for being my rock, my constant support, and my number one fan while successfully completing your own research. Without you I know that this journey would have been completely impossible. Thanks for taking care of the furry crew (Murphy, Lily, and Jane, who also deserve many thanks) when I got wrapped up in research. It has been a long, crazy adventure, but there is no one else in this world I would want to do it with or stand in a stream and get mauled by mosquitoes with.

Mom and Yvonne, thank you for being always supportive of my academic and professional endeavors, even if it means I only see you a couple of times a year. Dad, thank you for instilling in me from a young age to be proud in what I can accomplish. I hope that I continue to make you all proud. Mom, Dad, and Yvonne, I love you all.

It is hard to believe that this very, very long journey has come to an end. During my eight years at MTU, I have met, been guided, and received advice from many great people. I may have missed you here but know that I am forever grateful that I had a chance to cross paths with you.

List of Abbreviations

CDOM	Colored Dissolved Organic Matter
Chl- <i>a</i>	Chlorophyll- <i>a</i> Fluorescence
CI	Cyanobacteria Index
DO	Dissolved Oxygen
DR	Detroit River
GLCFS	Great Lakes Coastal Forecasting System
HAB	Harmful Algal Bloom
LOBO	Land/Ocean Biological Observation (buoy)
NOAA	National Oceanic and Atmospheric Administration
OWT	Optical Water Type
PC	Principal Component
PCA	Principal Component Analysis
PO ₄	Phosphate
WLE	Western Lake Erie

Abstract

Despite efforts to reduce the occurrence of harmful algal blooms (HABs) in western Lake Erie, blooms recur annually due to agricultural runoff, storms with high winds and heavy rains, and weak lake circulation patterns. The influence from river inputs on the spatial and temporal characteristics of HABs remains relatively unknown. The Detroit River, which contributes about 80% of the basin's total inflow can have a large influence on the spatial and temporal distribution of the bloom. To understand this, optically classified imagery, *in situ* water measurements, and meteorological and river discharge observations were compiled and synthesized to examine the spatiotemporal variability of the Detroit River, HABs, and their interaction. Results indicate the presence of a defined Detroit River plume, which varies in size depending on wind and water current conditions within the lake. While high discharge of the river has an impact on the entire basin, strong winds in the spring, fall, and during summer pushes the Detroit River further south into the basin. This increases the spatiotemporal interaction between the Detroit River and HAB by limiting northerly bloom extent and diluting bloom water conditions. These results reveal the importance of Detroit River impact on blooms. Here, I present a greater understanding of the Detroit River and its role in the lake aiding the ability to improve predictions of bloom spatial variability.

1 Introduction

Harmful algal blooms (HABs) in the Lake Erie western basin are a yearly occurrence despite efforts to reduce their summer arrival. Lake Erie HABs are dominated by several species of *Microcystis* (Bridgeman et al., 2012; Chaffin et al., 2013), which are cyanobacteria capable of producing microcystin, a toxin harmful to humans and wildlife (Falconer, 2005). Blooms also have a negative socioeconomic impact on Lake Erie's coastal communities, affecting drinking water, recreation, and tourism on the Great Lake (Wynne and Stumpf, 2015).

Western Lake Erie is considered prime habitat for bloom development due to its shallow waters and continual nutrient loading from surrounding agriculturally-impacted rivers (Kane et al., 2014). High wind speeds can mix the lake, resuspending into the water column sediments and nutrients, in particular phosphorus, and dormant cyanobacteria cells, further enabling the proliferation of blooms (Wynne et al., 2011). HABs are primarily driven by weak lake wide circulation patterns, which prolong bloom presence, and large storm events with high winds and heavy rainfall that bring agricultural fertilizer runoff into the lake from the Maumee River (Michalak et al., 2013; Millie et al., 2009; Stumpf et al., 2012). Intense spring rainfall in the Maumee River watershed increases phosphorus loading into the lake (IJC, 2014; Michalak et al., 2013), resulting in blooms of higher intensity and greater spatial extent during the summer growing season (Bertani et al., 2016; Bridgeman et al., 2012; Stumpf et al., 2012). The land use in the Maumee River watershed is approximately 75% agricultural (Moorhead et al., 2008) and contributes the majority of the phosphorus load into western Lake Erie (Kane et al., 2014).

While the Maumee River is the primary nutrient driver behind the recurring HABs in western Lake Erie, the Detroit River has a significant influence on Lake Erie's hydrodynamics and causes the lake to predominantly flow in a northwest to southwest direction (Beletsky et al., 1999; Millie et al., 2009; Bolsenga and Herdendorf, 1993). Additionally, the river is the main drainage route for the upper Great Lakes. The Detroit River may also have a greater impact on bloom duration and distribution in western Lake Erie due to dominance of lake circulation. HABs do not occur at or near the Detroit River

mouth since nutrient inputs from the Detroit River are significantly lower than that of the Maumee River (Steffen et al., 2014) and thus is not considered the primary driver of HABs (Colborne et al., 2019). In addition to low nutrient concentrations, the Detroit River discharge (average of $5300 \text{ m}^3 \text{ sec}^{-1}$) is significantly greater than the Maumee River discharge (average of $150 \text{ m}^3 \text{ sec}^{-1}$) (Bolsenga and Herdendorf, 1993). The higher river flow prevents blooms from occurring near the Detroit River mouth (Millie et al., 2009) due to constant water movement and mixing. HAB scum is rarely detected in the northern portion of the basin, particularly near the Detroit River mouth (Sayers et al., 2019). The river discharge instead creates an ecotone (Millie et al., 2009), resulting in a north to south gradient of change in turbidity and algal biomass (Binding et al., 2012). Turbidity and algal biomass are lowest nearest the Detroit River mouth and increases in concentration the further away from the river.

High discharge can also influence bloom extent and severity. Since the Detroit River is the main inflow into western Lake Erie, the basin becomes mostly comprised of waters from the Detroit River (Larson et al., 2013). Wind interactions with the Detroit River further impact HABs by altering the hydrography of the basin. Persistent periods of northerly winds increases mixing between the Detroit and Maumee River plumes, which dilutes the nutrient rich Maumee River waters and decreases bloom severity (Michalak et al., 2013; Millie et al., 2009). When the river plumes do not mix, more severe blooms can occur (Michalak et al., 2013) as dilution is lessened (Herdendorf, 1987).

In situ sampling through real-time monitoring buoys and field measurements monitor bloom and river water distribution and biological characteristics. Water quality monitoring measurements are used to quantify and identify HABs within the water column (Bridgeman et al., 2013) as well as improve or validate observations made via satellites. However, buoys are spatially limited, and their locations are fixed throughout the season. Physical forcing, such as river input and wind, can change buoy readings over a short period of time. Buoy measurements alone make it difficult to differentiate if bloom phase changes are due to physical (mixing and advection) or physiological (algal growth or decline) processes.

Remotely sensed satellite imagery is another method used to measure the spatiotemporal characteristics of HABs in western Lake Erie, as it offers a widescale view of the basin. Blooms are detected from satellite imagery, using algorithms that can estimate bloom presence, size, and intensity (Sayers et al., 2016; Wynne et al., 2013). However, satellite imagery datasets are not without limitations. Satellite imagery availability is limited to cloud free days (Bullerjahn et al., 2016; Zheng and DiGiacomo, 2017) and bloom detection can be difficult due to limitations in sensor capability and basin mixing (Wynne et al., 2013). Bloom and water mass detection via satellite imagery in Lake Erie can be difficult due to challenges in properly attributing spectral signatures to living and non-living particulate and dissolved matter. Lake Erie is an optically complex system that is dominated by phytoplankton, non-algal particles, and colored dissolved organic material (CDOM) (Moore et al., 2017). Current algorithms that identify bloom presence (Binding et al., 2013; Shuchman et al., 2013; Stumpf et al., 2012) focus on HABs and do not characterize all water types within Lake Erie. Thus, these algorithms are not designed to identify and delineate surface waters influenced by the Detroit River.

The overall spatial pattern and frequency of blooms in western Lake Erie has been studied (Wynne and Stumpf, 2015), but the direct impact of the Detroit River on bloom temporal and spatial distribution is unknown. While it is known that the Detroit River is the main hydrodynamic driver of the western basin (Beletsky et al., 2013) and can influence bloom severity (Michalak et al., 2013), though the river influence on HAB variability has typically been inferred. There is also a lack of continuous monitoring of Detroit River water quality characteristics (IJC, 2014), limiting knowledge about the river plume itself and how it influences HAB conditions. Due to a distinct optical difference between water from the river and water present within the lake, remote sensing can help identify the Detroit River in the basin (Moore et al., 2017, 2014). However, the physical and environmental influence of the Detroit River cannot be deciphered from satellite imagery alone. Given that the Detroit River primarily controls the hydrodynamic characteristics of the basin, it is hypothesized to impart a significant influence on the spatial and temporal distribution of HABs in western Lake Erie.

The aim of this study is to characterize how the Detroit River influences HAB presence, distribution, and duration across the western basin of Lake Erie. This research integrates in situ measurements, optically classified satellite imagery, meteorological observations, and river discharge measurements to determine the hydrodynamic influence from the Detroit River on bloom dynamics in western Lake Erie. Through the use of these data streams, this study addresses the following objectives: 1) utilize previously identified water masses within western Lake Erie to characterize spatial and temporal variability of the Detroit River plume and HABs over the course of a bloom growing season; 2) determine the primary physical and environmental drivers of the plume and HAB, and; 3) characterize the spatiotemporal influence that the Detroit River has on the distribution of HABs in western Lake Erie.

2 Methods

2.1 Study Site

The recurrent HAB problem in Western Lake Erie is exacerbated by the geophysical characteristics of the basin (Steffen et al., 2014). The average depth of entire lake is 19-meters, while the western basin has an average depth of 7-meters (Paul et al., 1982). The shallow depths allow the lake waters to warm quickly and makes it highly susceptible to sediment resuspension due to winds. Seasonally, predominant wind direction changes across the basin, which can influence the amount of mixing within the basin. Northeastern winds are mainly in the spring, whereas southwestern winds dominate in the fall (Niu et al., 2018). Winds during the summer bloom months are weak and vary in direction, allowing for bloom proliferation.

The two main rivers that drain into western Lake Erie are the Detroit and Maumee Rivers and account for approximately 90% of the total basin inflow. The Detroit River contributes about 80% of the total inflow into Lake Erie, while the Maumee River accounts for about 10% of the inflow (Bolsenga and Herdendorf, 1993; Millie et al., 2009). While its overall stream discharge rate is low compared to the Detroit River, the Maumee River contributes almost half of the nutrient loading into Lake Erie (IJC, 2014). The Detroit River has a greater influence on Lake Erie hydrodynamic characteristics and significantly impacts basin circulation (Millie et al., 2009; Herdendorf, 1987). When there are periods of strong or persistent north and northeastern winds, the Detroit River flows may reach the southwestern areas of the western Lake Erie basin (Millie et al. 2009). This causes the basin to be dominated by Detroit River waters as the Maumee River water flows “pile up” near the mouth of the river (Herdendorf, 1987).

Figure 2.1. Map of study area: western Lake Erie and location of buoy (LOBO).

2.2 Optically Classified Satellite Imagery

Satellite imagery classified into different optical water types was used to capture the characteristics of different kinds of waters, particularly the Detroit River, within western Lake Erie basin and their influence on HAB distribution. Two types of satellite imagery were used for this analysis; the first was the optical water type (OWT) classification developed by Moore et al. (2014). OWT classification employs spectral remote sensing reflectance ($R_{rs}(\lambda)$) to differentiate waters based upon optical signatures or varying contributions of in water constituents, such as phytoplankton, CDOM, and non-algal particulate matter in the water. Based on OWT classification, the Detroit River waters were discretely identified from satellite imagery, serving as a prime dataset for distinguishing spatial distributions of the Detroit River. MODIS imagery was processed as outlined in Moore et al. (2014) to identify different optical water types (OWTs) within the western Lake Erie.

Moore et al. (2014) identified seven different OWTs, classified from satellite spectral $R_{rs}(\lambda)$. Each OWT is characterized by the change in chlorophyll-*a* (chl-*a*) concentration and amount of absorption and backscattering. Backscattering is an indicator of the presence of particulate matter. OWTs 1 through 5 have an increasing chl-*a* concentration, whereas OWTs 6 and 7 have a lower mean chl-*a* than OWT 5. OWTs 4 through 7 have greater backscattering than OWTs 1 through 3, indicating a higher presence of living (e.g., phytoplankton) and non-living (e.g., sediments) particulate matter (Moore et al., 2014). The differentiation of water types, which in Lake Erie are dominated by chl-*a* and CDOM levels, improved river identification and how it acted upon the bloom in the lake's eutrophic, turbid waters

Detroit River persistence in the western basin was calculated from OWTs that were most closely associated with the Detroit River plume. OWTs that have the highest occurring frequency near the river mouth and match the field observed spectral signatures of the Detroit River were considered to be associated with the river. While a particular OWT may be associated with the river, this does not mean that the OWT cannot also be associated with a different water source. Persistence was calculated by determining the frequency of the dominant OWT at a pixel each time that particular pixel was classified. The dominant OWT was then used to delineate the approximate location of the surface river plume. Manual filtering was also used to isolate plume to WLE basin and to prevent potential overlap with bloom characteristics. Estimated Detroit River surface area was calculated by counting the number of pixels in each river delineation.

In addition to OWT classification, the cyanobacteria index (CI) was used to identify the spatial and temporal variability of HABs. Developed by NOAA's National Center for Coastal Ocean Science, it estimates size and presence of bloom using satellite imagery. Using the following equations, historical CI values from 2002-2011 were calculated from MERIS imagery (equations 1 and 2) and from 2012-2014 calculated from MODIS imagery (equations 3 and 4; Wynne et al., 2013; Wynne and Stumpf, 2015). The equations vary between sensors due to the differing spectral capability.

$$S_{2d}(681) = R(681) - R(665) - \{R(709) - R(665)\} \frac{(681 - 665)}{(709 - 665)} \quad (1)$$

$$CI_{\text{MERIS}} = -S_{2d}(681) \quad (2)$$

$$S_{2d}(678) = \rho_s(678) - \rho_s(667) - \{\rho_s(748) - \rho_s(667)\} \frac{(678 - 667)}{(709 - 667)} \quad (3)$$

$$CI_{\text{MODIS}} = -S_{2d}(678) \times 1.3 \quad (4)$$

The delineation of the HAB boundary was also based on 10-day composite imagery from Wynne and Stumpf (2015). Imagery was averaged to this time period to reduce potential cloud coverage and to capture periods of less turbid waters (Wynne and Stumpf, 2015). There were 15, 10-day composites for each year, from 2002-2014. Composites were resampled and re-projected to 500-meter resolution, the same as the OWT imagery, using NASA's image processing software, SeaDAS. Following convention established in previous literature (Stumpf et al., 2016; Stumpf et al., 2012; Wynne et al., 2013), severe bloom presence was identified when $CI > 0.001$, which is equivalent to a cell biomass of 10^{-5} cells mL^{-1} . Pixels with $CI > 0.001$ were flagged then used to delineate severe bloom boundaries throughout the growing season. This was also done with pixels with any CI value greater than 0. Bloom surface area was calculated for both instances by counting the number of pixels within the delineated boundaries. Surface area calculations were then compared to existing areal reports from Stumpf et al. (2012) and Bertani et al. (2017). Sandusky Bay was masked from the analysis due to HAB persistence within the bay throughout the season and its lack of spatial interaction with the western basin. HAB persistence was considered as all years (2002-2014) with measurable CI values. This persistence calculation was used when comparing to Detroit River persistence to find boundary changes and to help identify which water masses within which the *in-situ* datasets were measured in.

2.3 Environmental Data

Spring phosphorus loading from the Maumee River has a significant influence on the size and severity of HABs in western Lake Erie (Bertani et al., 2017; Obenour et al., 2014; Stumpf et al., 2012), but this does not influence the spatial and temporal variability of the Detroit River and was not included as it was not in the scope of this research. To identify and determine which environmental variables have the greatest impact on the Detroit River plume and bloom and how these characteristics seasonally vary, a variety of meteorological, chemical, and physical parameters were considered (Table 2.1).

Table 2.1. Data sources of environmental parameters and descriptions.

Data Source	Data Collected	Dates Included in Analysis
Land/Ocean Biogeochemical Observatory (LOBO) buoy	Phycocyanin, chlorophyll-a fluorescence, CDOM, PO ₄ , temperature, conductivity, turbidity, oxygen	June 11–October 9, 2013 June 3–October 9, 2014 (Hourly Sampling)
Toledo Harbor Light #2 Meteorological Station (www.glerl.noaa.gov/metdata//tol2/)	Wind speed, direction, and gust; air temperature	2009-2014 (5-minute intervals)
USGS Streamflow Data (www.usgs.gov/water)	Discharge, stream velocity (Detroit and Maumee Rivers)	2009- 2014 (Hourly Sampling)
Satellite Remote Sensing Imagery (Moore et al., 2014; Wynne and Stumpf, 2015)	Optically Classified MODIS imagery and Cyanobacteria Index imagery ¹	2002- 2014 (10-day composite)
Great Lakes Coastal Forecasting (www.glerl.noaa.gov/res/glcfs/)	Wind speed (northerly/westerly), advection, lake surface temperature, chlorophyll concentration (nowcast data)	2009- 2014 (6-hour intervals)

Real time water quality data measured by a Land/Ocean Biogeochemical Observatory (LOBO) buoy was used to monitor the temporal and spatial variability of bloom and non-bloom waters. Continuous observations of chl-*a*, phycocyanin, and CDOM fluorescence, oxygen, phosphate (PO₄), temperature, turbidity, and conductivity were recorded in the months of June through October in 2013 and 2014. The buoy was located near the center of the western basin (41.8255 N, 83.1936 W), enabling it to capture water characteristics from the river, bloom, and the lake itself. The LOBO buoy sampled at the surface and captured surface water characteristics.

Due to the significant hydrodynamic impact from the Detroit River (Millie et al. 2009; Beletsky et al. 2013) and the significance of the nutrient loading from the Maumee River (Wynne and Stumpf, 2015), only these two rivers were only considered in the analysis. Stream discharge data for the Detroit (USGS 04165710 Detroit River at Fort Wayne at Detroit, MI) and Maumee Rivers (USGS 04193500 Maumee River at Waterville, OH) were averaged into daily and 10-day averages (USGS, www.usgs.gov/water). Historical data measured by the USGS for the Detroit River began in October 2008 and because of this start date, environmental variable analysis begins in the summer of 2009.

Gridded wind data were acquired from the Great Lakes Coastal Forecasting System (GLCFS) nowcast, which is based on observed meteorological conditions occurring at the lake (www.glerl.noaa.gov/res/glcfs/). Wind information from this dataset included wind speed (m sec⁻¹) and northerly and westerly components of wind velocity. Average wind direction and wind stress were calculated from the gridded datasets. Wind stress (τ), measured in Pascals (Pa), was calculated using the method reported in Wynne et al. (2010):

$$\tau = \rho \times C_D \times w^2 \quad (5)$$

where ρ is air density (1.25 kg m⁻³) and C_D is the drag coefficient. C_D was determined by (Hsu, 1972):

$$C_D = 0.001 \times (0.69 + 0.081 \times w) \quad (6)$$

where w is mean hourly wind speed. Wind data were averaged to daily and 10-day periods, matching CI composite dates. Due to its proximity to the LOBO, wind speed

measurements were utilized from Toledo Light No. 2 OH (Station THLO1, at 41.826N 83.194W) to compare calculations. Gridded surface advection and lake surface temperature from the GLCFS were also included in the analysis. Both were averaged to daily and 10-day periods to match the same time period as the rest of the gridded data products.

2.4 Data Analysis

For calculation and quantitative comparison purposes, all data were temporally averaged to 10-day time periods, which created 15 timesteps for each year from June 1-October 31. OWT imagery was isolated by these dates and manually filtered to ensure the averaged scenes were cloud-free. River delineations were also created on the 10-day OWT averages. In addition to the 10-day analysis, finer time scales were used to understand physical changes in the basin over the course of the same time period. OWT and CI imagery were used to determine if the LOBO was sampling in the Detroit River, bloom, or the basin itself.

2.4.1 Bloom Sub-seasons

Time lagged correlation was used to determine the timing of biological response following a high wind event. Algal growth cell growth is biologically lagged following a large wind or storm event that creates basin mixing (Wynne et al., 2010). Time lags were calculated for variables that showed a delayed response, such as chl-*a* fluorescence and wind stress, and were then compared to rate of change calculations for water temperature and chl-*a*, as measured by the LOBO.

The summer bloom season was then divided into five time periods based upon temperature and chl-*a* fluorescence as captured by the LOBO and outlined in the literature (Bridgeman et al., 2013; Ho and Michalak, 2015; Stumpf et al., 2012). The time periods, later referred to as bloom sub-seasons, were June, July 1-20, July 22-August, September, and October. For this analysis, the time periods were the same for each year analyzed.

Since HABs are unable to proliferate early in the season due to cool late spring temperatures preventing cell growth, June was considered the pre-bloom period. HAB initiation generally is observed between July 1-20, depending partly on water temperature. Warm water can promote bloom development. The latter part of July through August is considered peak bloom season. HABs have a higher persistence during this time (Wynne and Stumpf, 2015) and dominate the basin. While HABs can still occur in September, bloom reoccurrence is affected by temperature and wind. Blooms that do occur in September are considered late blooms. Bloom occurrence may also occur in October, but HABs become severely limited by cooling temperatures although some have been observed this late. Blooms have occurred during those months due to extended summer temperatures into the fall season. The bloom sub-seasons were used to capture temporal variations in how the Detroit River influences the WLE basin and how it eventually interacts with the HAB.

2.4.2 Principal Components Analysis

Pearson's correlation and linear regression models were used to determine one-to-one relationships amongst buoy and field collected water quality variables. The response variable was either bloom or Detroit River surface areas, phycocyanin, or chl-*a* fluorescence. However, some variables were co-varied, requiring statistical analysis methods that allow for collinearity. Principal components analysis (PCA) was used to address multicollinearity issues present within the dataset. This analysis is useful for large datasets with many variables since it reduces the dimension, or size, of the data while preserving trends and patterns (James et al., 2013; Lever et al., 2017).

Prior to the PCA, all data was standardized. To ensure that data was not intra-correlated, sample randomness was tested 100 times. For both the buoy and gridded datasets, PCA was used to identify the in-water and other environmental variables that are most associated with differing water masses in WLE. The analysis was utilized to help distinguish which physical drivers, such as wind and river discharge, were most important in impacting the variability in the Detroit River and bloom, respectively.

Additionally, PCA was used to understand the seasonal variations captured by the in-water measurements.

The PCA transforms the dataset into a new dataset using new orthogonal, uncorrelated variables called principal components (PC). The generated number of PCs are based on the number of variables that are originally in the dataset. Each PC, which is a linear function of the original variables, explains a percentage of the variance of the original dataset and they are ordered from largest variance (PC1) to next largest (PC2), and so on (Olsen et al., 2012). Typically, if the original variables are highly correlated with each other, the first several PCs will account for a large percentage of the total variance and can be used to describe variations in water quality parameters as sampled by the LOBO and field measurements.

The variable loadings help to determine which variables contribute or describe the variability that each PC explains. The loadings represent the importance that the original variable has on each particular PC. It characterizes the correlation between the PC and the original variable. It is constrained between +1 and -1, indicating that if a PC contains a high loading for a particular variable, it is important in explaining an environmental process (Olsen et al., 2012). If the loading is low, it is not as important in influencing the variability of the dataset. The PCA also produces variable scores, which can be thought of as new values that represent the original variables that can be analyzed or interpreted to show spatial patterns in water quality parameters (Olsen et al., 2012). A significant loading score is determined by calculating the sum of all squares of loadings for each component, which should equal one when all variables contribute equally to the variance explained by a particular component (Holland, 2019). The significant loading score varies based upon the number of original variables being analyzed in the PCA. For the LOBO data, which had 14 variables in the analysis, loading scores greater than 0.277 were considered significant. For the gridded datasets, which had seven variables in the analysis, loading scores greater than 0.377 were considered significant. If the loading score for a particular variable is larger than the sum of all squares of all loadings combined, then it is considered a significant.

3 Results and Discussion

3.1 Spatial and Temporal Variability of the Detroit River

In western Lake Erie, all OWTs except 2 and 5 were present. Based upon persistence calculations from 2002-2014 (Figure 3.1), OWTs 1 and 6 are associated with the Detroit River plume due to their higher occurrence (>75% persistence) near the mouth of the river (Figure 3.2). Persistence provides a method to differentiate water masses and a bloom within the basin over time. OWTs 2 and 5 were not found in Lake Erie and were not included. Coarser temporal scales, such as yearly and monthly, also show the same persistence from OWTs 1 and 6 (not shown). The Detroit River drains the upper Great Lakes. Lakes Superior, Michigan, and Huron have lower absorption and scattering variability compared to Lake Erie (Binding et al., 2007; Moore et al., 2017; Peng and Effler, 2010), which results in clearer waters in Detroit River compared to waters in the western Lake Erie basin. OWT 1 water type has the lowest chl-*a* fluorescence and particulate matter compared to other OWTs, characteristics that are similar to the Detroit River.

Figure 3.1. OWT persistence for the western Lake Erie basin, 2002-2014.

Figure 3.2. Detroit River persistence in western Lake Erie, 2002-2014.

OWT 1 is more dominant in the spring (Figure 3.3a) within the Detroit River plume, while OWT 6 is more prevalent during the fall (Figure 3.3b). OWT 6 is related to basin mixing or increased turbidity, indicating that there is a greater amount of particulate matter (e.g. sediments) within the water column. WLE is typically more turbid in the fall due to waves caused by winds and river discharge (Niu et al., 2018), which is likely the cause of a shift in main water type.

Figure 3.3. Example of Detroit River seasonality. OWT changed from OWT 1 in June (A) and a more predominant presence of OWT 6 in October (B). The red line delineates the outline of the Detroit River plume.

Figure 3.4. Detroit River spatial pattern by percent frequency (by pixel). Analysis was completed from 2002-2014 for each 10-day period.

The Detroit River, or OWT 1 and 6, had the greatest average yearly persistence at or near the mouth of the river (northwestern section of the basin; Figure 3.4), expanding east towards the central basin and remaining near the Canadian shoreline. Although the plume predominantly occupied this space, it did expand beyond this area and cover the entire western basin. This occurred most frequently during the spring and early fall. The river plume spatially varied throughout the season due to discharge, surface advection, and wind forcing. The spatial variation was most evident through the changes in surface area detected by the OWTs, as depicted in Figure 3.4. The Detroit River has the greatest frequency in the northwest corner of the WLE basin, persisting directly at the river mouth more than 80% of the time. High frequencies continued at this location most of the season. Throughout June, identified as pre-peak bloom season, the Detroit River plume was the dominant water mass throughout the WLE basin. As the summer progresses, the river plume surface area decreased and stayed near the river mouth and Ontario shoreline. It became less prevalent in the basin. This was most evident

throughout August. Beginning in September, the river plume began to increase in size and influence, while in October it again became the dominant water mass of WLE, similar to early season characteristics.

Seasonal changes in the Detroit River discharge had a minimal impact on the river plume's surface area throughout the summer. From 2009-2014, Detroit River discharge varied an average of 3% over the entire study period, but it also fluctuated from year to year. In 2011 and 2014 there was a 10% variation, whereas in 2009, 2010, 2012, and 2013, discharge varied only 3 to 4% seasonally from average (Figure 3.5). When comparing river discharge to average river plume surface area, early and late season increases in discharge coincided with larger plume areas (Figure 3.6).

Figure 3.5. Detroit River discharge by year during bloom growing season, June through October 2009-2014. Average discharge for the entire time period is in red.

Large early bloom season (June) surface plume areas were likely residual spring discharge combined with strong northerly winds, which dominate in the spring (Niu et al., 2018). Late season (October) surface areas were influenced by an increase in fall storms and runoff. While the Detroit River discharge has limited variability, smaller plume areas were detected in the mid-summer months of July through August. River plume surface area likely decreased due to southerly winds pushing surface scum north, causing the plume to also move north along the shoreline of Canada. This influence was more prevalent in larger bloom years (2011 and 2013) and not in smaller bloom years, such as 2012. This influence is discussed below.

Figure 3.6. Average Detroit River discharge by composite date compared to Detroit River plume surface area, with regression from 2009 to 2014. Labels indicates the date 4 days after the start of a 10-day period (e.g., 09/03 refers to Aug. 30 through Sept. 8).

3.2 Spatial and Temporal Variability of HABs

HABs also experienced seasonal variations dependent on seasonal warming, surface advection, prevailing winds, and river discharge. The spatiotemporal areal coverage of a bloom (Figure 3.7) in the WLE basin is opposite of the Detroit River spatial variability (Figure 3.5). Throughout the summer bloom season, HABs usually did not occupy in the northwestern portion of the basin, near the mouth of the Detroit River and typically occupied the southwestern portion of the basin in Maumee Bay. This location is conducive to HAB development due to shallow lake depths, high nutrient availability, and shelter from winds (Sayers et al., 2019). Average peak HAB surface area from 2002 to 2014 was observed from August 30 through September 8 where it reached 3,083 km² and occupied approximately 95% of the basin. From that date on, HAB surface area declined due to a decrease in temperature and increase in wind events, conditions not suitable for HAB proliferation.

Figure 3.7. HAB spatial pattern by percent frequency (by pixel). Based on CI composites created by Wynne and Stumpf (2015). Analysis was completed from 2002-2014 for each 10-day period when there was any detectable CI.

HAB delineations created from CI imagery were overlaid on OWT images to determine which water types were most associated with the bloom. Based on frequency calculations similar to what was done on for the Detroit River, OWTs 4, 6, and 7 were found within the bloom boundaries near the mouth of the Maumee River (Figure 3.8). These water types indicate that there is high chl-*a* concentration and particulate matter (sediments), or CDOM. OWT 6 and 7 do appear to persist within Maumee Bay and is most likely due to increased concentrations of suspended sediments from either basin mixing or inputs from the Maumee River. OWT 6 was also matched to the Detroit River as well and this is discussed in a following section.

Figure 3.8. Example OWT and HAB delineation. The black line designates the bloom location. This composite covers a 10-day period between August 20-29, 2014.

While spring (March through June) Maumee River discharge drives bloom intensity (Stumpf et al., 2012), the Maumee River seasonal discharge also plays a role in bloom surface area from 2009-2014 (Figure 3.9). Similar to the Detroit River, the Maumee River experienced seasonal changes in discharge due to spring melt and heavy rainfall. Higher spring discharge and the lack of blooms in June, or early in the bloom growing season, resulted in smaller HAB surface areas as shown in Figure 3.10. When blooms were present in the basin (August), Maumee River discharge was lower than average ($34 \text{ m}^3 \text{ sec}^{-1}$ versus $150 \text{ m}^3 \text{ sec}^{-1}$). During peak bloom surface coverage, the average Maumee River discharge was approximately $12 \text{ m}^3 \text{ sec}^{-1}$. Summer (July through mid-September) flows, on average, tended to be lower than in the fall and spring. Low discharge in combination with overall calm summer conditions in the basin allowed the bloom to remain at the surface, resulting in surface scum formation.

Figure 3.9. Average Maumee River discharge by year during bloom growing season, June through October 2009-2014. Average discharge for the entire time period is in red.

Figure 3.10. Average Maumee River discharge by composite date compared to HAB surface area, with exponential regression from 2009 to 2014. Label indicates date 4 days after a 10-day period (09/03 refers to August 30 through September 9).

3.3 Spatiotemporal Detroit River and HAB Interactions

Detroit River discharge alone does not directly impact HAB severity or amount of cyanobacteria biomass in the lake (Michalak et al., 2013; Stumpf et al., 2016). In a comparison between river discharge and bloom severity, both linear and exponential

correlations showed a relatively weak relationship (linear $r^2 = 0.11$; exponential $r^2 = 0.41$). However, there may be some influence during times of weaker or less intense HABs. When the river plume regularly mixes with Maumee River discharge, the Detroit River dilutes nutrient rich Maumee waters (Michalak et al., 2013). Regardless of the impact on HAB severity, the Detroit River appeared to limit the northern extent of the bloom when comparing HAB composite imagery to river plume delineations from 2009 through 2014 (Figure 3.11). Previous HAB frequency maps have shown that blooms typically do not occur north of Monroe, Michigan due to the discharge of the Detroit River (Wynne and Stumpf, 2015).

The heat maps generated in this study delineated the areas where the river plume (Figure 3.11A) maintains its dominance during the six-year study period and confirmed that the river's dominance prevents blooms from occurring at the river mouth. While the surface area of the bloom can appear to stretch basin wide, the Detroit River has a well-defined boundary near the mouth of the river for approximately 70-75 composites (approximately 700 days). There were areas of overlap between the river and bloom, which may explain the association of OWT 6 to both. The delineations likely captured the turbidity gradient or mixing zone between the river and bloom. The turbidity gradient transitions from higher amounts of backscattering (bloom) to lower levels (Detroit River) (Moore et al., 2017) and also captured the resuspension of sediments that is occurring due to wind mixing (Moore et al., 2019). The OWT overlap also demonstrated that while a particular water type was associated with waters from a particular source, the OWT does not only identify either river or bloom influenced waters. Since each water type was defined by the optical properties of in water constituents and average optical conditions (Moore et al., 2014), mixing zones like the one identified in this study become associated with more than one water source.

Figure 3.11. Cumulative composite frequency heat maps of Detroit River (A) and total HAB (B) for 2009-2014. Warmer colors indicate higher frequency of occurrence. One composite is 10-days; color bar has a maximum of 80 composites or 800 days.

When comparing the bloom and river plume spatiotemporal characteristics during LOBO deployment periods in 2013 and 2014 (Figure 3.12), a clear boundary between the plume (to the north) and bloom (to the south) was maintained throughout the season, similar to the yearly (Figure 3.4/3.5) and composite analysis (Figure 3.10). The Detroit River again has a defined north-northeast plume within the WLE basin and acts as a barrier that prevents blooms from reaching the northern shores of WLE. Bloom surface scum or high chl-*a* concentration detection can occur near the mouth of the Detroit River, but only for up to four days (Sayers et al., 2019). While there are some instances where the bloom does move north (mid- to late July in 2013 and 2014), the Detroit River surface plume does eventually get pushed into the southern half of WLE (August through October). Because the Detroit River maintains its northern dominance, when combined with a strong northerly wind, it can cause bloom severity or biomass to increase in the southern portion of the basin (Michalak et al., 2013) due to waters “piling up” in this area.

The interactions between the Detroit River and HABs varied depending on timing within the bloom growing season and overall bloom spatial extent. In both years, bloom onset and detection did not occur until mid- to late July. The southernmost boundary of the river surface plume had more direct contact or actual interaction with the bloom in 2013 compared to 2014. This may have been due to the larger average Detroit River

plume surface area in 2013 (Table 3.1) throughout the season. The 2014 HAB was also considered part of what is referred to as a “down” bloom year, where the bloom had a smaller spatial surface extent than the previous year’s bloom (Sayers et al., 2019).

Table 3.1. Annual (May-October) average bloom and Maumee and Detroit Rivers indices for 2013 and 2014. Bloom surface area is calculated from the cyanobacteria index composite imagery (Wynne and Stumpf, 2015), where $CI > 0.001$. Detroit River surface area is calculated from OWT imagery where pixels are classified as OWT 1 and 6. Note that the total area of Western Lake Erie is 3284 km^2 (~12% of the lake) and total area of Lake Erie is $25,657 \text{ km}^2$ (Bolsenga and Herdendorf, 1993). Bloom severity index indicates the average bloom biomass during the year.

Year	Bloom Severity Index	Detroit River Discharge ($\text{m}^3 \text{ sec}^{-1}$)	Maumee River Discharge ($\text{m}^3 \text{ sec}^{-1}$)	Average Bloom Surface Area (km^2) (percent coverage)	Average Detroit River Surface Area (km^2) (percent coverage)
2013	8.5	4994	93	1070 (32.6%)	436 (13.3%)
2014	6.5	5566	71	1112 (33.9%)	347 (10.6%)

Figure 3.12. River (blue) and HAB (green) average spatial extent during the LOBO (red point) deployment in 2013 (top) and 2014 (bottom).

On occasion, a mixing area or barrier between the Detroit River and the HAB was evident from the OWT classification. The mixing area occurred more frequently in 2014 (Figure 3.12). This mixing zone acted like an optical gradient and indicates a shift from clearer (Detroit River) to more turbid waters (WLE) (Figure 3.12). Since the river “drains” the upper Great Lakes which are very clear, the Detroit River has a lower particulate load than the well-mixed waters of WLE in contact with the Maumee River. There is typically a band of water between the river plume (red) and HAB (black) associated with OWT 3. Particle scattering from phytoplankton defined this water type, which had low chl-*a* characteristics, and it was also predominately found in the central and eastern Lake Erie basins (Moore et al., 2014). When this water type was detected, both the bloom and Detroit River are present. The presence of this water type may indicate mixing between the river plume and bloom, with a decrease in phytoplankton or HAB biomass.

Figure 3.13. Detroit River (red) and HAB (black) delineations with OWT classification. While the Boundaries between these different masses may touch (A), it can also have a defined boundary or barrier between the two water masses (B). This barrier is most likely a mixing zone between the river and bloom.

3.4 Water Quality Characteristics of Detroit River and HABs

Due to its location within the WLE basin, the LOBO sampled within these different water masses throughout the bloom growing season. Using OWT and HAB imagery (Figure 3.12), field samples, and known environmental thresholds for blooms (Table 3.2), the LOBO data were categorized as Detroit River, bloom, or WLE basin waters. The classification of WLE, or unidentified, was designated when there were no corresponding satellite images, or when the buoy data were not assigned to either Detroit River or HAB waters. The unidentified classification designated potential mixing of water masses or when HAB water was mixed throughout the water column, diluting algal concentrations and causing classification to shift from bloom to uncertain.

Table 3.2. Environmental thresholds for bloom identification. (^A WHO 2004, ^B Millie et al. 2014, ^C Michalak et al. 2013, ^D Wynne et al. 2010, ^E Wynne and Stumpf, 2015)

Environmental Metric	Threshold
Chlorophyll-a Concentration	10- $\mu\text{g L}^{-1}$ ^A
Temperature (Optimal growth)	15°-27°C ^{B, C, D}
Wind Speed and Stress	<7.7 m sec ⁻¹ ^{D, E} or < 0.1 Pa ^{D, E}

In both 2013 and 2014, the LOBO sampled the Detroit River in June and late September, which are considered early and late bloom growing seasons, whereas it was in the bloom during bloom growing months in late July through October (Figure 3.14). During the peak bloom sub-season (July 22 through August), the LOBO never sampled within the Detroit River plume. Based on the delineation comparison depicted in Figure 3.12, the LOBO sampled for a greater amount of time in the mixing zone or barrier between the two water masses versus in the Detroit River or bloom.

The water chemistry characteristics measured by the LOBO varied depending on what water the buoy was surrounded by (average LOBO measured water characteristics listed in Section 7). Most notably, CDOM (measured in standardized units of Quinine Sulfate Dihydrate Equivalent, QSDE), chl-*a* fluorescence, and phycocyanin concentration varied the greatest between all three kinds of water. On average, the Detroit River had

lower CDOM ($7.27 \text{ QSDE} \pm 2.54$), chl-*a* ($2.24 \mu\text{g L}^{-1} \pm 1.86$), and phycocyanin ($0.66 \text{ ppb} \pm 1.44$), than during HAB sampling where all three characteristics were greater ($9.26 \text{ QSDE} \pm 3.50$; $4.16 \mu\text{g L}^{-1} \pm 3.10$; $6.59 \text{ ppb} \pm 6.54$). The differences in value is attributed to the fact that the Detroit River typically has lower particulate concentration than the rest of WLE (Moore et al., 2017) and usually has no detectable bloom indicators (Wynne and Stumpf, 2015). When the LOBO was not sampling in either the river or bloom, water characteristics varied for CDOM ($9.60 \text{ QSDE} \pm 3.64$), chl-*a* ($2.80 \mu\text{g L}^{-1} \pm 2.46$), and phycocyanin ($3.05 \text{ ppb} \pm 4.63$) compared to when it was sampling in WLE. The variability captured by the LOBO while sampling in WLE was most likely due to wind triggered resuspension of sediments and redistribution of the bloom (Moore et al., 2019). This can increase water turbidity (measured in Nephelometric Turbidity Units, NTU), which was captured by LOBO as WLE turbidity was slightly higher ($1.86 \text{ NTU} \pm 0.82$) than in the river ($1.66 \text{ NTU} \pm 1.14$) or HAB ($1.56 \text{ NTU} \pm 0.66$).

Figure 3.14. 2013 and 2014 LOBO time series with indication of what water the LOBO sampled in. Green point data is a field point sampled by GLERL at the LOBO. Green background indicates bloom and blue indicates Detroit River. White indicates LOBO was not sampling in either and considered WLE.

In a multivariate analysis of water quality parameters using LOBO and wind data, a PCA identified four PCs that explained 71.4% of the total variation (PC1: 27.3%; PC2: 20.6%; PC3: 13.0%; PC4: 10.5%). PC1 showed positive associations with CDOM, conductivity, water, and air temperatures and negative contributions with wind forcing variables. This is interpreted in the context of variable associations with PC 1: as wind forcing decreased, the water temperature increased along with CDOM and conductivity. PC1 implies that the LOBO captured changes in optical gradients and shifting water types in WLE; the water types were constantly moving and changing around the LOBO. Due to the location of the LOBO, it predominately occupied a transitional zone between the river plume and bloom. This zone indicates a shift in optical gradients and change in scattering properties that, in particular, the Detroit River has compared to the rest of the basin (Moore et al., 2017).

The remaining principal components (PC2, PC3, and PC4) were associated with other variables. PC2 showed positive associations between all wind characteristics, indicating that the LOBO measurements were impacted by strong wind events. PC3 indicated negative associations with chl-*a*, phycocyanin, and turbidity. PC4 showed positive correlations with dissolved oxygen (DO), chl-*a*, and wind direction. These relationships do somewhat vary when analyzing the LOBO time series within each bloom sub-season (Table 3.3; variable loading scores in Section 8). The negative associations between chl-*a*, phycocyanin, and turbidity may imply that while the LOBO was able to capture and sample the bloom, it was sampling in the bloom for a short period of time. WLE has high short term intra-seasonal variability since changes in wind stress or forcing can significantly change water characteristics in the basin (Bertani et al., 2017).

Table 3.3. Seasonal LOBO PCA variance explained by each principal component.
Variable loading scores are in Section 8.

PC	June	July 1-21	July 22-August*	September	October
1	33.8%	26.6%	28.2%	34.5%	46.7%
2	22.1%	21.5%	17.9%	23.8%	20.6%
3	11.9%	16.0%	12.7%	10.9%	10.9%
4	11.4%	14.3%	11.1%	7.3%	8.2%
Total	76.6%	78.5%	69.9%	79.1%	86.3%

* The addition of PC 5 (9.1%) increases total variance explained to 79.0%

Throughout the bloom season, wind played a large role in determining water quality characteristics. Most of the variation within the first two PCs for all sub-seasons had a significant portion of the variance related to wind characteristics (speed, gust, and stress), as shown in Figure 3.14 (loading values in Section 8). A large wind event can mix and redistribute either water mass throughout the system. If the bloom or Detroit River was being sampled by the LOBO during a time of high wind, it would be mixed throughout the water column and no longer be the dominant water mass. This may be indicative of OWT 3, which has low chl-*a* and phytoplankton presence (Moore et al., 2014). The river plume and bloom would not be fully detected by satellite imagery (Wynne et al., 2010) nor the buoy due to an increase in turbidity and other particulate matter.

Chl-*a* fluorescence, which was associated with bloom presence in the LOBO time series, showed no correlation or contribution to explained variance in the dataset until September through October. This was opposite of PO₄, which was correlated with other water chemistry parameters, such as CDOM and conductivity, early in the season (June), but becomes less significant later in the season. PO₄ does show some correlation with chl-*a* from July 1-21 in PC3, but it only accounts for approximately 12.8% of the variability within that month. This could be attributed to the residual spring nutrient loading into WLE from the Maumee River and the seasonal nutrient load tapering as the season progresses (Stumpf et al., 2012; Michalak et al., 2013).

Phycocyanin, another characteristic associated with bloom presence, was similar to chl-*a* and showed no large contribution to explained variance until PCs 3 and 4 starting in July (30.3% variance and decreases in succeeding months). Other environmental variables that contributed to the overall variance in PCs 3 and 4 were chl-*a*, water temperature, and turbidity. All four variables tended to covary together. When phycocyanin had a positive loading, the other three variables typically did as well, which typically occurs during bloom presence. Chl-*a* and phycocyanin are typically used as indicators (Stumpf et al., 2016) when HABs are present in warmer waters (Paerl et al., 2016). Additionally, turbidity has been shown to correlate with chl-*a* fluorescence

following wind events (Moore et al., 2019) due to mixing of sediments and cyanobacteria cells within the water column.

Figure 3.15. Component loadings for first five components of LOBO sampled data separated by bloom sub-seasons. The dotted line indicates the significant factor score, 0.277. See Table 3.3 for explained variance of PCs for each sub-season.

In October, or post-bloom, PC1 explained 46.7% of the variance and showed high positive contributions from conductivity, DO, water and air temperatures, and negative associations between all wind characteristics except direction. The variability captured in

PC1 may reflect the difference in bloom occurrence from 2013 and 2014. Typically, the bloom season is ending in October due to an increase in fall storm events and a decrease in water temperature (Wynne and Stumpf, 2015; Niu et al., 2018). This was the case in 2013, but a late season bloom occurred in 2014 due to sustained water temperatures over 15°C based on NOAA's experimental HAB bulletin from September 30 through October 10, 2014 (www.glerl.noaa.gov/res/HABs_and_Hypoxia/lakeErieHABArchive/). This temperature is considered optimal for HAB growth.

When the LOBO sampled in the Detroit River water, three PCs with eigenvalues greater than one were identified. These first three principal components explain 74% of the total variance (DRPC1: 37.3%; DRPC2: 21.7%; DRPC3: 15.0%; loading scores are in Section 9). DRPC1 showed strong positive associations between water temperature, CDOM, and PO₄. It had negative loadings from DO and PO₄. On average, the LOBO sampled within DR early in the bloom growing season. The amount of variation explained in DRPC1 with water temperature and PO₄ may imply seasonal changes versus the Detroit River discharge increasing the basin's temperature or nutrient concentrations. Nutrient concentrations in the spring are on average greater than the rest of the summer (Ho and Michalak, 2015). Instead, the river was sampled at the same time these seasonal processes were occurring. DRPC2 showed strong positive correlations between wind forcing characteristics: wind speed, gust, and stress. This indicated that when the LOBO was sampling within the Detroit River or begins to do so, it is following a change in wind speed or gust. The shift from one water mass to the Detroit River can be attributed to wind forcing. DRPC3 indicated negative associations between chl-*a* fluorescence, PC concentration, turbidity, and air temperature. On average, the Detroit River water mass had lower chl-*a* fluorescence and phycocyanin concentration than the rest of the basin. Also, these four variables typically identify HAB presence and should inherently be lower for the Detroit River.

Within bloom waters, the first four principal components explain 70.3% of the total variance (HABPC 1: 26.0%; HABPC 2: 23.5%; HABPC 3: 11.7%; HABPC 4: 9.0%; loading scores in Section 9). HABPC1 showed positive correlations with conductivity, CDOM, water and air temperature, and chl-*a* fluorescence. These water characteristics,

particularly due to their positive contribution to variance in PC1, were indicative of HAB presence. Each variable contributes its own explanation to bloom presence. First, unlike the Detroit River, the Maumee River and associated bloom has a higher conductivity and particle scattering (Moore et al., 2017). Additionally, cyanobacteria prefer warmer temperatures (Paerl et al., 2016), which helps sustain the bloom. Lastly, for this analysis, higher levels of chl-*a* fluorescence were indicative of a cyanobacterial bloom since it acts as a more stable indicator of HABs than phycocyanin, which has been shown to be highly variable due to light availability (Chaffin et al., 2012; Stumpf et al., 2016)

Unlike DRPC2, HABPC2 showed negative correlations between all of the wind forcing characteristics. The LOBO was in the HAB when there was no wind forcing or stress, which allows surface scum to form (Wynne et al., 2010) and detection by the buoy. Once there was a strong enough wind, the bloom mixes throughout the water column and less was sampled by the LOBO as it is vertically diluted in the water column. HABPC3 indicated a correlation between phycocyanin concentration and chl-*a* fluorescence. HABPC3 appeared to explain the variation of when the LOBO was in the bloom as both high phycocyanin and chl-*a* indicated a bloom was present around the buoy (Stumpf et al., 2016). HABPC4 showed negative associations between DO and wind direction, which indicated that mixing did not occur while the LOBO was sampling in the bloom. There was a positive association with PO₄, which may have indicated nutrient presence as the bloom continued to proliferate.

Both PCAs for the river and bloom were similar in terms of explaining the variability in PC1. However, the impact of wind forcing affected the variability of each water mass. Low winds cause HAB surface scums to form (Sayers et al., 2019), while higher winds cause water column mixing, diluting the bloom and increasing the presence of suspended sediments (Chaffin et al., 2012; Wynne et al., 2013). HAB scums that do form typically do so closer to the Maumee River mouth (Sayers et al., 2019) and not near the LOBO buoy, which was likely the reason winds were negatively associated when explaining variability during HAB sampling. For the Detroit River, wind forcing on surface waters may have pushed the river plume further south towards the buoy. During the summer, the Detroit River's inflow was less dominate (Niu et al., 2015) and any wind forcing changed

the circulation within the basin. Instead of causing Detroit River waters to mix within the basin, winds instead pushed the river plume south.

3.5 Environmental Drivers of Spatiotemporal Variability

Wind stress significantly impacted whether the LOBO was sampling in the Detroit River or HAB (Figure 3.16). In a low wind stress state ($< 0.05 \text{ Pa}$), the LOBO typically sampled in the HAB. As stated previously, calmer waters benefit HABs due to the lack of water mixing, which allows for surface scum formation. Both the river and HAB were sampled during high wind stress states ($> 0.1 \text{ Pa}$; wind speed of 7.7 m sec^{-1}). HAB detection during high winds was likely due to the lagged response of cyanobacteria cells to the wind shift. The HAB became diluted and cells were mixed into the water column, but response to mixing was not immediate. However, if a period of low wind followed a high wind, there would be another delayed response by cyanobacteria to float back to the lake surface prior to surface detection (Wynne et al., 2013).

Figure 3.16. 2013 and 2014 LOBO sampled chlorophyll-*a* fluorescence and phycocyanin during different wind stress states. Low wind stress is less than 0.05 Pa; medium wind stress is 0.05-0.1 Pa, and; high wind stress is greater than 0.1 Pa.

For all three wind states in both years, the scale or concentration of phycocyanin remained relatively the same, whereas chl-*a* fluorescence increased as wind stress decreased (Table 3.4). For both phycocyanin and chl-*a*, average values were relatively the same for each wind stress state. However, the highest chl-*a* fluorescence and phycocyanin concentrations occurred during low wind stresses (< 0.05 Pa). Unlike when water mixing occurs in both high and medium wind stress states, cyanobacteria cells are

able to gather at the surface, allowing them to increase in concentration and fluorescence (Wynne et al., 2010) as detected by the LOBO.

Table 3.4. Average chlorophyll-*a* fluorescence and phycocyanin concentrations during different wind stress states.

Wind Stress State	High		Medium		Low	
	2013	2014	2013	2014	2013	2014
Chlorophyll-<i>a</i> ($\mu\text{g L}^{-1}$)						
Minimum	0.48	0.85	0.44	0.81	0.45	0.08
Maximum	15.1	15.4	23.0	12.5	24.9	18.8
Average	3.62	3.94	3.63	3.00	3.76	2.84
Standard Deviation	2.87	3.01	3.08	3.01	3.33	2.40
Phycocyanin (ppb)						
Minimum	0.10	0.00	0.06	0.02	0.00	0.00
Maximum	8.62	23.8	16.7	23.2	72.3	47.6
Average	1.46	5.85	1.79	4.48	1.72	6.69
Standard Deviation	1.70	5.15	2.16	4.51	3.48	7.00

When the LOBO sampled in the Detroit River, PCA output implied that it occurred following a high wind event. For example, strong wind associated with a thunderstorm on August 14, 2014 caused a shift in the water mass that the LOBO detected (Figure 3.17A; B) from bloom to WLE waters. Wind stress induced mixing decreases detectable cyanobacteria concentrations at the surface (Moore et al., 2019). During 2013 and 2014, Detroit River discharge, on average, remained the same throughout the bloom season, but northerly winds can change water currents (Figure 3.17C), shifting water quality characteristics (Figure 3.17B) closer to Detroit River waters (low chl-*a* and turbidity).

Figure 3.17. Example of a change in water mass sampled by the LOBO due to high winds. Wind associated with a thunderstorm on August 12, 2014 (red outline in A) is depicted, indicating a change in water mass from bloom to WLE, most likely due to Detroit River waters coming from the north (C; arrows point in the direction of movement).

While the LOBO measurements offer some interpretation of how the spatiotemporal variation of the river and bloom are impacted by physical drivers, a regional analysis on the river and bloom itself using gridded datasets offered different insight on the importance of each of those drivers (PCA loading scores in Section 10). The PCA for the 2013 and 2014 Detroit River regional datasets, using satellite imagery, (Figure 3.18) identified three components with eigenvalues of one. The first three principal components explain 72.2% of the total variance (PC1: 34.2%; PC2: 23.0%; PC3: 15.0%). As discussed previously, the Detroit River discharge directly influenced the surface area of the river plume (Figure 3.7).

Figure 3.18. Component loadings for the first three components of Detroit River regional gridded data, 2013 and 2014. The dotted line indicates the significant component factor score, 0.378. (WTemp: water temperature, Celsius; EW_Wind: east/west wind speed; NS_Wind: north/south wind speed; AdvDir: advection direction, degrees; DRdis: Detroit River discharge, m³/sec; chl-a: chlorophyll-a fluorescence, mg/L)

The first PC for the Detroit River (34.2% variation explained) showed an opposite relationship between wind stress (positive loading) and water temperature (negative loading). This implied that water temperatures remained relatively low within the river plume. Detroit River plume surface temperatures have been shown to be lower than the rest of WLE (Niu et al., 2015). This was particularly the case following a high wind stress event; water surface temperatures appeared to remain low within the dataset. PC2, which explained 23.0% of the variation, also suggested that westerly/easterly wind also had a positive influence on the Detroit River surface plume. When using OWT imagery to detect the Detroit River, the river plume had a wider west/east surface area during the summer bloom season (Figure 3.12). However, the Detroit River discharge showed a negative association in the second component. This may be due to the direct link between

discharge and overall plume surface area; when Detroit River discharge increased, river surface plume area also increased in response.

In PC3, chl-*a* had a positive loading, which indicated that within the Detroit River plume, there was the potential for chl-*a* fluorescence presence. Gridded correlation analysis results between chl-*a* and the Detroit River discharge showed this positive association (Figure 3.19A). When warmer surface water temperatures were present, chl-*a* also appeared to be present. This positive relationship may have been caused by wind forcing since water movement in the basin is largely influenced by wind. Strong southerly winds and the response by water direction may cause the Detroit River to be pushed closer to the northern Lake Erie shore, allowing for warmer temperatures and bloom to occupy what is typically river water. However, the Detroit River discharge (Figure 3.19B) had a negative correlation with chl-*a*, which indicated that river inflow does not allow for the formation of surface scum or bloom presence near the mouth of the river (Sayers et al., 2019; Wynne and Stumpf, 2015).

Figure 3.19. Gridded correlation in averaged Detroit River plume, 2013 and 2014. Chl-*a* compared to lake surface temperature (SST; A) and river discharge (B).

For the regional HAB dataset, the first three components had eigenvalues greater than one (Figure 3.20). The three components explained 63.3% of the variance (PC 1: 26.8%; PC2: 21.6%; PC3: 14.9%; loading scores in Section 10). Unlike the Detroit River, wind characteristics had negative associations with other variables with each component. PC1 showed negative association for all directional wind speeds (U and V) and water

surface temperature. PC2 had positive associations between Maumee River discharge and water surface temperature, but these variables negatively related to wind stress. PC3 captured the negative association between advection direction and chl-*a*. Similar to when the LOBO was sampling in the HAB, wind negatively impacted bloom surface area; as wind stress or speeds increased, bloom surface area decreased. This was similar in PC2, where wind stress was negatively related to Maumee River discharge and water temperature. This was most likely due to the HABs reliance upon the Maumee River nutrient inflow and warmer water temperatures to proliferate (Stumpf et al., 2012; Wynne and Stumpf, 2015). Overall, the PCA on the regional HAB dataset captured the significance of wind forcing on HAB characteristics.

Figure 3.20. Component loadings for the first four components of HAB regional gridded data. Analysis was separated by bloom sub-seasons for 2013 and 2014. The dotted line indicates the significant component factor score, 0.378. (WTemp: water temperature, Celsius; EW_Wind: east/west wind speed; NS_Wind: north/south wind speed; AdvDir: advection direction, degrees; DRdis: Detroit River discharge, m³/sec; chl-a: chlorophyll-a fluorescence, mg/L)

4 Future Work and Research Implications

This analysis captured a limited temporal history of the water characteristics and HAB presence in the WLE basin. After the LOBO's deployment, NOAA GLERL, in partnership with other Great Lakes organizations, now operate a network of buoys throughout the WLE basin to continually monitor and detect blooms in real time (www.glerl.noaa.gov/res/HABs_and_Hypoxia/rtMonSQL.php). Many were deployed in response to the Toledo drinking water ban in 2014. Many of these buoys are sampling at a finer temporal scale than the LOBO, with data being reported and available online every 15 minutes. With an increase in spatial and temporal sampling, further analysis that includes more recent information would help further understand the seasonal characteristics and physical influences within both the bloom and Detroit River.

While the LOBO did capture the characteristics of both the Detroit River and bloom, the buoy spent a significant amount of time measuring characteristics of a transition or mixing zone between the two water masses. This study did not fully analyze or interpret this zone. This mixing zone also relates to the significant water characteristic changes that occur in WLE over a short period of time. This is due to its vulnerability to change from wind forcing and river discharge. Intra-seasonal variations in river discharge can increase water turbidity and change bloom surface area (Bertani et al., 2017). Both factors contribute to the optical complexities that are present in WLE. While there are existing bio-optical algorithms that detect WLE blooms (Wynne et al., 2011; Sayers et al., 2019), it does not identify or study the transitional zone or mixing areas. Further research in these more optically complex zones may help improve existing algorithms, but also may help better identify and further explain the Detroit River's influence on the northern boundary of the bloom.

Despite the fact that the temporal timeframe only covered two years, the research still provides valuable insight on the characteristics of the Detroit River surface plume. However, the Detroit River still lacks continual monitoring even with the deployment of more buoys in WLE. River characteristics (e.g., high discharge, boat traffic) do create some issues when deploying a buoy directly at the river mouth, but nonetheless are still useful when interpreting river impacts on the basin. *In situ* sampling does occur near the

mouth and within the river itself, but the Detroit River physical influence on the bloom is not well known. Even though the river itself does not contribute to bloom severity, its significant influence on the basin itself should elicit interest in Detroit River water quality characteristics.

5 Conclusion

This study primarily focused on the influence that the Detroit River has on the distribution of HABs in WLE and their primary physical and environmental drivers. Both the river and bloom had distinct spatial patterns throughout the WLE basin. While the two may overlap in spatial distribution, there are clear, defined locations in which the other is not found. There were clear optical boundaries as defined by satellite imagery.

Wind forcing played a significant role in both the bloom and river plume, but how wind affected the water characteristics in each varied. Wind, regardless of bloom sub-season, appeared to increase the spatial influence of the Detroit River whereas it mixed the bloom vertically into the water column. Seasonally, the influence that wind had varied. During the pre-bloom sub-season, wind helps contribute to future bloom growth, whereas in the peak-bloom sub-season and on, wind dissipates the bloom.

Overall, the time the LOBO spent in the bloom versus the Detroit River resulted in greater variability throughout the LOBO's temporal sampling. The LOBO sampled predominantly in the bloom or WLE basin for most of its deployment. Because of this, the LOBO's sampling varied; the bloom and basin had greater optical and in-water constituent variability when compared to the Detroit River. The LOBO also helped explain some of the spatial interaction between the bloom and Detroit River plume, most notably following high wind events.

Multiple data streams (e.g., satellite monitoring, *in situ* observations) are needed to fully characterize not only the spatiotemporal HAB dynamics and its interaction with physical forces in the basin, but to fully characterize the influence the Detroit River has on the bloom. Recognizing the importance of the river on HAB characteristics provides a more wholistic view of WLE HAB variability. While the Detroit River does not impact bloom intensity, it does play a role in its location, impacting the spatial variability of blooms within the WLE basin.

6 References

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7 Average LOBO Measured Water Characteristics

Table 7.1. 2013 and 2014 LOBO Sampled Water Characteristics by Water Mass

	Detroit River		HAB		WLE	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
CDOM (QSDE)	7.27	2.54	9.26	3.50	9.60	3.64
Conductivity (mmho/cm)	0.024	0.009	0.023	0.003	0.025	0.004
Chl-a (µg/mL)	2.24	1.86	4.16	3.10	2.80	2.46
DO (mg/L)	5.36	2.22	2.46	3.08	2.83	2.93
PO4 (µm)	0	0.037	0.001	0.135	0.025	0.055
Phycocyanin (ppb)	0.66	1.44	6.59	6.55	3.05	4.63
Water Temperature (°C)	21.0	2.0	22.5	2.1	22.4	2.4
Turbidity (NTU)	1.66	0.82	1.56	0.66	1.86	1.14
Air Temperature (°C)	20.5	3.13	20.7	3.7	21.1	3.9
Wind Speed (m/s)	6.16	2.52	5.26	2.62	5.98	2.61
Wind Gust (m/s)	7.08	2.91	6.12	2.98	6.90	3.02
Wind Direction (°)	83.6	144.3	148.3	116.8	142.7	127.9
Wind Stress (Pa)	0.074	0.070	0.058	0.110	0.072	0.075

8 PCA Loading Tables (LOBO Analysis)

Table 8.1. 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

	PC1	PC2	PC3	PC4
CDOM	0.307	0.276	-0.295	0.141
Conductivity	0.398	0.271	-0.001	-0.069
Chlorophyll- <i>a</i>	0.050	0.110	-0.519	0.334
DO	0.094	0.046	0.314	0.683
PO ₄	0.238	0.180	-0.062	-0.219
Phycocyanin	-0.150	-0.181	-0.615	-0.182
Water Temp.	0.371	0.225	0.117	-0.110
Turbidity	0.216	0.203	-0.305	-0.011
Air Temp.	0.373	0.165	0.118	-0.044
Wind Speed	-0.324	0.474	0.046	-0.034
Wind Gust	-0.333	0.468	0.042	-0.037
Wind Direction	-0.100	0.024	-0.196	0.543
Wind Stress	-0.327	0.456	0.008	-0.058

Table 8.2. June 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

June	PC1	PC2	PC3	PC4
CDOM	0.355	0.206	-0.372	0.131
Conductivity	0.384	0.078	-0.246	0.290
Chlorophyll- <i>a</i>	0.015	0.122	-0.208	-0.665
DO	-0.254	-0.197	0.535	-0.028
PO ₄	0.356	0.112	0.016	-0.050
Phycocyanin	0.333	0.098	0.313	-0.396
Water Temp.	0.347	0.000	0.293	0.351
Turbidity	0.345	0.126	0.213	-0.324
Air Temp.	0.236	-0.018	0.425	0.197
Wind Speed	-0.176	0.536	0.105	0.082
Wind Gust	-0.178	0.537	0.092	0.073
Wind Direction	-0.191	-0.071	-0.175	0.111
Wind Stress	-0.171	0.528	0.108	0.075

Table 8.3. July 1-21, 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

July 1-21	PC1	PC2	PC3	PC4
CDOM	0.248	0.371	0.143	-0.290
Conductivity	0.264	0.340	-0.126	-0.305
Chlorophyll- <i>a</i>	-0.016	0.093	0.601	0.080
DO	0.353	0.278	0.137	0.237
PO ₄	0.132	0.162	0.466	0.023
Phycocyanin	-0.056	-0.049	-0.036	-0.565
Water Temp.	0.318	0.016	-0.448	0.206
Turbidity	0.163	0.279	-0.067	-0.442
Air Temp.	0.365	0.101	-0.316	0.169
Wind Speed	-0.344	0.428	-0.116	0.126
Wind Gust	-0.358	0.417	-0.109	0.125
Wind Direction	0.309	0.154	0.140	0.357
Wind Stress	-0.348	0.405	-0.122	0.120

Table 8.4. July 22-August 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

July 22-August	PC1	PC2	PC3	PC4	PC 5
CDOM	0.262	-0.519	0.017	-0.001	-0.034
Conductivity	0.295	-0.386	-0.137	-0.164	-0.152
Chlorophyll- <i>a</i>	0.298	-0.323	0.253	-0.277	-0.013
DO	0.136	-0.359	-0.415	0.378	0.078
PO ₄	0.095	-0.088	-0.109	-0.028	-0.687
Phycocyanin	0.168	0.028	0.592	-0.373	-0.057
Water Temp.	0.152	0.168	-0.488	-0.376	-0.024
Turbidity	0.061	-0.242	0.134	0.129	0.568
Air Temp.	0.265	0.092	-0.258	-0.400	0.410
Wind Speed	-0.445	-0.260	-0.066	-0.249	0.049
Wind Gust	-0.455	-0.253	-0.068	-0.228	0.012
Wind Direction	-0.096	-0.216	0.220	0.328	-0.021
Wind Stress	-0.433	-0.258	-0.053	-0.271	-0.016

Table 8.5. September 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

September	PC1	PC2	PC3	PC4
CDOM	-0.395	-0.103	-0.076	0.042
Conductivity	-0.426	-0.123	0.072	0.043
Chlorophyll- <i>a</i>	-0.349	0.028	0.215	0.016
DO	0.119	0.229	0.620	0.093
PO ₄	-0.212	-0.082	-0.182	0.626
Phycocyanin	-0.054	-0.315	-0.515	-0.229
Water Temp.	-0.392	-0.061	0.271	0.079
Turbidity	-0.367	-0.155	-0.057	-0.203
Air Temp.	-0.300	-0.112	0.268	-0.431
Wind Speed	-0.161	0.508	-0.157	-0.150
Wind Gust	-0.159	0.513	-0.169	-0.076
Wind Direction	-0.153	0.130	-0.090	0.515
Wind Stress	-0.157	0.486	-0.224	-0.123

Table 8.6. October 2013 and 2014 LOBO PCA (bolded values are greater than the loading cutoff, 0.277)

October	PC1	PC2	PC3	PC4
CDOM	0.146	-0.486	0.239	-0.220
Conductivity	0.369	-0.198	-0.162	-0.098
Chlorophyll- <i>a</i>	-0.016	-0.493	0.450	-0.091
DO	0.349	-0.201	-0.187	-0.220
PO ₄	-0.119	0.193	0.112	-0.722
Phycocyanin	-0.284	0.083	0.525	0.147
Water Temp.	0.360	-0.060	-0.120	0.237
Turbidity	0.286	-0.226	0.293	0.061
Air Temp.	0.326	0.049	-0.123	0.163
Wind Speed	-0.302	-0.330	-0.237	0.118
Wind Gust	-0.311	-0.327	-0.215	0.126
Wind Direction	-0.165	-0.157	-0.367	-0.440
Wind Stress	-0.304	-0.315	-0.196	0.180

9 PCA Loading Tables (LOBO Water Mass Analysis)

Table 9.1. 2013 and 2014 LOBO in Detroit River PCA (bolded values are greater than the loading cutoff, 0.277)

	PC1	PC2	PC3	PC4
CDOM	0.392	-0.004	-0.086	-0.150
Conductivity	0.269	-0.220	-0.036	0.208
Chlorophyll- <i>a</i>	-0.010	0.190	-0.577	-0.235
DO	-0.319	0.140	-0.159	0.433
PO ₄	0.377	-0.179	0.060	0.022
Phycocyanin	0.005	0.149	-0.538	-0.473
Water Temp.	0.405	-0.210	-0.055	-0.028
Turbidity	0.253	0.078	-0.368	0.422
Air Temp.	0.241	-0.198	-0.315	0.402
Wind Speed	0.227	0.494	0.134	0.075
Wind Gust	0.223	0.494	0.148	0.044
Wind Direction	-0.315	0.126	-0.221	0.333
Wind Stress	0.209	0.498	0.117	0.087

Table 9.2. 2013 and 2014 LOBO in HABs PCA (bolded values are greater than the loading cutoff, 0.277)

	PC1	PC2	PC3	PC4
CDOM	0.380	-0.227	0.268	0.009
Conductivity	0.386	-0.135	0.015	0.162
Chlorophyll- <i>a</i>	0.342	-0.216	0.337	-0.113
DO	0.239	-0.174	-0.175	-0.579
PO ₄	0.043	-0.032	0.213	0.364
Phycocyanin	-0.081	0.146	0.637	0.187
Water Temp.	0.411	-0.077	-0.282	0.206
Turbidity	0.269	-0.155	0.256	0.094
Air Temp.	0.379	0.028	-0.330	0.187
Wind Speed	-0.218	-0.507	-0.064	0.140
Wind Gust	-0.226	-0.505	-0.039	0.127
Wind Direction	-0.029	-0.200	0.255	-0.563
Wind Stress	-0.198	-0.498	-0.091	0.138

10 PCA Loading Tables (Gridded Water Analysis)

Table 10.1. HAB regional PCA 2013/2014 (bolded values are greater than the loading cutoff, 0.377)

	PC1	PC2	PC3	PC4
SST	-0.467	0.421	-0.053	-0.081
E/W Wind	-0.604	-0.168	-0.027	-0.060
N/S Wind	-0.594	0.103	0.099	0.100
Wind Stress	-0.245	-0.644	0.004	-0.177
Advection Direction	0.058	0.220	0.419	-0.866
Maumee River Discharge	-0.022	0.552	-0.337	0.063
Chl- <i>a</i>	0.016	-0.125	-0.835	-0.442

Table 10.2. Detroit River Plume regional PCA 2013/2014 (bolded values are greater than the loading cutoff, 0.377)

	PC1	PC2	PC3	PC4
SST	-0.529	0.342	-0.091	0.088
E/W Wind	0.297	0.570	0.019	-0.014
N/S Wind	0.362	0.367	-0.305	0.071
Wind Stress	0.550	0.239	0.112	-0.200
Advection Direction	0.012	0.156	0.853	0.450
Detroit River Discharge	0.362	-0.535	0.203	-0.237
Chl- <i>a</i>	-0.259	0.237	0.342	-0.830