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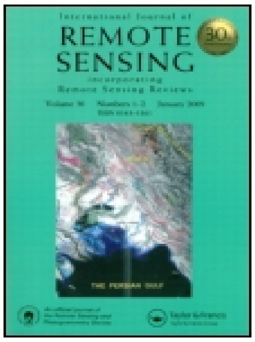

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Cyanobacteria blooms in three eutrophic basins of the Great Lakes: a comparative analysis using satellite remote sensing

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ABSTRACT

Blooms of harmful cyanobacteria (cyanoHABs) were mapped for three eutrophic basins (western basin of Lake Erie, WBLE; Green Bay, Lake Michigan, GB; and Saginaw Bay, Lake Huron, SB) in the Great Lakes from 2002 to 2013 using Moderate Resolution Imaging Spectroradiometer (MODIS) ocean colour imagery. These blooms were examined in relationship to basic meteorological and environmental parameters. Annual cyanoHAB extent trends were generated using two modified remote-sensing approaches. The first approach was a modified bio-optical chlorophyll retrieval algorithm enhanced with empirical relationships to estimate water column cyanoHABs (MCH), whereas the second approach uses near-infrared (NIR) reflectance to quantify the surface scums of cyanoHABs (SSI). The development and application of the SSI are unique products in the Great Lakes and may have generic application to ecological and public health issues. Satellite-derived cyanoHAB estimates agreed well with *in situ* observations (89% accuracy). The annual cyanoHAB trends (MCH and SSI) for WBLE, SB, and GB were not similar for the 2002–2013 analysis period. A recent trend of increasing cyanoHABs was noted in WBLE but not in GB or SB. Moreover, extensive and persistent surface scums were observed in WBLE but not in GB or SB. Meteorological parameters were similar among the basins; however, significant differences in spring discharge of the dominant river were observed among basins. Spring discharge was a significant predictor of cyanoHAB occurrence in WBLE but not in GB and SB. Wind-induced sediment re-suspension events were common during the bloom period in WBLE but not in GB or SB and these events were highly correlated with cyanoHAB occurrence. The differences among basins in the role of riverine discharge and re-suspension suggest local factors are more important than regional factors in controlling cyanoHAB dynamics within these three basins in the Great Lakes.

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1. Introduction

Colonial cyanobacteria (blue-green algae) commonly occur in many eutrophic regions throughout the world (Bianchi et al. 2000; Vahtera et al. 2007; Joehnk et al. 2008; Qin

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et al. 2010; Schindler, Hecky, and McCullough 2012). When conditions are suitable, large blooms of cyanobacteria may be common in these waters. Excessive loading of phosphorus and other nutrients from rivers and streams plays an important role in bloom occurrence as well as prolonged durations of sunlight and warm temperatures (Robarts and Zohary 1987; Rapala et al. 1997; Ibelings et al. 2003; Kanoshina, Lips, and Leppänen 2003; Paerl, Hall, and Calandrino 2011). Some cyanobacteria produce toxins (Sivonen 1996; Codd, Morrison, and Metcalf 2005) and toxin concentrations in cyanobacteria blooms (cyanoHAB) may have serious potential negative impacts on aquatic resources, public health, and community economics (Rinta-Kanto et al. 2005; Ouellette, Handy, and Wilhelm 2006). Evidence suggests cyanoHAB occurrences are increasing worldwide in both freshwater lakes and inland seas (Otten and Paerl 2011). One unique trait of cyanoHABs is their ability to form surface scums due to vacuolation (Van Rijn and Shilo 1985; Klemer et al. 1996). Scums have been linked to very high concentrations of toxins and are easy to come into contact with during recreational activities (i.e. boating, fishing, etc.), thus making their detection a potentially important aspect of any cyanobacterial monitoring programme (Bartram and Rees 1999).

One species of cyanobacteria that is capable of producing large toxic blooms is *Microcystis aeruginosa*. Blooms of this cyanobacterium are reoccurring annual events within the eutrophic waters of the Great Lakes, most notably in the western basin of Lake Erie (WBLE) (Vanderploeg et al. 2001; Bridgeman, Chaffin, and Filbrun 2013), but also in Saginaw Bay (SB) in Lake Huron (Fahnenstiel et al. 2008) and Green Bay (GB) in Lake Michigan (De Stasio et al. 2008) (Figure 1). These basins are similar in that each has a dominant river in which a large percentage of the total basin-wide nutrient load is delivered (Maumee River, WBLE; Fox River, GB; and Saginaw River, SB). Although all

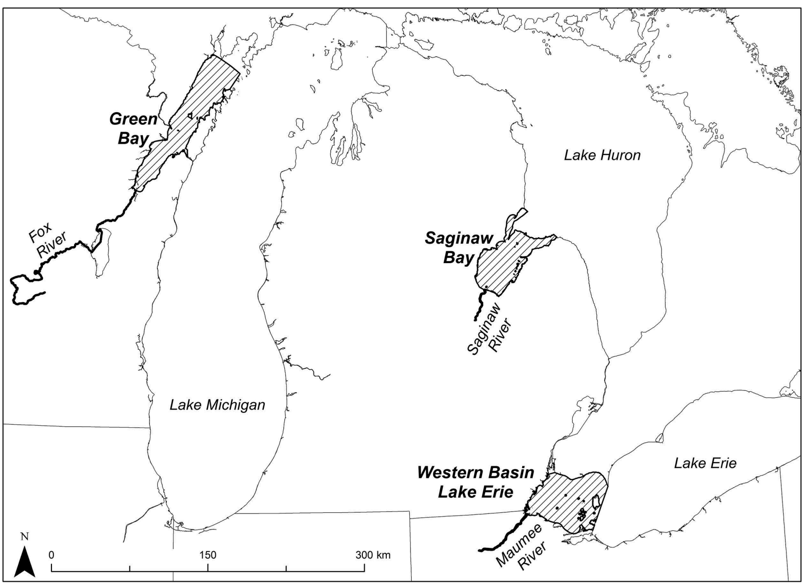

Figure 1. Map of areas analysed for cyanoHAB occurrences in the Great Lakes. Hatched areas indicate the basins included in analysis. The dominant river (nutrient source) for each basin is also labelled on the map.

three of these basins are shallow, eutrophic bodies of water within a larger freshwater system, the historical patterns of cyanoHAB across these three regions have not been examined. Lake Erie has exhibited an increasing trend in HAB occurrences starting in the 2000s, and culminating in the largest bloom ever recorded in 2011 (Michalak et al. 2013; Bridgeman, Chaffin, and Filbrun 2013). The National Oceanic and Atmospheric Administration (NOAA) experimental HAB bulletin has indicated an even larger bloom might have taken place in 2015 (http://www.glerl.noaa.gov/res/HABs_and_Hypoxia/lakeErieHABArchive/). The mid-1990s saw the reoccurrence of large blooms of cyanobacteria in SB, concurrent with the wide-scale establishment of invasive zebra mussels, and continue to be observed in the late summer period (Bierman et al. 2005; Millie et al. 2009). GB has seen a recent change in the phytoplankton community towards a more frequent dominance of cyanobacteria following the invasion of zebra mussels in 1992 (De Stasio et al. 2008). Although cyanoHABs have been documented in all three basins in the Great Lakes, more than a decade of extensive *in situ* and satellite-based monitoring in WBLE has led to a functional understanding of the annual cyanoHAB dynamics within this basin (Bridgeman, Chaffin, and Filbrun 2013; Michalak et al. 2013; Obenour et al. 2014). Much less is known about the annual cyanoHAB occurrence trends and the controlling factors in GB and SB.

Satellite remote sensing provides the potential for long-term spatial and temporal synoptic monitoring of cyanoHAB events in the Great Lakes, and thus can help quantify the trends in cyanoHABs. This basin-scale mapping potential has resulted in the development of cyanobacteria satellite mapping algorithms that are sensitive to the abundance of cyanobacteria and pigments other than chlorophyll and the unique near-surface abundance associated with cyanoHAB. One such pigment, phycocyanin, is found in cyanobacteria and has been used to document the presence of cyanobacteria from remote sensing (Gons, Otten, and Rijkeboer 1991; Dekker 1993; Simis, Peters, and Gons 2005; Kutser 2004, 2009). The ability to differentiate blue-green algae from other bloom-forming algae is critical to distinguishing cyanoHAB. Wynne et al. (2008) developed an approach based on the Fluorescence Line Height (FLH) algorithm (Abbott and Letelier 1999), which exploits the spectral shape of cyanobacteria absorption features in the red and 'red edge' portions of the electromagnetic spectrum using Medium Resolution Imaging Spectrometer (MERIS) satellite imagery. Stumpf et al. (2012) used this approach to further quantify cyanoHAB in the WBLE from 2002 to 2011 and relate the annual bloom extent to river discharge. With the failure of MERIS in April 2012, new approaches using operational satellite systems are required to continue important cyanoHAB monitoring activities throughout the Great Lakes and other regions.

The overall objective of this study is to characterize the annual historical trends of cyanoHABs in the three basins (WBLE, SB, and GB) in the Great Lakes from 2002 to 2013. These trends will be used to determine whether they are similar or dissimilar among basins as well as to explore the basic relationships with a number of possible controlling factors including temperature, precipitation, river discharge, re-suspension, and watershed land cover. These comparisons might provide useful information on the relative roles of regional (climate) or local (nutrient) control of cyanoHABs in the Great Lakes. In WBLE, the recent increase in cyanoHABs has been linked to nutrient loading and climate change (Stumpf et al. 2012; Michalak et al. 2013). A comparison of cyanoHABs in areas of the same geographic region (Great Lakes) may provide insights into the role of regional climate since the three study areas are in the same region, and relatively similar climatic effects have been noted in this region (McCormick and Fahnenstiel 1999). Thus, if regional climate change effects are driving the recent trends in cyanoHABs in WBLE, we would expect to see relatively similar trends in GB and SB. On the other hand, if local factors are controlling cyanoHABs in areas of the Great Lakes, we might expect the recent trends in cyanoHABs in WBLE, GB, and SB to be more dissimilar. Although regional climate factors may contribute to cyanoHABs in some areas of the Great Lakes, we believe that local factors are more important in controlling cyanoHABs in the Great Lakes. We hypothesize that recent trends in cyanoHABs will not be similar among areas of the Great Lakes, and that local factors will explain a significant amount of the annual variability within any basin. A better understanding of the controlling factors that drive cyanoHAB occurrences can lead to better adaptive management remediation efforts. To evaluate these trends and relationships with key variables, we used two satellite-based approaches. The first was a modified chlorophyll algorithm supplemented with empirical relationships to detect cyanoHAB in the Great Lakes. The second approach used a near-infrared (NIR) surface reflectance method to determine the extent of cyanoHAB surface scums. This second approach is novel in the Great Lakes and has the potential for widespread generic use, across sensor platforms, which may include utility in early public health warning systems.

2. Methods

2.1. *Field and environmental data*

Discrete samples from the near-surface region (0–1 m) were taken with a modified clean Niskin bottle (Fitzwater, Knauer, and Martin 1982; Fahnenstiel et al. 2002). Surface scums were sampled with 500 ml Nalgene bottles used horizontally to capture the surface scum. Once back in the lab, the contents of the Nalgene bottle were placed in a high light incubator and scums were allowed to reform at the top of the bottle, at which time they were carefully sampled with a syringe. Samples for pigment analyses were filtered onto Whatman GF/F filters, extracted with appropriate solvent, and analysed fluorometrically. For chlorophyll *a* samples, filters were extracted with N, N-dimethylformamide (Speziale et al. 1984) and analysed on a Turner Designs fluorometer calibrated with chlorophyll *a* standards. Filters for phycocyanin determination were extracted in phosphate buffer (Ricca Chemical, pH 6.8) using two freeze–thaw cycles, followed by sonication (Horváth et al. 2013). Relative fluorescence was measured on a Turner Aquafluor fluorometer and converted to phycocyanin concentration using a series of dilutions of a commercial standard (Sigma-Aldrich).

Air temperature and precipitation data were obtained from airport records near western basin Lake Erie (KTOL), Green Bay (KGRB), and Saginaw Bay (KMBS). Monthly and annual mean values were created from daily measurements. Mean river discharge values for the dominant rivers in proximity of the cyanoHABs (Maumee River, WBLE; Fox River, GB; and Saginaw River, SB; see Figure 1) were generated from daily observations provided by USGS (http://waterdata.usgs.gov/nwis/rt).

Wind-induced sediment re-suspension events were calculated using the United States Army Corps of Engineers Wave Information Studies (WIS) hindcast wave climatology data. The WIS wave data include significant wave height, period, and direction for a densely spaced series of 'virtual wave gauges' at various depth ranges throughout the Great Lakes. For this analysis, wave data stations in WBLE, GB, and SB were selected corresponding to areas where cyanoHAB occurrences were the most frequent (i.e. Maumee Bay, southeast part of SB, southwest part of GB). The stations used in this analysis were 92,112 in WBLE, 94,163 in GB, and 93,050 in SB. Daily mean WIS wave parameters from 2002 to 2013 were derived from hourly observations, and used to calculate bottom shear stresses following the model from Schwab et al. (2006). A sediment re-suspension event was defined as when the horizontal stress at the bottom of the water column exceeded 0.1 Pa (Fukuda and Lick 1980). The number of days where bottom stress exceeded 0.1 Pa was recorded for the July–September period for each of the three basins.

2.2. *cyanoHAB mapping and detection*

Two approaches were used to map cyanoHABs in the Great Lakes using Moderate Resolution Imaging Spectroradiometer (MODIS) ocean colour satellite data. The first approach uses a modification of the CPA-A algorithm (Shuchman et al. 2006, 2013) with two empirical relationships to link specific high chlorophyll *a* concentrations to likely cyanoHABs (the modified CPA/HAB approach). The second approach involves the application of a cyanoHABs scum index that detects the presence of cyanobacteria surface scums (surface scum index, SSI).

The semi-analytical Color Producing Agent (CPA) algorithm (Shuchman et al. 2013) that accurately derives accurate chlorophyll *a* concentrations in the Great Lakes was modified and implemented to map HAB events from 2002 to 2013. The CPA Algorithm (CPA-A) simultaneously retrieves concentrations of chlorophyll *a*, suspended minerals (SMs), and coloured dissolved organic matter (CDOM) from satellite reflectance imagery through the use of lake-specific hydro-optical models. The hydro-optical models are the average optical cross sections of chlorophyll, SM, and CDOM absorption as well as chlorophyll and SM backscatter across the visible spectrum. The hydro-optical model values used in this study were derived from extensive inherent optical property and *in situ* water chemistry measurements made in Lake Erie during the historical bloom season and are reported in Shuchman et al. (2013). The CPA-A was successfully validated in the Great Lakes (Shuchman et al. 2013), including the phytoplankton-rich Lake Erie, thus verifying the usefulness of this approach in accurately retrieving chlorophyll *a* concentration from MODIS.

Because the CPA-A does not directly detect blue-green algae abundance, a modified approach is needed to determine the presence of cyanoHAB. We chose an approach that utilized the CPA-A, but was supplemented with empirical relationships between other environmental variables and chlorophyll *a* to predict cyanobacteria abundance. It must be pointed out that the empirical relationships developed in this study are specific to the Great Lakes, and may not have broad application in other regions. Cyanobacteria photopigment, phycocyanin, is related to the chlorophyll *a* concentration in WBLE. Measurements of surface chlorophyll *a* and phycocyanin concentrations from WBLE

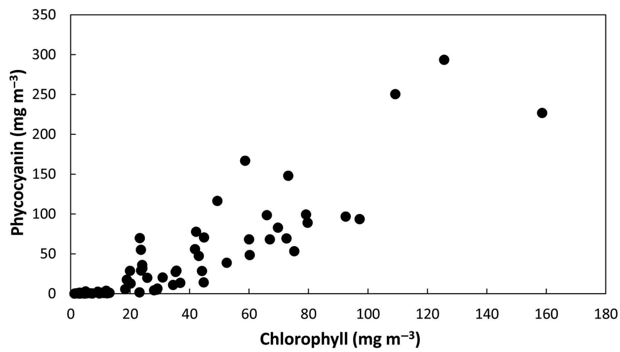

Figure 2. Surface chlorophyll *a* concentration *versus* phycocyanin concentration measured in WBLE during the 2011 July–October bloom period.

during the 2011 bloom period (July–October) were compared to identify a quantitative relationship between the two pigments (NOAA/GLERL data). Figure 2 is a scatterplot of chlorophyll *a* (x-axis) *versus* phycocyanin (y-axis). As is clearly observable from the plot, extremely small quantities (<5 mg m^{-3}) of phycocyanin are detected at chlorophyll *a* concentrations less than approximately 18 mg m^{-3}, whereas large quantities of phycocyanin (5–300 mg m^{-3}) were observed when chlorophyll *a* concentrations were >18 mg m^{-3}. These relationships suggest that high chlorophyll concentrations are generally associated with cyanoHAB. A segmented regression analysis (SegReg – http://www.waterlog.info/segreg.htm) was performed to determine the appropriateness of a chlorophyll *a* threshold value of 18 mg m^{-3} for cyanoHAB classification. The segmented regression analysis results indicated a statistically significant breakpoint threshold between 12 and 20 mg m^{-3} of chlorophyll *a* (the segmented model coefficient of explanation (0.78) is greater than the non-segmented model coefficient of determination, R^2 (0.77)). Thus, a threshold of 18 mg m^{-3} chlorophyll *a* was used to determine cyanoHAB. A second empirical relationship was used to further limit the probability of any false-positive cyanobacteria identification. Whereas high chlorophyll *a* concentrations in Lake Erie are often associated with cyanobacteria, diatoms and large green algae can also exhibit large chlorophyll concentrations (Munawar and Munawar 1976; Millie et al. 2009). These other algae often occur early or late in the vegetative growing season when the water temperatures are cooler than 20°C, whereas cyanobacteria prefer warmer temperatures (Millie et al. 2009). Data collected from NOAA/GLERL during 2005–2012 showed no significant cyanoHAB in WBLE, GB, or SB when the water temperatures were <20°C. This relationship is supported by the work of Stumpf et al. (2012), where no significant cyanobacterial blooms in Lake Erie prior to June were noted when the mean water temperatures were <20°C. Thus, using these two relationships between cyanobacteria and environmental variables, our modified CPA-A HABs (MCH) approach was used to detect cyanoHAB in the Great Lakes.

The second approach used to map cyanoHABs in the Great Lakes was SSI. A surface scum measure is important as extensive sampling in Lake Erie and elsewhere has indicated that extremely large concentrations of *Microcystis* (i.e. those affecting public health) are often found in floating algae mats or surface scums (Zohary and Robarts 1990), which are associated with high toxin concentrations (Chorus and Bartram 1999; Carmichael 2001;

NOAA/GLERL data). Historically, traditional chlorophyll mapping algorithms have not been able to simultaneously retrieve both surface algal scum and water column phytoplankton due to optical water complexity and imperfect atmospheric correction routines (Kutser 2009). To address this important public health issue, a methodology has been developed that can detect surface scum occurrences independent of chlorophyll concentration and may be applied to a variety of sensing platforms, including unmanned aerial vehicles, with limited sets of available wavelengths. This approach uses the NIR portion of the electromagnetic spectrum to determine whether or not scums are located at the water surface. Similar methods have been implemented to observe surface blooms in other freshwater lakes (Matthews, Bernard, and Robertson 2012; Hu 2009; Hu et al. 2010; Peng, Wang, and Jiang 2008), most notably Lake Taihu in China; however, several of these approaches rely on specific sensor bands (i.e. MERIS 709 and 754 nm bands, Matthews, Bernard, and Robertson 2012) not available to MODIS or require more rigorous scattering corrections (Hu 2009) that are not as well understood in the Great Lakes region as on the open ocean. For the simple classification of surface scum presence, we elected to use the simple SSI approach as no tuning is required to produce time-series estimates for the three basins of interest and it has more generic application.

The SSI is an implementation of the normalized difference vegetation index, which is a commonly used method in terrestrial vegetation biomass estimation. Solar radiation in the visible spectral region (400–700 nm) is absorbed by green vegetation as a source of energy in the process of photosynthesis. Conversely, NIR (wavelength >700 nm) radiation is predominantly scattered by green vegetation as the energy level per photon in this spectral region is insufficient for photosynthesis (Tenhunen et al. 1980). These fundamental properties are exploited in Equation (1):

$$\mathrm{SSI} = \left(\frac{(\mathrm{NIR}) - (\mathrm{VIS})}{(\mathrm{NIR}) + (\mathrm{VIS})}\right) > 0, \qquad (1)$$

where NIR is the spectral reflectance in a NIR wavelength and VIS is the reflectance in a visible wavelength, usually red. Note only positive values of the ratio are classified as a surface scum; thus the SSI values range from 0 to 1. Moreover, NIR radiation is also highly absorbent in water, making the distinction between surface algae scum (filaments above or in close proximity to the air water interface) and all other water constituents apparent in SSI values. The new SSI maps positive values as surface scum by exploiting the observed high reflectance in the NIR relative to the red reflectance.

These two HAB mapping approaches (MCH and SSI) use MODIS satellite imagery provided freely from the NASA Ocean Bio-geochemical Processing Group (http://oceancolor.gsfc.nasa.gov/). MODIS bands 9–13 (band centres: 443, 488, 531, 547, 667 nm) were used in the MCH, and MODIS bands 1 (645 nm) and 2 (858 nm) were used in the SSI. All cloud-free (>75%) images were acquired for the three basins for the 2002–2013 period. MODIS Level1A data were acquired and processed to Level2 using SeaDAS (V6.4). A fixed model pair aerosol correction approach was applied to the images to ensure high NIR reflectance due to scum was not interpreted as atmospheric aerosols. The resulting atmospherically corrected reflectance data were compared with several *in situ* reflectance measurements (Shuchman et al. 2013) with good agreement, indicating that this method produces acceptable reflectance data for cyanoHAB mapping in the Great Lakes waters.

The MCH and SSI were applied to all images. The resulting classified images were summarized to produce the annual extent statistics. Note for the analysis presented in this article, the MCH and SSI provide the presence and absence of cyanoHABs and are not quantitative estimates of bloom abundance. The classified images were also summed each year to produce cyanoHAB heat maps, which delineate the number of days cyanoHABs occurred at any given location in each of the three basins.

2.3 *Validation of the cyanoHAB mapping method*

The two cyanoHABs mapping approaches (MCH and SSI) were evaluated by comparing the field observations of cyanoHAB events in WBLE, GB, and SB. The accuracy of these approaches was evaluated on a pixel-by-pixel basis using comparisons between the two satellite HABs mapping approaches and *in situ* sampling. MODIS satellite images were identified and obtained within ±24 hours of a given field observation. This near-coincident data set ensures a reasonable comparison can be made between *in situ* and satellite observations.

These selected images were processed with the MCH approach. The output maps were queried at each matching sampling station using a 3-by-3 pixel average surrounding the actual sampling point. Spatial averaging was applied to account for cyanoHAB movement between the field sampling time and the image acquisition time. The retrieved satellite classification type (cyanoHAB or no cyanoHAB) was compared to the measured chlorophyll value and the presence of cyanoHAB at each corresponding site. If the satellite retrieval indicated cyanoHAB and the *in situ* data reported chlorophyll *a* values >18 mg m^{-3} with cyanoHAB noted from field sampling, then the modified CPA-A was deemed successful. The algorithm was also considered successful if the satellite retrieval indicated no cyanoHAB presence, the field chlorophyll value was <18 mg m^{-3}, and no cyanoHAB was noted in the field samples. During the five sampling years (2008, 2009, 2010, 2011, and 2013) there were 24 matches between sampling dates and clear satellite images in WBLE (11 days), GB (2 days), and SB (11 days). Sampling dates used in this comparison ranged from July to October. These matches produced 118 sampling station point comparisons to evaluate the modified MCH mapping approach in all three basins.

The new SSI was evaluated using data sets collected from WBLE in 2011 and 2013 and GB in 2012. There was no *in situ* scum data available for comparison in SB during the study period. There were a total of five satellite images, coincident with *in situ* scum (radiometer indicated) observations producing 40 matchups. Sampling sites with positive SSI values and *in situ* scums were compared to the satellite-derived surface scum image using a 3-by-3 window.

Standard statistical analysis (Spearman Rank correlation and ANOVA with post hoc analysis – TukeyKramer) was used for all comparisons (MATLAB). Statistical significance was set at alpha = 0.05.

3. Results

To determine the applicability of the new approaches for mapping the cyanoHAB extent in the Great Lakes, the output (MCH and SSI) was validated against *in situ* observations in WBLE, GB, and SB. Our new cyanoHABs mapping products agreed well with the *in situ*

Table 1. Classification error matrix for MCH *versus in situ* observations. MCH correctly classified 103 out of 118 comparisons for an overall accuracy of 87% and kappa of 0.74.

	In Situ			
	HAB	No HAB	Total	Users accuracy (%)
MCH				
HAB	46	9	55	84
No HAB	6	57	63	90
Total	52	66	118	
Producers accuracy (%)	88	86	**Overall accuracy (%) = 87 Kappa = 0.74**	

Table 2. Classification error matrix for SSI *versus in situ* observations. SSI correctly classified 37 out of 40 comparisons for an overall accuracy of 93% and kappa of 0.83.

	In Situ			
	Scum	No Scum	Total	Users accuracy (%)
SSI				
Scum	11	1	12	92
No Scum	2	26	28	93
Total	13	27	40	
Producers accuracy (%)	85	96	**Overall accuracy (%) = 93 Kappa = 0.83**	

cyanoHAB observations. The MCH approach performed well when cyanoHABs were both present (88%) and not present (86%), producing an overall mapping accuracy of 87% and kappa of 83%with the majority (nine) of misclassifications representing an over-prediction of HAB presence by MCH (Table 1). There were only six occasions where the satellite MCH failed to correctly classify as a cyanoHAB with respect to the field data. The misclassifications were likely due to mixed pixels as the misclassified points were near the edge of the algal bloom. The validation misclassification due to mixed pixels was an issue in the period of early bloom initiation (June/early July) and much less so during the period of bloom maximum extent (August–early October). The SSI approach also performed well when cyanoHAB scums were both present (85%) and not present (96%), yielding an overall mapping accuracy of 93% and kappa of 74% (Table 2). This successful validation demonstrates the applicability of our approaches to map cyanoHAB occurrences in the Great Lakes.

The annual cyanoHAB extent trends (derived from MCH) for WBLE, SB, and GB were not similar for the 2002–2013 period (all $r < 0.10$, all $p > 0.05$). The recent increasing trend in cyanoHAB occurrence observed in WBLE was not seen in GB or SB (Figure 3). In WBLE the maximum extent of cyanoHABs occurred in 2011 and 2013, whereas in SB the maximum extent occurred in 2002 and 2006 and in GB the maximum extent occurred in 2002 and 2012 (Figure 3). CyanoHAB surface scums were more common in WBLE than in SB and GB, where SSI values never exceeded 8 km^2 (Figure 4). In Lake Erie the maximum SSI values occurred in the same years as the MCH maximum, i.e. 2011 and 2013.

Significant temporal and spatial variabilities in cyanoHAB occurrences were observed within and among basins. The cyanoHAB occurrences range from 0 to 28 days in WBLE and SB, and from 0 to 14 days in GB (Figures 5–7). In the WBLE, cyanoHAB events most often occur in the southwestern area near the mouth of the Maumee River. Long-lasting cyanoHAB events were also observed in 2011 and 2013 around the islands to the west. Very few cyanoHAB events were observed near the mouth of the Detroit River in the north, with the exception of 2011. CyanoHAB events in SB occurred most frequently in

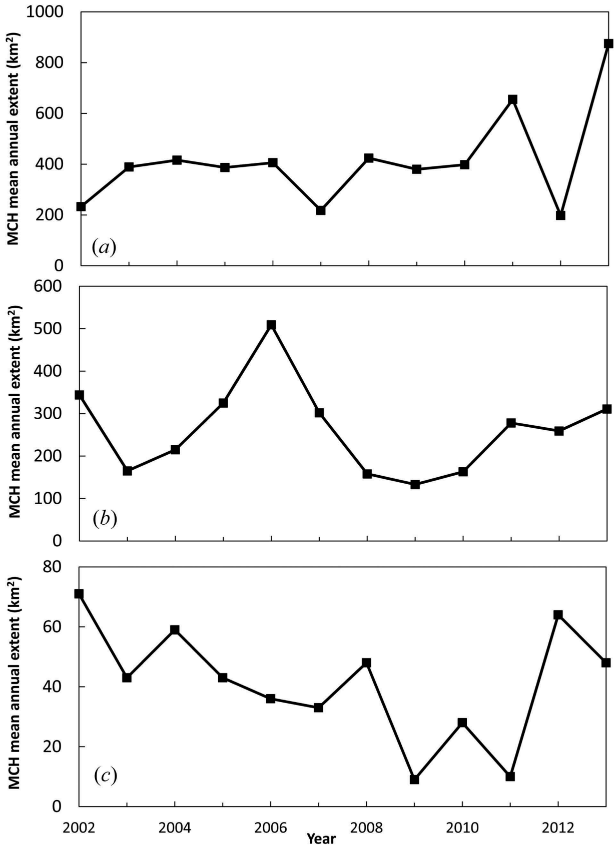

Figure 3. MCH-derived mean annual cyanoHAB extent for (*a*) WBLE, (*b*) SB, and (*c*) GB from 2002 to 2013.

the southeastern portion of the basin away from the mouth of the Saginaw River. Similar to WBLE, cyanoHABs in GB were most often observed near a dominant river mouth, the Fox River; however, the persistence was low (<7 days).

Annual mean air temperature (Celsius – °C) trends among the three basins were very similar for the 2002–2013 period (Figure 8). Although the trends among basins were highly correlated (all $r > 0.75$, all $p < 0.05$), there were significant differences in the mean values from 2002 to 2013 ($p < 0.05$; WBLE = 10.5°C, GB = 7.7°C, SB = 8.8°C). Annual mean air temperature explained more variance in cyanoHAB extent for WBLE than both mean and maximum summer (June–August) air temperatures (mean annual $R^2 = 0.22$, $p = 0.12$; mean summer $R^2 = 0.04$, $p = 0.53$; maximum summer $R^2 = 0.04$, $p = 0.56$). There was little explanatory difference between the three air temperature variables in SB (mean annual $R^2 = 0.12$, $p = 0.28$; mean summer $R^2 = 0.13$, $p = 0.24$; maximum summer $R^2 = 0.02$, $p = 0.67$) and GB (mean annual $R^2 = 0.03$, $p = 0.57$; mean summer $R^2 = 0.02$, $p = 0.66$; maximum summer $R^2 = 0.05$, $p = 0.50$).

Mean annual precipitation trends varied among basins during 2002–2013 (Figure 9). Mean precipitation trends for WBLE correlated significantly with SB ($r = 0.52$, $p < 0.05$), but not GB ($r = 0.25$, $p > 0.05$). There was no significant correlation between trends in the

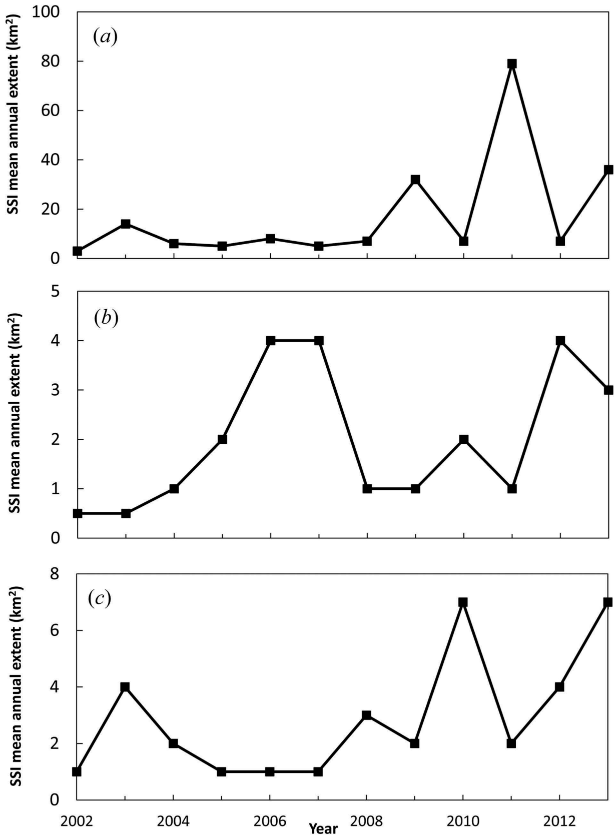

Figure 4. SSI-derived mean annual surface scum extent for (*a*) WBLE, (*b*) SB, and (*c*) GB from 2002 to 2013.

mean values for GB and SB ($p > 0.05$). For mean values during the study period (2002–2013), the only significant difference was noted between WBLE and SB ($p < 0.05$) (WBLE = 2.5 mm, SB = 1.8 mm, GB = 2.2 mm).

Mean annual and spring (March–June) discharge, Q, trends for the Maumee, Fox, and Saginaw Rivers were also compared from 2002 to 2013 (Figure 10(*a*,*b*)). There were no significant correlations (all $r < 0.40$, all $p > 0.05$) for mean Q, both annual and spring periods (March–June), among any of the three rivers. There were no significant differences in the overall mean spring Q among the rivers (Maumee River = 261 $m^3\ s^{-1}$, Fox River = 186 $m^3\ s^{-1}$, Saginaw River = 224 $m^3\ s^{-1}$; all $p > 0.05$); however, the Maumee River annual mean Q value (184 $m^3\ s^{-1}$) was significantly different from both Fox River (123 $m^3\ s^{-1}$) and Saginaw River (134 $m^3\ s^{-1}$) values ($p < 0.05$).

Mean spring and annual Q for the Maumee, Fox, and Saginaw Rivers were compared to both mean MCH and SSI cyanoHAB values for WBLE, GB, and SB from 2002 to 2013. Only for WBLE were significant relationships developed for the Q values and cyanoHABs measures (cubic for SSI, linear for MCH), and better predictors were developed for spring than for annual Q values. For spring Q values and annual SSI, a significant cubic (Figure 11(*a*)) relationship was observed (y = 3.29e-06x^3 − 0.002x^2 + 0.42x − 20.5, $R^2 = 0.77$, $p < 0.05$). There was no significant linear relationship between mean spring

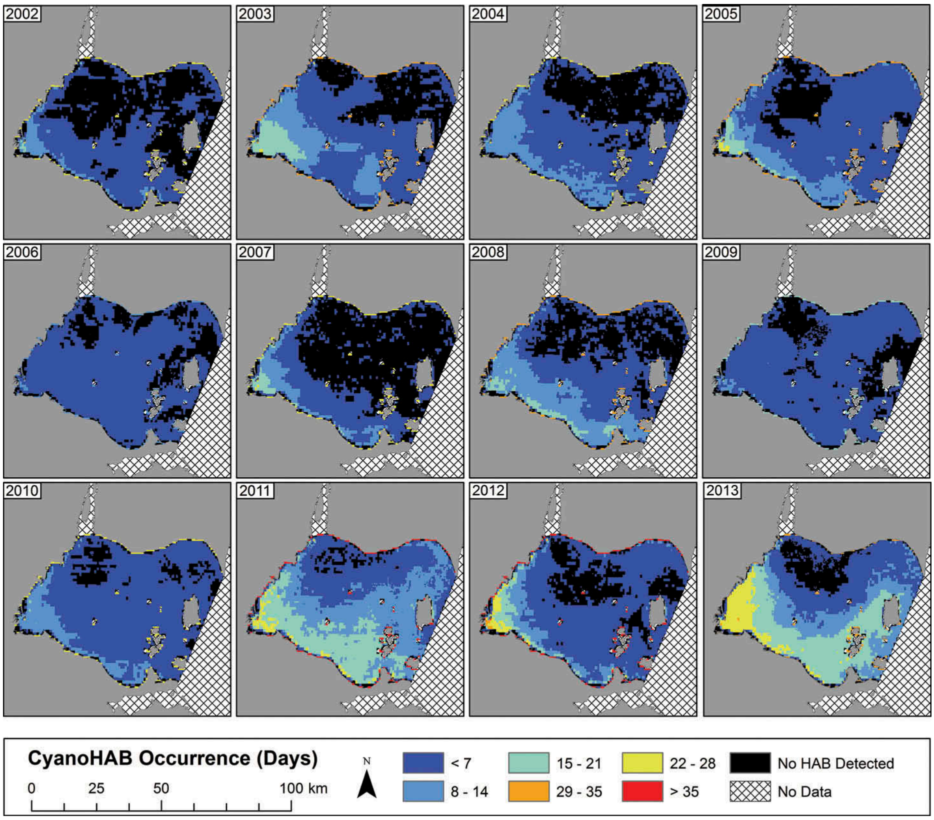

Figure 5. CyanoHAB occurrence maps for WBLE from 2002 to 2013. Coloured areas indicate the number of days cyanoHABs were present whereas areas in black experienced no cyanoHAB presence.

Q and MCH values for the Maumee River from 2002 to 2013; however, the relationship became significant (Figure 11(*b*), $y = 0.84x + 155$, $R^2 = 0.50$, $p < 0.05$) when 2013 was removed from the data set as a statistical outlier defined as greater than two standard deviations (σ = 188 km^2) from the mean (415 km^2). For SB and GB, no significant relationships were observed, either linear or cubic, between spring *Q* and mean annual MCH or SSI values from 2002 to 2013 (Figure 11(*c*–*f*)). For annual *Q* and annual HABs (MCH and SSI), there were no significant relationships between the mean annual *Q* and MCH values for any of the three rivers; however, the relationship between the Maumee River and the WBLE MCH values again became significant ($y = 1.6x + 88$, $R^2 = 0.49$, $p < 0.05$) when 2013 was removed from the data set. There was also a significant cubic relationship observed between Maumee River annual *Q* and SSI values ($y = 3.82\text{e-}05x^3 - 0.02x^2 + 3.34x - 166.4$, $R^2 = 0.76$, $p < 0.05$). There were no significant relationships, either linear or cubic, between the annual *Q* and annual MCH or SSI values for GB or SB from 2002 to 2013 (all $p > 0.05$).

Strong wind events are possible meteorological drivers for cyanoHAB occurrence in the Great Lakes (Millie et al. 2009; Michalak et al. 2013). Wind-induced sediment re-suspension events were summed for the bloom period (July–September) in WBLE, GB,

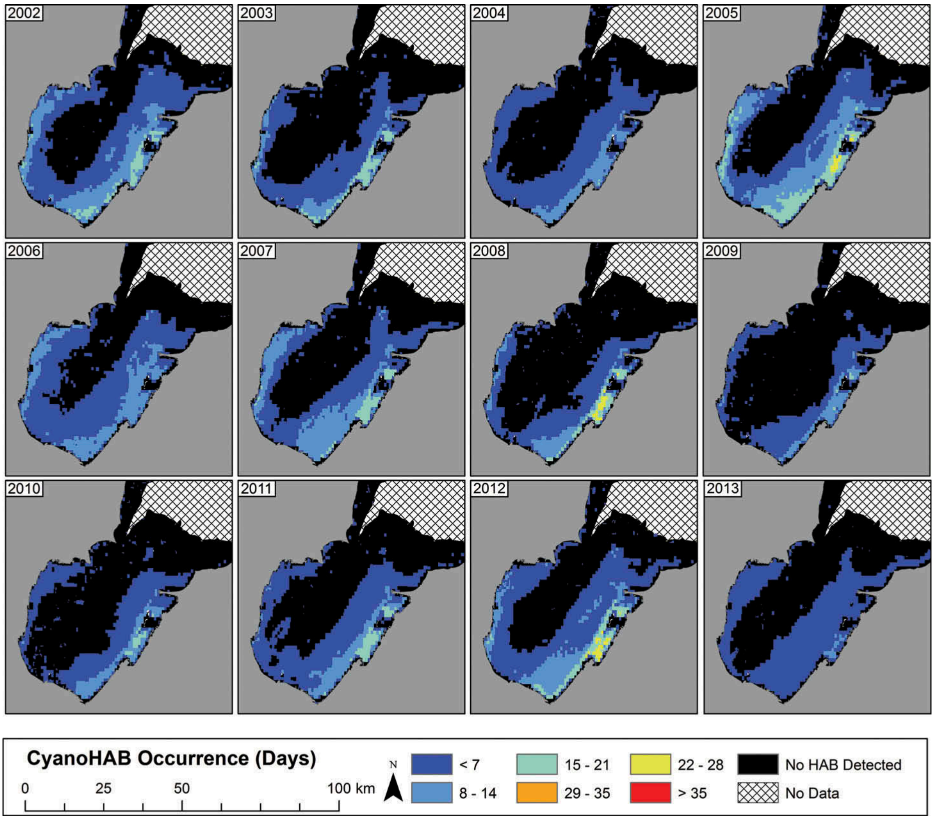

Figure 6. CyanoHAB occurrence heat maps for SB from 2002 to 2013. Coloured areas indicate the number of days cyanoHABs were present whereas areas in black experienced no cyanoHAB presence.

and SB for 2002–2013. The number of bloom period sediment re-suspension events varied considerably in WBLE, with a maximum of 11 in 2011 and a minimum of 0 in 2007 (Figure 12). During the study period (2002–2013), there were no strong wind-induced re-suspension events in GB and only one in SB in 2012. These notable differences among regions are probably the result of bloom station location and not meteorological differences among basins.

In WBLE wind-induced sediment re-suspension events during the bloom period (July–September) were compared to mean annual MCH and SSI values. Significant relationships were identified for both MCH (Figure 13(*a*), $y = 39x + 308$, $R^2 = 0.40$, $p < 0.05$) and SSI values (Figure 13(*b*), $y = 6.1x + 0.76$, $R^2 = 0.69$, $p < 0.05$). The points at the high end of the regression lines in Figure 13(*a*,*b*) correspond to the 2011 cyanoHAB event.

4. Discussion

The usefulness of the new MCH and SSI approaches for estimating the water column and surface scum cyanoHAB extents in the Great Lakes has been demonstrated in this

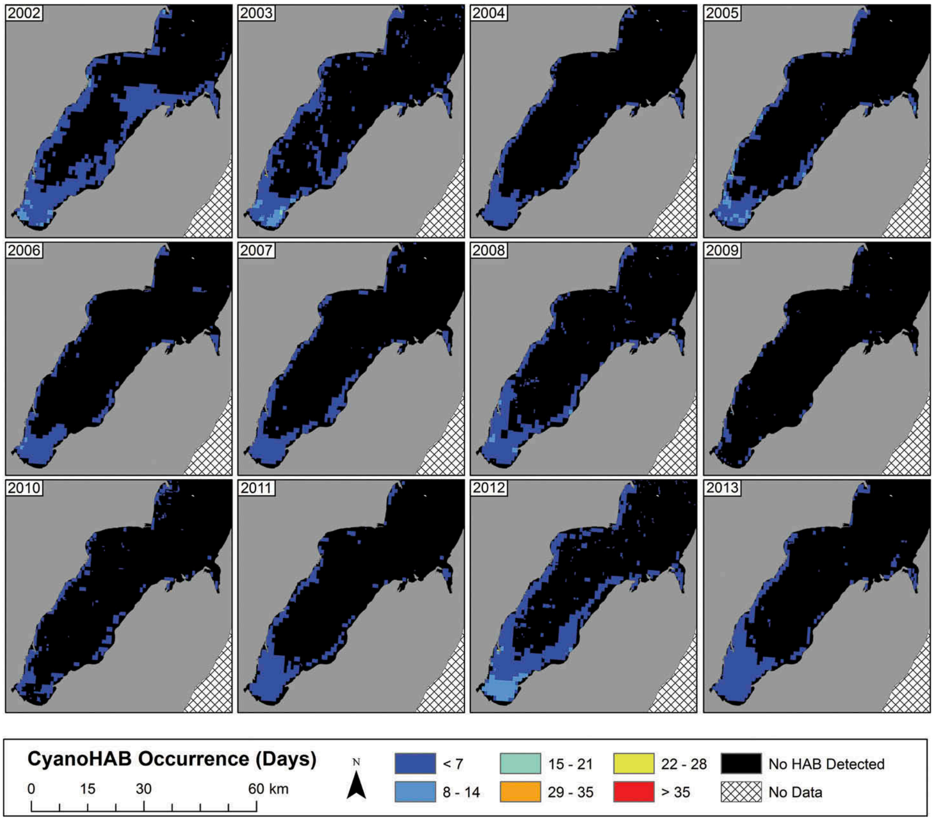

Figure 7. CyanoHAB occurrence heat maps for GB from 2002 to 2013. Coloured areas indicate the number of days cyanoHABs were present whereas areas in black experienced no cyanoHAB presence.

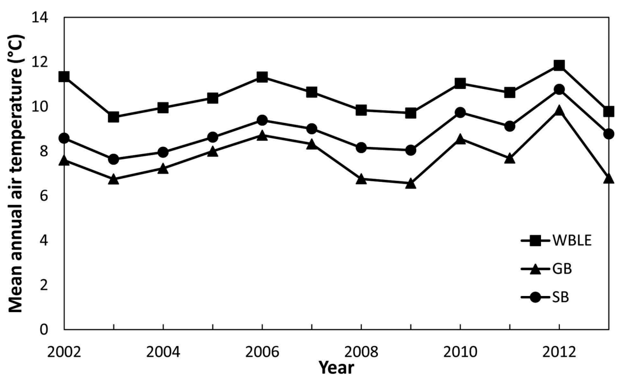

Figure 8. Mean annual air temperature for WBLE, GB, and SB from 2002 to 2013.

study. These two new products augment the HABs mapping product (i.e. cyanobacteria index, CI) developed for western Lake Erie (Wynne and Stumpf 2015; Wynne et al. 2008; Stumpf et al. 2012). Our new cyanoHAB extent products produced annual trends that are similar to those achieved by prior investigators using the MERIS sensor, which has bands

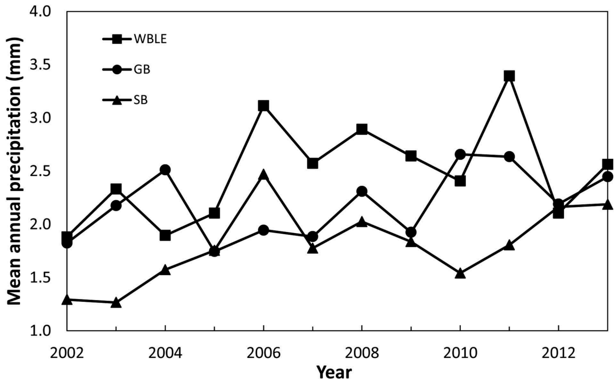

Figure 9. Mean annual precipitation for WBLE, GB, and SB from 2002 to 2013.

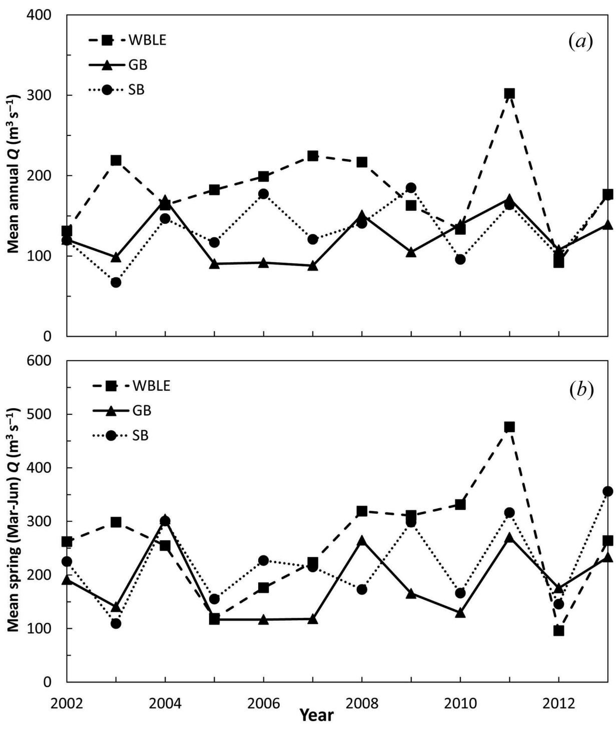

Figure 10. (*a*) Mean annual river discharge, *Q*, for WBLE (Maumee River), GB (Fox River), and SB (Saginaw River). (*b*) Mean spring (March–June) river discharge, *Q*, for WBLE (Maumee River), GB (Fox River), and SB (Saginaw River). Note that the y-axis scale ranges are different.

sufficient for detecting phycocyanin directly. For example, both MCH and SSI mean annual extent trends compared well with estimates reported by Stumpf et al. (2012) for the 2002–2011 period (MCH R^2 = 0.66, $p < 0.05$; SSI R^2 = 0.91, $p < 0.05$). The WBLE cyanoHAB occurrence maps (Figure 5) generated in this study also show similar patterns as those presented by Wynne and Stumpf (2015), where the most persistent and intense blooms tend to be located in Maumee Bay and along the southern shore of WBLE. The

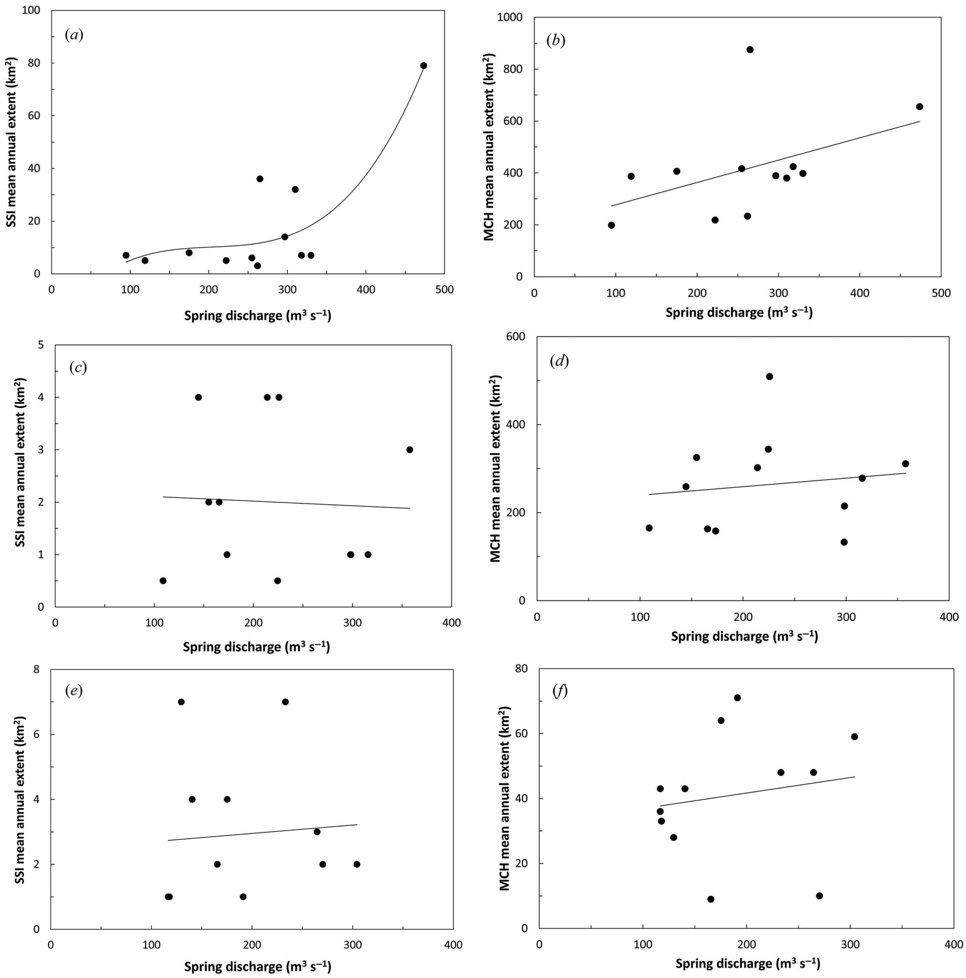

Figure 11. (*a*) SSI mean annual extent *versus* spring discharge for WBLE ($y = 0.0008x^2 - 0.2844x + 29.226$, $R^2 = 0.75$, $p < 0.05$). (*b*) MCH mean annual extent *versus* spring discharge for WBLE with 2013 removed as a statistical outlier ($y = 0.84x + 155$, $R^2 = 0.50$, $p < 0.05$). (*c*) SSI mean annual extent *versus* spring discharge for SB ($p > 0.05$). (*d*) MCH mean annual extent *versus* spring discharge for SB ($p > 0.05$). (*e*) SSI mean annual extent *versus* spring discharge for GB ($p > 0.05$). (f) MCH mean annual extent *versus* spring discharge for GB ($p > 0.05$).

maps presented by Wynne and Stumpf (2015) also show very little cyanoHAB occurrence in the Detroit River outflow in the northern end of WBLE. Moreover, this study reports for the first time satellite-derived cyanoHAB estimates in GB and SB. Our two new approaches have three advantages over those that rely on phycocyanin detection bands: (1) MCH uses a multi-spectral bio-optical model to deconvolve observed spectra into water constituent concentrations, thus eliminating the need for pure cyanobacteria spectra; (2) it can be applied to other sensors with sufficient spectral specifications to produce accurate chlorophyll *a* concentrations to extend time series continuity; and finally (3) it expressly delineates surface scum accumulations, which often indicate areas of public health concern (i.e. extremely high toxin content). These new approaches have

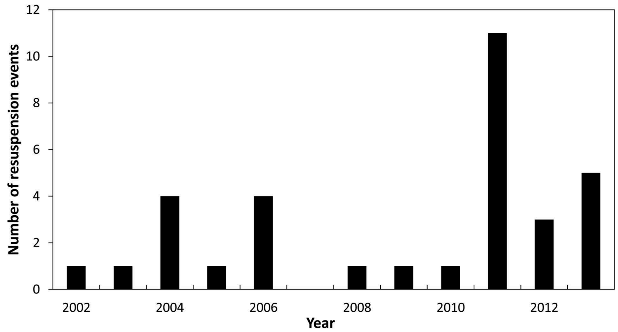

Figure 12. The number of wave-induced sediment re-suspension event occurrences in the cyanoHAB period (July–September) for WBLE from 2002 to 2013.

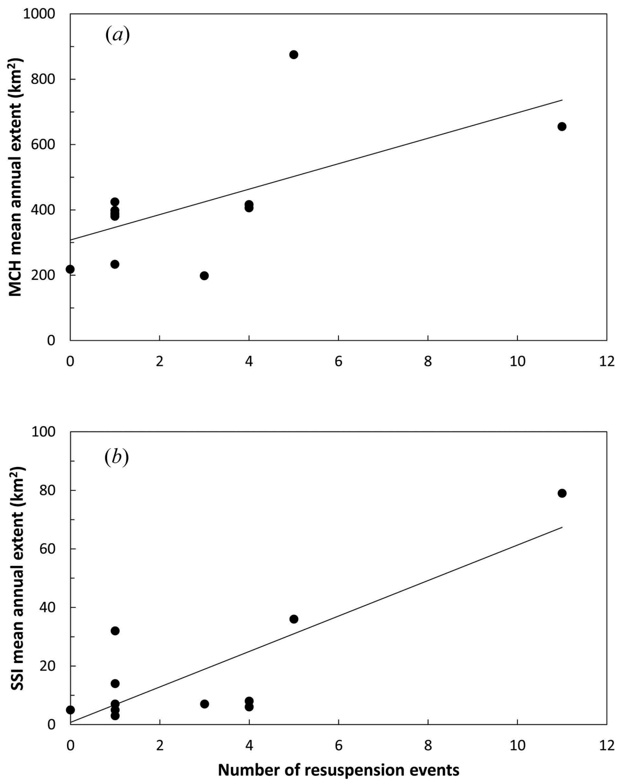

Figure 13. The number of sediment re-suspension events in the bloom period (July–September) from 2002 to 2013 for WBLE *versus* (*a*) MCH-derived mean annual cyanoHAB extent ($y = 39x + 308$, $R^2 = 0.40$, $p < 0.05$). (*b*) SSI-derived mean annual surface scum extent ($y = 6.1x + 0.76$, $R^2 = 0.69$, $p < 0.05$).

provided several new insights into the role of regional and local control on cyanoHAB occurrence in the Great Lakes.

Mean annual HAB extent trends among WBLE, GB, and SB from 2002 to 2013 varied among the study period, and, in particular, demonstrated a departure in recent years.

Both mean annual MCH and SSI extents were significantly different among basins with extensive and persistent HAB events in 2011 and 2013 in WBLE, whereas GB and SB experienced mild events in those years. Thus, the recent trend of increasing HABs in WBLE noted by Michalak et al. (2013) was not found in SB or GB. Furthermore, there were drastic differences in cyanoHAB persistence among basins, with parts of WBLE experiencing cyanoHAB conditions for more than 30 days in recent years (2011–2013), whereas GB and SB are under those conditions for less than 15 days. These dissimilarities in extent and duration indicate substantial annual differences in controlling factors among the basins and/or locally varying relationships between these controlling factors and cyanoHAB occurrence.

The recent increase in cyanoHABs in WBLE has been attributed to increased nutrient loading (local control) and climate change (regional) (Michalak et al. 2013). Because no increase in cyanoHABs was noted in either SB or GB in recent years, it is likely that dissimilarities in these environments are likely more important in controlling the annual cycle of cyanoHABs than regional climate. Climate change may increase the frequency of cyanoHABs within all eutrophic basins in the Great Lakes, but controlling local factors (nutrients, invasive species, etc.) need more attention for the mitigation of cyanoHABs.

Although these three shallow, eutrophic basins in the Great Lakes appear to be similar, they have important differences. For example, the basins vary tremendously in morphometry (i.e. mean depth, retention time, etc.), land use, and latitude (i.e. meteorology) within each basin. Water depth characteristics for the three basins are considerably different, undoubtedly affecting the hydrodynamic processes including water column mixing and sediment re-suspension (WBLE mean ~7.5 m, maximum <20 m; GB mean 16 m, maximum >30 m; SB mean ~4.5 m inner bay and 15 m outer bay, maximum >40 m). The hydraulic retention time of each basin also varies (WBLE ~35 days, SB ~60 days, GB ~290 days) considerably, thus affecting the dispersion rates of phosphorus and other nutrients delivered from river discharge. Agricultural land use, through fertilization practices, is the primary upland source of nutrients into the dominant rivers, and varies among basins. For example, agricultural land use in the Maumee River watershed is almost two-fold greater than both Saginaw and Fox River watersheds (Maumee River ~80%, Saginaw River ~48%, GB ~44%). Locational differences of the basins with respect to latitude also play a key role in meteorological dissimilarities. For example, significant differences in the mean annual air temperature were observed between basins, where GB was cooler than both SB and WBLE, which was probably related to latitudinal variation.

These basin differences contribute to the dominant role that local factors play in controlling the annual trend in cyanoHABs even though nutrient loading in all three basins is dominated by one or two rivers. The role of these major rivers in controlling annual HABs varies as evident by the relationships between river discharge and cyanoHAB extent. Only for WBLE were significant relationships developed between spring (March–June) river discharge, Q, of the Maumee River and both SSI (cubic) and MCH (linear) extents, excluding 2013. No significant relationship was observed between spring *Q* and cyanoHAB occurrence for either GB (Fox River) or SB (Saginaw River). Similarly, several spring monthly discharge rates (March–May) exhibited significant relationships with cyanoHAB extents in WBLE. In GB and SB, only a few monthly discharge rates were correlated with cyanoHABs and most were from summer and fall

(June–September). The stronger relationship between discharge of the Maumee and WBLE cyanoHABs might be surprising given the Saginaw River and the Fox River contributes almost 90% and 70% of the loading to SB and GB, respectively, whereas the Maumee River contributes only 40% of the nutrient loading to the WBLE.

Our relationships between spring *Q* and cyanoHABs in WBLE are similar to those relationships noted by other investigators. Stumpf et al. (2012), using MERIS data for 2002–2011, developed a predictive model between spring *Q* and cyanoHABs in WBLE. The cubic relationship established between SSI and spring *Q* for WBLE was expected as Stumpf et al. (2012) observed a similar relationship between spring *Q* and their annual CI concentrations. Both of these relationships are heavily influenced by the 2011 cyanoHAB occurrence, which has been documented as the most severe on record (Bridgeman, Chaffin, and Filbrun 2013; Michalak et al. 2013). Obenour et al. (2014) proposed a Bayesian model linking cyanoHAB size to total phosphorus loading from the Maumee River. Obenour et al. (2014) also note that WBLE is becoming increasingly susceptible to extensive blooms, independent of loading, suggesting other environmental processes may ultimately be controlling bloom formation. These other potential controlling processes may be responsible for the observed large MCH extent in 2013 while Maumee spring *Q* for that year (261 $m^3\ s^{-1}$) was very similar to the 2002–2013 mean Maumee *Q* (265 $m^3\ s^{-1}$). Presently, there has been no attempt to apply these approaches to the other eutrophic basins in the Great Lakes where cyanoHABs occur. The results of this study demonstrate the apparent inability of spring *Q* to predict the cyanoHAB extent in SB or GB, suggesting that other local factors (basin morphometry, physical mixing and forcing, delivery of nutrients, local meteorology, etc.) influence the development of cyanoHABs.

The importance of local factors in controlling HABs in these basins extends to meteorological forcing such as re-suspension or complete water column mixing. Despite the general similarity of basins, only one of these regions (WBLE) had a large number of sediment re-suspension events during the bloom period. Moreover, the number of re-suspension events was related to the cyanoHAB extent in WBLE. In SB and GB very few events were noted, most likely due to the location of the bloom areas within each basin and the basin morphometry. Previous investigators have noted the possibility that sediment re-suspension is an important seeding mechanism for cyanoHAB. Bottom sediment reservoirs in WBLE have been shown to contain cyanobacteria cells that, when released back into the water column through wave-induced re-suspension, can contribute to bloom formation (Rinta-Kanto et al. 2009). Michalak et al. (2013) hypothesized for the 2011 WBLE bloom that strong winds and associated re-suspension events immediately preceding bloom onset contributed to rapid initial bloom formation; however, it was also suggested that a higher frequency of quiescent conditions after bloom onset was more conducive to bloom growth (Millie et al. 2009). The exact relationship between cyanoHAB events and meteorological forcing in these three basins needs to be examined with greater temporal (days-weeks) and spatial (1 km to tens of kilometres) resolution. The results of this study have demonstrated for WBLE that more frequent re-suspension events in the bloom period (July–September) are moderately associated with larger annual HAB extents.

The local differences among cyanoHAB occurrences in these three basins extend to physical/biological factors as well. Large-scale scums (high SSI values) were noted in

WBLE but not in SB or GB despite the presence of large cyanoHABs in all three environments. For example, WBLE produced large mats (>30 km^2) of surface scum in 2011 and 2013, whereas GB and SB produced limited scum (<8 km^2) for the study period. Scums in WBLE accounted for up to 10% of the total HAB extent, but in GB and SB they account for less than 1%. These observed differences in scum occurrence are not unique to the Great Lakes as cyanoHAB surface scums have been shown to vary considerably in different waterbodies throughout the world (Jupp, Kirk, and Harris 1994; Quibell 1992; Galat and Verdin 1989). Some evidence suggests that cyanoHAB scum formation is a mechanism to achieve dominance over other phytoplankton communities, and is regulated by biological and physical parameters (Paerl and Ustach 1982). However, it is not clear whether physical (calm periods, etc.) or biological (physiological difference associated with clonal variations, etc.) factors are dominant in contributing to the variability among scums in these three Great Lakes basins.

One of the most important contributions of this study is the refinement and application of an index that can classify the presence of surface scum accumulations of cyanobacteria in the Great Lakes, and likely many other environments. Cyanobacteria often form surface scums (Zohary and Robarts 1990; Paerl and Ustach 1982; Sellner 1997) where extremely high cell densities are found. High toxin concentrations are often associated with these scums, and health organizations have used the presence of scums as an important health signal (Bartram and Rees 1999). Because of this link between scums and the possible high concentrations of toxins, our approach not only is useful for tracking HABs but may also serve as an initial public health alert. Moreover, because this approach does not depend on local empirical relationships such as MCH or any specific calibration, and is defined directly for apparent optical properties, it could likely be used as a generic scum classification index. Thus, it is likely that we have developed a simple, generic classification approach capable of providing useful public health information on cyanoHABs from remote-sensing platforms.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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