Sub-Indicator: Algal Bloom Extent

Overall Assessment

Status: Poor

Trends:

10-Year Trend (2014-2023): Unchanging

Long-term Trend (2012-2023): Unchanging

Rationale: Algal blooms are regularly observed in the western basin of Lake Erie, Green Bay (Lake Michigan), Saginaw Bay (Lake Huron), and Lake St. Clair. Algal bloom occurrences are very limited in the shallow waters of Lake Ontario but have occurred notably within Hamilton Harbour and Bay of Quinte in Ontario. Episodic algal blooms have been reported in Lake Superior over the last decade, particularly in the western arm of the lake and in the Apostle Islands area, but for the most part these blooms are infrequent, short-lived, small in area, and localized to the shallow regions of the lake. This sub-indicator utilizes satellite-derived bloom metrics (see "Methods" section) that consider the annual extent (by percent coverage) of algal blooms in the shallow (≤ 16 m) waters of each of the five Great Lakes. These shallow areas were chosen as the focus of this report based on the recommendation of ≤ 15 m in Binding et al. (2015). However, the study area was adjusted to ≤ 16 m due to the resolution of the available bathymetric data. Imagery from the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite is used to identify probable algal bloom occurrences in these shallow areas when critical conditions are met for cyanobacteria algal bloom proliferation (i.e., surface water temperature > 20 °C and chlorophyll-a concentration > 18 mg/m3; see Sayers et al. 2016, 2019). This metric does not indicate algal boom duration or concentrations of toxins but has been shown to accurately detect cyanobacteria algal bloom presence and extent within western Lake Erie, Saginaw Bay, and Green Bay; it therefore is expected to be reliable for bloom detection in the shallow areas throughout the lakes. This report does not consider the deeper, offshore areas of the Great Lakes because satellite imagery suggests blooms rarely occur in those areas. The 12-year period between 2012 and 2023 was the focus of the analyses in this report because these were the years in which VIIRS data was available for the Great Lakes. As such, we reported 10-year trends (from 2014-2023) and used the full 12-year time series to represent the long-term trend for this report. Based on available data and the present approach, slightly more than 20% of the assessed shallow-water area of the Great Lakes experiences algal blooms and conditions are therefore assessed as Poor (Fig. 1). This is driven largely by the algal blooms in western Lake Erie, which account for a relatively large portion of the shallow (≤ 16 m) areas of the Great Lakes, and to a lesser extent those in Green Bay and Saginaw Bay. Based on data from 2014-2023, the extent of algal blooms in the shallow areas of the lakes is declining, but not significantly, so the 10-year trend is therefore assessed as Unchanging.

Lake-by-Lake Assessment

Lake Superior

Status: Undetermined

10-Year Trend (2014-2023): Undetermined

Long-term Trend (2012-2023): Undetermined

Rationale: Algal blooms are not spatially prevalent in the cold, deep and low productivity waters of Lake Superior, and are difficult to observe by satellite in nearshore waters. The average annual bloom extent in the shallow-water

area that is currently observable via satellites has remained at less than 1% of those shallow areas since 2021, which suggests that algal bloom conditions are Good (Fig. 3). However, the remote sensing methods used in this report are unable to evaluate most of Lake Superior's shallow-water areas due to spectral interference from land (Fig. 4). Reports of non-toxic, ephemeral blooms in shallow areas have increased since the beginning of the analysis period for this report (2012); and some of these events have been notable. These blooms are often associated with severe storm events which can deliver unusually high amounts of nutrients from the watershed (Sterner et al., 2020). Localized, ephemeral blooms have been documented in the Duluth Superior Harbor (since 2012), around the Apostle Islands (since 2015), near Thunder Bay (in 2019), and near Terrace Bay, ON (in 2020). In 2012, after a record-breaking flood event in Duluth, blooms were detected in about 10% of the Lake Superior shallow water area extending from the nearshore into the open waters of the western arm of Lake Superior. Given the limitations of detecting ephemeral blooms in parts of the lake where blooms have most often occurred, the status and the 10-year and long-term trend were assessed as Undetermined in this report (see Discussion section).

Lake Michigan

Status: Fair

10-Year Trend (2014-2023): Unchanging

Long-term Trend (2012-2023): Unchanging

Rationale: Cyanobacteria blooms are reported in many of the river mouths along the western shore of Lake Michigan and eutrophic embayments such as Muskegon Bay and Green Bay (Fig. 6). The algal bloom occurrence heat maps indicate algal blooms are most prevalent on the southern end of Green Bay where the Fox River drains into the embayment (Fig. 7). In more severe bloom years (e.g., 2012, 2020), the blooms extend further north along either the eastern or western shorelines of Green Bay. Blooms consistently occurred in 5-20% of the shallow areas of Lake Michigan during 2012-2023 and the average coverage between 2021 and 2023 was 14%. Conditions were therefore assessed as Fair (Fig. 5). Regression analysis for both the 10-year and 12-year data record suggests that that the trend is Unchanging. These trends largely reflect conditions in Green Bay, where blooms are most common and extensive.

Lake Huron

Status: Fair

10-Year Trend (2014-2023): No Trend

Long-term Trend (2012-2023): No Trend

Rationale: Lake Huron is generally oligotrophic throughout the offshore and in many shallow regions, but experiences algal blooms in some embayments, most notably Saginaw Bay in the summer months (Fig. 9). Between 2012-2023, algal blooms occurred in 8-20% of the shallow-water area in 7 of 12 years, but did exceed 20% of the shallow-water area in 2012-2014 and 2019-2020 (Fig. 8). During 2021-2023, the average coverage of algal blooms in the shallow-water areas was about 14%, so conditions in Lake Huron are therefore assessed as Fair and the trend is Unchanging due to the lack of a significant temporal trend from 2012-2023 or 2014-2023 (Fig. 8). The status of algal blooms in Lake Huron largely reflects conditions in Saginaw Bay, where algal blooms are the most common and extensive (Fig. 10), especially in the southeastern section. This algal bloom trend assessment is consistent with Wynne et al. (2021), which noted an unchanging trend in cyanobacteria biomass from 2000 to 2019 for Saginaw Bay.

Lake Erie

Status: Poor

10-Year Trend (2014-2023): Unchanging

Long-term Trend (2012-2023): Unchanging

Rationale: Lake Erie continues to experience algal blooms, most notably in the western basin. Remote sensing heat maps (Fig. 13) indicate that since 2015, algal blooms occur annually along the Ohio shoreline, in the mouth of Maumee River (Matson et al., 2020) and also extend halfway up the Michigan shoreline. Blooms also regularly occur in the central basin, primarily along the southern shore and occasionally occur in the eastern basin (Fig. 12). Since 2012, percent coverage has typically ranged between 40-60% of the shallow-water area with four years exceeding 60% (2012, 2015, 2016, and 2021) and 2021 exceeding 70%. The average coverage between 2021-2023 being 54%. Neither the 10- or 12-year data record shows a significant trend, so the status and trend are Poor and Unchanging, respectively (Fig. 11).

Lake Ontario

Status: Good

10-Year Trend (2014-2023): Unchanging

Long-term Trend (2012-2023): Unchanging

Rationale: Annual algal bloom percent coverage for Lake Ontario from 2012-2023 derived from VIIRS satellite data was consistently very low, with little to no evidence of algal blooms over the time period. Sparse blooms are occasionally observed in the shallow waters and cover small amounts of area (Figs. 14, 15), with more notable events occurring along the far eastern shoreline. While the methods used in this report are unable to detect blooms that occur in some shallow areas of the lake with known bloom occurrences (i.e., Hamilton Harbour and Bay of Quinte) due to spectral interference from the adjacent land (Fig. 15), these blooms would not account for more than 5% of the shallow-water area if they were detected by the satellite. Average bloom coverage from 2021-2023 was 0.2% and conditions based on the assessed area are therefore considered Good. There was no discernable trend in the amount of detectable bloom coverage from 2012-2023 or 2014-2023, so the trend is considered Unchanging (Fig. 14).

Status Assessment Definitions

Status assessments were based on the average shallow-water (areas ≤ 16 m deep) areal extent of suspected algal blooms during 2021-2022 according to the VIIRS data. Bloom extent estimates were compared to the following thresholds to determine status:

Good: <5% of the shallow-water area assessed (based on average extent for 2021-2023) experienced algal bloom conditions.

Fair: 5-20% of the shallow-water area assessed (based on average extent for 2021-2023) experienced algal bloom conditions.

Poor: >20% of the shallow-water area assessed (based on average extent for 2021-2023) experienced algal bloom conditions.

Undetermined: Data are not available or are insufficient to assess the condition of the ecosystem components.

See Methods section for a description of metrics.

Note that bloom extent estimates for each lake exclude a small (for Lakes Erie, Huron, and Michigan) to moderate (for Lakes Superior and Ontario) portion of shallow-water areas along the shoreline due to limitations of this satellite approach in shallow water adjacent to land. The status assessments in this report reflect conditions in assessed shallow-water areas. Conditions in the unassessed areas are discussed in the Discussion section below.

Blooms are difficult to detect in Lake Superior given these methods. Given the differences in blooms between Lake Superior and the other lakes, these thresholds are not applied to Lake Superior. Results for Lake Superior are described in the Discussion section below, but status and trends are assessed as Undetermined for this cycle.

Trend Assessment Definitions

Trend assessments were performed using regression analysis of average annual bloom extent and the following criteria:

Improving: Algal bloom extent estimates show a significant ($p < 0.05$) decrease in average Algal bloom extent over the time period in question.

Unchanging: Algal bloom extent estimates show no significant change ($p > 0.05$) over the time period in question.

No Trend: The trend is not statistically Improving or Deteriorating and there is high variability in the data. No Trend is different from Unchanging (which would be used when the trend is not statistically significant and has low variability (i.e., stable).

Deteriorating: Algal bloom extent estimates show a significant ($p < 0.05$) increase in average Algal bloom extent over the time period in question.

Undetermined: Data are not available or are not sufficient to report on a trend.

Endpoints and/or Targets

The endpoint for this sub-indicator report is that all lakes should have minimal occurrences and extent of algal blooms. This target should ensure that cyanobacteria biomass remains at levels that do not produce concentrations of toxins that pose a threat to human health in the waters of the Great Lakes. The method used to estimate bloom extent in this report does not include in situ toxicity data. Toxicity data will likely be included in future reports.

Sub-Indicator Purpose

The purpose of this sub-indicator is to assess potential harm to human health, pets, and other organisms or ecosystems from algal blooms, particularly harmful algal blooms (HABs).

Ecosystem Objective

This sub-indicator best supports work towards General Objective #6 of the 2012 Great Lakes Water Quality Agreement, which states that the waters of the Great Lakes should “be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote the growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem.”

To this end, waters should be safe for drinking and recreational use and substantially free from toxic and/or high abundances of noxious cyanobacteria or algae that may harm humans, animals, or ecosystem health or have other significant adverse effects.

Methods

Algal blooms are highly dynamic in space and time, leading to severe limitations of in situ sampling for capturing whole lake conditions, identifying areas of potential concern, and documenting long-term trends. Bloom monitoring capabilities have been enhanced greatly by advancements in satellite remote sensing, offering the spatial coverage and temporal repeat visit times required for comprehensive, synoptic monitoring of bloom conditions across the Great Lakes. Multiple remote sensing algorithms are used to extract chlorophyll concentrations or cyanobacteria biomass to describe the spatial extent or intensity and severity of algal bloom conditions in the Great Lakes and the climatological record of satellite imagery allows interpretations of historical trends over basin-wide features. The maturity of science in algorithm and product development is such that several operational remotely sensed algal bloom products are now available for the Great Lakes and are distributed to the research and water-resource management stakeholder community (e.g., NOAA's HABTracker, Stumpf et al., 2016, and ECCC's EOLakeWatch, Binding et al. 2021). Acknowledging that there are a large number of algorithms and sensors available to the community, the focus here is on the processing streams of operational remote sensing products for algal blooms delivered by the Michigan Tech Research Institute (MTRI). The algorithm approaches are based on detecting key bio-optical properties of algae and cyanobacteria (e.g., absorption, backscatter, fluorescence) across the electromagnetic spectrum using semi-analytical inverse models developed by MTRI. MTRI generates annual estimates of remote sensing derived mean and maximum algal bloom areal extents for western Lake Erie, Saginaw Bay, and Green Bay. MTRI also uses this approach to generate annual extents of surface cyanobacteria scums in the western basin of Lake Erie.

MTRI's approach for assessing algal bloom extent in Green Bay, Saginaw Bay, and western Lake Erie is a modified Color Producing Agent Algorithm for HABs (MCH). Taken from Sayers et al. (2019), "the MCH approach was a modification of the Color Producing Agent Algorithm (CPA-A), a semi-analytical bio-optical chlorophyll-a retrieval algorithm which simultaneously optimizes estimated concentrations for all three optically active constituents (chlorophyll, non-algal particles, and colored dissolved organic matter, CDOM) using a hydro-optical model derived from extensive in situ measurements collected in western Lake Erie" (Shuchman et al., 2006, Shuchman et al., 2013). For algal bloom detection, the CPA-A is enhanced with empirical relationships between chlorophyll-a and environmental variables (e.g., water surface temperature) and is leveraged using the observed linear relationship between surface chlorophyll-a and phycocyanin pigment concentrations to estimate surface water algal blooms. In this approach, a threshold value of 18 mg/m3 of chlorophyll-a was used to classify pixels as algal blooms based on segmented regression analysis (Sayers et al. 2016).

For this report, these methods have been applied to all shallow-water areas of the Great Lakes which were defined as all areas ≤ 16 m deep similar to the nearshore/offshore delineation of satellite-derived water clarity used in Binding et al. (2015). A cutoff of 16 m was used rather than the 15 m in Binding et al. (2015) to delineate the nearshore due to limitations in the resolution of the bathymetric dataset used. The annual shallow-water algal bloom extent estimates from 2012-2023 were generated for each lake using the MTRI CPA-A applied to VIIRS satellite data. For each year, cloud-free image pixels were processed with the CPA-A from the April-October period. A cyanobacteria bloom occurrence was recorded if a pixel had a chlorophyll-a concentration value ≥18 mg/m3 and a surface temperature ≥20°C in at least one image for the April-October period. For each year, the percent of the total shallow-water area that experienced at least one day of an algal bloom was computed as the assessment metric. Trends in the algal bloom occurrence metric from 2012-2023 were established for each lake

and tested for statistical significance (i.e., linear regression). It should be noted that because this methodology does not include empirical relationships to better define blooms as harmful in areas outside of western Lake Erie, Green Bay, and Saginaw Bay, this metric is aimed at identifying cyanobacterial blooms of any composition which may or may not be harmful.

The status thresholds for algal bloom spatial extent were chosen as <5% of the lake nearshore area with algal bloom coverage representative of Good conditions, between 5-20% representative of Fair conditions and >20% as representative of Poor conditions. (Table 2.0). These ranges were based on a priori knowledge of bloom coverage and seasonal and episodic events from historical satellite data and on-water field sampling of algal blooms for each of the Great Lakes. These values could be reevaluated in the future with input from the Great Lakes algal bloom community, to ensure that each lake has an appropriate threshold.

Discussion

Background

Algal blooms, including cyanobacterial harmful algal blooms (cHABs) and/or harmful algal blooms (HABs) are a global issue in eutrophic waters with high nutrient loadings. cHABs/HABs can be differentiated from 'non-harmful' (i.e., nuisance) blooms by their impacts on water quality and biota, generally associated with the production of toxins. Nuisance algal blooms (NABs) are a separate subclass of algal blooms whose impact on the ecosystem is generally associated with elevated levels of biomass and not with the production of toxins. cHABs/HABs and NABs can have detrimental impacts on ecosystem services provided by water bodies and negatively impact aesthetics or recreational use of water bodies. Prior to remediation in the late 1970s, cHABs/HABs and NABs were a major problem in many offshore and shallow-water areas in the Great Lakes (e.g., Watson et al. 2008, 2009) and at that time, the risk of toxins had not been widely recognized and concerns focused on reduced aesthetics, taste and odour (T&O), food web structure, beach/intake/net fouling and economic impacts. Lake-wide remediation efforts initiated in the 1980s were mainly directed towards the reduction of point-source nutrient loading, and successfully mitigated many toxic and nuisance algal bloom impairments with progress largely gauged against the management reduction targets for Total Phosphorus (TP) and chlorophyll a (chl-a) (see Nutrients in Lakes sub-indicator report).While cHABs/HABs and NABs overlap in their causes and impacts, NABs (e.g., Cladophora) were not included in the estimates or analyses in this report. The MTRI analysis defines surface phytoplankton and does not capture benthic nuisance algae.

Most algal blooms in the Great Lakes are reported in the shallow-water areas (Figure 2). These areas are most prone to shoreline development issues, a greater influx of nutrients, and to some extent, increased public awareness. The size of shallow-water (≤ 16 m) zones varies from approximately 1-10% of the total lake area in Superior to 60-90% in Erie. Likewise, the area of influence of physical factors varies between lakes (e.g., runoff, erosion, thermal bar formation, upwelling/down-welling, alongshore/nearshore/offshore currents, circulation patterns, surface/groundwater inputs, lake level regulation, ice formation, etc). As a result, the shallow-water zones are highly dynamic, and there is significant spatiotemporal variance in the biomass and composition of phytoplankton communities. Additionally, bloom extents in the shallow-water areas are somewhat underestimated using the present methods due to spectral contamination from nearby land and benthic reflectance in the shallow-water areas closest to land. The amount of area where satellites could not observe bloom conditions was greater in Lakes Superior and Ontario, which have particularly narrow shallow-water zones. For each lake, the spatial extents of algal blooms reported in this approach represent the extents detected in areas visible to the satellite.

Current State of Algal Blooms in the Great Lakes

Lake Superior: Episodic bloom events have been reported in Lake Superior over the last decade, but for the most part blooms are infrequent, short-lived, small in area, and localized to the immediate shallow-water region. Blooms have been shown to correspond with lake warming and extreme rainfall events (Sterner et al., 2020). A catastrophic flooding event in 2012 seeded a large areal bloom that extended into the open waters of the western arm of Lake Superior near Duluth. Another notable bloom event near Duluth in 2018 extended from the nearshore into the open water areas of the lake and as a result is not well represented in Fig. 3 due to the shallow-water focus of this report. Blooms have also been observed around the Apostle Islands since 2015, Thunder Bay, ON in 2019, and Terrace Bay, ON in 2020 (Figure 1). Blooms in Lake Superior appear to be predominantly driven by extreme storm events coupled with an increase in length of the growing season. The most common bloom-forming species in Lake Superior is typically *Dolichospermum lemmermannii*, a species that has not been shown to produce toxins yet in open water samples from Lake Superior. At Barker's Island, in the inner harbor of the Twin Ports (Duluth, MN and Superior, WI), a sample collected from a short-lived bloom, with the duration on the order of hours contained the cyanotoxins microcystin (just above US EPA Swimming Advisory levels at 8.7 ug/L) and saxitoxin (at the level of detection, 0.022 ug/L). The sample contained two other species in addition to *Dolichospermum lemmermannii*, and these taxa could be the toxin producers (Wisconsin DNR, personal communication). The shallow-water bloom events are typically wind-driven and last for hours. These observations are evidentiary from stakeholders in the region and from targeted in-lake monitoring programs which have documented 50 bloom events in the nearshore Lake Superior waters since 2012 (Lafrancois and Reinl 2024).

The remote sensing bloom metrics used here offer the benefit of being able to look back in time and provide objective measures of bloom conditions throughout much of the shallow-water areas not afforded by in-lake bloom monitoring efforts. However, there are some limitations related to the land adjacency effects (spectral interference) that pose challenges for measuring remotely sensed water parameters near land and which generally require shallow-water corrections for bottom reflectance. Furthermore, blooms in Lake Superior have typically been documented below the 18 mg/m3 chlorophyll threshold that was chosen for consistency across all of the Great Lakes. Therefore, the reported metrics underrepresent some of the reported shallow-water and lower biomass bloom events that are known to have occurred in recent years. Despite limitations of this approach in some shallow-water areas, algal blooms are likely to be occurring in much less than 5% of the lake's shallow-water area. Recognizing the limitations in the current approach combined with the anecdotal increases in bloom reports in some shallow-water areas, we classified the status as well as trends of algal blooms in Lake Superior from 2012-2023 and 2014-2023 as Undetermined. Advances in remote sensing technology and further algorithm development for this region will improve our ability to monitor and assess the highly dynamic, low biomass blooms in the immediate nearshore areas in Lake Superior in the future.

Lake Michigan: In Lake Michigan, algal blooms have been reported in some coastal regions and eutrophic embayments such as Green Bay, WI and in many of the drowned river mouths along the eastern shore of the lake. The average annual bloom spatial extent in Green Bay has remained stable over recent years, with no significant trend observed between 2012-2023 (Fig. 5). There has been substantial seasonal and inter-annual variability in bloom extent over this time period. Several years experienced particularly low bloom extent percent coverage (e.g., 2019) while other years (e.g., 2020) had much higher percent coverage of blooms. The bloom occurrence heat maps reveal that the blooms are concentrated at the southern end of Green Bay where the Fox River drains into the Bay. In more severe bloom years (e.g., 2012, 2020), the algal blooms extend further north along either the eastern or western shorelines (Fig. 7).

Lake Huron: Lake Huron is generally limited by low nutrients in most areas but experiences algal blooms in some shallow-water areas, most notably in Saginaw Bay and Sturgeon Bay (Georgian Bay). Cyanobacteria blooms were

reported in the early 1980s (Bierman and Dolan, 1981), but toxicity was not reported until after the early 2000s (Brittain et al. 2000, Vanderploeg et al, 2001). Since 2012, algal bloom extent accounted for approximately 8-29% of the shallow-water area. While regression analysis indicated that the trend for algal blooms in Lake Huron is not significant, it was assessed as No Trend due to significant interannual variability (Fig. 8). In Saginaw Bay, where blooms are most common and extensive, algal blooms have been observed along most of the inner bay's coastline, with the blooms most frequently extending just east of the mouth of the Saginaw River (Fig. 10). With the exception of the heaviest bloom years, algal blooms are rarely observed in more than 40% of clear satellite images during the algal bloom growing season.

Lake Erie: Lake Erie continues to experience cyanobacteria blooms throughout the western basin and infrequently along the Ohio and Pennsylvania shorelines of the central basin (Fig. 12). Lake St. Clair was not included in this current analysis, but blooms in this location are referenced in McKay et al. (2020). The heatmap time series (Fig. 15) indicates that between 2012 and 2020, much of the western basin of Lake Erie was susceptible to algal blooms, with the waters near the Detroit River being the primary exception. Blooms are predominantly observed along the southern shore of Lake Erie, extending from Maumee Bay to Lakeside Marblehead, and even further into the central basin of Lake Erie in the more extreme bloom years. The blooms are most persistent near the mouth of the Maumee River, often being observed in more than 60% of the clear satellite images during the harmful algal bloom growing season. Since 2012, algal blooms occurred on at least one occasion in 40% to 70% of Lake Erie's shallow-water area. No significant change has been observed in the bloom extent from either 2012-2023 or 2014-2023, so the trend is assessed as Unchanging.

Lake Ontario: Algal bloom occurrences are very limited in the shallow waters of Lake Ontario but have occurred notably within Hamilton Harbour and Bay of Quinte in Ontario (McKindles et al., 2020). Annual (2012-2023) algal bloom percent coverage for Lake Ontario derived from the VIIRS satellite data often had little to no detectable algal blooms. As such, algal bloom conditions in Lake Ontario are assessed as Good and the trend is Unchanging as there is no significant change over this time period (Fig. 14). We recognize that relatively large portions of the shallow-water areas could not be assessed in the central and eastern parts of the lake, including the aforementioned areas where blooms are known to occur. However, the blooms that occur in these areas would not account for more than 5% of the nearshore area of the lake if they could be detected by satellite using the current method. Therefore, the current assessment likely reflects recent conditions. As indicated for Lake Superior, future advancements in technology and analytical approaches will improve future assessments of algal bloom conditions in Lake Ontario.

Linkages

Linkages to other sub-indicators in the indicator suite include:

- Nutrients in Lakes – Algal bloom growth is sensitive to the nutrient levels in the lakes. Lake Erie blooms in particular have been shown to be particularly sensitive to soluble reactive phosphorus loadings (Baker et al., 2014; Kane et al., 2014).
- Water Quality in Tributaries – Nutrient loading from tributaries ends up in the Great Lakes where it becomes available for cyanobacteria growth. Tributaries have also been shown to contribute cyanobacterial seed stock to the larger lakes (e.g., Conroy et al., 2014; Davis et al., 2014; Reinl et al., 2020; Kreiling et al., 2024).
- Dreissenid Mussels – Zebra and quagga mussels modify the ecosystem in a number of ways that might preferentially favor cyanobacteria, including increased light availability, selective filtration, and increased

nutrient retention in nearshore areas through the nearshore shunt (Vanderploeg et al., 2001, Barbiero and Tuchman 2004; Hecky et al., 2004).

- Surface Water Temperature – Expected increases in temperature could favor cyanobacteria which have optimal growth rates at higher temperatures than other phytoplankton species and also expand the bloom season (Paerl and Huisman 2009; Ibelings et al., 2021).
- Precipitation Amounts – Bloom extent and severity in Lake Erie is significantly related to the level of spring discharge (Sayers et al., 2016; Sayers et al., 2019; Stumpf et al., 2012) and the Lake Superior blooms have been linked to large storm events (Sterner et al., 2020).
- Long-term changes in physical conditions – It is expected that factors such as rising air and surface water temperatures and more frequent storm events will favor cyanobacteria growth (Paerl and Huisman 2009; Ibelings et al., 2021), though the specific impacts will likely vary by region based on the specific regional drivers of blooms (Ibelings et al., 2021).

Citizen Science, and other Bodies of Knowledge

Western Lake Erie and Saginaw Bay are routinely monitored by a variety of groups including NOAA GLERL and CIGLR. Regions with less established monitoring programs often rely on citizens to report suspected blooms. Each of the states and provinces intersecting the Great Lakes has their own established mechanism for reporting blooms. Additionally, the bloomWatch app is a relatively new tool from the Cyanobacteria Monitoring Collective that allows users to report suspected blooms along with photos. The U.S. EPA is working to integrate bloomWatch reports into their data systems to make the data more available to stakeholders.

Assessing Data Quality

Data Characteristics	Agree	Neutral or Unknown	Disagree	Not Applicable
Data are documented, validated, or quality-assured by a recognized agency or organization	X			
Data are from a known, reliable and respected generator of data and are traceable to original sources	X			
Geographic coverage and scale of data are appropriate to the Great Lakes Basin	X			
Data obtained from sources within the U.S. are comparable to those from Canada				X
Uncertainty and variability in the data are documented and within acceptable limits for this sub-indicator report	X			
Data used in assessment are openly available and accessible	No	Data are available upon request		

Data Limitations

In the Great Lakes, algal blooms are monitored using a variety of in situ and remote methods. In situ monitoring for algal blooms in Lake Erie is generally widespread but monitoring in the other lakes (Michigan, Huron, Superior, Ontario) is sparse and largely reactive to observations and reports from local resource managers and the public. The remote sensing approach used in this report has the benefit of much higher spatial and temporal coverage than can be attained through traditional field sampling. However, satellite observations of algal blooms are limited by cloud cover and the spatial, temporal and spectral resolution of the satellite sensors. Satellites also typically detect only surface algal biomass, so imagery should be interpreted as not capturing the full vertical distribution of algal cells. While satellite imagery provides a good estimate of the extent of a surface bloom (e.g., elevated chlorophyll-a concentration), it is not yet possible to determine if the bloom is harmful (produces toxins or taste and odor compounds) based on the satellite imagery alone. Current satellite assets and algorithms are somewhat limited in their ability to detect algal blooms in the immediate nearshore environment due to spectral contamination from nearby land and benthic reflectance. Future work utilizing other satellite sensors, including the European Space Agency, Medium Resolution Imaging Spectrometer (MERIS) imager or the Sentinel Ocean and Land Colour Imager (OLCI) will have a higher spatial resolution and could provide better characterization of algal blooms but would still have limitations in the very nearshore regions in the Great Lakes. The approach used in this report has also not been specifically validated for use outside of Green Bay, Saginaw Bay, and western Lake Erie. However, the criteria used for identifying algal blooms in these areas is likely accurate in the shallow areas assessed here. Future reports may include both in situ and remotely sensed data to address these limitations.

Additional Information

Various assessment approaches have been developed to assess algal blooms in the Great Lakes. Future reporting on this sub-indicator will take into consideration these assessment approaches to ensure consistent binational messaging.

Report Authors

Karl Bosse, Michigan Technological Research Institute, Ann Arbor, MI (krbosse@mtu.edu)

Michael Sayers, Michigan Technological Research Institute, Ann Arbor, MI (mjsayers@mtu.edu)

Andrea Vander Woude, NOAA Great Lakes Environmental Laboratory, Ann Arbor, MI (Andrea.VanderWoude@noaa.gov)

Caren Binding, Environment and Climate Change Canada, Burlington, ON (Caren.Binding@ec.gc.ca)

References

Baker, D. B., Confesor, R., Ewing, D. E., Johnson, L. T., Kramer, J. W., and Merryfield, B. J. 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. *Journal of Great Lakes Research*, *40*(3), pp.502-517.

Barbiero, R.P. and Tuchman, M.L., 2004. Long-term dreissenid impacts on water clarity in Lake Erie. *Journal of Great Lakes Research*, *30*(4), pp.557-565.

Bierman VJ, Dolan DM. 1981. Modeling of Phytoplankton-Nutrient Dynamics in Saginaw Bay, Lake Huron. Journal of Great Lakes Research, 7(4):409-439.

Binding CE, Greenberg TA, Watson SB. Rastin S., Gould J. 2015 Long term water clarity changes in North America's Great Lakes from multi-sensor satellite observations. Limnol. Oceanogr. 6: 1976–1995

Binding, CE, Pizzolato, L & Zeng, C. 2021. EOLakeWatch; delivering a comprehensive suite of remote sensing algal bloom indices for enhanced monitoring of Canadian eutrophic lakes. Ecological Indicators, Volume 121, 106999, https://doi.org/10.1016/j.ecolind.2020.106999.

Brittain, S.M., Wang, J., Babcock-Jackson, L., Carmichael, W.W., Rinehart, K.L., Culver, D.A., 2000. Isolation and characterization of microcystins, cyclic heptapeptide hepatotoxins from a Lake Erie strain of *Microcystis aeruginosa*. J. Great Lakes Res. 26 (3), 241–249

Conroy, J. D., Kane, D. D., Briland, R. D., and Culver, D. A. 2014. Systemic, early-season Microcystis blooms in western Lake Erie and two of its major agricultural tributaries (Maumee and Sandusky rivers). *Journal of Great Lakes Research, 40(3)*, pp.518-523.

Davis, T. W., Watson, S. B., Rozmarynowycz, M. J., Ciborowski, J. J., McKay, R. M., and Bullerjahn, G. S. 2014. Phylogenies of microcystin-producing cyanobacteria in the lower Laurentian Great Lakes suggest extensive genetic connectivity. *PloS one, 9(9)*, e106093.

Hecky, R.E., Smith, R.E., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N. and Howell, T., 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*(7), pp.1285-1293.

Ibelings, B.W., Kurmayer, R., Azevedo, S.M., Wood, S.A., Chorus, I. and Welker, M., 2021. Understanding the occurrence of cyanobacteria and cyanotoxins. *Toxic cyanobacteria in water*, pp. 213-294. CRC Press.

Kane, D. D., Conroy, J. D., Richards, R. P., Baker, D. B., and Culver, D. A. 2014. Re-eutrophication of Lake Erie: Correlations between tributary nutrient loads and phytoplankton biomass. *Journal of Great Lakes Research, 40(3)*, pp.496-501.

Kreiling, R. M., Givens, C. E., Baker, A. C., Kiesling, R. L., Dantoin, E. D., Perner, P. M., Sterner, S. P., Gierke, K. J., and Reneau, P. C. (2024). Role of tributary cyanobacterial and nutrient transport and sediment processes on cyanobacterial bloom initiation in Lake Superior nearshore. *Journal of Great Lakes Research 51(1),* 102409.

Lafrancois, B. and K.L. Reinl. 2024. Lake Superior cyanobacterial bloom reports, 2012 - present ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/89d1b199d4bdb8d82847c7f39d1018be (Accessed 2024-12-20).

Matson, P.G., Boyer, G.L., Bridgeman, T.B., Bullerjahn, G.S., Kane, D.D., McKay, R.M., McKindles, K.M., Raymond, H.A., Snyder, B.K., Stumpf, R.P. and Davis, T.W., 2020. Physical drivers facilitating a toxigenic cyanobacterial bloom in a major Great Lakes tributary. *Limnology and oceanography*, *65*(12), pp.2866-2882.

McKindles, K., Frenken, T., McKay, R.M.L. and Bullerjahn, G.S., 2020. Binational efforts addressing cyanobacterial harmful algal blooms in the Great Lakes. *Contaminants of the Great Lakes*, pp.109-133.

Paerl, H. W., and Huisman, J., 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environmental microbiology reports*, 1(1), pp.27-37.

Reinl, K.L., Sterner, R.W., Lafrancois, B.M. and Brovold, S., 2020. Fluvial seeding of cyanobacterial blooms in oligotrophic Lake Superior. *Harmful Algae*, *100*, pp.101941.

Sterner, R.W., Reinl, K.L., Lafrancois, B.M., Brovold, S. and Miller, T.R., 2020. A first assessment of cyanobacterial blooms in oligotrophic Lake Superior. *Limnology and Oceanography*, *65*(12), pp.2984-2998.

Stumpf, R.P., Wynne, T.T., Baker, D.B., Fahnenstiel, G.L., 2012. Interannual variability of cyanobacterial blooms in Lake Erie. PloS ONE, 7(8), e42444 doi:10.1371/journal.pone.0042444

Stumpf R.P., Johnson L.T., Wynne T.T., Baker D.B. 2016. Forecasting annual cyanobacterial bloom biomass to inform management decisions in Lake Erie, Journal of Great Lakes Research, 42 (6), pp. 1174 - 1183

Vanderploeg, HA, Liebig JR, Carmichael WW, Agy MA, Johengen TH, Fahnenstiel GL, and Nalepa TF, 2001, Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. Can. J. Fish. Aquat. Sci. 58, 1208–1221

Watson, S.B & Boyer, G.L., Nearshore Areas of the Great Lakes 2009. State of the Lakes Ecosystem Conference 2008 Background Paper. Harmful Algal Blooms (HABs) in the Great Lakes: Current Status and Concerns.

Watson SB, Ridal J, & Boyer, GL, 2008. Taste and odour and cyanobacterial toxins: impairment, prediction, and management in the Great Lakes. Can. J. Fish. Aquat. Sci. 65(8): 1779-1796

Watson S.B., Burley, M., Borisko, J., Lalor, J., 2009. Bay of Quinte Harmful Bloom Programme Phase 1. Bay of Quinte RAP Annual Report https://www.bqrap.ca/wp-content/uploads/documentlibrary/Bay_of_Quinte_Annual_Report_2009_R.pdf#page=28

Wynne, T.T., Stumpf, R.P., Litaker, R.W. and Hood, R.R., 2021. Cyanobacterial bloom phenology in Saginaw Bay from MODIS and a comparative look with western Lake Erie. *Harmful Algae*, *103*, p.101999.

List of Figures

Figure 1. Percent of Great Lakes Basin shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 2. Great Lakes wide 2014 (top panel) and 2023 (bottom panel) shallow-water algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) derived from VIIRS satellite data. Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in Gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Figure 3. Percent of Lake Superior shallow-water area (areas <16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 4. Lake Superior 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Figure 5. Percent of Lake Michigan shallow-water area (areas ≤16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data

within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 6. Lake Michigan 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Figure 7. Algal bloom occurrence "heat maps" for Green Bay from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

Figure 8. Percent of Lake Huron shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 9. Lake Huron 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Figure 10. Algal bloom occurrence "heat maps" for Saginaw Bay from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

Figure 11. Percent of Lake Erie shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 12. Lake Erie 2023 algal shallow-water bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Figure 13. Algal bloom occurrence "heat maps" for the western basin of Lake Erie from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

Figure 14. Percent of Lake Ontario shallow-water area (areas ≤ 16 m deep) where at least one algal bloom (i.e., chlorophyll-a greater than 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Source: Michigan Tech Research Institute.

Figure 15. Lake Ontario 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom

occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

Last Updated

State of the Great Lakes 2025 Report

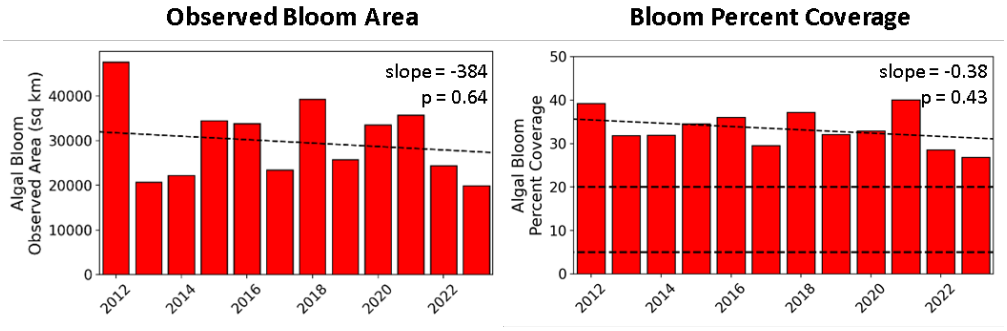
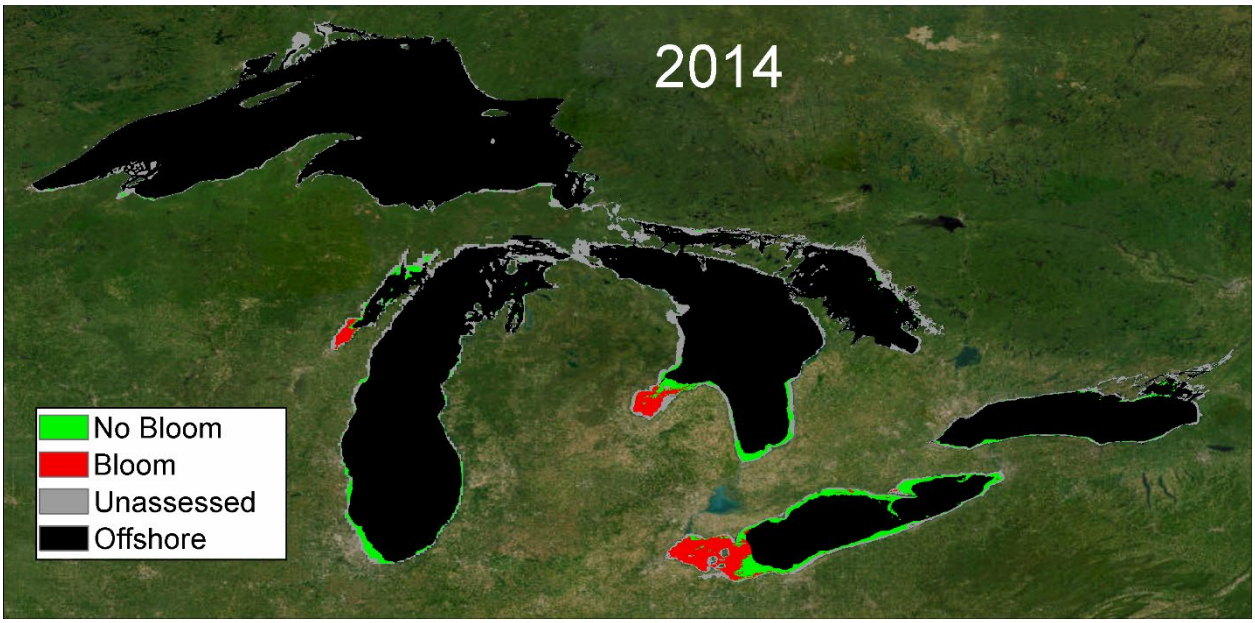


Figure 1. Percent of Great Lakes Basin shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.



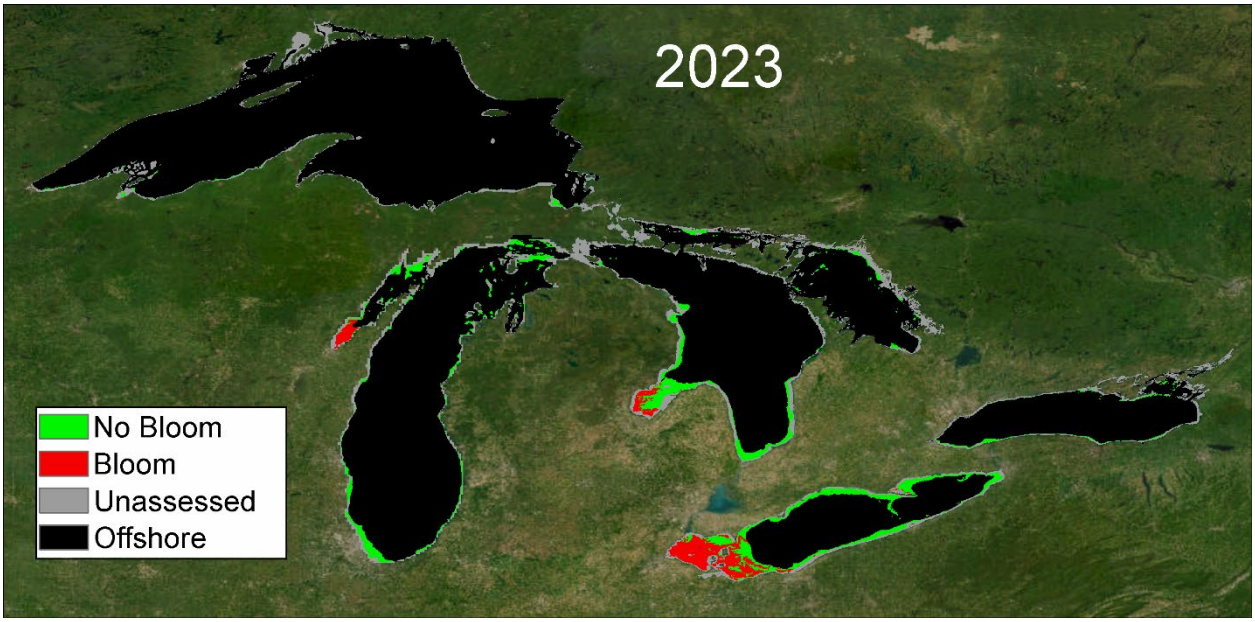


Figure 2. Great Lakes wide 2014 (top panel) and 2023 (bottom panel) shallow-water algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) derived from VIIRS satellite data. Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in Gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

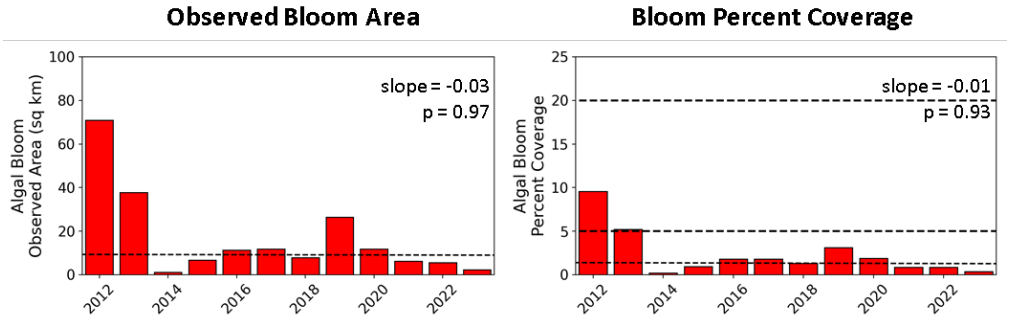


Figure 3. Percent of Lake Superior shallow-water area (areas <16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

Figure 4. Lake Superior 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

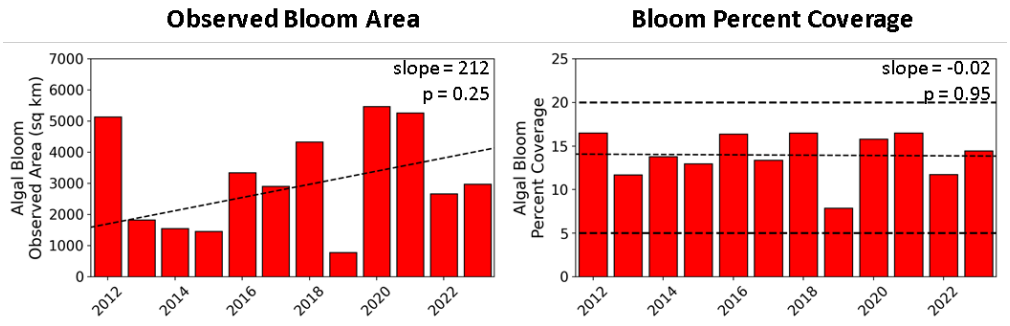


Figure 5. Percent of Lake Michigan shallow-water area (areas ≤16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

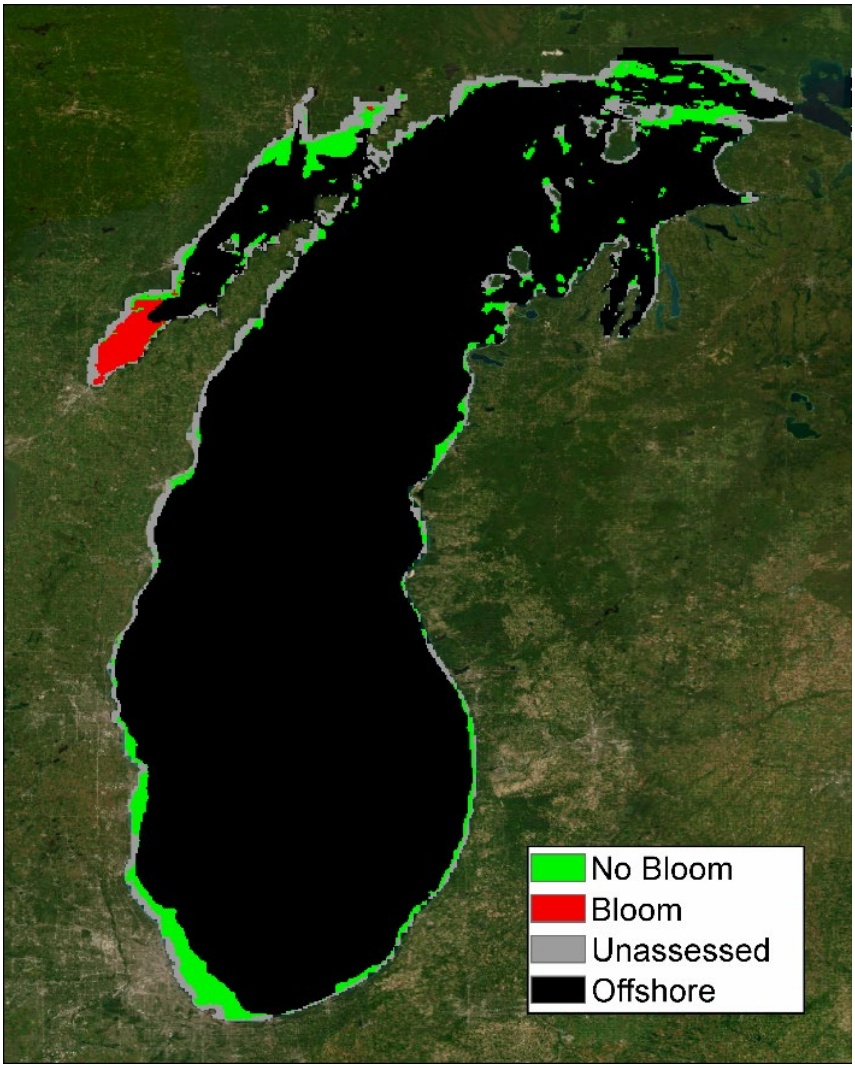


Figure 6. Lake Michigan 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

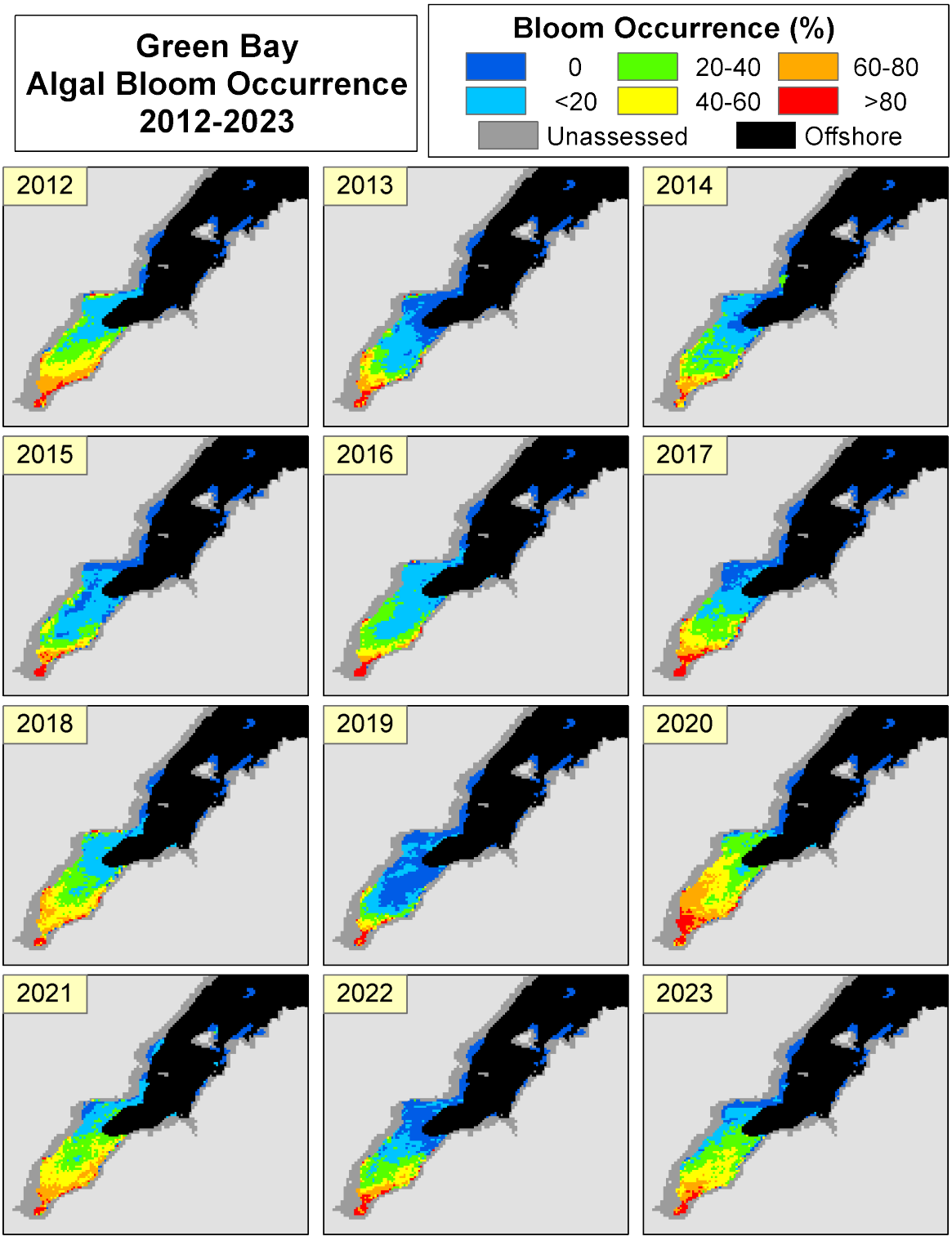


Figure 7. Algal bloom occurrence "heat maps" for Green Bay from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

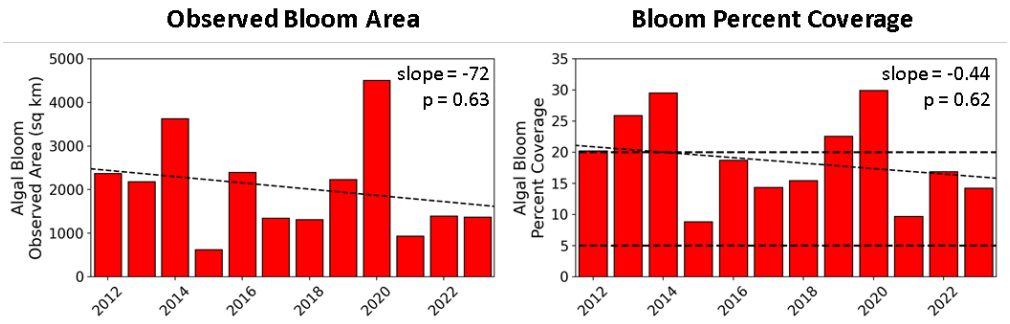


Figure 8. Percent of Lake Huron shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

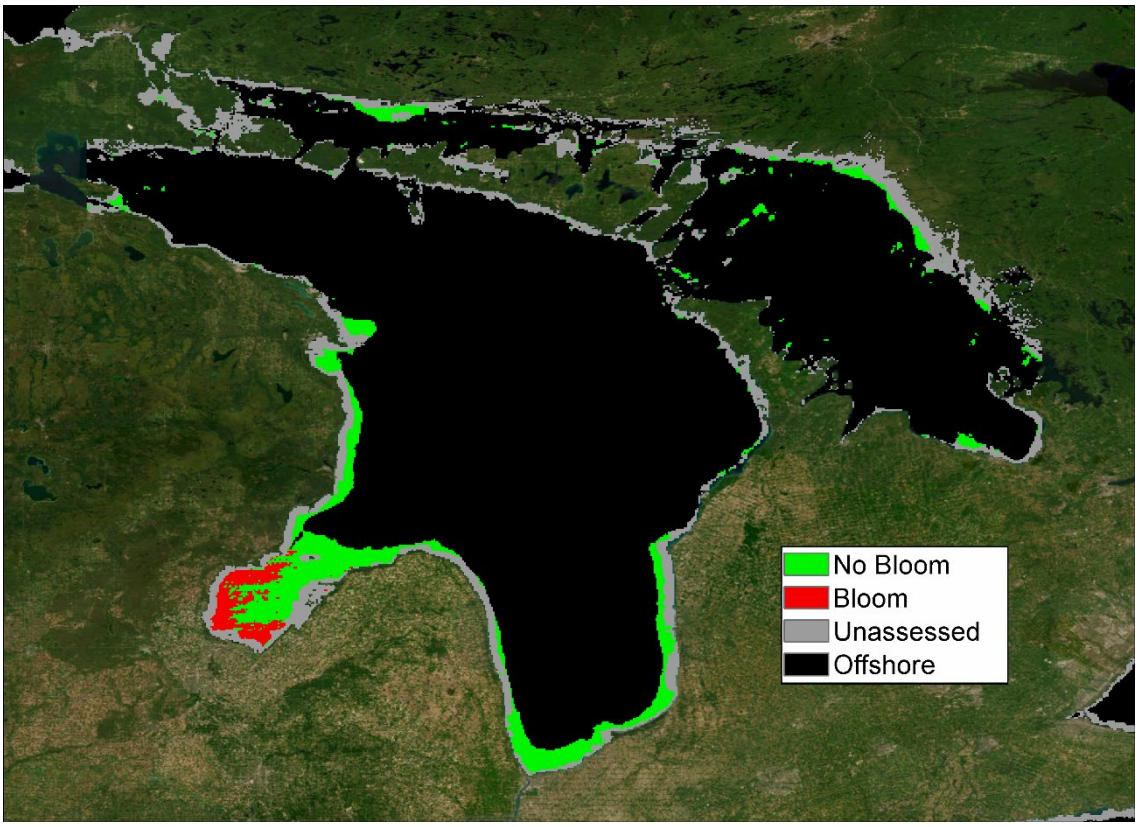


Figure 9. Lake Huron 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

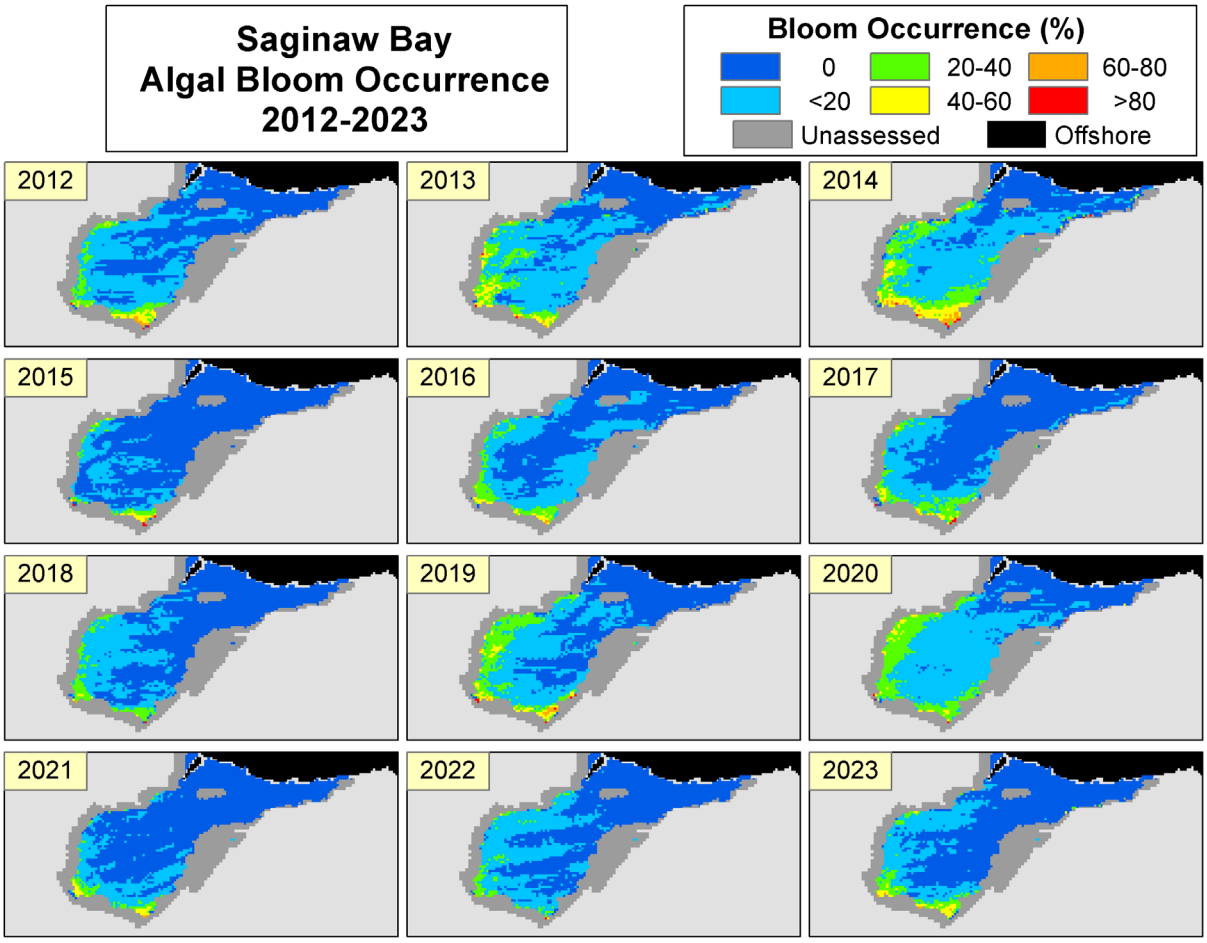


Figure 10. Algal bloom occurrence "heat maps" for Saginaw Bay from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

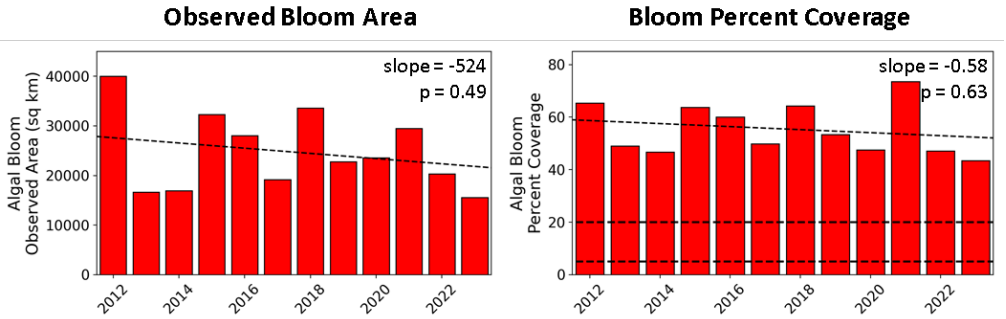


Figure 11. Percent of Lake Erie shallow-water area (areas ≤ 16 m deep) where at least one bloom (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Bloom percent coverage thresholds (5% and 20%) used in status assessments are also included for reference. Source: Michigan Tech Research Institute.

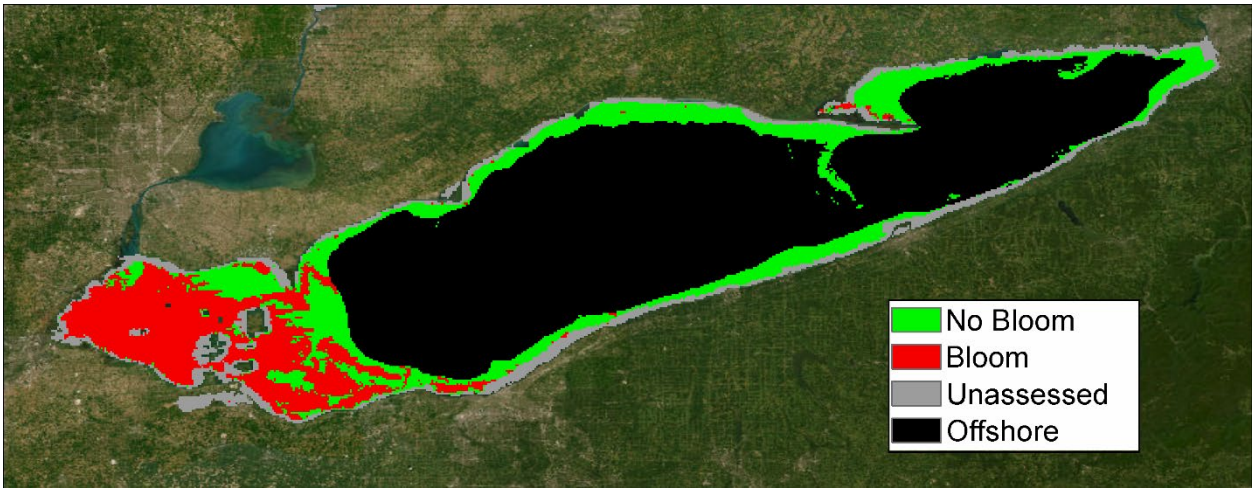


Figure 12. Lake Erie 2023 algal shallow-water bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.

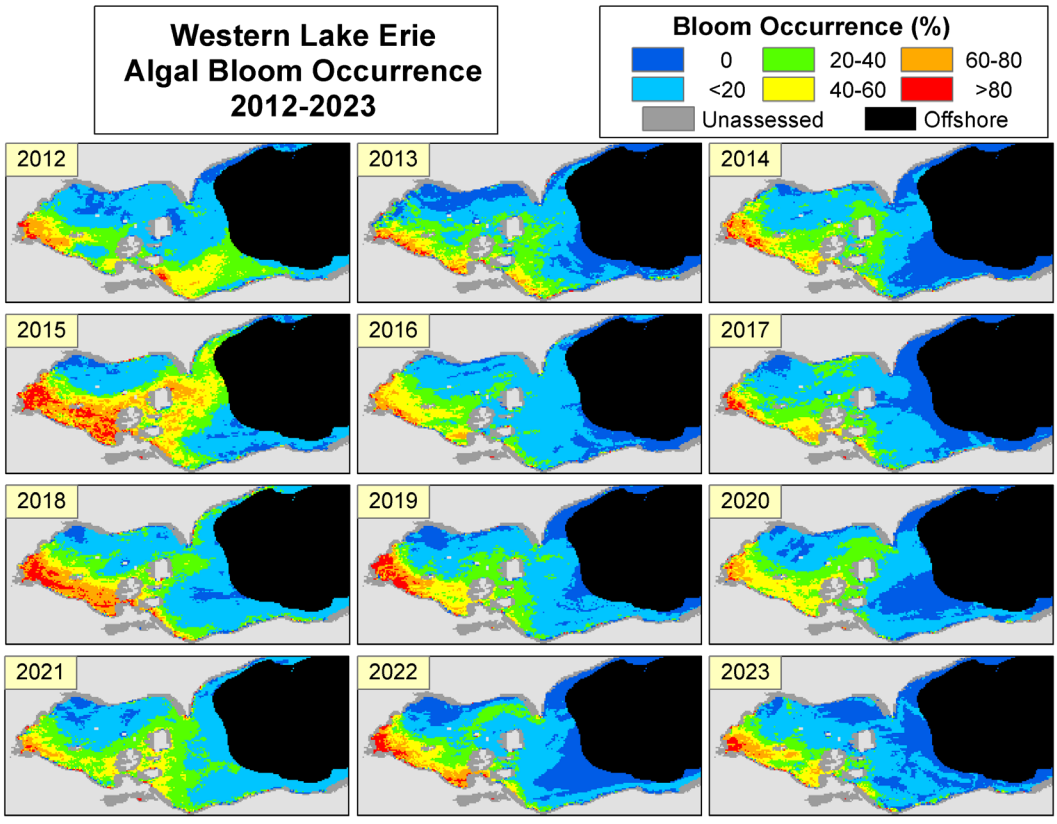


Figure 13. Algal bloom occurrence “heat maps” for the western basin of Lake Erie from 2012 to 2023. Colored areas indicate the percent of satellite observations that algal blooms were present whereas areas in black were not assessed due to lack of clear imagery or to spectral interference from land. Source: Michigan Tech Research Institute.

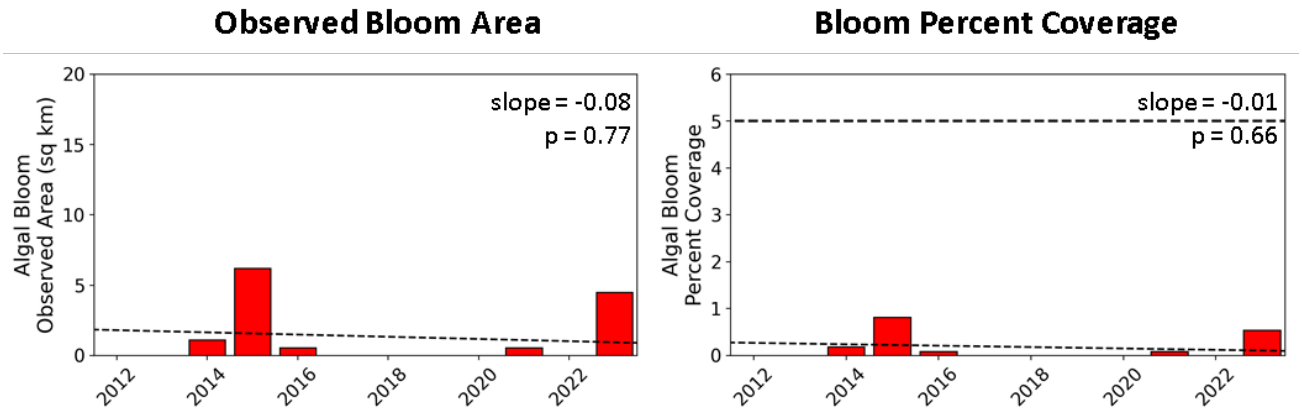


Figure 14. Percent of Lake Ontario shallow-water area (areas ≤ 16 m deep) where at least one algal bloom (i.e., chlorophyll-a greater than 18 mg/m3 and surface temperatures >20 °C) occurrence was detected from VIIRS satellite data within the April-October period of each year (2012-2023). Ordinary Least Squares (OLS) linear regression line is plotted. Source: Michigan Tech Research Institute.

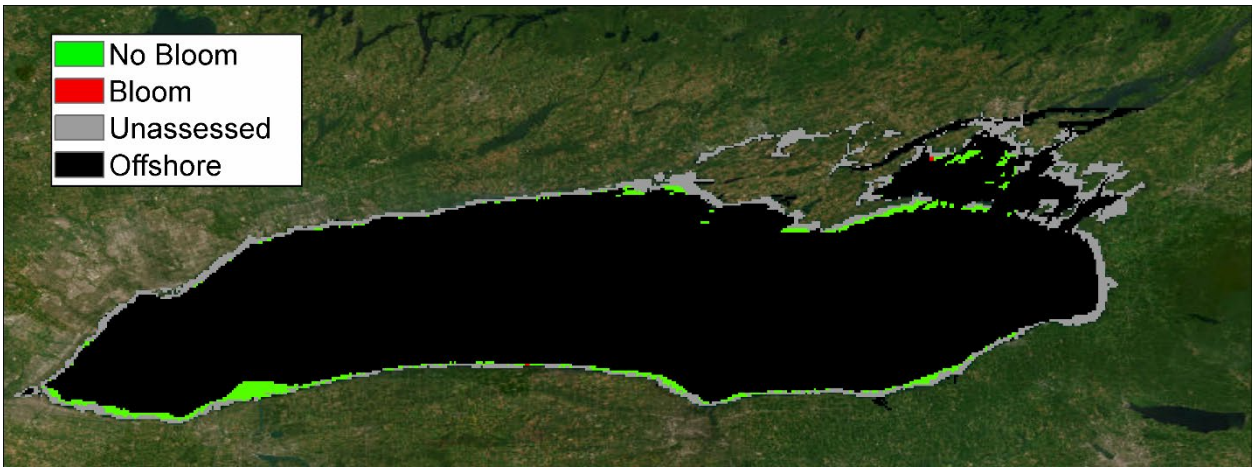


Figure 15. Lake Ontario 2023 shallow-water algal bloom occurrences derived from VIIRS satellite data, algal bloom occurrences (i.e., chlorophyll-a > 18 mg/m3 and surface temperatures >20 °C). Red areas indicate bloom occurrences (1 or more occurrences) while green areas experienced no bloom. Areas in gray were unobservable by VIIRS. Source: Michigan Tech Research Institute.