Harmful Algal Blooms (HABS)

Overall Assessment
Status:
Trend:
Rationale:

Lake-by-Lake Assessment
Lake Superior
Status: Good
Trend
Rationale: There is very little quantitative current information on HABs in Lake Superior. To our knowledge, severe HABs outbreaks have not been documented recently in this lake. Algal biomass remains mostly at low levels, although there may be some local impairment near shoreline development.

Lake Michigan
Status: Fair
Trend:
Rationale: Cyanobacteria blooms are reported in some coastal regions in eutrophic embayments such as Green Bay, Muskegon Bay and in many of the river mouths along the eastern shore. Shoreline and beach fouling by *Cladophora* represent a source of bacteria for beaches and groundwater, trapping bacterial flora during their growth and providing substrate for further bacterial activity during decay.

Lake Huron
Status: Fair
Trend:
Rationale: Lake Huron is generally oligotrophic in most areas, but experiences potentially toxic HABs occur in some inshore areas, notably Saginaw Bay develops toxic summer outbreaks of *Microcystis aeruginaosa*.

Lake Erie
Status: Fair to Poor
Trend:
Rationale: Lake Erie is the most heavily impaired by planktonic HABs, particularly in the last two years where satellite images of extensive surface blooms of Microcystis and other HABs have been posted on many websites (e.g. NOAA). Toxic HABs and their causes are a particular concern and the focus of several recent studies.

Lake Ontario
Status: Fair
Trend:
Rationale: Blooms of cyanobacteria and related impairments (toxins, taste-odour compounds) occur on an annual basis in some inshore areas, notably AOCs.

Purpose of the Indicator
- To assess potential harm to human, other organisms or ecosystems through from planktonic or benthic/attached algal blooms.

Ecosystem Objective
Waters should be safe for drinking (>25m people rely on the Great Lakes for drinking water) and recreational use and substantially free from toxic and/or high abundances of noxious cyanobacteria or algae that may harm human, animals or ecosystem health or have other harmful effects. While cyanobacteria produce a wide variety of toxins, hepatotoxic Microcystins (MCs) are the most persistent and common toxins currently reported across the Great Lakes. This generally holds true for many areas of the Great

Lakes but not for all, especially some embayments and nearshore waters where benthic algae may be the greatest risk. Other toxins such as anatoxin-a has been found in embayments but are relatively rare in occurrence thus this indicator will focus on a single class of toxins. Benthic/littoral cyanobacteria such as *Lyngbya* or algae - particularly *Cladophora* and *Spirogyra* - also show widespread occurrence in the nearshore zone and represent a different type of threat to the ecosystem. However the route cause for benthic HABs (elevated nutrients) remains similar to the route cause for pelagic HABs. Using a combined metric enables monitoring for changes in both general types of blooms.

Ecological Condition
Background
Harmful Cyanobacterial and algal (algae here denotes both eukaryotic algal taxa and Cyanobacteria) blooms (HABs) are a global issue in eutrophic waters with high anthropogenic (and/or natural) nutrient loading (e.g. Hallegraeff 1993). HABs are differentiated from 'non-harmful' blooms by their qualitative impacts on/threats to: i) water quality, biota or physico-chemical characteristics; ii) health risks from toxins or heightened microbial activity; iii) aesthetics or recreation (Pearl 1988). Prior to remediation in the late 1970s, HABs were a major problem in many offshore and inshore areas in the Gt. Lakes (e.g. Watson and Boyer 2008) where concerns focussed on reduced aesthetics, taste-odour (T&O), foodweb structure, beach/intake/net fouling and economic impacts. Lakewide remediation efforts initiated in the 1980s were mainly directed towards the reduction of point-source nutrient loading, and successfully mitigated many HAB impairments with progress largely gauged against identified target management goals of TP and chlorophyll a (chla) and TP. Recently there has been a resurgence in blooms in the Lakes, and an additional new concern with their potential for the production of toxins* which were unidentified in the 1970s. However, current management continues to target planktonic (subsurface) chla as a measure of total algal biomass and productivity, which is often an irrelevant metric of these events.

(*Note - Toxins are only recently recognized as a threat and with few historical data, this perception is based more on anecdotal evidence and not quantified; reports may be biased by increasing public awareness; most sites are not monitored, many blooms are not identified and visible blooms are not the only sources.)

Most focus is on visible HABs caused by planktonic toxic cyanobacteria, but HABs are also caused by blooms of *Cladophora* and other benthic/littoral macroalgal proliferation, which along with planktonic outbreaks have also shown an apparent resurgence particularly in the lower Great Lakes. Because these events are often episodic, and vary seasonally and interannually in severity and spatial coverage, it is difficult to implement appropriate research, monitoring and management programmes, particularly in these vast and spatially complex waterbodies where sampling is often subject to weather and vessel access. It should be noted that blooms may not be restricted to the lakes themselves but have been reported recently in major embayments, tributaries and connecting channels (below).

Many blooms in the Great Lakes are reported from the inshore areas which are most prone to shoreline development issues and the influx of nutrients. This also, to some extent, reflects an increased amount of local public vigilance and complaints. The size of inshore zones varies from ~1-10% in Superior to 60-90% in Erie, as does the influence of physical and climatic factors (runoff, erosion, thermal bar, upwelling/downwelling, alongshore/inshore/offshore currents, circulation patterns, surface/ground water inputs, ice formation, etc.). The coastal regions show highly dynamic spatial-temporal variance in the boundaries supporting littoral and planktonic communities spatial and the offshore-inshore material exchange.

As noted above, HABs in the Great Lakes are caused by a variety of species. Major impairments include: i) noxious / toxic metabolites (odour, toxins); ii) fouling (beaches, nets, intakes); iii) aesthetics and economic impacts including beach closures, vi) modified nutrient turnover and sequesterment/translocation (via cell bound fractions); vii) increased bacterial activity, viii) adverse effects on food web integrity. Importantly their appearance is often unlinked with current LaMP targets – i.e. offshore nutrient and chla levels

Key aspects of HABs
- These are summarized in detail in Watson and Boyer 2008, but some key points are summarized below:
- HABs cause significant economic harm. Annual estimates vary, but range up to annual costs of 4.6

billion /yr (USA) in response monitoring, fisheries, tourism, public health & advisory, lost revenue & property value.

- Not all HABs are caused by cyanobacteria or resemble green paint or pea soup. They are caused by many species and vary in colour from green to red and brown.
- Blooms are not all surface scums & can be hard to identify or anticipate Some are mixed through the water column, grow in deep water layers, under ice or as benthic/attached mats.
- Cyanobacteria produce many toxins which fall into three major categories, based on their activity: liver toxins (hepatotoxins), neurotoxins & irritants. These vary in stability and toxicity. Microcystins (hepatoxins; also carcinogens) are the most stable & most prevalent across the Great Lakes and can persist after a bloom has died and disappeared.
- Toxins, T&O, visible blooms, cell counts/biomass/chla may or may not be related. Toxins are odourless & colourless; there is often a very poor relationship between toxins and T&O, which are derived from separate biochemical pathways, one or many species, and cell-specific variance in production.
- Blooms are difficult to define, measure (& predict).
- They can show rapid variations in space & time.
- With calm conditions (or overnight) buoyancy-regulating cyanobacteria can float to the surface and are carried large distances by wind/waves, creating patches of very high toxin levels along beaches.
- Variance among analytical and sampling methods often generates inconsistencies among reported levels.
- Fluorescence-based, cell counts and other abundance measures (e.g. molecular, biochemical) are often poorly correlated due to wide variance in pigment content, photo-acclimation and cell composition. Furthermore, there are often among-analyst differences in taxonomic identification.

Additional Information

The term ‘algal ‘bloom’ is a non quantitative descriptor for visible increases in free-floating or attached algal/cyanobacterial density, often manifested as scums, mats or water colour. Harmful algal blooms are differentiated as having harmful socioeconomic or ecological effects and may be caused by algal/cyanobacteria species belonging to many major taxonomic groups. Most concern is with HABs caused by cyanobacteria (CHABs), which include toxic blooms, caused by a subset of cyanobacterial species with the capacity to produce one or more toxins neurotoxins, hepatotoxins or dermatotoxins) and currently the only known sources of algal toxins in inland waters that directly affect humans.

Detrimental health effects from benthic algal accumulations on the shore are more difficult to quantify but may result in socioeconomic and ecological damage (Table 1).

Great Lakes: current status of HABS

Toxins: The most commonly reported toxins in the Great Lakes and other waters are microcystins (MCs) produced by numerous cyanobacteria species; some of which (e.g. Microcystis spp.) bloom in the Lakes (e.g. Boyer 2007). In Lakes Ontario and Erie, anatoxin-a and saxitoxins have been detected at high and low levels, respectively (Boyer 2007). While Cylindrospermopsis is present in Great Lakes and its surrounding watersheds, the toxin cylindrospermopsin previously associated with this genus has not been confirmed for these waterbodies. Analysis of numerous samples across the Lakes has shown no detectable levels of BMAA , a toxin of new concern in some areas. The question of BMAAs and the link to Alzheimer’s continues to be debated. There are no data on the occurrence of lipopolysaccharides (LPS), produced by all cyanobacteria and widely believed to cause gastroenteritis, skin/eye irritations, hay fever, asthma and blistering (although this is debated; e.g. Stewart *et al*. 2006).

Taste and odour (T&O) impairment is widespread in the Great Lakes. T&O has no known human health effects, but can impart significant consumer alarm and treatment/economic costs and function in foodwebs as powerful chemical signals (e.g. Watson 2003). T&O is caused by numerous compounds by numerous algal and non-algal biota along with anaerobic breakdown of any excessive bloom material.

Other issues i.e. benthic HABs (*Cladophora*, Lyngbya, Chara). Despite a significant reduction in these impairments in the 1980s-90s, there has been a significant resurgence in this problem which is now widespread in the Lower Lakes, notably in areas affected by a combination of diffuse shoreline or tributary influx of nutrients and colonised by dressenid mussels. The link among these factors to growth and biomass is, however, obscured by the dynamic physical nature of the inshore zone, sloughing off and difficulties with sampling.

Great Lakes: current status of HABS in individual lakes
As noted above, there are no long term data or rigorous monitoring programmes in place across most of the lakes, and only a qualitative assessment of the current status in each lake can be made.

There is very little quantitative current information on HABs in Lake Superior. To our knowledge, severe HABs outbreaks have not been documented recently in this Lake. Algal biomass remains mostly at low levels, although there may be some local impairment near shoreline development.

Cyanobacteria blooms are reported in some coastal regions in eutrophic embayments such as Green Bay, Muskegon Bay and in many of the river mouths along the eastern shore of Lake Michigan. Shoreline and beach fouling by *Cladophora* represent a source of bacteria for beaches and groundwater, trapping bacterial flora during their growth and providing substrate for further bacterial activity during decay.

Lake Huron is generally oligotrophic in most areas, but experiences potentially toxic HABs occur in some inshore areas, notably Saginaw Bay develops toxic summer outbreaks of Microcystis aeruginaosa. These blooms appear to be genetically distinct with a greater MC production capacity than HABs populations of M. aeruginosa in western Lake Erie (Dyble *et al* 2008). Highest toxin levels occur in shallow regions with high TP concentrations. Blooms have been reported from Sturgeon Bay in 2006-07, but no recent data is available (Diep *et al*. 2006). Recently, complaints of fish-net fouling by attached chlorophytes have increased (*Spirogyra cf circumlineata*, *Stigeoclonium*; Watson and Milne, unpublished). Rotting mats of beached green macroalgae are increasingly impacting aesthetics, recreation and tourism along some shorelines, notably Saginaw and more recently, the S.E., largely caused by *Cladophora* and Chara, respectively, with the detection of human fecal indicators (*E. coli*, *Enterococcus*) and evidence of differential survival in the beached mats and in situ beds of the macroalgae (Lake Huron Binational Partnership 2008-2010 Action Plan 2008). *Cladophora* is more clearly associated with suspected nutrient discharge while Chara is more widespread and not clearly linked to local inputs (Howell *et al*. 2005).

St. Clair River/Lake St. Clair/Detroit River's status is Fair. Recent reports and surveys do not identify algal blooms as a problem across most of LSC, as also indicated by generally low chla levels (~3-5ug/L; Lake St. Clair Canadian Watershed Technical Report; Watson unpublished). However, recent satellite images and anecdotal reports indicate blooms in the SE region of LSC near the mouth of the Thames. Lyngbya mats have also been found in the western shoreline areas associated with macrophyte stands; also in the DR (Trenton Channel) (Watson unpublished).

Lake Erie is the most heavily impaired by planktonic HABs, particularly in the last two years where satellite images of extensive surface blooms of Microcystis and other HABs have been posted on many websites (e.g. NOAA). Toxic HABs and their causes are a particular concern and the focus of several recent studies (e.g. MERHAB, BGSU, Heidelberg).

General trends: Overall, the data indicate an apparent deterioration, and shifts in external/internal physical/ chemical/ biological regimes - notably in the West basin. These are not easily assessed using current monitoring methods and measures, particularly where basin-wide averages and/or surface (1m) chla are considered (Ghadouani & Smith 2005). Studies suggest an increase in the severity of blooms in the West Basin and some inshore areas of the north shore (Point Pelee, Rondeau Bay, Long Point), and a decline in overall chla and total and/or eutrophic species biomass in the offshore regions of the Central and East Basins. Pre-remedial cyanobacterial was predominated by N-fixers (Aphanizomenon, Anabaena), while many of the recent blooms have been dominated by non fixers, notably Microcystis and Planktothrix spp suggesting changes in nutrient supply or dreissenid activity. Nevertheless, significant blooms of N-fixing Anabaena (cf lemmermanni) occur in both west and east basins (Watson, unpublished).

Immense surface blooms (>20 km^2) have been recorded in the Western basin near the Maumee and Sandusky Rivers (e.g. Rinto-Kanto *et al*. 2005). Microcystins (MCs) are the most common cyanobacterial toxins measured in Erie. Data from 2000–2004 measured a wide range in MC levels from detection limits (in 2002) to >20µg/L (in 2003). Toxicity is not restricted to the West: in 2003, highest MC concentrations were measured from Maumee, Long Point Bay and Sandusky Harbour. Neurotoxins (anatoxin–a, saxitoxin, neosaxitoxin) occurred at or near detection limits in the open lake waters. Samples collected across the lake between 2003 & 2008 showed the greatest proportion of samples (72-77%) with detectable MC levels from the West Basin (Figure 1), although only ~5% had levels above 1µg/L.

Toxins are not always produced by the same species, by the dominant taxa, or on a consistent basis. Microcystis blooms from Maumee have shown 5-100% variance in genetic potential for MC production. Recent molecular work has shown that blooms upstream in the Maumee R. are not a source of toxic Microcystis spp. to W Lake Erie, but the two populations arise independently (Kutovaya *et al* 2010). In fact Planktothrix can be the major source of MC toxins in Maumee Bay and Sandusky Harbor where cyanobacteria are dominated by non-producers (e.g. Aphanizomenon, Anabaena; Rinto-Kanto *et al*. 2005; Boyer 2007). Most impairment occurs at shorelines and beaches and can be manifested as fish/bird kills. Lyngbyatoxins (inflammatory/vesicatory and tumour-promoting) were not detected e.g. in the mats of Lyngbya wollei proliferating in the Maumee and Detroit Rivers (below).

Cylindrospermopsis raciborskii, first identified in Sandusky Bay 2005, may develop localized biomass but to date, cylindrospermopsin or deoxycylindrospermopsin has been detected in these areas. The highly variable morphology of this and other species may lead to misidentification as an Aphanizomenon issatchenkoi or Rhaphidiopsis curvata

Geosmin and 2-MIB are likely the cause of annual musty-muddy odour problems in drinking water in supplies in the West basin (e.g. Toledo). Significant odour is produced by extensive rotting mats of shoreline attached algae (below). The planktonic cyanobacterial taxa which are currently problematic in Erie (*Microcystis** and the local strain of *Planktothrix*) do not produce these or other T&O compounds which commonly impair drinking water supplies.

(*Note – *Microcystis* produces ß-cyclocitral; however, this is rapidly removed by most water treatment methods.)

Severe impairments by thick mats of the cyanobacterium Lyngbya wollei reported in the mouth of the Maumee (West Basin) at sites with high ambient P in the overlying water between 2006-09 appear to have abated this past year (Watson *et al*. 2008b; Western Lake Erie Waterkeeper Association unpublished). Extensive mats of attached green algae, notably *Cladophora* are showing an increase in abundance along some northern shorelines, although there are no recent data (post 2008) available on distribution.

Blooms of cyanobacteria and related impairments (toxins, taste-odour compounds) occur on an annual basis in some inshore areas, notably AOCs of Lake Ontario. Sporadic outbreaks of high MC levels and cyanobacteria blooms have been recorded in Hamilton Harbour, Bay of Quinte, Oswego Harbor and most recently, Sodus Bay (Watson and Boyer 2008, Watson *et al*. 2010a,b; Boyer unpublished). Spatial and temporal levels of MCs in the Bay of Quinte, Hamilton Harbour, Oswego Harbor (now delisted) and the Rochester Embayments indicate periods of severe impairment of inshore sites by windblown accumulations of toxic material, where MC levels can reach levels in excess of 500 µg/L. Microcystins and toxigenic Microcystis are also commonly found in many of the nearshore regions and embayments that span the northern Coast of New York State (Hotto *et al*, 2007). While microcystins are certainly the toxin of most concern in Lake Ontario, recent surveys indicated the widespread occurrence of low concentrations of anatoxin-a in near-shore and off-shore sites (Boyer 2007; Yang 2007, unpublished). The organism responsible for anatoxin-a production is currently unidentified. Other toxins (saxitoxins and cylindrospermopsin) are rare.

Studies have identified three T&O patterns over the past 5 years which are caused by geosmin and/or 2-MIB. Recently, there have been no severe T&O impairments to drinking water in intakes from Lake Ontario, although anecdotal reports of T&O from the St Lawrence River (J. Ridal, personal communication) . Benthic algal impairment continues to be major problem in many areas, with issues of plant intake and beach fouling (Higgins *et al*. 2008). Severe impairment is also manifested by benthic mats of the cyanobacteria Lyngbya cf. wollei and epiphytic Gloeotrichia recently identified in the St. Lawrence River near the confluence of nutrient-rich tributaries (Vis *et al*. 2008). As with the Maumee populations, these mats of *Lyngbya* are non-toxic but show high geosmin production, likely the source of extensive drinking water T&O impairment in the Montreal area.

Linkages
Increasing nutrient inputs from diffuse and point sources, climate change (severe storm events, differences in insulation/harmful irradiation, ice-cover and mixing), and invasive species (e.g. *dreissenid* mussels) in the Great Lakes may lead to increased frequency, distribution and severity of both inshore (attached/benthic) and offshore algal blooms and favour the predominance of cyanobacteria.

Management Challenges/Opportunities
There are a number of issues that relate to our effectiveness to monitor and apply this indicator:

There is a critical need for a coordinated, interagency monitoring programme, which employs standard methods; different sampling regimes and analytical protocols employed by individual studies affect data comparability and interpretation of long-term trends.

Basin-wide seasonal means, used widely to gauge trophic levels, do not resolve temporal / spatial differences in biomass and taxa, and thus cannot identify problem areas and/or potential drivers.

Littoral/benthic, epiphytic and meroplanktic algal populations are not addressed by most sampling programmes, yet can account for a high proportion of algal productivity, or represent seed beds where surface blooms originate.

Alternative measures of algal abundance and productivity are often poorly correlated, as are measures of light regime. Chla continues to be a target measure for management, yet there are often poor correlations among chla, total algal biomass and levels of impairment. Secchi depth estimates visible light attenuation, which can differ significantly (seasonally and spatially) from PAR extinction.

Toxins should be systematically investigated, particularly in high risk source-waters, using regular monitoring at recreational areas and intake zones, mid-late summer spatial surveys during high risk periods and an alert level framework such as developed by the World Health Organization (Watzin *et al*. 2006). More effective criteria for T&O would include regular measures of the most problematic compounds (e.g. geosmin, MIB) in source waters and municipal supplies, and comparison against their odour threshold levels.

Nutrient levels may, or may not predict toxin or odour outbreaks .Blooms are often local and inshore in origin and can spread over considerable areas as surface scum.

Incidental reports, media releases and websites may inflate or misrepresent these issues. Most attention is focused on surface scum, which inevitably bias samples and perceived severity.

Comments from the Authors
There are few long term data collected on HABs and more specifically, toxins, in the Great Lakes, making trend analysis difficult. Differences in sampling regimes and analytical protocols (e.g. surface or integrated sampling; taxa enumeration; toxin analyses) utilized in past studies affects the ability to compare data and determine long term trends in toxins and bloom occurrences. Attention is most often focussed on shoreline scums or algal material visible at the surface, particularly for inland waters where many reported blooms are caused by attached macroalgae (*Cladophora*, *Lyngbya*) or large, buoyancy-regulating cyanobacteria. These buoyancy-regulating taxa can produce rapid surface accumulations from populations through the mixed layer or deep living/benthic populations. Concentrated surface scum appear/disappear and migrate rapidly with changes in vertical mixing, currents and wind activity. These can produce rapid changes in toxin levels along a waterfront or cover extensive areas in large lakes, and are difficult to sample, quantify or predict. Beach and shoreline sampling programmes require multiple sub-sites to capture this envelope of

spatial/temporal variance in risk and impairment, which are poorly represented by basin-wide seasonal means. Sampling regimes in the Great Lakes are often sparse (both temporally and spatially) and are likely to miss spatial and temporal peaks in cyanobacterial/algal abundance.

Assessing Data Quality

Insert "x" under the statement that best corresponds with each data characteristic

Data Characteristics	Strongly Agree	Agree	Neutral or Unknown	Disagree	Strongly Disagree	Not Applicable
1. Data are documented, validated, or quality-assured by a recognized agency or organization						
2. Data are traceable to original sources						
3. The source of the data is a known, reliable and respected generator of data						
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin						
5. Data obtained from sources within the U.S. are comparable to those from Canada						
6. Uncertainty and variability in the data are documented and within acceptable limits for this indicator report						
Clarifying Notes:						

Acknowledgments

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Impairment	Mechanisms	Affected agents
Drinking/recreational water integrity	Taste and odour, poor aesthetics	Drinking/recreational water
Source water quality and function	Anoxia from decaying material Reduced water transparency etc.	Multiple ecosystem (fish and wildlife; internal nutrient loading etc); Tourism/ recreational; property value
Fouling	Industrial intakes Fish nets Beaches/shorelines	Drinking/hydro/other industries; aquaculture/tourism/ recreational; waterfront and property value
Elevated shoreline and beach bacterial/ pathogen levels	Entrain/facilitate growth of pathogenic microbiota	Tourism/ recreational; property value
Biomagnification (toxins, taste)	Taint fish /shellfish/other	Recreational/food/aquaculture; ecological (foodweb transfer)
Ecological	Multiple; include cell/tissue damage, growth inhibition, teratogenic, toxigenic (toxins, irritants, shading, allelopathic interactions, inadequate food quality, etc)	Multiple foodweb levels

Table 1. HABs Impairments - Socioeconomic and Ecological
Qualitative assessment only at this point; could be developed into more quantitative measures.

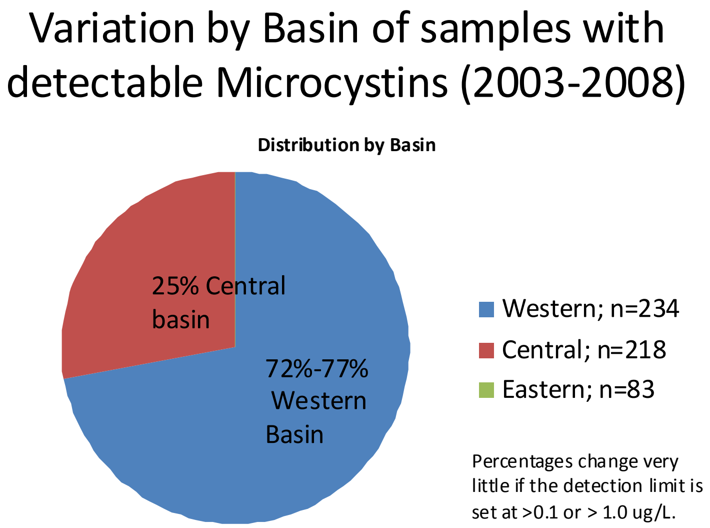

Figure 1. Lake Erie: percent of all samples collected between 2003 & 2009 with detectable levels of MC toxins.
Source: Greg Boyer, SUNY; unpublished