Water Clarity

New Indicator

Overall Assessment

Status: Undetermined*

Trend: Mostly improving, with the exception of Lake Erie and select near-shore locations

Rationale: Overall improvement over the Great Lakes between the periods 1979-1986 and 1997-2005, with the exception of central and western Lake Erie which displays significant deterioration, and regional near-shore deterioration across all other lakes.

Lake-by-Lake Assessment

Lake Superior

Status: Undetermined*

Trend: Mostly improving

Rationale: Unchanging to moderate improvement in offshore waters with some deterioration in near-shore zones such as Thunder Bay and Duluth.

Lake Michigan

Status: Undetermined*

Trend: Mostly improving

Rationale: Unchanging to moderate improvement offshore with minor deterioration near-shore in Green Bay and southern shores near Chicago.

Lake Huron

Status: Undetermined*

Trend: Mostly improving

Rationale: Unchanging to minor improvements in Georgian Bay, with broadly improving water clarity offshore Lake Huron. Isolated deterioration in water clarity is evident in Saginaw Bay.

Lake Erie

Status: Undetermined*

Trend: Western and central basin deteriorating, eastern basin improving

Rationale: Lake Erie showed deterioration in Secchi Depth of up to 2m in the central and western basins and Lake St Clair between the observation periods 1979-1986 and 1997-2005 whereas the eastern basin showed an improvement of up to 2m.

Lake Ontario

Status: Undetermined*

Trend: Improving

Rationale: Lake Ontario showed lake-wide increases in Secchi Depth of up to 4m between the observation periods 1979-1986 and 1997-2005. Isolated deterioration in water clarity is evident in some regional near-shore areas.

*Secchi Disk Depth is a complex combination of the effects of all particulate and dissolved materials on the transmission of light through the water column and as such could be detrimental (or advantageous) to different ecosystem components and indeed different water bodies at varying thresholds. For this reason a clear threshold upon which a water body can be judged “good” or “poor” with respect to its impact on aquatic ecosystems is not straightforward. A Secchi depth of 0.5m attributable entirely to a pure mineral particulate concentration may not be as much of a concern to the ecosystem as a 0.5 m Secchi depth attributable to a harmful algal bloom. As such, it was deemed inappropriate to assign a status for this indicator at the present time.

Purpose

- To estimate historical conditions and recent trends in lake-wide water clarity over the Great Lakes from satellite-measured aquatic colour.
- To highlight regions of potential water clarity impairment.

Ecosystem Objective

Water clarity is an important supporting element in assessing the ecological status of a water body through its direct linkages to ecosystem processes. These processes include, but are not limited to defining the photic depth within which photosynthesis is possible, defining light availability to benthic communities, and monitoring the impact of invasive species, climate change, and implemented management practices. While there is little specific reference to water clarity in the GLWQA, aside from the direct effects of point-source pollution discharges on local light transmission (Annex 1, IIc), this indicator supports annex 11 (1c); surveillance and monitoring, through the evaluation of water quality trends in the Great Lakes.

Ecological Condition

Background

Water clarity is directly related to the particulate and dissolved materials contained within the water, which in combination determine the degree to which light is attenuated in the upper water column. Secchi Disk Depth (the depth in meters at which a white disk is no longer visible from the surface) is a commonly used, low cost descriptor of water transparency routinely performed in monitoring programs and offers the only multi-decadal historical measure of water clarity. Secchi Depth is often used as a surrogate estimate of phytoplankton biomass, as an indicator of eutrophication (Carlson, 1977). However, the optical properties of lakes are not just determined by phytoplankton, but also by suspended inorganic and organic particles, and dissolved organic matter. Therefore, the indicator described here is treated as a broad measure of water clarity, although some causal links may be discussed based on prior knowledge of the lake system.

The introduction of non-native invasive species, point-source discharges, nutrient loading and resulting eutrophication and harmful algal blooms, as well as mandated programs to reduce phosphorus loadings have all led to notable fluctuations in water clarity in the Great Lakes over the years (Environment Canada, 2001). Despite several detailed studies (Makarewicz et al., 1999; Barbiero & Tuchman, 2004, Howell et al., 1996), however, sparse spatial coverage and the discontinuous nature of ground-based monitoring often preclude reliable conclusions regarding long-term lake-wide changes in water clarity. Earth observation satellites offer regular, high resolution synoptic views of the lakes, which may provide more robust evidence of spatial and temporal trends in water clarity than point sampling alone.

Satellites measure the amount, and spectral quality, of light leaving the water's surface after interacting (through absorption and scattering) with dissolved and particulate materials. For this reason, satellite-measured aquatic colour signals can be interpreted in terms of coloured water quality parameters such as phytoplankton, mineral sediments and dissolved organic materials. A range of empirical through analytical bio-geo-optical modeling methods may be adopted to reach a quantitative measure of a specific water quality indicator. Imagery from the Coastal Zone Color Scanner (CZCS) has been used to produce monthly images of the Great Lakes for the period 1979-1985, offering an historical view of water clarity conditions. By merging this with imagery from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) for the period of 1998-2006, it is possible to assess time-series evolution of water quality trends for the Great Lakes, documenting the extent to which the Great Lakes have changed over the last three decades. This time-series can be interpreted in terms of changes in water clarity, showing seasonal and inter-annual variability of bright-water episodes such as phytoplankton blooms, re-suspension of bottom sediments, and whiting events (whereby highly scattering calcium carbonate is precipitated out of solution under specific temperature and pH conditions) (Binding et al., 2007).

Measure

Satellite-derived water clarity is determined using a simple empirical relationship between Secchi Depth and the satellite-measured water-leaving radiance (nLw) at 555 nm, in the green portion of the visible spectrum, where the effects of mineral and algal particulate scattering on light penetration are broadly similar and can be treated in bulk. Particulate scattering enhances the apparent brightness of the water, therefore the more turbid a waterbody is, the brighter the remote sensing signal. Methods for the lake-wide water clarity analysis and some nearshore analysis are presented in full in Binding et al. (2007).

The near-shore water clarity analysis in this report is estimated with Landsat satellite imagery by utilizing the reflectance of water penetrating light in the visible portion of the electromagnetic spectrum. Water clarity is estimated by observing the depth at which light is no longer reflected from the bottom of the lake. This depth is derived by correcting imagery for water constituent reflectance leaving only reflectance from the lake bottom (Lyzenga 1981, Lyzenga et al. 2006). Historical trends in near-shore water clarity were monitored over time using the Lyzenga technique with Landsat 5 and Landsat 2 satellite imagery for the following locations: Sleeping Bear Dunes Nation Lakeshore on Lake Michigan; Point Clark on Lake Huron; Port Maitland on Lake Erie; and Pickering on Lake Ontario. The satellite source (Landsat) and dates of analysis were chosen to reflect the least amount of interference from natural phenomena. Recent water clarity/optical depth maps for these four specific Great Lake locations as well as lake clarity field sampling results from two surveys in 2009 and 2010 off the shore of Sleeping Bear Dunes National Lakeshore provide a Landsat analysis of water clarity in the near-shore zones.

Endpoint
Water clarity is determined by a whole suite of dissolved and particulate material that may constitute a "poor" status under differing concentrations and may or may not have a detrimental effect on a range of ecosystem components. To the authors' best knowledge there are currently no target water clarity levels for the Great Lakes. Therefore, there has been no assessment of the "status" of each lake. Instead, this report focuses on trends in water clarity over the last three decades relative to historical average conditions. The only reference to water clarity within the GLWQA is within Annex 1 IIC - PHYSICAL properties where it describes variations in the Secchi depth by 10% in reference to substances attributable to municipal, industrial or other discharges and their effect on light transmission. There is no discussion of non-point source turbidity (natural sediment resuspension, algal blooms, etc.) which will constitute the vast majority of the remote sensing signal.

Trends in Water Clarity in the Great Lakes
While satellite imagery is available for the entire Great Lakes, methods using MODIS and MERIS to analyse water clarity on the entire lake have only been fully validated for Lakes Erie and Ontario. As such, it is possible to discuss trends for these two lakes in a quantitative manner with regard to a calibrated Secchi depth product. Results for the remaining lakes will be discussed in a qualitative manner from changes in water brightness (i.e. water-leaving radiance, nLw). Ongoing validation exercises will allow for a quantitative assessment of the remaining lakes for the next SOLEC indicator report.

Lake Superior Lake Superior exhibits by far the lowest overall levels of turbidity (i.e. lowest nLw) across the Great Lakes and has shown moderate further improvements in water clarity between the 1979-1985 and 1998-2005 observation periods, with little change in mid-lake conditions. Some near-shore regions show evidence of a moderate decrease in water clarity; in particular near Thunder Bay and Duluth. Intra-annual variability in water clarity has decreased between the two observation periods.

Lake Michigan Lake Michigan water clarity broadly increased between the two observation periods, with notable increases in water clarity in the northern lake, no significant change in the southern offshore regions, and localized decreases in water clarity on the southern shores near Chicago and in Green Bay. Intra-annual variability in nLw decreased between the two periods and notably so in the years since 2002, suggesting a decrease in the intensity of brightness events (commonly whiting events or algal blooms in August/September each year).

A case study (in the next section) of the Landsat data analysis of near-shore water clarity at Sleeping Bear Dunes National Lakeshore describes the detailed improvements of water clarity along the north-eastern shore of Lake Michigan between 1974-2009.

Lake Huron Lake Huron water clarity broadly increased between the two observation periods, with Georgian Bay showing only a modest increase. Saginaw Bay is highlighted as the region experiencing the greatest reduction in water clarity on the lake. Intra-annual variability has remained fairly consistent while the background water clarity conditions have improved.

There has also been an increase in the near-shore water clarity/optical depth from 1979 through 2009 (figures 3 & 4). While some variability can be seen in the Landsat analysis, the general trend has been an increase from 8 meters to 13.5 meters of optical depth over the 30 year observation period. The increase in water clarity/optical depth over this time is largely attributed to some key events in the Great Lakes areas. The invasion of the Zebra and Quagga mussels have played a key role as they found Lake Huron to be prime habitat and have exhibited their success as filter feeding organisms. In addition to the invasive species was the Great Lakes Water Agreement in 1972 which set the stage for decreases in nutrient discharge and the institution of best management practices, in respect to waste water discharge into the Great Lakes.

Lake Erie In contrast to all the other lakes, Lake Erie shows a marked increase in both the magnitude and variability in nLw levels between the two time periods (Fig 5d). Figure 5 presents the derived Secchi depth for the two periods; during 1979-1985 lake-wide Secchi depths ranged from 2 to 4.5 m, while by 1998-2005 lake-wide Secchi depths ranged from 1.5 to > 6m. The geographic distribution varied significantly between the two periods; Secchi depths of 4m or greater, while widespread during 1979-1985, were confined strictly to the eastern basin during 1998-2005. Figure 5c shows relative increases in Secchi depths in the eastern basin up to and exceeding 2m. Additional analysis confirms a more than doubling of spring-time Secchi depths in the eastern basin between the two observation periods. In contrast, the central and western basins underwent a period of decreasing water clarity, with average reductions in Secchi depth of 1-2m. Imagery confirms that Lake Erie has changed from fairly uniform lake-wide water clarity conditions to strong east-west water clarity gradients of up to 5m. Despite historical reports of localised dramatic decreases in algal biomass in the years following the zebra mussel invasion (Barbiero & Tuchman, 2004), image analysis suggests this did not result in significant increases in water clarity in the western basin suggesting water clarity here is driven more by mineral resuspension signals.

In contrast to the lake-wide water clarity changes described above, the near-shore water clarity/optical depth in Lake Erie near Port Maitland has not shown any significant change based on the Landsat analysis (figures 6 & 7). Similar to the near-shore location in Lake Ontario, this near-shore location in Lake Erie has not shown any increase or decrease in the past 20 years.

Lake Ontario Average Secchi depths over Lake Ontario as estimated from CZCS and SeaWiFS imagery for the periods 1979-1985 and 1998-2005 respectively are presented in figure 7. Secchi depths are largely uniform across the lake at around 3-4m for the 1979-1985 period and increase notably to 6-8m by the 1998-2005 period. Figure 7c confirms that the entire lake appears to have undergone significant improvements in water clarity, with lake-wide increases in Secchi depth of between 2 and >4m.

The absence of large regions of bottom sediment re-suspension in Lake Ontario suggests these changes may be attributed to bio-chemical changes, either a reduction in biological productivity or a reduction in the intensity/frequency of whiting events. Further analysis identified the largest monthly change to be in April, with a more than doubling of Secchi depths, suggesting a decline in the extent of the spring bloom on the lake. Millard et al. (2003) observed a lake-wide decline in chlorophyll between 1990 and 1996, attributing it to the combined effects of nutrient loading controls and the mussel invasion. Further evidence suggests a reduction in the frequency/intensity of whiting events in agreement with the effect of calcium uptake by mussels on lake water clarity.

In contrast to the lake-wide increases in water clarity, the remotely sensed satellite-derived information on near-shore water clarity indicates little change in optical depth in Pickering, Ontario, located on the north shore of Lake Ontario (Figure 8). While the data set does change annually, there is no significant change that would indicate an increase or decrease in water clarity/optical depth (figure 9). This could be partially attributed to anthropogenic influences from the surrounding urban areas, river discharge and the level of agricultural practices surrounding this part of Lake Ontario.

Near-Shore Water Clarity: Special Case Study

Water Clarity in Sleeping Bear Dunes National Lakeshore has been of significant interest in the remote sensing program at Michigan Technical Research Institute (MTRI). Over the period between 1974 and 2009, significant improvements in water clarity were found (figures 11 & 12). The increase in red colour (figure 12) from 1974 to 2009 indicates dramatic increases in the aerial extent over which the lake bottom is visible over the 35 year period.

Upon further research and discussions with Lake Michigan ecologists, it is suggested that these changes in water clarity have been related to the increase in invasive species (especially Zebra and Quagga mussels), best management practices, and political agreements such as the Great Lakes Water Quality Agreement. In particular, the increase in water quality over the past 20 years (figure 13) is very likely due to the large amount of water filtering due to the invasion of Zebra and Quagga mussels, leading to much greater habitat availability for benthic algae such as *Cladophora* (Auer 2010, Tomlinson 2010), leading to associated issues of *Cladophora* algae beach fouling and avian botulism outbreaks (VanSumeren and Breederland 2008).

An intensive field investigation was completed along the Sleeping Bear Dunes National Lakeshore in 2009 and again in 2010 as part of a GLRI-funded *Cladophora* mapping effort. In 2009 and 2010, MTRI joined with the University of Michigan Marine Hydrodynamic Laboratory (UMHL) to investigate the growth of *Cladophora* algae in the Sleeping Bear Dunes National Lakeshore coastal area in Lake Michigan.

In both 2009 and 2010, Secchi disc measurements were recorded in locations throughout the study area using standard Secchi disc transparency (SDT) methods (figure 14). Additionally, *Cladophora* samples were collected by a diver along with a remotely controlled video camera that was towed by the research vessel through the water.

There is a noticeable difference between the Secchi measurements at Sleeping Bear Dunes National Lakeshore between August 27, 2009 and July 8, 2010 (figures 14 & 15). The average depth in 2009 is 9.08 meters, while in 2010 the average Secchi depth is 7.25 meters. While the sample locations from 2009 to 2010 are not exactly the same, a few locations are within close proximity to one another. Specifically, site A4 in 2009 and site C8S in 2010 are the same location, but in 2009 the Secchi reading was 7.32 meters and in 2010 the measurement was 6.95 meters. Also, Site C2 in 2009 and site C1 in 2010 are the same location, but the measurements are different. Site C2 in 2009 had Secchi reading of 11.28 meters, and site C1 in 2010 was recorded at 6.28 meters. This analysis of direct Secchi depth measurements demonstrates how much variability can occur from one year to the next, most likely due to algal blooms in the water column.

Linkages

Water clarity is important as a broad indicator of lake water quality and ecosystem status which reflects a variety of ecosystem processes and is both impacted by and has impacts upon a wide range of other indicators.

Harmful algal blooms/Phytoplankton: Water clarity dictates the photic depth and the quantity of light available for primary productivity. In addition, light quantity and quality (that is the spectral characteristics of the light field) has been shown to be significant in driving selective species dominance (e.g. cyanobacteria, Bennet and Bogorad, 1973) therefore playing a key role in determining species assemblages within the lakes.

Benthic Communities/Cladophora: Water clarity will again determine the depth to which light penetrates and therefore dictates the areal extent of benthic vegetation, with increasing water clarity resulting in an abundance of benthic algal mats.

Mussels: Water Clarity has been used as a primary indicator in monitoring the impact of filter feeding on the water quality of the Great Lakes.

Nutrients: Water clarity combined with prior knowledge of the lake system can be used as an indicator of eutrophication provided the contribution to water clarity from mineral particulate turbidity is known or constant.

Fish habitats: Water clarity is known to be a factor in determining the location of feeding/spawning grounds and is therefore an important indicator for broader understanding of fish habitat and population dynamics.

Management Challenges/Opportunities

The broad nature of water clarity as a measure of Great Lakes water quality is valuable in that it encompasses a variety of in-water constituents (algal blooms, mineral resuspension, point-source loadings) and therefore responds to, and thus be an indicator of, a wide variety of processes. However, it is this broadness that makes it a complex indicator to assign thresholds in order to define the status of a waterbody as “good”, “fair” and “poor”. Water clarity can be both advantages and detrimental to different components/processes within an ecosystem which adds to the uncertainty in threshold definition.

Satellite remote sensing methods have been developed to distinguish algal from mineral turbidity which may go some way to further understanding the complex nature of this indicator although at present this data is not available over an extended time period to allow a reliable trend analysis. Freely available satellite imagery of the Great Lakes combined with effective modeling and image processing methods allows for cost-effective ongoing monitoring of the trends discussed in this report and potential elucidation of emerging responses of Great Lakes water clarity to both natural and anthropogenic induced change.

Comments from the author(s)

Although the Landsat derived historical timelines of water clarity/optical depth were produced for the near-shore areas in the Great Lakes, it is also important to note that this near-shore dataset is limited. Each date reporting water clarity/optical depth is a singular representation for that specific moment in time. The data from a specific date reflects any meteorological, stream and river discharge, anthropogenic, and Lake current phenomena that may have occurred on or recently before the acquisition. Documentation of the phenomena listed above needs to be generated for this data, as well as future water clarity documentation.

These data limitations do not apply to the MODIS and MERIS lake-wide time series analysis due to the significantly improved temporal resolution of those sensors.

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	X					
2. Data are traceable to original sources	X					
3. The source of the data is a known, reliable and respected generator of data	X					
4. Geographic coverage and scale of data are appropriate to the Great Lakes basin	X					
5. Data obtained from sources within the U.S. are comparable to those from Canada						X
6. Uncertainty and variability in the data are documented and within acceptable limits for this indicator report			X			
Clarifying Notes: Satellite-derived Secchi Depths are predicted with an RMSE of <25% of the mean for Lakes Erie and Ontario. All other lakes are described in a qualitative manner only as the product uncertainty has not been fully assessed.						

Acknowledgments

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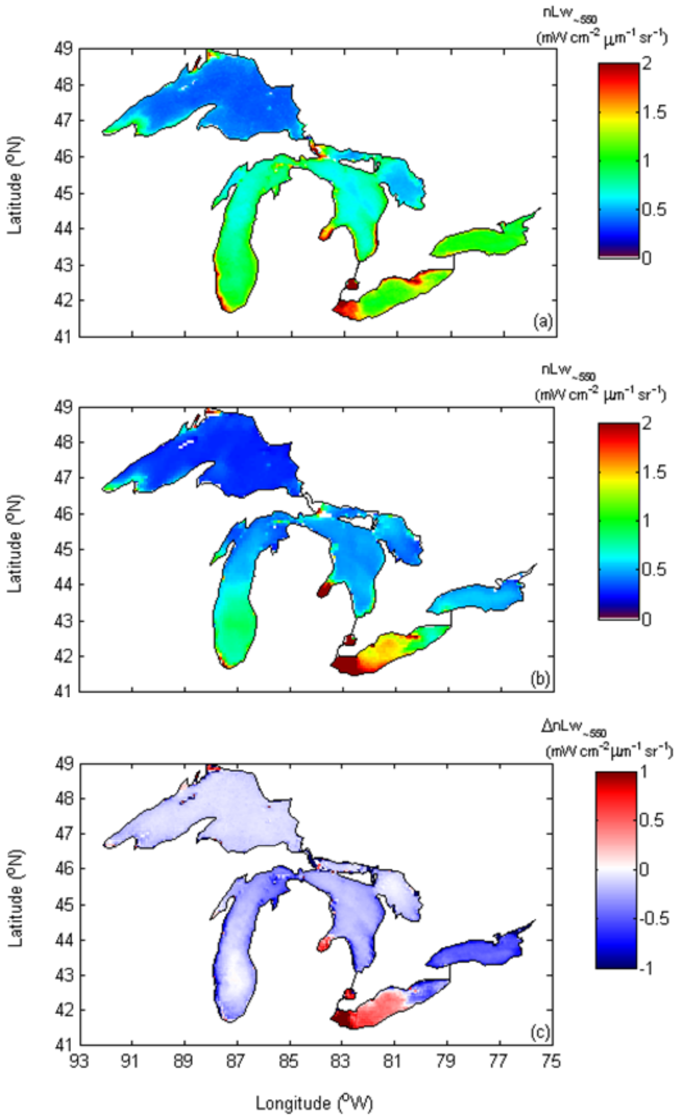
Last Updated
SOLEC 2011



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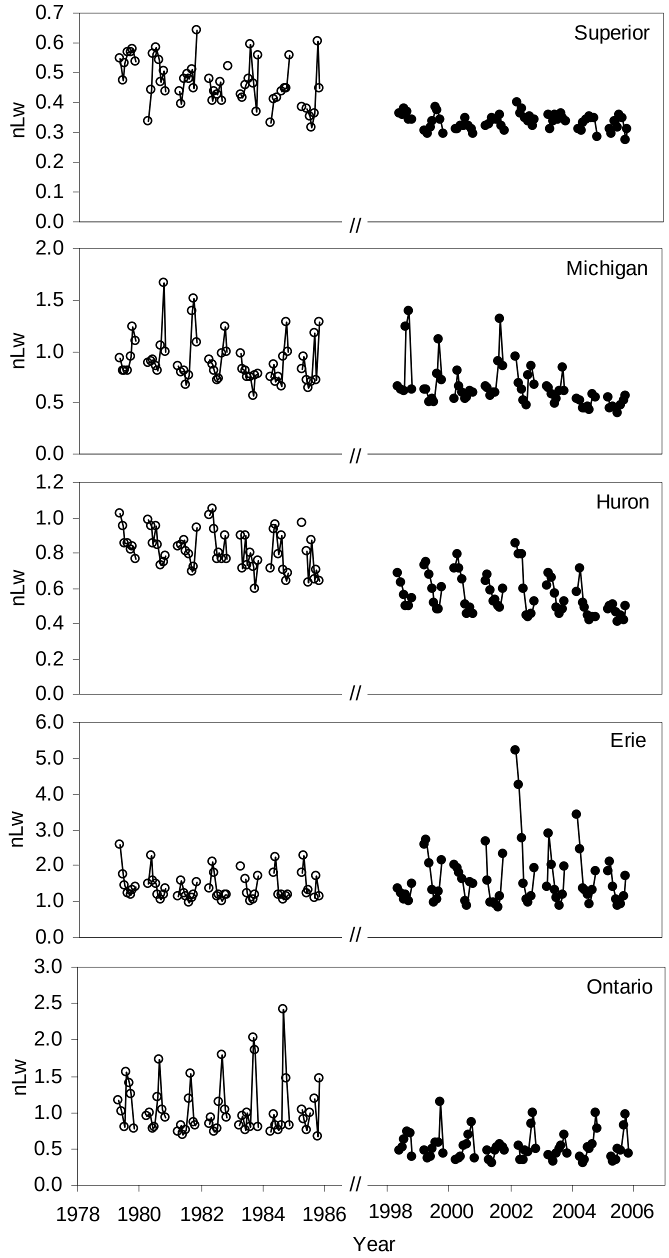

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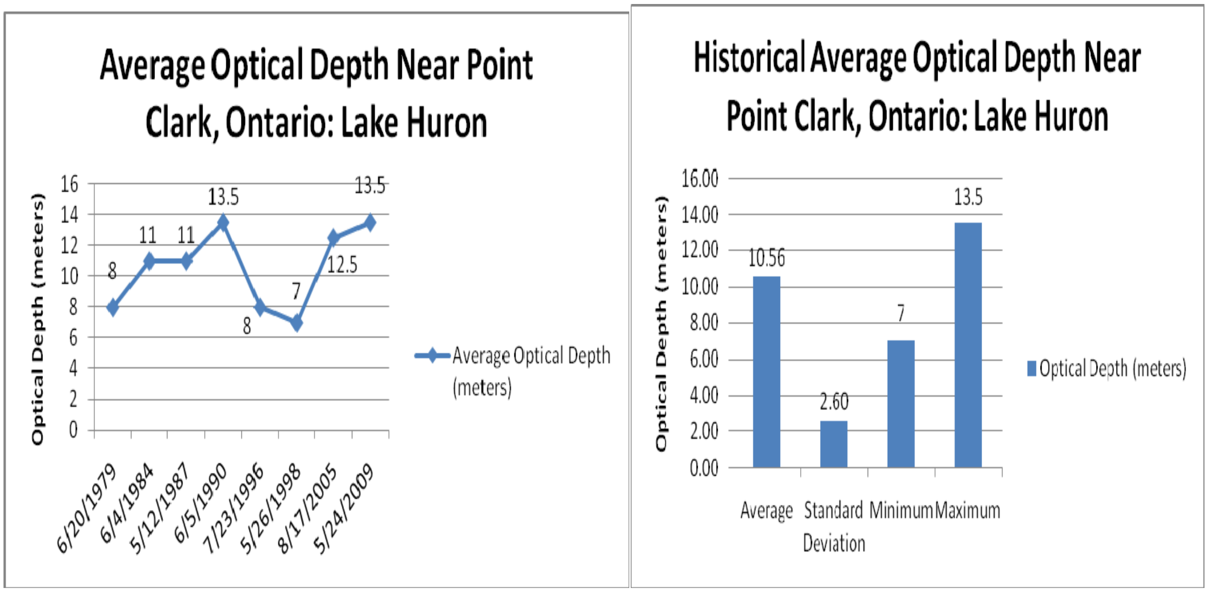

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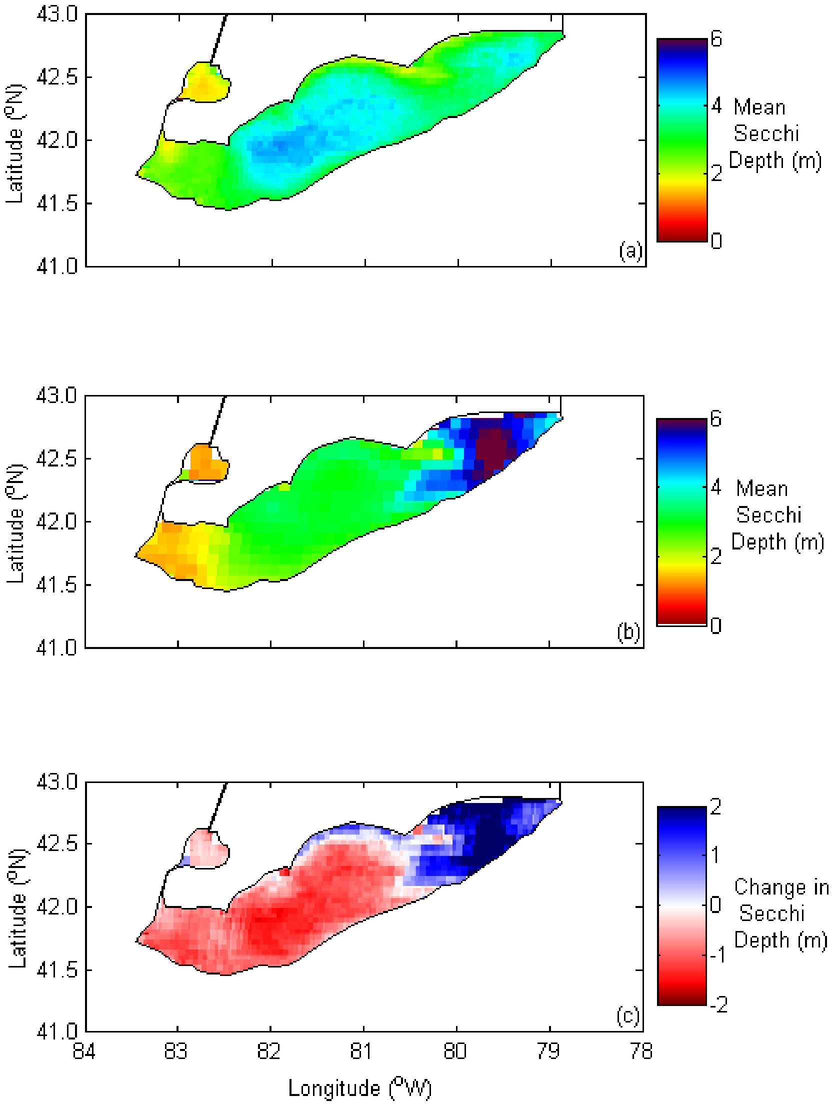

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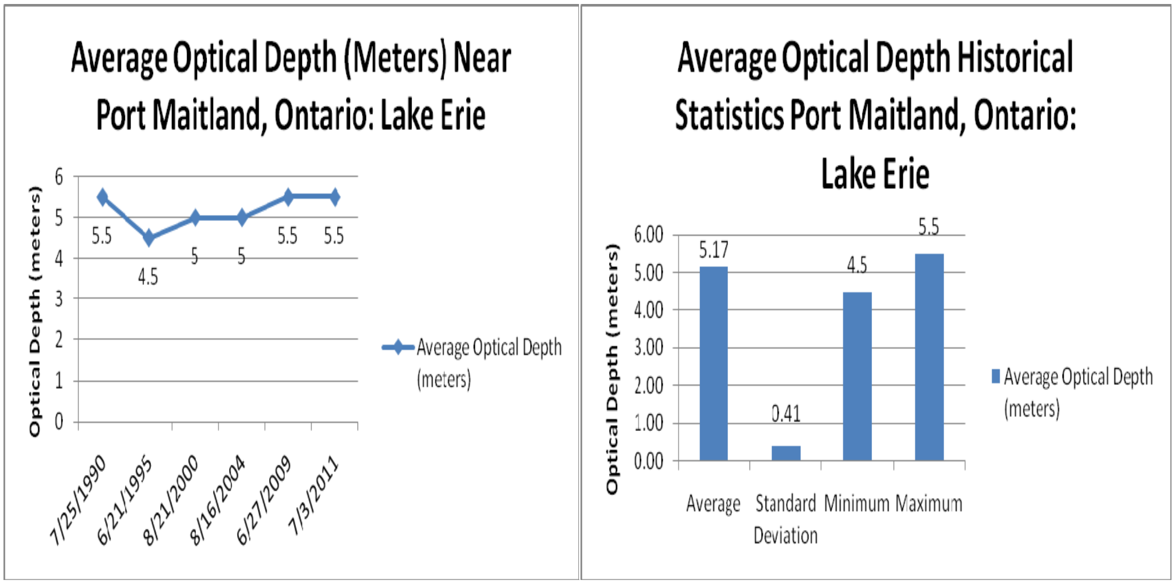

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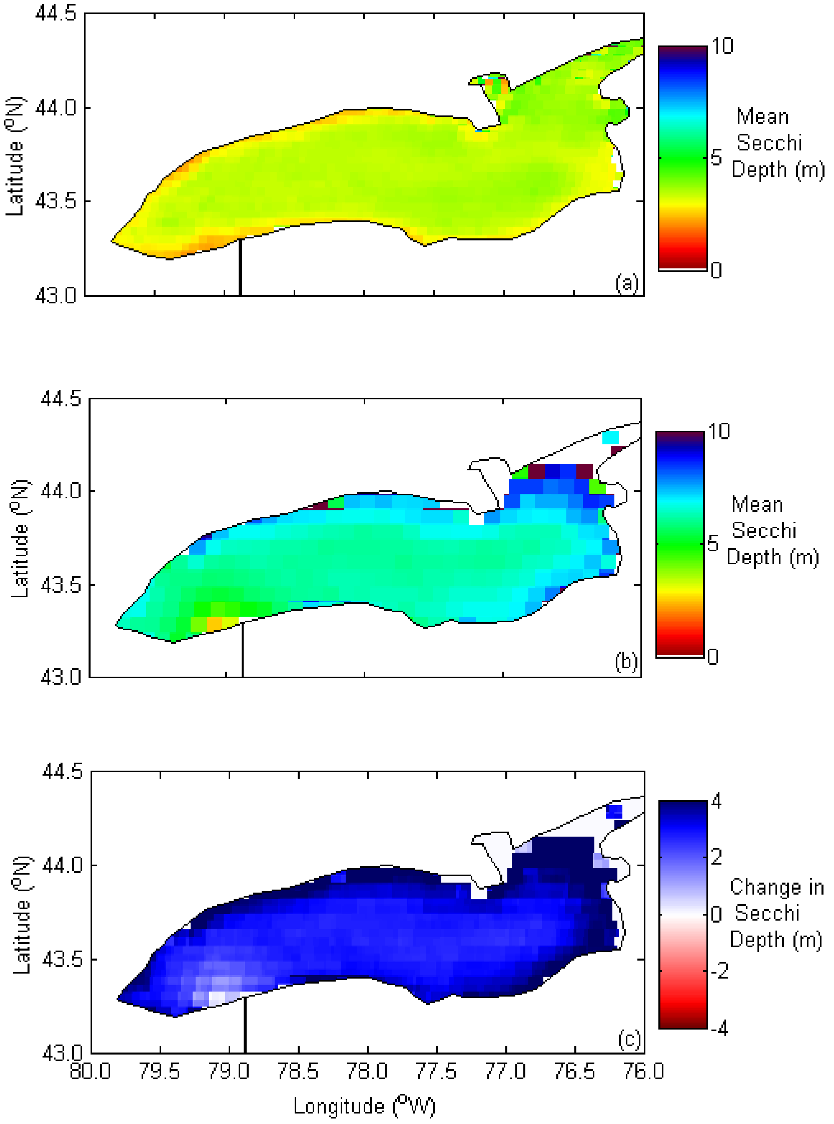

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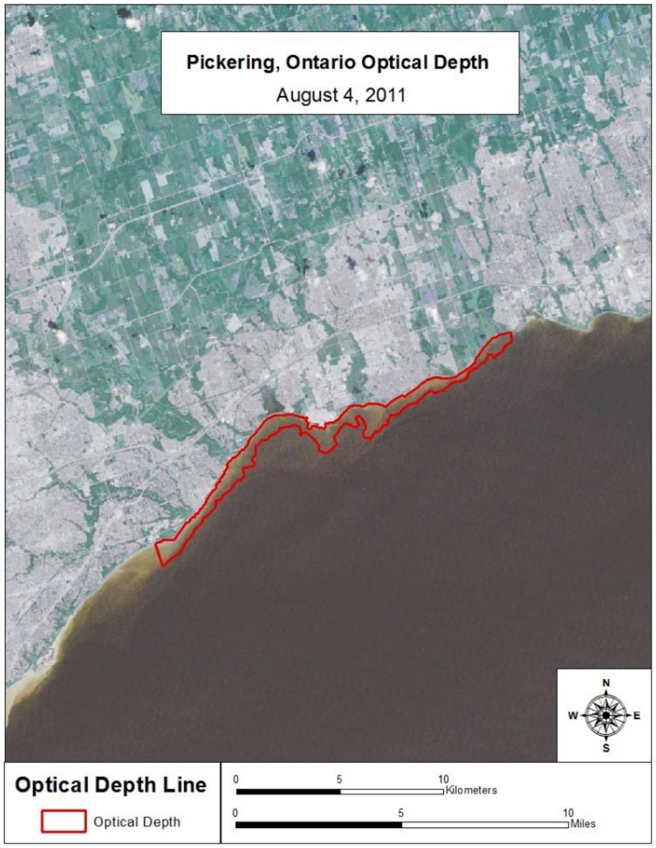

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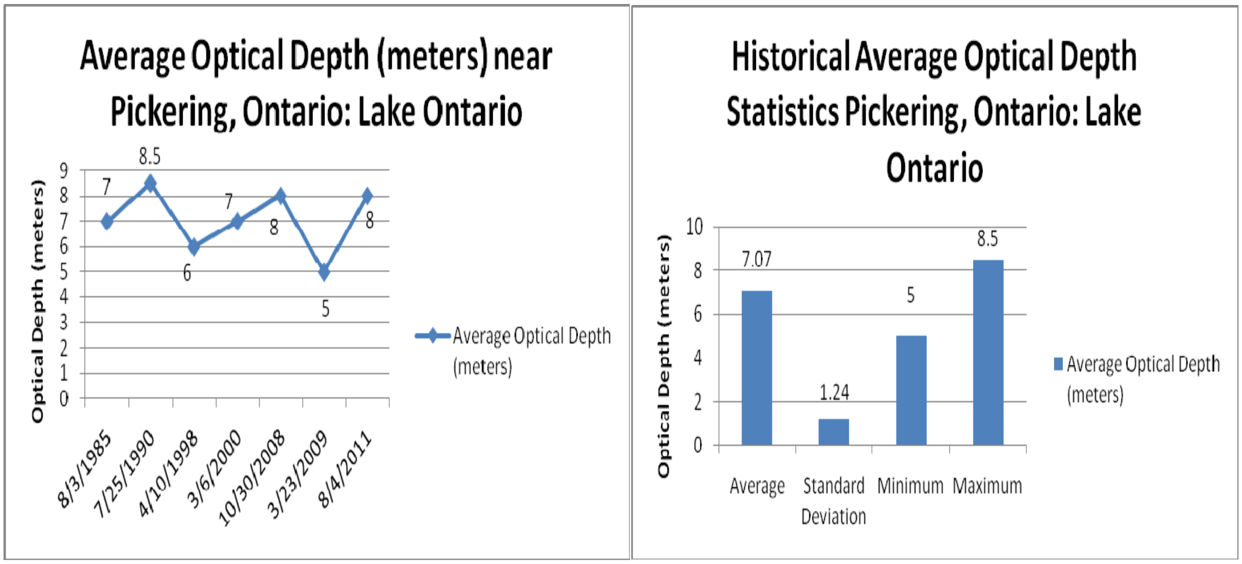

Figure 10: Average water clarity/optical depth a) derived from Landsat, over time near Pickering, Ontario between August 1st 1985 to August 4, 2011; b) Historical statistics of average water clarity/optical depth between 1985 and 2011.


Sleeping Bear Dunes National Lakeshore

Figure 11: Reference map, from Landsat, showing 2009 and 2010 field data collection location study area, Sleeping Bear Dunes National Lakeshore.

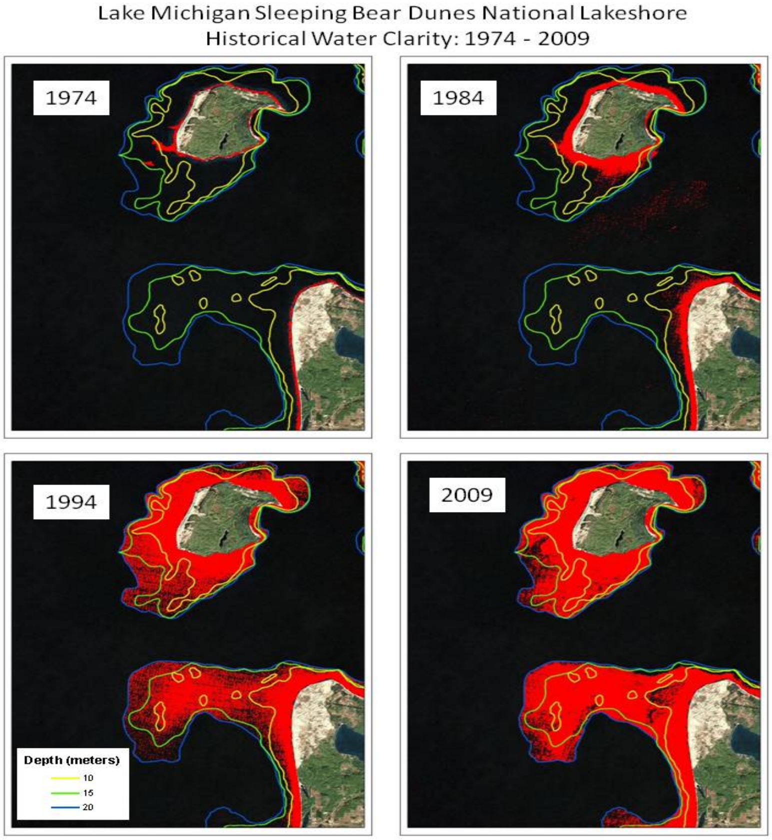
Lake Michigan Sleeping Bear Dunes National Lakeshore
Historical Water Clarity: 1974 - 2009

Figure 12: Historical water clarity/optical depth, derived from Landsat, at Sleeping Bear Dunes National Lakeshore from 1974 to 2009.

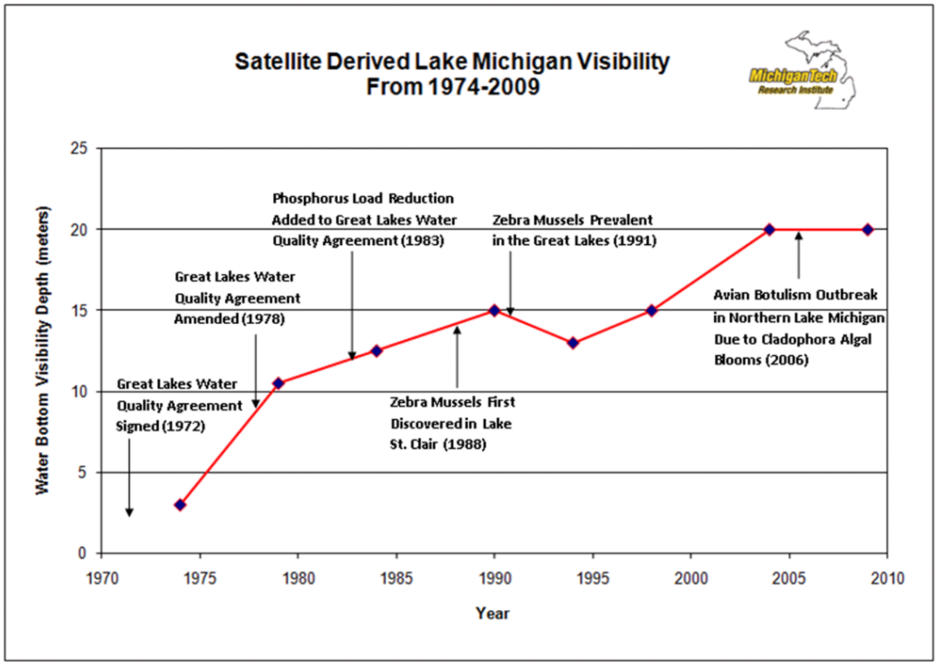

Figure 13: Water clarity plot derived from satellite imagery using the depth invariant index 1974-2009.

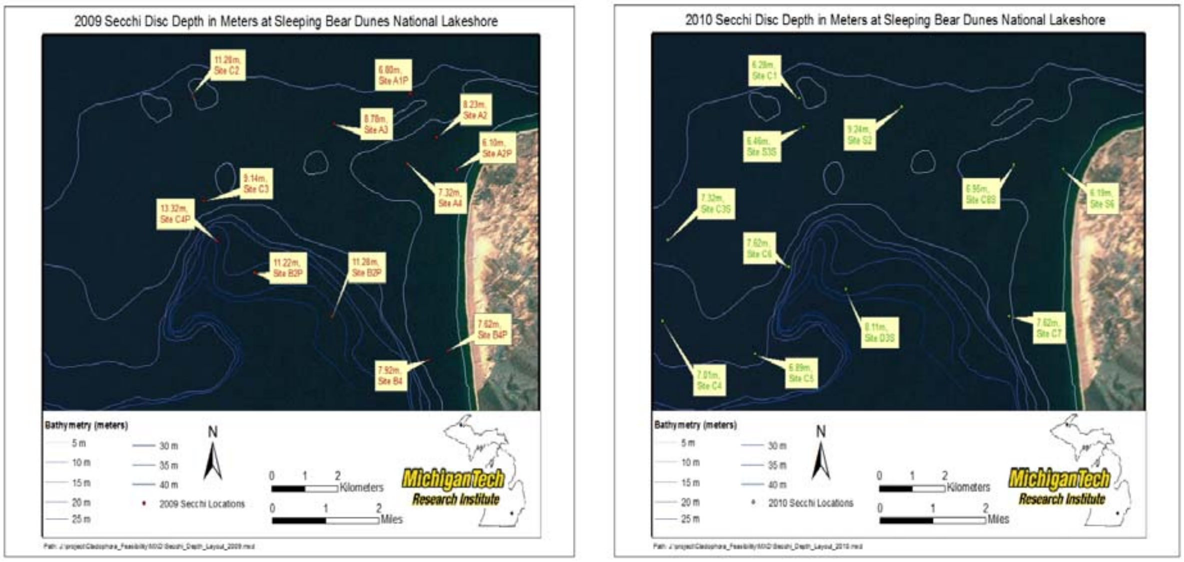

Figure 14: August 27, 2009 Secchi Disc Depth in Meters at Sleeping Bear Dunes National Lakeshore on a) August 27, 2009 and b) July 8, 2010

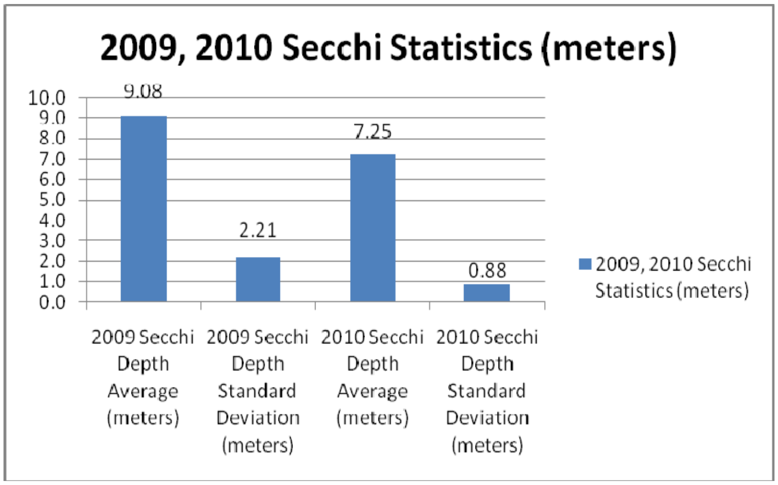

Figure 15: 2009 and 2010 Secchi Disc Measurement Statistics.