ARTICLE IN PRESS
JGLR-01162; No. of pages: 9; 4C:
Journal of Great Lakes Research xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Journal of Great Lakes Research
journal homepage: www.elsevier.com/locate/jglr

Water clarity of the Upper Great Lakes: Tracking changes between 1998–2012

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ARTICLE INFO

Article history:
Received 5 September 2015
Accepted 4 November 2016
Available online xxxx

Keywords:
Remote sensing
SeaWiFS
MODIS
Laurentian Great Lakes
Kd490
Quagga mussels

ABSTRACT

Water clarity trends in three upper Great Lakes, Lakes Superior, Michigan, and Huron, were assessed via satellite imagery from 1998 to 2012. Light attenuation coefficients (Kd_{490}) from SeaWiFS and Aqua MODIS satellites compared favorably with in situ measurements. Significant temporal and spatial trends and differences in Kd_{490} were noted within all three of the lakes. Lake-wide average Kd_{490} for Lake Superior did not exhibit any changes between 1998 and 2012. Annual Kd_{490} values for Lake Huron, however, showed a significant negative trend during the study period using both SeaWiFS and MODIS datasets. Similarly, annual Kd_{490} values of Lake Michigan declined between 1998 and 2010. Only in the offshore waters (>90 m depth) of northern Lake Michigan did Kd_{490} increase but just after 2007. Photic depth increased significantly in both Lake Michigan (≈5 m), and Lake Huron (≈10 m) when comparing annual Kd_{490} for pre- (1998–2001) and post-dreissenid mussel (2006–2010). At seasonal level, significant decreases in Kd_{490} in lakes Michigan and Huron were mainly noted for the spring/fall/winter mixing periods. After these recent changes in water clarity, lake-wide photic depths in lakes Michigan and Huron superseded Lake Superior; thus, making Lake Superior no longer the clearest Great Lake. Several factors (e.g. filtering activities of quagga mussels, phosphorus abatement, climate change, etc.) are likely responsible for these large changes.

Introduction

The Laurentian Great Lakes are the largest freshwater system in North America and contain over 20% of the world's surface freshwater (Cayton et al., 2006). Surprisingly, many system-wide and ecosystem related processes in these lakes are not fully understood. Moreover, these lakes have been subject to many climatic and environmental changes. While a major decline in total ice coverage for Great Lake (71%) has been observed between 1973 and 2010 (Wang et al., 2011), nutrient loading into the Great Lakes (i.e. phosphorus) has decreased for all the lakes, including the upper lakes, (Lake Superior, Lake Michigan and Lake Huron (Dolan and Chapra, 2012)) with least change in loading observed in Lake Superior. Concurrently, many non-indigenous species have become established in the Great Lakes (Mills et al., 1993; Vanderploeg et al., 2002).

Among the most significant non-indigenous species in terms of ecological impact are zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*). Quagga mussel impacts have been noted in many regions of the upper Great Lakes (Fahnenstiel et al., 2010b; Kerfoot et al., 2010; Nalepa and Fahnenstiel, 1995; Nalepa et al., 2010). Chlorophyll concentration and primary production in Lake Michigan have exhibited major declines (Kerfoot et al., 2010; Fahnenstiel et al., 2010a; Yousef et al., 2014) during the spring isothermal period which have been linked to quagga mussel populations. In Lake Michigan, Fahnenstiel et al. (2010a) reports a 66% decline in chlorophyll concentration and 50% decline in primary production between 1998 and 2008. Kerfoot et al. (2010) also observed an increase in water transparency. Similarly, Yousef et al. (2014) documented significant increase in spring water clarity of mid-depth region in Lake Michigan between 1998 and 2010. Changes in Lake Michigan productivity were temporally and spatially consistent with quagga mussel filtration activities (Fahnenstiel et al., 2010a; Yousef et al., 2014). Lake wide changes are not limited to Lake Michigan. Researchers have observed significant decline in chlorophyll concentrations in Lake Huron between 1998 and 2006 (Barbiero et al., 2011). These changes have been attributed to a combination of nutrient loading reduction in phosphorus and quagga mussels. In addition, the overall water clarity status of these lakes and the year to year temporal and spatial variability (e.g. different basins, or nearshore vs. offshore) are uncertain on a lake-wide scale.

Remote sensing provides frequent snapshots of the Great Lakes and captures lake-wide events (e.g. spring algal bloom in southern Lake Michigan; Mortimer, 1988; Lesht et al., 2002; Kerfoot et al., 2008,

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http://dx.doi.org/10.1016/j.jglr.2016.12.002
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2010). But, validation and verification of direct satellite-derived products are the primary steps necessary before any attempt to interpret spatial and temporal changes in satellite-derived imagery. In regard to water clarity and photic depth, Kd_{490} has routinely been used to estimate total light availability in water column (Lee et al., 2005; Morel et al., 2007). Kd_{490} is the extinction coefficient of the 490 nm wavelength of visible light. Gordon and McCluney (1975) found that Kd_{490} was the deepest penetrating wavelength and best suited to predict the depth of the photic zone in the sea. Also, more relevant to the Great Lakes, our in situ data from the upper Great Lakes suggested that 490 nm wavelength was the deepest penetrating wavelength (Shuchman et al., 2013). Finally, Kd_{490} is linearly related to Kd_{PAR}, which represent the extinction of PAR (photosynthetically available radiation) irradiance in the water column (Morel et al., 2007).

Here, we evaluate the relation of the light-attenuation coefficient (Kd_{490}) in the upper Great Lakes to satellite imagery products directly available for the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua). It should be noted that satellite-derived algorithms for Kd_{490} are mainly designed for oceanic conditions, and their performance had to be tested for Great Lakes. Spatiotemporal analysis of Kd_{490} should also reveal important information about the lake-wide heterogeneity of this variable. Using Kd_{490}, we have documented the long-term trend of underwater light climate for the upper Great Lakes. We also compared the temporal trends of water clarity in the upper Great Lakes and hypothesized that significant difference in water clarity trends would be found in Lake Michigan and likely Huron, but not for Lake Superior.

Methods

In situ Kd_{490}

In situ Kd_{490} measurements were made using a Satlantic profiling radiometer (http://satlantic.com/profiler). These samples were collected at various locations (Fig. 1) over the span of a few years. Lake Huron was sampled during the June of 2006, 2008, and 2010. Lake Michigan's dataset was collected during June of 2008 and 2010, and Lakes Superior's samples were collected during the August of 2007 (Shuchman et al., 2013). The Satlantic Profiling multi-channel Radiometer (SPMR) and the Multi-channel Surface Reference (SMSR) instrument package recorded downwelling irradiance (ES, ED) and upwelling radiance (LU) through the water column at predetermined

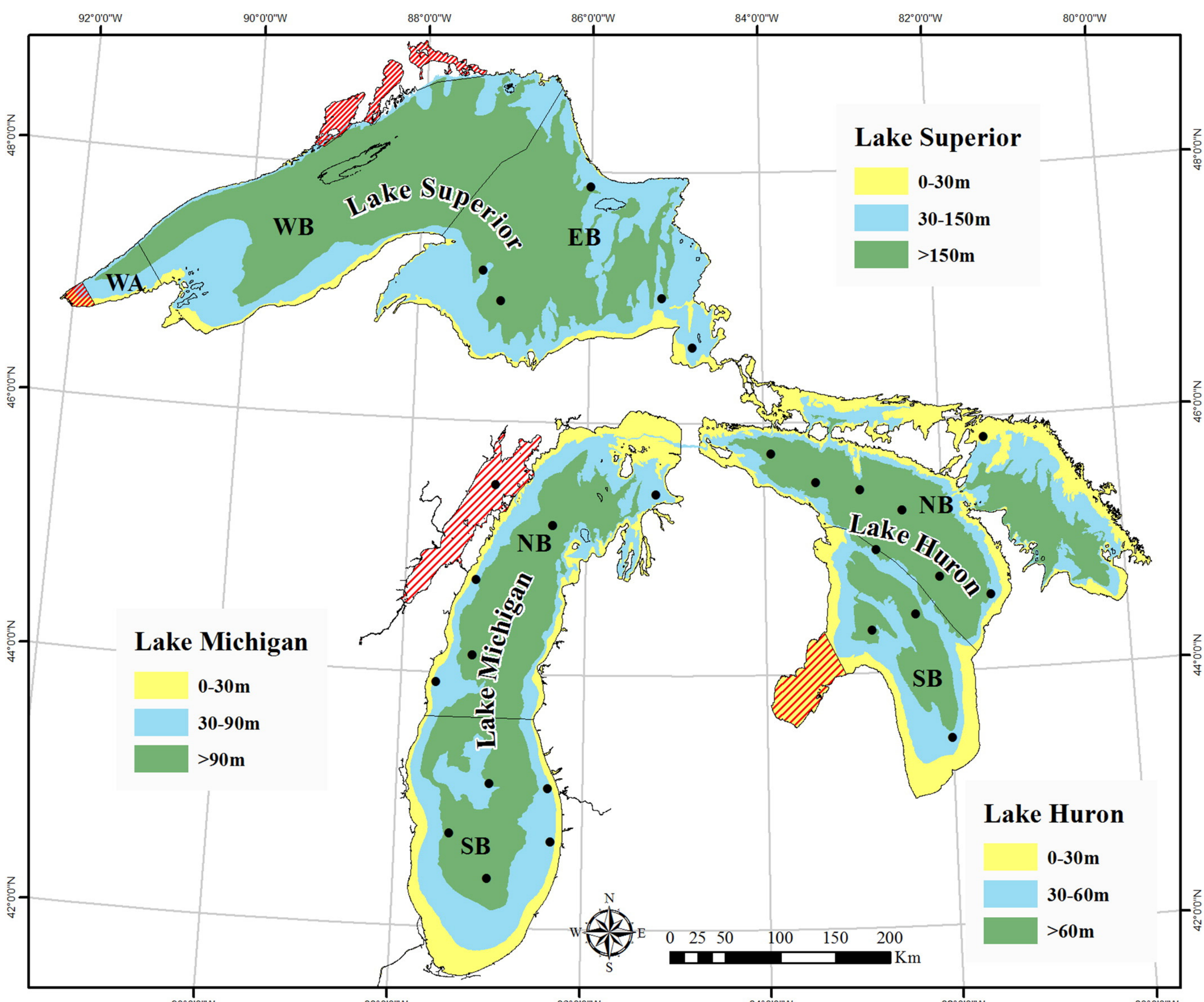

Fig. 1. Three Upper Great Lakes with their sub-basins and depth zones. The color legends represent depth zone for each lake, and the line crossing lakes divide them into sub-basins. Black circles represent the location of ground truth sites. The hatched areas (Duluth harbor area, Lake Superior; Green bay, Lake Michigan; Saginaw Bay, Lake Huron) were removed from Kd_{490} (m^{-1}) analysis due to optical complexity and lack of in situ data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Yousef, F., et al., Water clarity of the Upper Great Lakes: Tracking changes between 1998–2012, J. Great Lakes Res. (2016), http://dx.doi.org/10.1016/j.jglr.2016.12.002

depth intervals and wavelengths (between 350 and 800 nm at 2 nm intervals). The instrument was deployed through the water column until reaching 1% of surface light was reached (euphotic zone depth). From the collected data, Kd can be determined for every wavelength at each depth level by calculating the loss of irradiance from the previous depth level. Gordon and McCluney (1975) demonstrated that 90% of the remote sensing radiance originates from the first optical depth (or the depth that Kd_{490} is ~37% of its surface value). Consequently, the remote sensing Kd_{490} values are calculated for the first optical depth (Mueller, 2000). Regarding in situ Kd_{490} measurements, however, two points are worth mentioning. Firstly, various factors (such as deep chlorophyll layer or DCL, sediment plumes and resuspension, etc.) can alter the attenuation of light (Kd_{490}) at different depths. Secondly, and in contrast to remote sensing Kd_{490}, in situ Kd_{490} was routinely measured to 1% of surface light. Therefore, to ensure that in situ Kd_{490} is representative of the entire water column and is also comparable to remote sensing Kd_{490}, the following procedure was implemented. At each in situ station, Kd_{490} values were vertically averaged for all the replicate measurements to produce average Kd_{490} to the euphotic depth. These values were then used to find the first optical depth (depth of 37% of surface light) for each station for each measurement (Werdell and Bailey, 2005). Mean optical depth of each station was then calculated by averaging all available optical depth estimates. Finally, the average in situ Kd_{490} for the first optical depth was compared with remote sensing Kd_{490}.

Kd_{490} validation

NASA's (National Aeronautics and Space Administration) SeaWiFS and MODIS algorithms (KD2S and KD2M, respectively) were used to convert remote sensing reflectance (Rrs) to Kd_{490}. KD2S and KD2M are developed from empirical relationships between satellite reflectance and in situ Kd_{490} measurements (Mueller, 2000). Clouds and lake ice were masked (using OceanColor meteorological ancillary data) before any further processing. Furthermore, very nearshore pixels (2 km band around the shoreline) were removed to avoid the effects of Rayleigh scattering from the land and shoreline. Validation of the Kd_{490} estimates was performed by comparing the average value of a 3×3 pixel (~3 km × 3 km) window for coincident or near-coincident (~1 day) remote sensing Kd_{490} versus in situ Kd_{490} measurements using model II linear regression (lmodel2 package in R).

Kd_{490} spatial analysis and euphotic depth

Time series datasets of each of the upper Great Lakes were constructed for both MODIS (2003 — 2012) and SeaWiFS (1998 to 2010). The Duluth Harbor area, Thunder Bay, Black Bay, and Nipigon Bay in Lake Superior, Green Bay in Lake Michigan, and Saginaw Bay in Lake Huron were excluded from our analysis due to both the lack of in situ Kd_{490} measurements and the optical complexity of these waters (Fig. 1). Each of the upper Great Lakes were further divided into sub-region basins and depth zones to investigate spatial variability of Kd_{490}.

Lake Superior was divided into western basin (WB), eastern basin (EB), and the western arm (WA) of the western basin (Fig. 1). Each basin was further divided into three depth zones: 0–30 m (nearshore), 30–150 m (mid-depth), and >150 m (offshore) depth zones (Sierszen et al., 2011). Lake Huron was divided into northern (including North Channel and Georgian Bay) and southern basins (Fig. 1) with each basin further broken down into three depth zones: 0–30 m (nearshore), 30–60 (mid-depth), and >60 m (offshore; Nalepa et al., 2007). Finally, Lake Michigan was divided into northern and southern basins (Fig. 1) with each basin divided into three depth zones: 0–30 m (nearshore), 30–90 m (mid-depth), and >90 m (offshore; Nalepa et al., 2010; Yousef et al., 2014).

To understand the magnitude of temporal changes in water clarity of each of the upper Great Lakes, annual lake-wide Kd_{490} values (only for SeaWiFS) were divided into two time blocks; pre- (1998–2002) and post-dreissenid mussels (2006–2010). These time blocks are selected based on the density of dreissenid mussels (after Nalepa et al., 2007, 2010). Although dreissenids were present in lakes Michigan and Huron prior to 2002, they were in an early stage of invasion with low numbers compared to our post-dreissenid period. The Kd_{490} values for each of these time blocks were combined and averaged and finally compared to one another using *t*-test for each lake. Additionally, annual mean Kd_{490} was compared among the lakes for the pre- and post-mussel time blocks using *t*-test. Euphotic depth (depth where 1.0% of the surface irradiance is available) was also derived from Kd_{490} values. The value of photic depth is given by $4.6/Kd_{490}$ (Kirk, 1994) and was calculated at the yearly level for the lake-wide results.

Finally, to grasp the spatiotemporal changes in water clarity, we used both simple linear regression model and segmented linear regression (SLR; R package) model for all three lakes (including basins and depth zones) at yearly and monthly levels. While both models are excellent first approaches to small datasets, SLR further helps to capture break points and changes in the slope of the trend line. Results from SLR are presented only for those datasets that had a significant break point or change in the trend (or slope of the fitted model). Here in this study, the slope of the linear regression models is used in order to detect meaningful/significant break points. To determine if the slope of the linear trend is meaningful (either negative or positive), we used F-test to compare the slope of the linear fit against slope = 0 (indicative of no trend). While the sign of the slope (negative or positive) shows the type of trend (decreasing or increasing), the F-test determines whether the slope is significantly different from zero. Furthermore, ANOVA test was employed to investigate the Kd_{490} differences among depth zones of each lake (e.g., comparing 0–30 m vs. 30–90 m, 0–30 m vs. >90 m, and 30–90 m vs. >90 for Lake Michigan) at annual level.

Results

Kd_{490} validation

Comparisons between remote sensing Kd_{490} retrieval algorithms and in situ Kd_{490} values yielded encouraging results. All comparisons were highly significant with slopes near one. SeaWiFS predictions, when compared with in situ Kd_{490} exhibited a better linear relationship than MODIS predictions (SeaWiFS, slope = 0.85; MODIS, slope = 0.76; Fig. 2) but had poorer fit (SeaWiFS, $R^2 = 0.72$, $n = 21$; MODIS, $R^2 = 0.88$, $n = 32$); however their slopes were not significantly different.

Pre- and post-mussel Kd_{490} analysis

The results of pre- and post-mussel comparisons of the lake-wide Kd_{490} were significant for both lakes Michigan and Huron ($p < 0.01$). Kd_{490} for Lake Huron exhibited a decline of 0.02 m^{-1} (from 0.112 in pre- to 0.091 in post-mussel period) whereas Kd_{490} values for Lake Michigan dropped 0.013 m^{-1} (from 0.121 in pre- to 0.108 in post-mussel period). Lake Superior, in contrast, remained unchanged during the same period ($p > 0.05$) with Kd_{490} values of 0.11 m^{-1} (Table 1). Consequently, mean annual euphotic depth in Lake Huron significantly increased from 41 ± 5 m in 1998–2002 to 51 ± 4 m for 2006–2010. In Lake Michigan, mean annual euphotic depth changed from 38 ± 3 m in 1998–2002 to 43 ± 2 m for 2006–2010 (Table 1). Mean annual euphotic depth for Lake Superior photic remained 42 ± 2 m between 1998 and 2012.

Comparing the annual mean Kd_{490} among lakes for pre- and post-mussel periods, lakes Michigan and Huron become significantly clearer than Lake Superior during the post-mussel period. Lake Michigan exhibited significantly higher Kd_{490} values than Lake Superior during the pre-mussel era (0.121, and 0.111, respectively; $p = 0.004$). However, when comparing the post-mussel Kd_{490} values between these two lakes, the pattern switched, and Lake Michigan had significantly lower Kd_{490}

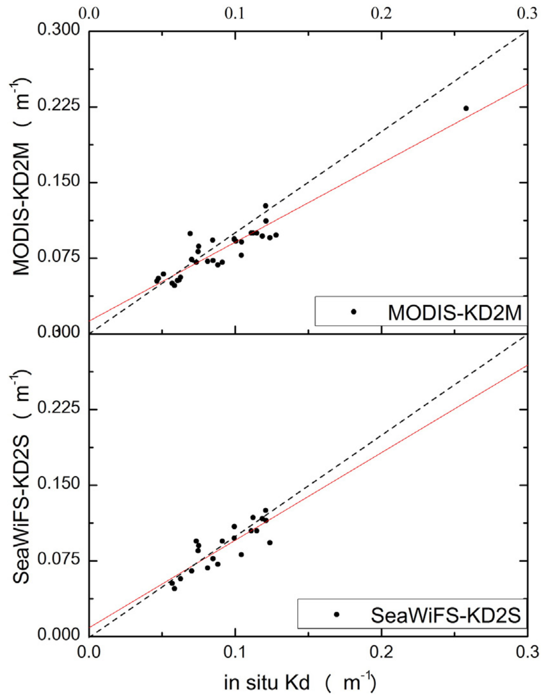

Fig. 2. Comparison between in situ Kd_{490} (m^{-1}) and remote sensing Kd_{490}. SeaWiFS (lower panel), having a slope closer to 1, represented the in situ data better than MODIS (upper panel), even though SeaWiFS had a poorer fit compared with MODIS ($R^2 = 0.72$, and 0.87, respectively). Model II simple linear regression was used to compare satellite estimates with in situ measurements.

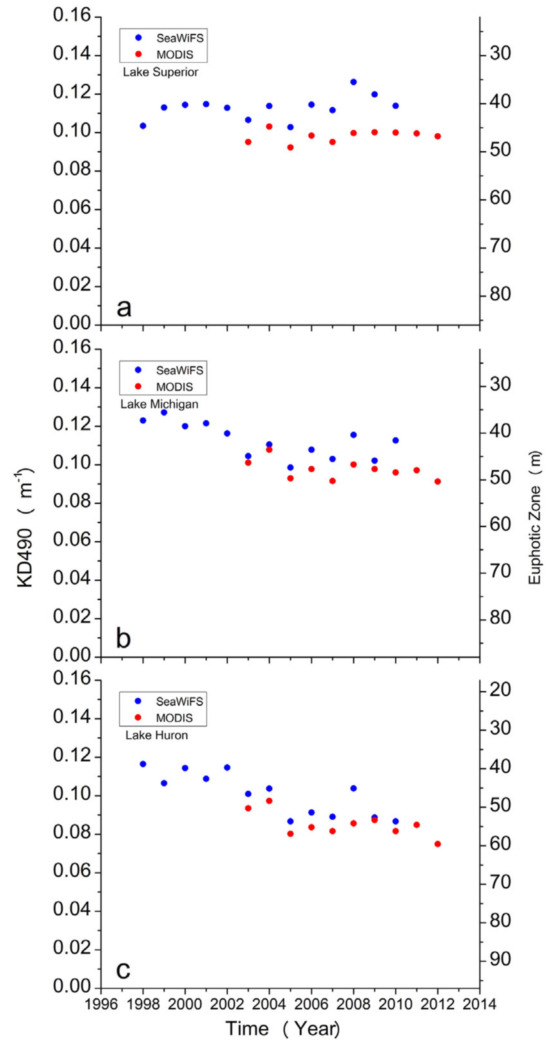

Fig. 3. Lake-wide yearly estimates of Kd_{490} (m^{-1}) for a) Lake Superior, b) Lake Michigan, and c) Lake Huron using MODIS and SeaWiFS imagery. Simple linear regression fit results are presented in Table 2. Right y-axis presents the annual euphotic depth in meters.

values (0.108, and 0.117, respectively; $p = 0.02$). Similar comparison between Lake Huron and Lake Superior showed that while Kd_{490} values for these two lakes were similar during pre-mussel period (0.112, and 0.111, respectively; $p = 0.43$), Lake Huron had significantly lower Kd_{490} values than Lake Superior for post-mussel period (0.091, and 0.117, respectively; $p = 0.0001$). Finally, when comparing Lake Michigan and Lake Huron, annual Kd_{490} values for Lake Huron were significantly lower than Lake Michigan values during both time periods (pre-mussels, 0.121, and 0.112, $p = 0.003$; post-mussel, 0.108, and 0.091, $p = 0.001$, respectively).

Kd_{490} trend analysis

At the lake-wide scale, annual mean Kd_{490} varied significantly over time among the lakes. Looking at the results of linear regression model, Kd_{490} values exhibited no significant trend for Lake Superior between 1998 and 2012 (Fig. 3a; SeaWiFS, slope = 0.0007, $R^2 = 0.14$; MODIS, slope = 0.0003, $R^2 = -0.03$, Table 2). The yearly mean value of Kd_{490} for Lake Superior was 0.11 m^{-1} for SeaWiFS and 0.10 m^{-1} for MODIS. In contrast, for Lake Michigan, the SeaWiFS mean annual Kd_{490} exhibited significant negative trend (Fig. 3b; SeaWiFS, slope = −0.002, $R^2 = 0.41$) although the MODIS Kd_{490} trend was not significant (MODIS, slope = −0.0008, $R^2 = 0.17$). At monthly level for Lake Michigan, significant negative trends in both SeaWiFS and MODIS values were found mostly during the late winter/spring months (SeaWiFS, February, March, April, May, June, and August had significant negative trends; MODIS, April and May had significant negative trends; Fig. 4, and Table 3).

For Lake Huron, annual lake-wide Kd_{490} values exhibited significant negative trends for both datasets (Fig. 3c; SeaWiFS, slope = −0.002, $R^2 = 0.64$; MODIS, slope = −0.001, $R^2 = 0.36$; Table 2). At monthly level, these declines were primarily driven by decreases in Kd_{490} during winter and spring as significant negative trends were found in January,

Table 1
Pre-establishment of dreissenid mussels and post-mussel yearly mean values of Kd_{490} (m^{-1}) and euphotic depth (m; ±2SD) for three Upper Great Lakes from SeaWiFS (1998–2010). Asterisks represent significant differences between means (* = significant, $p < 0.01$).

Lake	Pre-mussels (1998–2002)		Post-mussels (2006–2010)	
	Mean Kd_{490}	Mean euphotic depth	Mean Kd_{490}	Mean euphotic depth
Superior	0.11	42 ± 2	0.11	42 ± 2
Michigan*	0.121	38 ± 3	0.108	43 ± 2
Huron*	0.112	41 ± 5	0.091	51 ± 4

Table 2
Linear fit parameters to lake-wide Kd_{490} (m^{-1}) at yearly level for upper Great Lakes. Asterisks represent significant negative trends ($p < 0.05$). Statistical information are results of simple linear regression models fitted to data points for SeaWiFS (1998–2010) and MODIS (2003–2012) sensors.

Lake	Sensor	Slope	p value	Adj. R-sqr.
Superior	SeaWIFS	0.0007	0.11	0.14
	MODIS	0.0003	0.41	−0.03
Michigan	SeaWiFS*	−0.002	0.01	0.41
	MODIS	−0.0008	0.13	0.17
Huron	SeaWiFS*	−0.002	0.0006	0.64
	MODIS*	−0.001	0.04	0.36

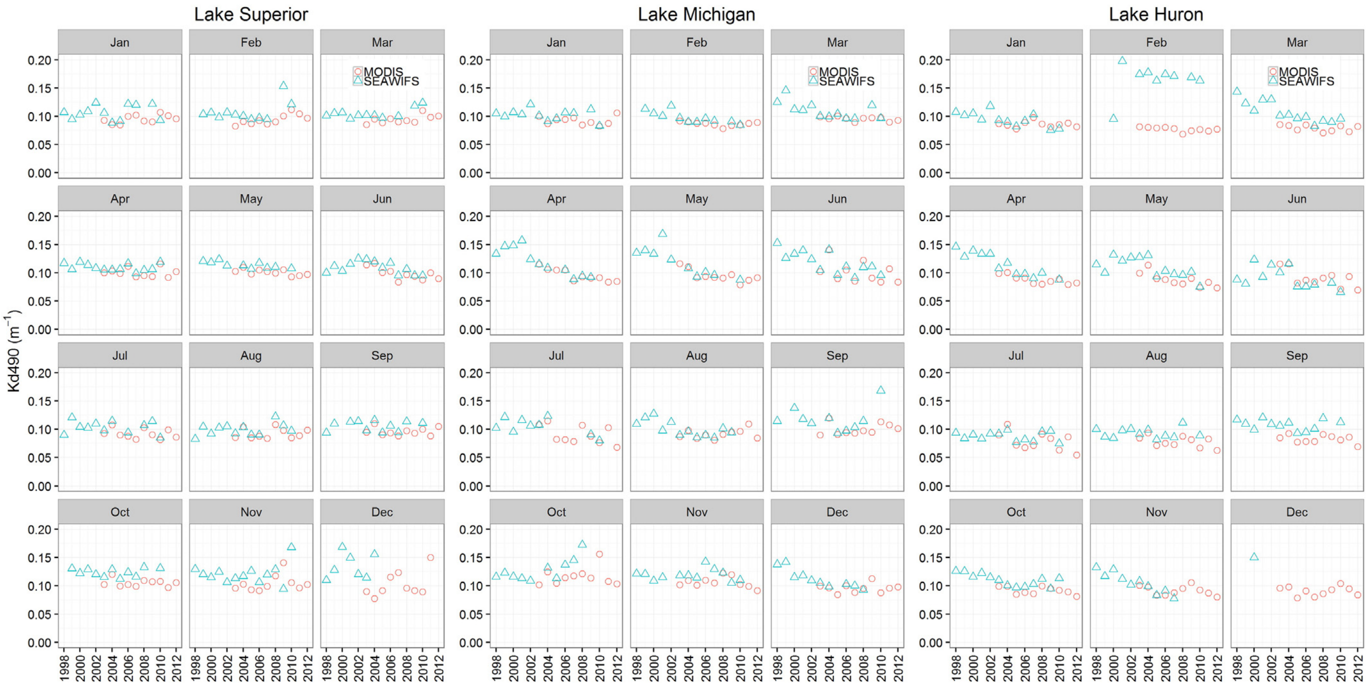

Fig. 4. Lake-wide monthly average Kd_{490} (m^{-1}) for three upper Great Lakes. Data from both satellite missions (SeaWiFS = circles, and MODIS = triangles) are presented here. For linear regression results and significant trends, refer to Table 3.

March, April, May for SeaWiFS and April, May and June for MODIS (Fig. 4, and Table 3).

Sub-basins

For each lake, significant differences were noted among spatial regions, either by depth zone and/or basin. For Lake Superior water clarity did not exhibit significant temporal trends in any large spatial regions, depth or basin ($p > 0.05$) for the time period of observation; however, the WA values for Kd_{490} were significantly higher than those of the WB and EB for both SeaWiFS and MODIS. The WB and EB were similar (SeaWiFS and MODIS means for WA, WB, and EB; 0.33 and 0.24 m^{-1}, 0.10 and 0.09 m^{-1}, and 0.13 and 0.1 m^{-1}, respectively; Fig. 5a and d). Moreover, Kd_{490} values were significantly different among depth regions (means, 0–30 m = 0.29 and 0.23 m^{-1}, 30–150 m = 0.14 and 0.12 m^{-1}, and >150 m 0.10 and 0.09 m^{-1}, respectively; Table 4) with highest values in nearshore areas (0–30 m) and lowest in offshore regions (>150 m).

Table 3
Linear fit parameters to lake-wide Kd_{490} (m^{-1}) at monthly level for lakes Michigan and Huron. Only results with slopes significantly different from zero are presented here.

Lake/satellite	Month	Slope	*p* value
Michigan/SeaWiFS	February	−0.003	0.004
	March	−0.002	0.03
	April	−0.006	0.0002
	May	−0.006	0.003
	June	−0.004	0.003
	August	−0.003	0.01
Michigan/MODIS	April	−0.003	0.0004
	May	−0.003	0.01
Huron/SeaWiFS	January	−0.002	0.01
	March	−0.004	0.003
	April	−0.005	0.0001
	May	−0.003	0.02
	October	−0.002	0.009
	November	−0.006	0.0004
Huron/MODIS	April	−0.002	0.008
	May	−0.003	0.007
	Jun	−0.004	0.03

The southern basin of Lake Michigan exhibited significant negative trends in Kd_{490} for both SeaWiFS and MODIS values (slopes, −0.0017 and −0.0013, *p* value = 0.003, 0.014, respectively); whereas SeaWiFS and MODIS values for the northern basin did not exhibit significant negative trends (slopes, −0.0012 and −0.0003, *p* value = 0.13, 0.59, respectively). However, mean SeaWiFS and MODIS values for both basins were not significantly different during the study period (northern = 0.11 and 0.10 m^{-1} and southern = 0.11 and 0.10 m^{-1}). For the southern basin, a significant temporal negative trend in Kd_{490} were noted for both SeaWiFS and MODIS values for the 30–90 m and >90 m depth regions (slopes, 30–90 m = −0.0017 and −0.0014; >90 m, −0.0016, −0.0015) but not for the nearshore <30 m region (slopes, −0.0010 and 0.0012). Kd_{490} values of specific depth regions in the northern basin did not exhibit any significant trend during the study period (slopes, <30 m −0.0001 and 0.0006; 30–90 m, −0.0018 and −0.0005: >90 m, −0.0004; Fig. 5b and e), with the exception of the SeaWiFS >90 m region (slopes = −0.0014). Also, for the northern basin >90 m region, SLR model determined a significant break point after 2007 where Kd_{490} showed an upward trend (SeaWiFS, breakpoint = 2007, *p* = 0.02, slope1 = −0.003, slope2 = 0.005). Mean Kd_{490} values for the nearshore region (0–30 m) across the entire lake were significantly different from those in the two deeper regions (30–90 m and >90 m) for both SeaWiFS and MODIS values (means, 0–30 m = 0.14 and 0.12 m^{-1}, 30–90 m = 0.12 and 0.10 m^{-1}, >90 m = 0.11 and 0.09 m^{-1}).

Even though basin-wide yearly trends did not exhibit significant declines in Kd_{490} for the northern basin of Lake Michigan, a few significant monthly negative trends were noted primarily during the winter/spring periods for all depth zones (0–30 m, Feb and April-SeaWiFS; 30–90 m, Feb., April, and May-SeaWiFS, April-MODIS; >90 m, Feb., April, May, Jun, and Aug-SeaWiFS, April and May-MODIS). For the southern basin, the most significant negative trends also were noted during the winter/spring period (0–30 m, March, and April-SeaWiFS; 30–90 m, Feb., March, April, May, and Aug-SeaWiFS, April-MODIS; >90 m, March, April, May, June, and Aug-SeaWiFS; April and May-MODIS, Table 3).

For Lake Huron, similar negative trends in SeaWiFS and MODIS Kd_{490} values were noted for both northern and southern basins (slopes, northern = −0.0020 and −0.0015 m^{-1}, southern = −0.0032 and

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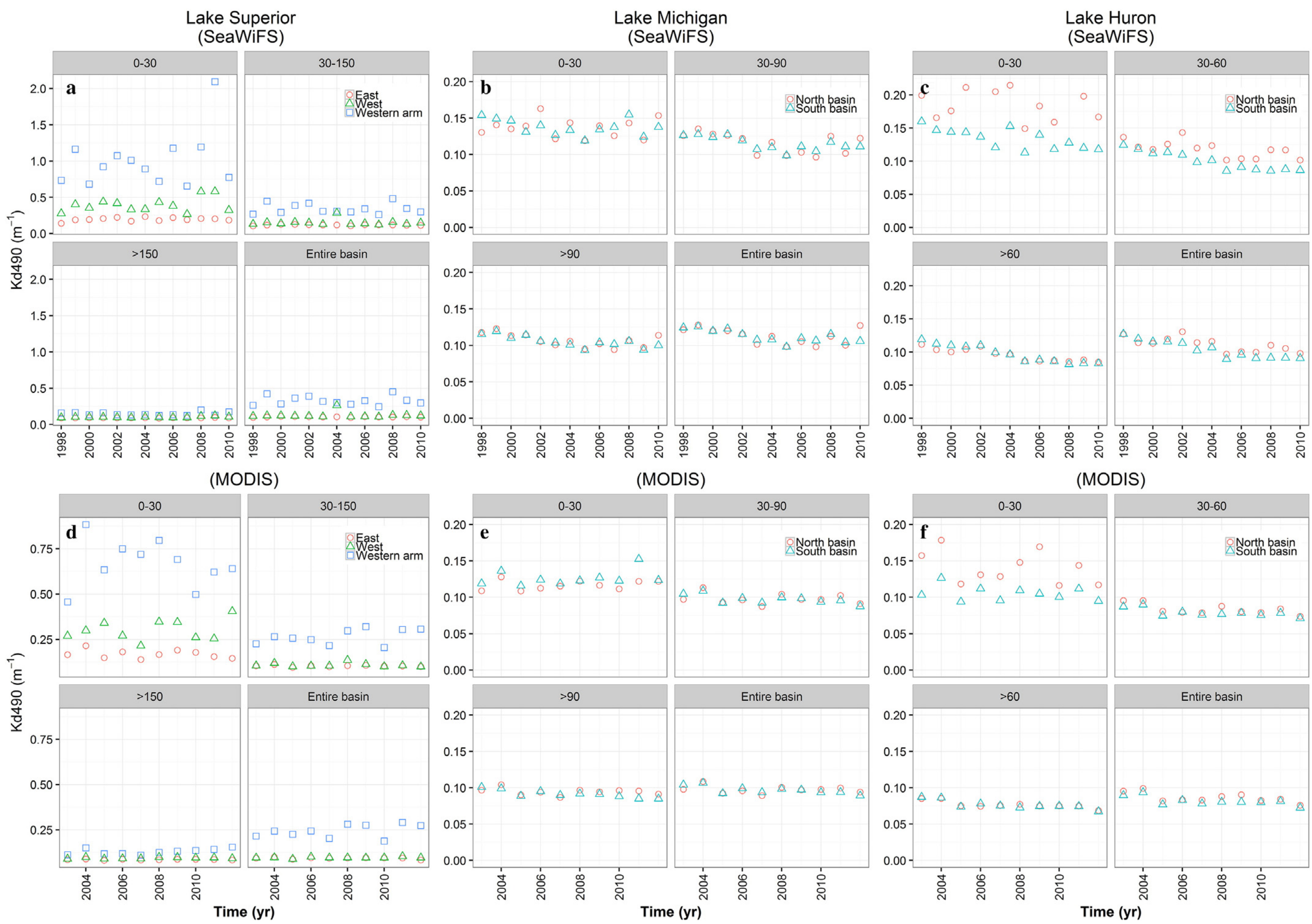

Fig. 5. Lake-wide annual Kd_{490} (m^{-1}) estimates for sub-regions (sub-basins and depth zones of a, d) Lake Superior, b, e) Lake Michigan, and c, f) Lake Huron from SeaWiFS (top panels) and MODIS (bottom panels). Simple linear regression model was fitted to each sub-region dataset. Note scale changes on the y-axis.

-0.0014 m^{-1}) and mean values from both basins were not significantly different (means, northern = 0.11 and 0.09 m^{-1}, southern = 0.10 and 0.08 m^{-1}). While the 0–30 m depth region exhibited no significant negative trends in both SeaWiFS and MODIS Kd_{490} values during the study period, significant negative trends were noted for both SeaWiFS and MODIS values from the 30–60 m and >60 m depth regions (slopes, 30–60 m = -0.0027 and -0.0015, >60 m = -0.0024 and -0.0014; Fig. 5c and f). Additionally, Kd_{490} values from the nearshore region (0–30 m) were significantly different from the two deeper regions (30–60 m and >60 m), but values from the two deeper regions were not significantly different from each other (means, 0–30 m = 0.15 and 0.12 m^{-1}, 30–60 m = 0.10 and 0.09 m^{-1}, >60 m = 0.09 and 0.08 m^{-1}; Table 4).

Similar to Lake Michigan, most of the monthly negative trends in Lake Huron Kd_{490} values were found primarily during the winter/spring and fall months in both basins and mostly in deeper depth zones. Only one significant negative trend in Kd_{490} values was noted for the 0–30 m depth zone for any month (southern region March-SeaWiFS). For the 30–60 m region, monthly negative trends in SeaWiFS values were noted for both basins during January, March, April and November, but only in southern basin in May and in northern basin in October (Table 3). MODIS values in the 30–60 m region exhibited negative slopes in both basins during April, May and June. For the >60 m region, significant negative trends in Kd_{490} values were noted in both basins during January, March, April, May, October and November (SeaWiFS) and April, May and June (MODIS).

Table 4
Annual mean Kd490 (m^{-1}) values of three depth zones from SeaWiFS (1998–2010) and MODIS (2003–2012) sensors.

	SeaWiFS			MODIS		
Lake Superior	**0–30 m**	**30–150 m**	**>150 m**	**0–30 m**	**30–150 m**	**>150 m**
	0.29	0.14	0.1	0.23	0.12	0.09
Lake Michigan	**0–30 m**	**30–90 m**	**>90 m**	**0–30 m**	**30–90 m**	**>90 m**
	0.14	0.12	0.11	0.12	0.1	0.09
Lake Huron	**0–30**	**30–60 m**	**>60 m**	**0–30**	**30–60 m**	**>60 m**
	0.15	0.1	0.09	0.12	0.09	0.08

Although trends in SeaWiFS and MODIS values were statistically similar most of the time, actual SeaWiFS and MODIS values were not similar for the period of overlapping measurements (2002 − 2010). SeaWiFS Kd_{490} values were 10.5% higher than MODIS values (paired *t*-test, $p = 0.01$) when yearly values from all three lakes were compared for the 2002–2010 period. The relationship between SeaWiFS and MODIS Kd_{490} values was similar among years, with the possible exception of 2008 when the difference was slightly larger. If 2008 values are excluded, the SeaWiFS values were still significantly higher than MODIS values ($p = 0.09$; SeaWiFS 10% higher than MODIS).

Discussion

In this paper, the validity and applicability of satellite Kd_{490} products were examined for the Great Lakes. Comparison of satellite Kd_{490} values with in situ measurements was necessary validation prior to using them to assess water clarity and overall water quality in the upper Great Lakes. Given recent changes in phytoplankton abundance and productivity in the upper Great Lakes (Fahnenstiel et al., 2010a; Evans et al., 2011; Yousef et al., 2014), recent lake-wide trends in water clarity are of much interest. In addition, this work can be used as a reference for future applications of Kd_{490} in Great Lakes water quality studies. Nonetheless, it should be noted that there are some uncertainties associated with nearshore estimates of Kd_{490} which could be related to false bottom reflectance (hence falsely higher Kd recordings), greater heterogeneity within the water column due to sediment re-suspension, and/or atmospheric mis-correction nearshore. Even though there are some approaches to correct some of these problems (e.g., removing pixels close to shoreline), nonetheless, the nearshore estimates, particularly those near river mouths, should be treated with care.

NASA satellite-derived Kd_{490} values can be used to characterize water column clarity and photic zone depth in the upper Great Lakes. Good agreement was found between in situ Kd_{490} and satellite Kd_{490} for both sensors (SeaWiFS and MODIS). Comparisons for both satellite-derived $Kd_{490}$with in situ and satellite-derived values showed slight underestimates of Kd_{490} (10–15%), and therefore predicted greater water clarity relative to in situ measurements, but the trends in Kd_{490} values were robust as no yearly bias was noted over the study period. Similar good agreement between satellite products and in situ measures of water clarity exist in marine environments (Mueller, 2000; Werdell and Bailey, 2005). Binding et al. (2007) reported good agreement between SeaWiFS and Coastal Zone Color Scanner (CZCS) 555 nm water leaving irradiance and Secchi disk depths in Lake Erie.

In this study, we excluded several embayments (Green bay, Saginaw Bay, etc.) from our analysis due to their complex optical nature and lack of sufficient in situ data. Problems such as sediment resuspension, lake bottom return (as a result of extremely clear water in nearshore region), and river plumes severely change the optical properties of water in these regions and hence hinder the successful application of many satellite driven products. In order to address this problem, future studies should focus on application of hyperspectral imagery in these environments. Similarly, application/adaptation of existing coastal ocean algorithms, which are designed for similar environments, could be equally advantageous. Finally, and with no doubt, additional in situ samples from these regions are necessary. Currently, the lack of frequent in situ observations in these nearshore waters are evident in the Great Lakes region, and future efforts should allocate proper and equal sampling effort toward these embayments.

Although slightly different, predicted Kd_{490} (slopes and means) from SeaWiFS and MODIS were statistically similar for each of the upper Great Lakes. It should be noted that the two sensors were different in some band-settings and operational intervals. While the two overlap during the period between 2003 and 2010, SeaWiFS existed prior to MODIS (since 1998) and MODIS is still operating after SeaWiFS failed in 2010. Moreover, the observed differences between the two sensors are not specific to the Great Lakes. Morel et al. (2007) noted the differences between Kd_{490} products from SeaWiFS, MODIS and MERIS. The sources of these differences are native differences among band settings, calibration and sensor drift and the nature of the linear empirical algorithms used to calculate Kd_{490}.

Noteworthy trends in Kd_{490} were found for lakes Huron and Michigan during the study period (1998–2012). Kd_{490} values can be easily converted to euphotic zone (Kirk, 1994), and euphotic zone depths are a more universally available measure of water quality. Euphotic depths of both lakes Michigan and Huron increased significantly during the study period from 1998 to 2010. Unlike lakes Huron and Michigan, no significant changes were noted in Lake Superior for the same time period.

Because phytoplankton are one of the main light absorbing factors in the Great Lakes (Perkins et al., 2013), recent trends in euphotic zone depth in lakes Michigan and Huron are not surprising given recent changes in phytoplankton abundance. In the case of southern Lake Michigan, various researchers (Fahnenstiel et al., 2010a, 2010b; Kerfoot et al., 2010; Mida et al., 2010), have reported large declines in phytoplankton and a dramatic decline in primary production during the spring isothermal period. Fahnenstiel et al. (2010a) reported a decline in spring chlorophyll concentration (66%) and primary production (70%). Similarly, Kerfoot et al. (2010) found 56–78% decline in spring chlorophyll *a* concentration between 2001 and 2008 using shipboard measurements and SeaWiFS estimates. The reported declines were limited to isothermal periods (Pothoven and Fahnenstiel, 2013) and summer values in Lake Michigan have remained unchanged. Similar declines in phytoplankton abundance have been observed in Lake Huron after 1998–2002 period where Barbiero et al. (2011) reports a 40–50% decline in chlorophyll concentration during the spring period using SeaWiFS imagery.

In Lake Michigan, researchers have associated recent changes in phytoplankton to filtering role of quagga mussels (*Dreissena rostriformis bugensis*). This association was based on temporal coherence between the observed changes and physical characteristics of the water column as well as experiments comparing filtering rates and growth rates (Nalepa et al., 2010; Vanderploeg et al., 2010; Fahnenstiel et al., 2010a). Quagga mussels arrived in Lake Michigan around 2000 and were distributed throughout the entire lake by 2005. Isothermal conditions during winter and spring allows complete vertical mixing of the lake (Kerfoot et al., 2010), which in turn gives mussels (while residing on lake bed) continuous access to the entire water column. Similarly, Yousef et al. (2014) found spatial correlation between mussel density and changes in bio-optical properties of the southern region of Lake Michigan, and noted a more significant decline at mid-depths, something that was also noted here.

Our results are consistent with previous observations on declines in phytoplankton abundance and Kd_{490} (Fahnenstiel et al., 2010a; Yousef et al., 2014, Rowe et al., 2015). First, larger declines were noted during the winter/spring isothermal period when mussels are in contact with complete water column. Second, Kd_{490} trends were consistent with known densities of mussels. The largest declines in Kd_{490} were found in the mid-depth region which is the area of greatest mussel densities (Nalepa et al., 2010). In the region 0–30 m where zebra mussels were already established in the mid 1990s (Nalepa et al., 2008), no significant changes in Kd_{490} were found from 1998 to 2012. Finally, Kd_{490} in the >90 m region varied between the north and south basins where mussel densities were lowest and variable (Nalepa et al., 2010; Rowe et al., 2015). In the southern basin, where mussel densities were increasing in the >90 m region, significant decreases in Kd_{490} were found; however in the northern basin >90 m region an increase in Kd_{490} was noted. This could be in response to the recent decline in mussel densities observed in this region (Rowe et al., 2015). Moreover, spring values (April and May) in Lake Michigan declined more in mid-depth (30–90 m) waters than in offshore (>90 m) waters which is similar to the results noted by Yousef et al. (2014) for the southern basin of Lake Michigan.

Even though changes were larger in Lake Huron, the link between water clarity increases and mussel filtrating activities may not be as definitive as Lake Michigan. In support of the role of mussels, most of the declines in Kd_{490} were limited to mid-depth and offshore waters during the isothermal condition (winter, spring and fall). However, Barbiero et al. (2011) suggest that the observed changes in Lake Huron is only partially related to quagga mussel's filtration activities. This conclusion was based on lower densities of quagga mussels in Lake Huron as compared to Lake Michigan. However, because Lake Huron had lower phytoplankton abundance than Lake Michigan prior to quagga mussel colonization and perhaps since it is shallower than Lake Michigan, lower densities of mussels may have a larger impact expressed on an areal basis. Without more information on filtering rates in Lake Huron, it is difficult to conclusively link recent declines to mussels. The linkage between mussel filtering impacts and changes in water clarity in Lake Huron can be complicated due to limited knowledge of quagga mussel densities, unknown mussel filtering rates, and complex physical mixing where water can travel many kilometers in the generation time of phytoplankton. Even though mussel filtration impacts are still probably the best explanation for the recent increases in water clarity noted in Lake Huron, other factors should be considered.

Phosphorus (P) loading is another possible important factor that could explain the recent changes in Great Lakes Kd and chlorophyll. However, observed P loading trends in the upper Great Lakes remains controversial but results suggest a greater possible role for phosphorus in Lake Huron compared to the other two upper lakes. While Robertson and Saad (2011) and Dolan and Chapra (2012) both observed significant decline in P loading into Lake Huron, neither study found a significant decline in P loading for Lake Michigan since 1980. Thus, the relative roles of phosphorus loading vs. mussel filtration may be lake specific, and merits further investigation for Lake Huron. Other factors (e.g., zooplankton grazing, decrease in carbonate precipitation, and climate change) that might be responsible for the increases in water clarity in lakes Michigan and Huron over the study period do not have as much support as mussel filtration and P loading and are unlikely to be important (Fahnenstiel et al., 2010a).

Lake-wide analysis of water optical properties also revealed significant spatial variability in all three lakes. These results further challenges the effectiveness of extrapolations made from observations at spatially limited stations to lake-wide conditions. Generally, and as was expected, water clarity was lower in nearshore regions of all the lakes and increased offshore. Despite similar values for the two large regions of Lake Superior, euphotic depth from the western arm were approximately an order of magnitude less than those found in the two basins. Therefore, spatial extrapolations, which are common in traditional limnological studies, become very difficult and questionable in these large systems. While a single monitoring station might capture the overall trend of water related parameters, reliance on its results for calculation of basin wide estimates (i.e. primary production in Lake Superior or its carbon budget) will be associated with high errors due to spatial variations. This becomes more important when monitoring stations are in areas that might be affected by factors such as shallow depth sediment resuspension, river plumes, coastal wetlands and embayments. Nonetheless, in situ point values are highly complementary to remotely sensed estimations and are essential for validation and calibration efforts.

Finally, one of the most startling and interesting result of this study is that Lake Superior is no longer the clearest of the upper Great Lakes. In fact, Lake Superior is now the third clearest water of the upper Great Lakes as it was easily passed by lakes Michigan and Huron (Fig. 3b). Water clarity in Lake Michigan, with the history of being mesotrophic (Schelske and Stoermer, 1972), has now reached to values similar to Lake Superior (Fig. 3c). This is a change of significant historical and ecological importance. Historically, Lake Superior has been considered the clearest lake among all the other Great Lakes (Bukata et al., 1995), and that is no longer true. More important may be the ecological implications of the large increases in water clarity in lakes Huron and Michigan. Many invertebrate and vertebrate distributions and ecology may be changed with the large increases in water clarity. Recently in Lake Michigan, Vanderploeg et al. (2012) reports that the increase in water clarity has been positively correlated with *Bythotrephes longimanus* abundance, a predatory cladoceran. Meanwhile, increase in water clarity has been negative correlated with the biomass of the *Daphnia* and *Bosmina*. This is likely because Bythotrephes are visual predators and the increase in light availability seems to have increased their foraging efficiency. Further changes in the behavior of both invertebrates and vertebrates can be expected in Lakes Huron and Michigan. All the above changes in the physical and biological dynamics of the lake emphasize the need for a more holistic approach in studying the Great Lakes. Remote sensing compliment these field based studies and provide a reliable and cost effective tool to grasp the “bigger picture”.

Acknowledgements

This investigation was supported by NASA Roses grant # NNX09AU88 and NASA Carbon Monitoring grant #NNX12AP94G. We are thankful to the Ocean Biology Processing Group (OBPG, NASA) for their support and technical comments. This is Contribution No. 27 of Great Lakes Research Center (GLRC) at Michigan Technological University. We would like to thank the EA, George Leshkevich, and 3 anonymous reviewers for their helpful comments and thoughtful review of this manuscript.

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Please cite this article as: Yousef, F., et al., Water clarity of the Upper Great Lakes: Tracking changes between 1998–2012, J. Great Lakes Res. (2016), http://dx.doi.org/10.1016/j.jglr.2016.12.002