

Changes in the Optical Properties of Lake Michigan by the Invasive Species *Dreissena bugensis* (Quagga Mussel)

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Abstract

The non-indigenous species *Dreissena bugensis* (quagga mussel) became the dominant benthic bivalve in Lake Michigan by 2004 due to its rapid proliferation and extreme filtering abilities. Their takeover is re-engineering the physical and biogeochemical processes of Lake Michigan on an ecosystem scale. This study focused on their impact on the optical properties of the water column throughout the lake. Analyses were done using CTD data that was collected from 1993 – 2012 from three sampling stations. Based on photosynthetically active radiation (PAR) measurements in the water column, the extinction coefficient (k_d) for every 25 cm depth interval was estimated, along with the depth of 1% light penetration for each CTD data set in the 19-year time span. A Student's t-test was applied to test for a significant increase in the depth of 1% light penetration before and after the quagga mussel invasion, which found significance at the deep mid-lake station, and less pronounced changes at the near-shore stations. Analyses were also done to compare seasonal variation in the optical properties before and after the quagga mussel invasion, which further indicated significant changes at the deep mid-lake station, but less pronounced changes at near-shore sampling stations. Comparative analysis of the extinction coefficient, percent transmission, and fluorescence measurements suggests that detection of the presence of thin layers in the water column may be possible.

Keywords: Extinction Coefficient, Invasive Species, Light Attenuation

1. Introduction

The introduction of an invasive species can often have significant impacts at an ecosystem scale (Kostecki et al., 2011). Invasive species have the ability to outcompete native species and take advantage of unutilized niches in the surrounding environment. Quagga mussels are an invasive species that arrived in Lake Michigan in ballast waters of transoceanic ships in 1997. These benthic bivalves are exceptional filter feeders that can rapidly filter phytoplankton (microscopic algae) and particles that absorb, occlude and scatter light in the water column (Baldwin & Mayer, 2002). When quagga mussels reproduce, each female sends millions of eggs into the water each year to be fertilized (Ram & Karim, 2012). The veligers, planktonic larvae of the quagga mussels, live suspended in the water column until they begin to form their calcium carbonate shells and sink to the lakebed. This process enables them to spread to different regions of the lake. They are able to feed and reproduce in even the coldest areas in the lake, which reach 0.5°C, and are able to live not only on the hard rocky surfaces, but also the soft sand or clay-covered lakebeds (Baldwin & Mayer, 2002; Wittmann & Chandra, 2010). Their reproductive abilities and resilience in cold temperatures allow the quagga mussel to exploit the entire Lake Michigan basin. Their numbers are estimated to be in the hundred trillions (10^{13}) and by 2004 they became the dominant benthic bivalve in Lake Michigan (Fahnenstiel, Nalepa, & Pothoven, 2010).

Long-term studies of late winter/early spring indicate a precipitous decline in offshore phytoplankton abundance and production from the mid-1980's to the present (Fahnenstiel, Pothoven, et al., 2010). Not only are phytoplankton populations being rapidly filtered out by adult quagga mussels on the lakebed, but they are being grazed upon by the veligers that are living suspended in the water column until maturation (Kerfoot et al., 2010). In addition, there have been significant declines in spring chlorophyll and phosphorous concentrations as well as silica and nitrate utilization (Fahnenstiel, Nalepa, et al., 2010). Decrease in silica concentrations suggests that the diatom populations are also being affected by the quagga mussel invasion. The large spring diatom bloom, a persistent phenomenon of Lake Michigan in previous decades, has now disappeared (Evans, Fahnenstiel, & Scavia, 2011). Diatoms are a food source to many small fish. Therefore, the lack of a diatom bloom is evidence that the quagga mussel invasion is causing impacts up the entire food chain.

A decrease in the populations of all trophic levels of the Lake Michigan food web could have broad implications on its optical properties. When light enters a water column, the irradiance decays exponentially with depth due to absorption and scattering of photons by phytoplankton, dissolved organic matter (DOM) and particulate matter in addition to water itself. Since 1993, teams led by scientists at the Great Lakes WATER Institute have sampled water quality and column profiles at designated Lake Michigan locations. We hypothesized that depths of 1% light penetration at near-shore and offshore sampling stations in Lake Michigan have increased after quagga mussel establishment.

The impact of quagga mussels on light attenuation may vary with water temperature. The maximum density of water occurs at a temperature of 4°C. Surface temperatures lower than 4°C combined with wind-driven turbulence cause deeper, warmer water to rise through the water column, leading to vertical and horizontal mixing of the lake during typical winter conditions, allowing the mussels to have access to the entire water column. Temperatures greater than 4°C cause stratification to occur in the water column, inhibiting mussel access to surface water. We hypothesized that a change in water clarity will be most pronounced during periods of sub 4°C surface temperatures, and that samples during these periods will show increased 1% light penetration (1% light depth) after quagga mussel establishment.

2. Materials and Methods

Our data draws from an ongoing series of field measurements conducted in Lake Michigan from 1993 to present day. The data set encompasses physical and chemical properties of the water column, including pressure-derived depth, temperature, fluorescence, conductivity, oxygen saturation, pH, oxidation-reduction potential, percent transmission, and photosynthetically active radiation (PAR) values.

Measurements were primarily conducted using a Sea-Bird SBE 25 CTD (conductivity, temperature, depth) instrument affixed with multiple modular sensors, including a biospherical quantum meter that measured the spectral waveband of 400 to 700 nm, and a transmissometer that measured 660 nm wavelength absorption over a 25 cm path length. The CTD instrument was lowered at an average speed of 0.15 meters per second from the side of a research vessel and performed 8 scans per second descending the depth of the sampled water column. When possible, the instrument was lowered on the sun side of the vessel to minimize the effect of shadows cast by the ship on PAR measurements. Researchers also used a hand-lowered PAR sensor to supplement CTD light measurements, and plankton nets were used to capture plankton at varying depths of the water column for chemical analysis.

Measurements were conducted at sample stations at fixed longitudinal and latitudinal coordinates across Lake Michigan. These stations were chosen to provide a broad survey of near-shore and offshore locations in the lake. The stations were visited during research cruises on varying dates each year.

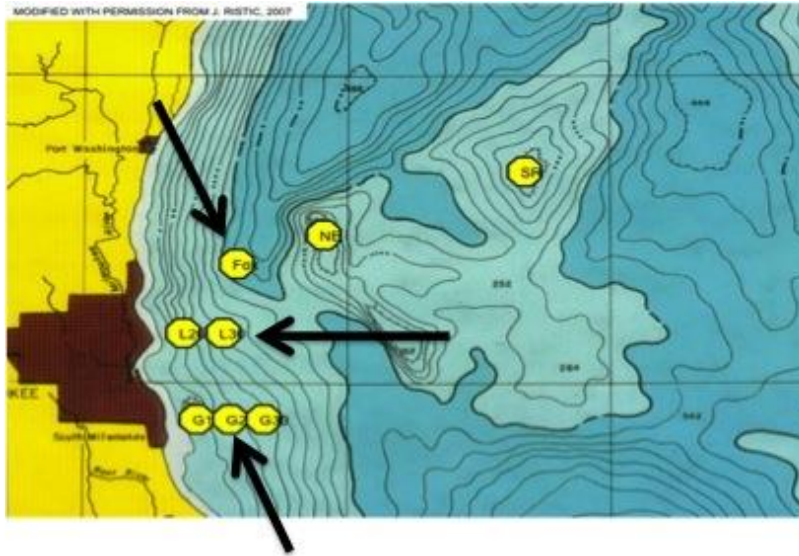


Figure 1: Map of Lake Michigan highlighting data sampling stations with arrows indicating where data for our analyses were collected.

The CTD data was initially extracted from the instrument in HEX format. These files were then batch processed via Sea-Bird software, during which all data were binned into 25 cm depth intervals, and the HEX files were converted into ASCII format. Using MATLAB software, we implemented a program that exported ASCII data into a given Microsoft Excel template, and exported all CTD data into individual XLS files, and personally analyzed each XLS file for the Fox Point, Linnwood 20, and Green Can 20 stations.

Each XLS file contained tabs that aggregated the depth-dependent or pressure-dependent values for each water column property, as well as separate tabs containing a macroinstruction-generated scatter plot for each property versus depth. During our analysis of each file, we focused primarily on the information that presented depth-dependent PAR, transmission, and fluorescence data, as they are the variables most related to light extinction.

Light attenuation in water is expressed by the extinction coefficient of light (k_e). A manipulation of the Beer-Lambert law gives the following equation:

$$I(z) = I_0 e^{k_e z} \quad (1)$$

In Equation 1 above, $I(z)$ is the PAR value at depth z , k_e is the extinction coefficient, z is the depth, and I_0 is the surface PAR value. This shows that the extinction coefficient may be directly estimated from the slope of an \ln PAR versus depth graph. To this end, in each XLS file, we linearized the PAR data by calculating the natural logarithm of each PAR value and appended the results to the existing table. We then plotted the \ln PAR data against depth and manually fitted trend lines on each graph to assess the slope of \ln PAR. During this process, we observed that more than one trend line was occasionally necessary to properly capture the behavior of the \ln PAR graph, indicating the polyphasic nature of light extinction in the water column (Figure 2). Nevertheless, for our first iteration of calculating the extinction coefficient, we used the trend line that was closest to the surface.

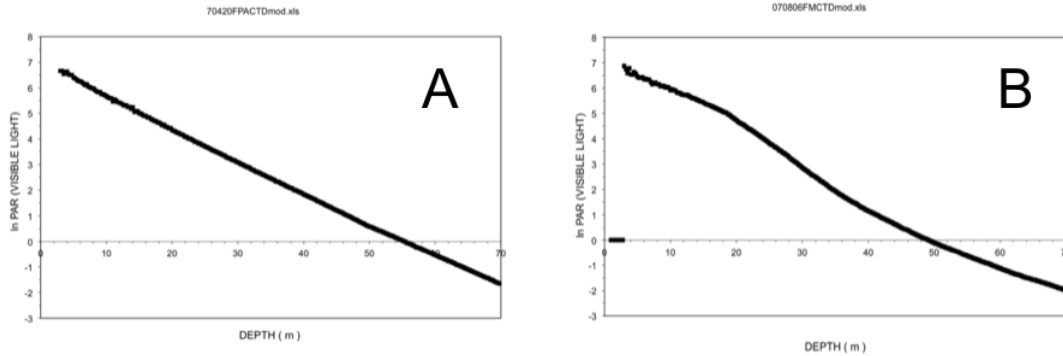


Figure 2: Both graphs show the natural logarithm of the PAR (lnPAR) versus depth from CTD casts at the Fox Point station A) cast taken on 20 April 2007, which shows single slope for the k_e B) cast taken on 6 August 2007, which shows multiple slopes during the stratified season

The primary indicator value we wanted to calculate for each sample date was the 1% depth, defined as the depth at which 1% of surface PAR intensity level remained in the water column. This depth is significant because it is used to estimate the deepest place in the water column where photosynthetic organisms can survive. We calculated the 1% light depth directly from our k_e values according to the equation: $z = \ln(0.01)/k_e$. We then plotted the 1% depths for each station we analyzed - Fox Point, Green Can 20, and Linnwood 20, - in a scatter plot against the post-1900 date and performed an unpaired one-tailed t-test to test for significant difference between samples taken in a period prior to quagga mussel invasion (1993 to 2003) and after quagga mussel invasion (2004 to 2012). We also created box and whisker plots to compare the median 1% light depth between the pre-quagga and post-quagga periods. Finally, we tested our seasonality hypothesis by comparing pre-quagga and post-quagga 1% depths from sample dates during which the surface temperature was greater than 4°C, indicating non-mixing conditions, and less than 4°C, indicating mixing conditions.

In an effort to refine our methodology of calculating 1% light depths, we used central differencing, via running three point averages, to estimate the instantaneous slope values of the lnPAR versus depth plot for each sample date. This allowed us to produce a set of extinction coefficients that reflected the depth-dependent nature of light attenuation in the water column on a finer scale, and that may lead to a more accurate 1% light depth. However, during the process of recalculating our extinction coefficients, we encountered positive k_e values that by basic laws of physics didn't make sense, since light should always decrease while descending the water column. We attributed these values to the bobbing motion of the research vessel while sampling with the CTD instrument, and attempted to correct the noisiness in the data by performing a five point running average on the original PAR values. This simple smoothing algorithm was indeed successful in eliminating positive k_e values after we performed our central differencing calculations on the smoothed lnPAR data.

Another derivation of the Beer-Lambert law:

$$\ln\left(\frac{I}{I_0}\right) = \int_0^z k_e(s) ds \quad (2)$$

allowed us to integrate over our new k_e values to find the 1% light depth, or the depth at which the right term of the equation above equaled:

$$\ln\left(\frac{I}{I_0}\right) = \ln\left(\frac{1}{100}\right) = -4.0651 \quad (3)$$

We wrote a MATLAB program that implemented the trapezoidal rule to estimate the k_c integral at each successive depth, and determined the depth at which the accumulated integral was closest to the value above. These values served as our new, refined 1% light depths, and we performed the full complement of comparisons for pre-quagga and post-quagga sample dates for these new depths.

3. Results

3.1 Pre And Post Quagga Mussel Invasion

The data shows that there is an overall downward trend in the 1% light depth over the 19-year time span for the three sampling stations (Figure 3). However, this trend is more pronounced at certain stations. Using a Student's t-test comparison of the mean 1% light depth before the quagga mussel invasion, 29.79 m, and after their invasion, 36.98 m, we find a significant change with a p value of $2.025e-09$ for the Fox Point station. We also find significance when comparing the Linnwood 20 sampling station. Before the quagga mussels arrived, the mean depth of 1% light penetration was 27.77 m and after their invasion the mean depth was 34.46 m. The comparison gives us a p value of $1.418e-03$. We do not find significance when comparing the mean 1% light depth for the Green Can 20 station. Before the quagga mussels invaded the lake, the mean 1% light depth was 30.54 m and after their establishment the mean depth was 34.68 m. From the t-test comparison, we calculate a p value of 0.1108, which does not support a significant change.

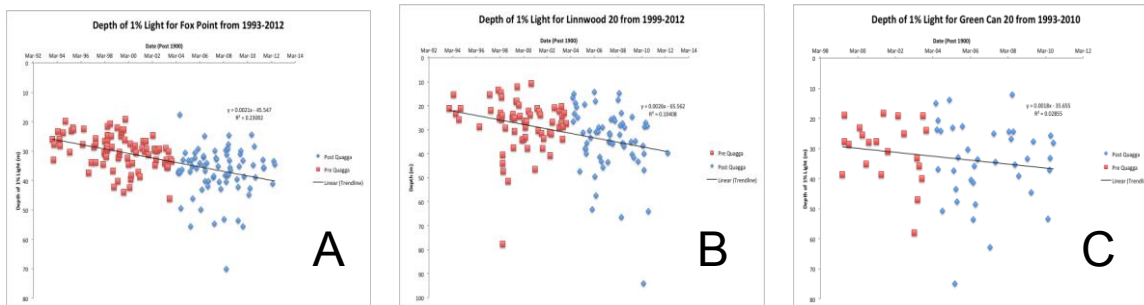


Figure 3: Depth of 1% Photosynthetically Active Radiation (PAR) for A) Fox Point, B) Linnwood 20, C) Green Can 20 against date from 1993-2012

3.2 Seasonality Comparison

Initial analyses did not show any clear shift in the seasonality of light penetration at any of our sampling stations (Figure 4). Therefore, a Student's t-test was used to compare the seasons before and after the quagga mussel invasion. The Student's t-test comparison indicates that the stratified season showed a more significant change in the 1% light depth. A box and whisker plot (Figure 5A) shows the comparison of the means and quartiles for each season between the pre and post quagga mussel data for Fox Point. Like the Fox Point station, the Linnwood 20 sampling station showed a greater increase in light penetration during the stratified season (Figure 5B). This comparison could not be done for the Green Can 20 station because there was not enough mixed season data.

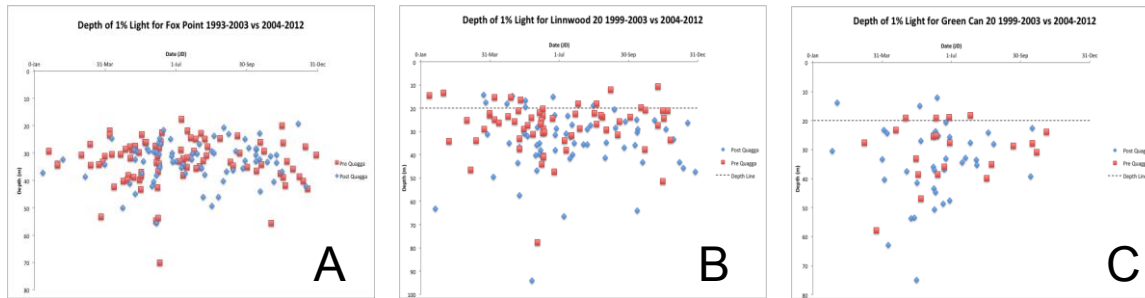


Figure 4: Depth of 1% PAR for A) Fox Point, B) Linnwood 20, and C) Green Can 20 showing before quagga mussels and after quagga mussels against date in Julian days.

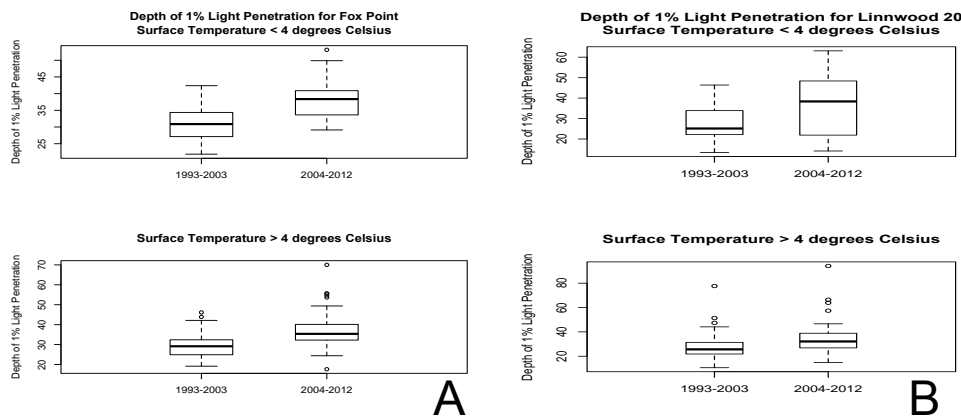


Figure 5: Depth of 1% PAR for A) Fox Point and B) Linnwood 20 when surface temperature is below 4°C and above 4°C, before and after quagga mussels

4. Discussion

Our results suggest that the invasive quagga mussels are having ecosystem level effects on the Lake Michigan. Their impact is most prominent in deep lake regions as shown in our analyses of the Fox Point station data, but the more turbid near-shore regions, Linnwood 20 sampling station, are also experiencing increased light penetration. Although Linnwood 20 is only 20 m deep, calculations have shown that 1% light penetration would potentially go much deeper than 20 m before and after the quagga mussel invasion. An increase in the 1% light depth, however, tells us that there is increased irradiance penetrating the water column and reaching the lakebed. We did not find a significant change at the near shore Green Can 20 sampling station. Green Can 20 is located directly outside the Milwaukee Harbor where the Milwaukee, Kinnickinnic, and Menomonee Rivers meet. The plume of the rivers replenishes detritus, colored dissolved organic matter, and nutrients, along with increasing turbidity and sediment disturbance (Millie et al., 2002). All these factors can contribute to why we don't see a significant increase in the 1% light depth at the Green Can 20 sampling station.

An increase in the 1% light depth signifies decreasing phytoplankton and zooplankton populations, DOM, and nutrients (Fahnenstiel, Nalepa, et al., 2010). These declines affect not only water clarity, but also food and nutrient availability to the upper trophic levels. This has impacted the Lake Michigan sport fisheries to the point where they are now virtually nonexistent (Cuhel & Aguilar, 2013). A decrease in light absorption by photosynthetic organisms allows more light to be absorbed directly as heat impacting the overall temperature of the lake. Many lake species are dependent on annual temperature shifts for their reproductive, feeding and growth cycles (Winder & Schindler, 2004). Studies done on species of the planktonic genus *Daphnia* have shown that even moderate warming of a lake

system during the stratification period has direct effects on its population dynamics and stability (Wagner et al., 2013). This can have implications for species interaction as well. Higher trophic levels rely on blooms of planktonic species growth during certain times of the year and a shift or a lack of a bloom will register up the food web (Winder & Schindler, 2004).

The increase in light penetration was most significant for the stratified season, which does not support our hypothesis. During the mixing season, currents drive horizontal mixing, and changing water densities, due to temperature shifts, enable vertical mixing. This mixing, and thus turbidity and sediment disturbance, is constant whether the mussels are present or not. Therefore, changes in water clarity during winter months may not be as susceptible to quagga mussel impacts. This could explain why water clarity is greatest during the stratified season. Also, mixing allows the mussels to feed on any planktonic organisms that are present during the mixing season. The late-winter bloom that once occurred in Lake Michigan arose during the mixing season, therefore mussels could have decimated their populations before the stratified season began (Kerfoot et al., 2010). Stratification would be a sanctuary for a much less prevalent planktonic population than before the quagga mussel invasion. In addition to the adult quagga mussels benthic filtration, veligers that are the result of late spring and summer spawning, are able to penetrate the stratified upper water mass and graze upon what is left of the planktonic community (Kerfoot et al., 2010). The combination of these two factors may be the reason why we see the greatest change in clarity during the stratified season.

5. Future Work

While doing our analyses of the extinction coefficient, k_e , we noticed a strong correlation between our calculated k_e curve and the percent transmission data (Figure 6). Where there is a minimum valley in the transmission, there is a corresponding maximum peak in the k_e . Not only does this highlight the deep chlorophyll maximum (DCM), but we also see smaller, less extreme peaks and valleys before and after the DCM. These may be indicators of thin layers in the water column, which are large horizontal areas where phytoplankton, zooplankton or sediment congregate as a result of a physical irregularity in the water column, such as a thermocline or halocline (Talapatra et al., 2013). Most studies have focused on the occurrence of these phenomena in marine systems, but few studies have addressed freshwater systems (Rinke et al., 2009). Ongoing studies in marine waters use a variety of high tech equipment such as echo sounders and acoustic Doppler current profilers in order to locate thin layers in the water column (Benoit-Bird, Cowles, & Wingard, 2009; McManus et al., 2003). Our future work will include the use of the CTD for transmission, fluorescence and temperature measurements and our MATLAB code that calculates the k_e while on station. Once we have the water column profile and get the k_e curve, we will take water samples at the depths where we see the correlations between transmission minimum and k_e maximum. Thus, not only will this study be one of the few to address thin layers in freshwater systems, but will also be using a relatively low tech and inexpensive tool to detect them.

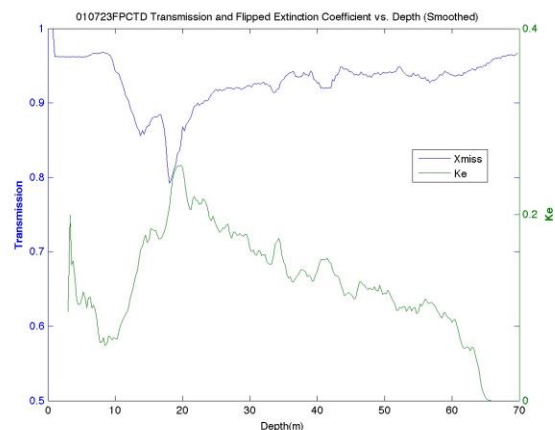


Figure 6: Percent transmission and extinction coefficient plotted against depth for Fox Point CTD cast on July 23, 2010.

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