

**Monitoring Water Quality and Submergent Aquatic Vegetation of  
Lower Green Bay Wetlands and Influences of the Cat Island Chain  
Re-establishment Project**

by

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A thesis submitted in partial fulfillment of  
the requirements for the Degree of

**MASTER OF SCIENCE  
In  
ENVIRONMENTAL SCIENCE AND POLICY**

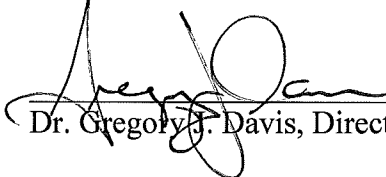
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January 2015

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## **DEDICATION**

In dedication to my mother, Diane Wellington Flood

## **ACKNOWLEDGEMENTS**

I would like to thank the Wisconsin Department of Natural Resources (DNR), the Nature Conservancy, and the Cofrin Center for Biodiversity for their contributions to this research. I am also grateful for the data collected and shared through the Wisconsin DNR to make the vegetation survey possible. I also thank Patrick Robinson, Patrick Forsythe, Mike Grimm, Bob Howe, Gary Fewless, Bud Harris, Vicky Harris, Laurel Last, Dave Lawrence, Jesse Weinzing, Chelsea Gunther, the Cat Island Chain Advisory Committee, Brown County, and United States Army Corps of Engineers for their assistance and contributions. This project was funded by a grant from the U.S. Environmental Protection Agency, CFDA #66.469.

## ABSTRACT

*The loss of the Cat Island Chain (CIC) in Green Bay, Lake Michigan has been a suspected factor in the reduction and degradation of important aquatic habitat. The CIC re-establishment project wave barrier (completed in 2012) was designed, in part, to positively impact aquatic habitat by reducing wave-related stress and subsequently improving water clarity and promoting aquatic vegetation (AV) growth. The objectives of this study were to 1) quantify potential effects of the wave barrier on water quality, wave energy, light extinction, and abundance and distribution of AV; 2) assess the existing aquatic seed-bank on the lee side of the barrier; 3) and determine the survival and growth of transplanted AV propagules and *Schoenoplectus acutus* (hardstem bulrush) plugs on the lee and windward sides of the barrier. Our study found differences in water quality conditions between the windward and leeward sides of the wave barrier changed over time, with poorer water quality conditions varying between the windward and leeward sites based upon temporal changes in climatic variables; however, transplanted propagules and hard-stem bulrush plugs had greater growth and survivability on the leeward side of the wave barrier. Analysis of the existing AV distribution and seedbank also provided evidence of widespread propagule limitation in the leeward aquatic habitat. Overall, the results of the research suggest the potential for increased AV abundance due to the wave barrier, especially with some facilitated vegetation re-establishment efforts; however, further research is needed to better understand this potential and the possible effects of other factors, such as Lake Michigan water levels, sediment resuspension, and the impacts of tributary runoff.*

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## INTRODUCTION

Aquatic vegetation (AV) is critical to the well-being of coastal wetlands. AV has been widely recognized as an important component of coastal wetlands that provides food and shelter for fish, wildlife, and macroinvertebrates (Korschgen *et al.*, 1988; Bowyer *et al.*, 2005; Stafford *et al.*, 2007). AV helps to stabilize aquatic sediments by reducing wave energy and current velocities, allowing suspended material deposition, reducing sediment resuspension, and improving water clarity (Madsen *et al.*, 2001). Uptake of carbon and nutrients by AV inhibits nuisance algal blooms (Barko and Smart, 1981) and plays an essential role in the metabolism and energy flow within the ecosystem (Eckblad *et al.*, 1984; Barko *et al.*, 1991). Overall, AV is an excellent indicator of physical and chemical condition (Adamus and Brandt, 1990), as well as wetland health (Neckles, 1994; Small *et al.*, 1996; Gallegos, 2003).

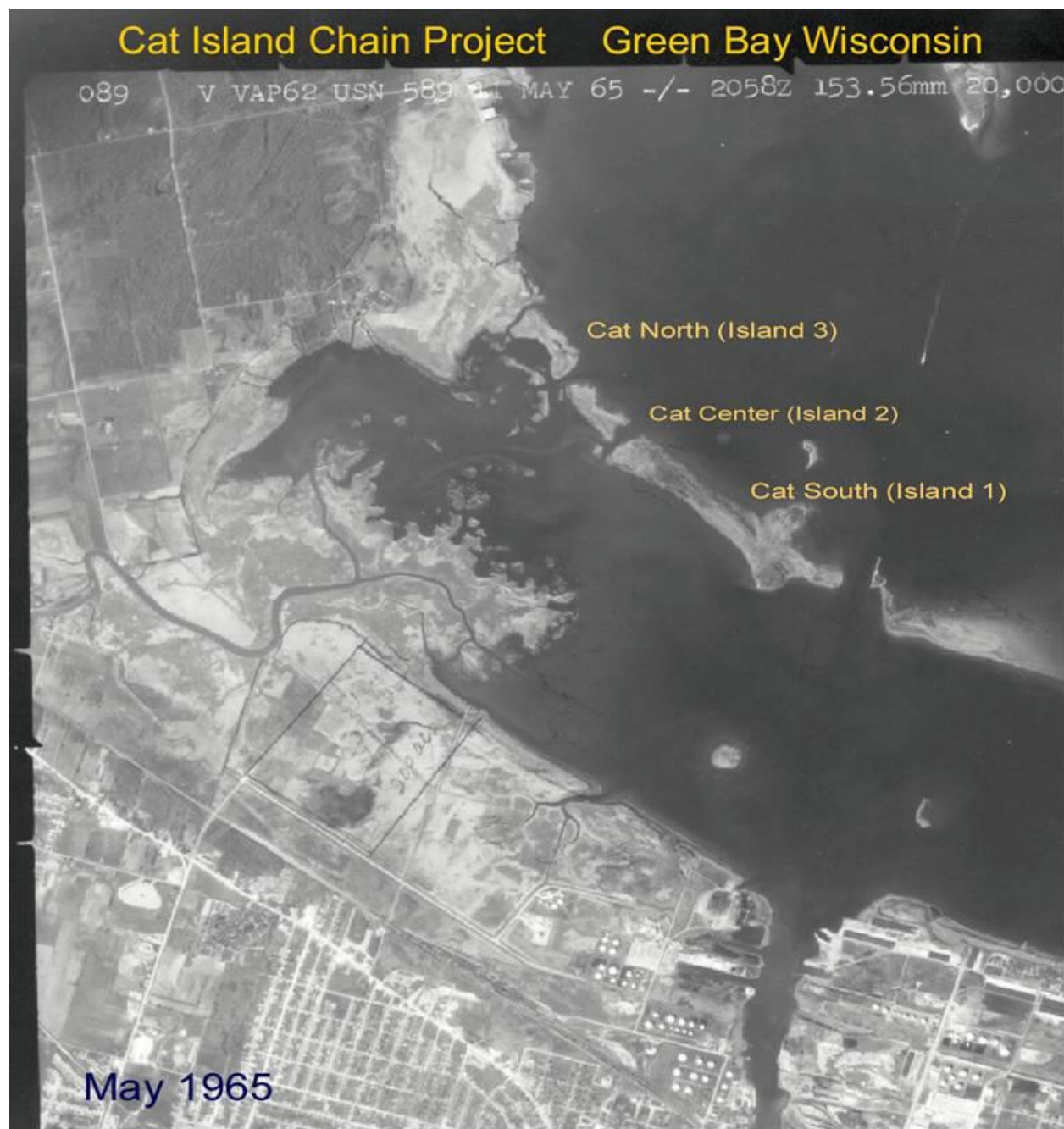
AV is influenced by a variety of limnological conditions. Various studies have emphasized the relationship between AV growth and the availability of light, as influenced by factors such as dissolved organic carbon, algal biomass, and water depth (Middelboe and Markager, 1997; Vestergaard and Sand-Jensen, 2000; Lacoul and Freedman, 2006). Other studies have cited the importance of sediment nutrients and sediment type (Pearsall, 1920; Barko and Smart, 1986; Xie *et al.*, 2005); trophic status as related to nutrient chemistry (Hutchinson, 1975; Srivastava *et al.*, 1995; Toivonen and Huttunen, 1995; Jeppesen *et al.*, 2000); physical influences such as slope, wind and wave action, and changes in hydrology (Madsen *et al.*, 2001; van Geest *et al.*, 2003; Schutten *et al.*, 2004); and biological factors like competition between different macrophytes, allelopathy, grazing, and shading by periphyton (Gopal and Goel, 1993; Lauridsen *et al.*, 1993; Weisner *et al.*, 1997), as these conditions can limit the distribution of AV.



Degradation of AV has been significant in marine and freshwater coastal wetland areas of the United States (Orth and Moore, 1983; Orth *et al.*, 2006; Waycott *et al.*, 2009). Coastal wetlands associated with the mouths of freshwater tributaries have proportionally experienced the greatest declines, due to direct watershed inputs of nutrients, sediments, and dissolved organic matter (Cercio and Moore, 2001; Kemp *et al.*, 2004; Dobberfuhl, 2007). Within the Great Lakes Basin, wetland losses have been estimated at 70% in the United States and 68% in Canada south of the Precambrian Shield (Snell, 1987).

The Cat Island Chain (CIC), which occurred along the Green Bay coast offshore from Peter's Marsh and Atkinson Marsh (Figure 1; Frieswyk and Zedler 2007), provided important ecological services to lower Green Bay, as do other barrier island systems. Barrier islands are long, narrow coastal landforms that typically form along wave-dominant coasts. The CIC once protected the wetlands at the mouth of the Fox River and Duck Creek from high-energy storms, ice damage, and sediment re-suspension (Brown County, 2011). Being protected from the destructive energy of high winds and waves allows the establishment of AV communities on the landward side of barrier islands (Hester *et al.*, 2005). The wildlife habitat value of barrier island AV is significant, providing nesting sites for shore birds and essential breeding habitat for fish and invertebrate species (Godfrey, 1976; Mendelssohn *et al.*, 1987; Ritchie *et al.*, 1995).

In 1973, the majority of the CIC was lost to severe erosion caused by powerful spring storms and high water levels (Frieswyk and Zedler, 2007). Since the loss of the islands, lower Green Bay has faced long-term wetland degradation from waves penetrating nearshore waters and from human-related activities (i.e. wetland filling, shoreline development; Brown County, 2011). The re-establishment of the CIC, first suggested in a 1982 Great Lakes Fishery Commission Technical Report (Harris *et al.*, 1982), has been carefully planned to restore



**Figure 1:** Aerial photograph of the historic Cat Island Chain (1965). Photo courtesy of Smith 2005.

the historic island chain and reverse ecological degradation. The project consists of constructing a 4 kilometer wave barrier, from the western shore of Green Bay to the Fox River shipping channel, followed by several decades of filling the three islands with dredge material removed from the Fox River shipping channel. The islands themselves will provide 110 hectares of terrestrial habitat, while the wave barrier aims to protect another 495 hectares of aquatic habitat occurring leeward of the CIC project. The Cat Island Chain restoration project wave barrier (Figure 2), in place to serve as the foundation of the islands and to protect the leeward side from storm and ice damage, was completed in 2012. The total cost of constructing the wave barrier was just over \$18.3 million.

Prior to this research, no ongoing monitoring was being done to examine the potential impacts caused by the installation of the wave barrier. The establishment of the wave barrier was anticipated to benefit leeward side coastal wetland habitat by creating conditions similar to those associated with other barrier island chains, such as reductions in wave energy and associated improvements in water quality and light extinction. The wave barrier is also expected to promote establishment and expansion of AV communities, offering quality habitat for fish and wildlife populations. Lower Green Bay is designated as an Area of Concern by the U.S. Environmental Protection Agency, and the overall effects of the CIC restoration project could also contribute to efforts to improve Beneficial Use Impairments and, ultimately, delist the site.

The overall objective of this study was to examine the impacts of the CIC wave barrier on water quality, wave energy, and AV restoration potential. The specific objectives of this study were to 1) quantify potential effects of the wave barrier on water quality, wave energy, light extinction, and abundance and distribution of AV; 2) assess the existing aquatic seed-bank on the lee side of the barrier; 3) and determine the survival and growth of transplanted AV propagules and

*Schoenoplectus acutus* (hardstem bulrush) plugs on the lee and windward sides of the barrier. Results from this study will provide insight into potential strategies for achieving fish and wildlife habitat enhancement goals for this Area of Concern.



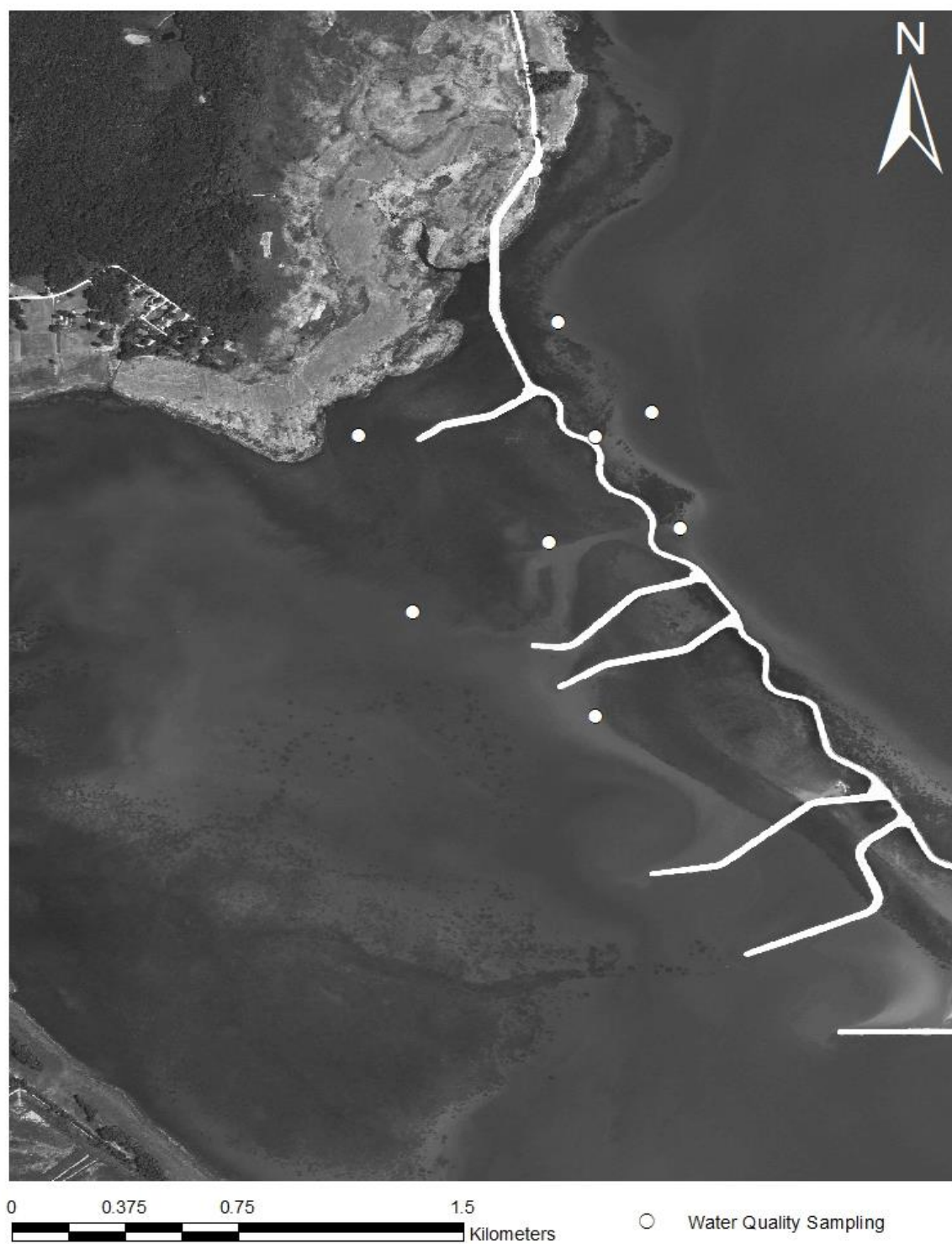
**Figure 2:** Aerial photograph of the Cat Island Chain restoration project wave barrier (2013). Photo courtesy of the U.S. Army Corps of Engineers.

## METHODOLOGY

### Water Quality and Wave Velocity Analyses

Water samples were taken each week for 11 weeks between June 20th and September 5th, 2013, during relatively calm climatic conditions. Water quality, wave velocity, and light extinction were examined at eight locations, four windward and four leeward of the wave barrier (Figure 3). Sampling points were randomly selected a priori but adjusted as necessary in the field to ensure selection of wadable areas. Sampling points were located using a handheld GPS unit. Water samples were taken with a WILDCO 2.2L horizontal PVC Van Dorn water sampler (Wildlife Supply Company, Yulee, FL, USA) at a depth of 30 centimeters.

Water samples were taken ten minutes after arriving at each sampling site to allow any disturbed sediment from movement to dissipate prior to sampling. Water samples collected for total suspended solids and total volatile solids analyses were placed in quart-sized bottles and then immediately sealed and labeled for transport to the laboratory for analysis. Water samples for chlorophyll *a* analysis, which provides a surrogate measure of algal biomass, were field filtered with 47mm Millipore filters (Millipore Corporation, Billerica, MA, USA). Millipore filters were subsequently folded and sealed in labeled plastic capsules, wrapped in aluminum foil, and placed on ice to be transported to the laboratory for analysis. The amount of water filtered for each sampling point was determined by the Secchi depth, as clearer water needs a larger volume of water filtered to collect enough algae for analysis (Betz and Howard, 2009). Sampling points with Secchi depths less than 30 centimeters filtered 50ml of water, Secchi depths between 30 and 45 centimeters filtered 100ml of water, and Secchi depths greater than 45 centimeters filtered 200ml (Betz and Howard, 2009).



**Figure 3:** Locations of all water quality sampling points at the Cat Island Chain.



Chlorophyll *a* filters, bottled water samples and lab slips were sent to the Wisconsin State Laboratory of Hygiene (Madison, WI, USA) within 24 hours of collection to analyze total suspended solids (DNR Parameter 530), volatile suspended solids (DNR Parameter 535), and chlorophyll *a* (DNR Parameter 99717). Chlorophyll *a* was analyzed using ESS INO Method 151.1 rev 5. Total suspended solids and volatile suspended solids were analyzed using ESS INO Method 340.1 rev 10. The difference between total suspended solids and volatile suspended solids was used to calculate ashed solids values (Robinson, 1996). Chlorophyll *a* in µg/l was converted to the dry weight of planktonic algae in mg/l, which was found by multiplying chlorophyll *a* in µg/l by 0.07 (Breukelaar *et al.*, 1994). Ashed solids and planktonic algae dry weight values were then subtracted from total suspended solids to calculate detritus, the remaining component of total suspended solids.

Light extinction data was collected with a LI-250a light meter (LI-COR, Inc., Lincoln, NE, USA). Quantum scalar irradiance (µmol/m<sup>2</sup>/s) was measured every 10 cm from the surface to the lake bottom after waiting ten minutes to allow any disturbed sediment to resettle before sampling. At each sampling point, light data was recorded under consistent weather conditions (e.g., direct sunlight, partial cloud cover). Light extinction coefficients (meters<sup>-1</sup>) were calculated using Lambert's Law:

$$k = (\ln I_0 - \ln I_z) / z$$

where *k* represents the light extinction coefficient, *I*<sub>0</sub> is the irradiance measured at the water surface, *I*<sub>*z*</sub> is the irradiance at the lakebed, and *z* is the difference in depth from the two irradiance measurements.

Wave velocity, a function of wave energy, was measured with a Marsh McBirney Flo-Mate 2000 (Hach Company, Loveland, CO, USA) velocity meter (Robinson, 1996). At each

sample point, water velocity was measured at the water surface, the lake bottom, and at mid-depth with the velocity meter pointed north and then with the velocity meter pointed south. Maximum wave velocity was documented at each point by recording the highest value that was measured based upon the six readings (i.e, north-water surface, north-lake bottom, north-mid-depth, south-water surface, south-lake bottom, and south-mid-depth). Water depth was also recorded at each sampling point.

We used a repeated measures analysis of variance (ANOVA) to test for differences in leeward and windward light extinction, wave velocity, total suspended solids, total volatile solids, and chlorophyll *a*. Repeated measures ANOVA was also used to examine time and time-treatment interactions. Stepwise regression tests were used to analyze the relationship between light extinction and ashed solids, detritus, chlorophyll *a*, and wave velocity for both the leeward and windward sites. All statistical analyses were performed using SAS (Version 9.3).

### Vegetation Analyses

AV points from a previous Wisconsin Department of Natural Resources survey (2010) were resurveyed for vegetation density and diversity in 2013 and followed the same point-intercept sampling methodology (Figures 4 and 5; Hauxwell *et al.*, 2010). AV surveys were done at two sites, one occurring on the leeward side of the CIC wave barrier (referred to as Duck Creek Delta), and the other being Dead Horse Bay, a site that is approximately 5 kilometers north of the CIC project and unaffected by the wave barrier. At Duck Creek Delta 207 points were sampled and 288 points were sampled at Dead Horse Bay. Sample points were relocated with a Garmin GPSmap 62s GPS unit either by boat or on foot, depending on water depth. At





**Figure 4:** AV Rake Pull Survey Locations for Duck Creek Delta (2010 & 2013). All survey points of the Duck Creek Delta are leeward of the CIC wave barrier (207 sample points).



**Figure 5:** AV Rake Pull Survey Locations for Dead Horse Bay (2010 & 2013). All survey points of Dead Horse Bay serve as a control area, located outside of the area of influence for the CIC wave barrier (288 sample points).

each point, the head of a double-sided rake was lowered into the water until it reached the bottom and then fully rotated twice. After two rotations, the rake was removed from the water and the total density and species density were measured on a scale of 0 to 3, where 0 had no vegetation sampled and 3 had a rake head full of vegetation (Hauxwell *et al.*, 2010). Specimens were later verified in the lab. Water depth was recorded at each survey point and the dominant sediment type was recorded as mucky, sandy, or rocky at each survey point.

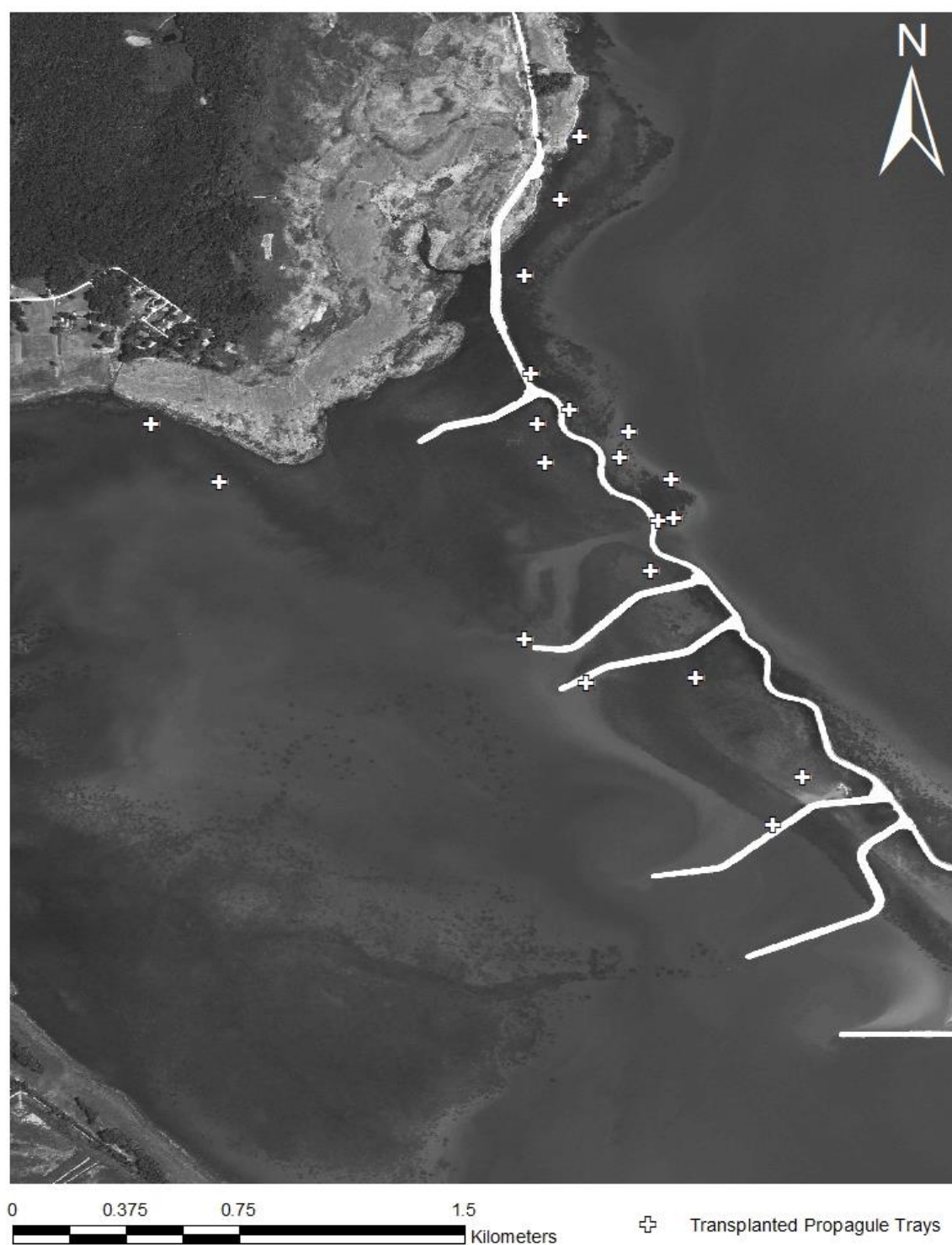
Species presence and approximate distribution were mapped using ArcGIS. The datum for the maps was WGS 1984 and Brown County Digital Orthoimagery was used as the base layer. ESRI spatial analyst buffer tool was used to develop polygons to a specified distance of 250m around sample points with target species present. To remove any overlap, all buffers were dissolved together into a single feature. To improve aesthetic quality, the smooth polygon cartography tool was used. Importantly, the approximate distributions represent an estimate of the area with potential coverage by aquatic macrophyte species. The maps are not intended to suggest that all areas within a polygon will be vegetated; in fact, we know from field observations that the macrophyte coverage within the lower bay is patchy and that some of the area within a given polygon will not include aquatic macrophytes. The maps should be interpreted as showing the extent of the area that could include AV or a particular aquatic macrophyte species, rather than the extent of the area that does include AV or a particular aquatic macrophyte species. . Maps for each macrophyte species by site for 2010 and 2013 were produced, along with maps of approximate submergent macrophyte distribution.

We used chi-square analysis to test for presence and absence data of AV between the 2010 Wisconsin Department of Natural Resources AV sampling and our 2013 survey at the Duck Creek Delta and Dead Horse Bay. This Chi-square test analyzed changes in AV over time

for a littoral wetland affected (Duck Creek Delta) and a littoral wetland unaffected (Dead Horse Bay) by the CIC wave barrier.

Sediment samples were also collected at the CIC site to analyze the existing propagule bank on the leeward side of the barrier. Submerged sediment was collected at multiple locations at a water depth ranging from 5 cm to 60 cm to assure a diverse seed-bank. Sediment was then taken to a greenhouse facility, mixed thoroughly and placed into 13.25 liter plastic germination trays (38.7 cm x 29.2 cm), approximately 5 centimeters in depth. The CIC sediment was distributed evenly into twenty trays and kept in the greenhouse under temperature and humidity conditions comparable to Green Bay during the growing season. Sediment was also collected from Lake Noquebay (45°15'30"N, 87°54'30"W), Marinette County, WI, to compare species composition and density. Lake Noquebay is noted for native AV species richness and diversity and relative absence of invasive species (Brenda Nordin, personal comm.; Gary Fewless, personal comm.), which was desirable for this research to examine the potential for transplanted propagule survival in the bay. Lake Noquebay sediment was distributed into forty 13.25 liter plastic trays, twenty to be kept in the greenhouse and twenty to be transplanted into the lakebed at the CIC (Figure 6). All transplant trays were installed at the CIC site on June 17-18, 2013. Transplanted trays with Noquebay sediment were kept submerged using 23 centimeter landscape stakes. Ten transplant trays were randomly placed at georeferenced locations on each side of the wave barrier and were monitored biweekly for species-specific stem counts. Water depth was also recorded at each transplant tray location.

Greenhouse sediment trays were monitored between June and September 2013. Ten trays from CIC and Lake Noquebay were watered lightly and the other ten trays were inundated with 5 centimeters of water to promote germination of different AV forms (i.e., submergent and



**Figure 6:** Locations of all transplanted propagule trays at the Cat Island Chain.

emergent) occurring in the seed bank. All trays were watered every two days to prevent drought and heat exposure. Sediment trays were given a month to germinate in the greenhouse before they were surveyed weekly for stem counts of each occurring species.

In addition to the already described propagule analyses, four-hundred *Schoenoplectus acutus* (hard-stem bulrush) plugs were transplanted at the CIC site. *S. acutus* plugs were planted at twenty plots that were each one square-meter in size. Ten of the plots were located windward of the wave barrier and ten were located leeward of the wave barrier, with twenty plugs concentrated at each plot and a total of two-hundred plugs on each side (Figure 7). All plugs were transplanted to the site on June 27-28, 2013. Plugs were planted approximately 10 cm to 15 cm into the lakebed and at a range of 12 cm to 60 cm in water depth. At each plot, *S. acutus* plugs were planted in rows of four or five and were measured biweekly for stem count and stem length.

An unbalanced ANOVA test, an ANOVA test for unequal sample sizes, was used to test for significant differences in stem counts between germination trays; Fisher's least significant difference (LSD) method was used to examine pairwise differences when significance was present. CIC sediment in the greenhouse (n=20), Lake Noquebay sediment in the greenhouse (n=20), and transplanted Noquebay trays at the CIC on the leeward (n=10) and windward (n=10) side were compared.

An unbalanced ANOVA test was also used to test whether stem counts of *S. acutus* differed between leeward and windward transplants. Square root transformations were used to transform count data and 0.5 was added to zero values prior to transformation (Montgomery, 1991). Stem count data from late-August were used to assess the transplant tests, as they were the most recent surveys conducted before AV senescence began to be observed. Chi-square





**Figure 7:** Locations for all *S. acutus* (hard-stem bulrush) transplants at the Cat Island Chain.

analysis was performed using Microsoft Excel (2013). All other statistical analyses were performed using SAS (Version 9.3).



## RESULTS

### Water Quality and Wave Velocity Analyses

No significant differences between light extinction ( $p = 0.5797$ ), wave velocity ( $p = 0.7313$ ), total suspended solids ( $p = 0.9207$ ), total volatile solids ( $p = 0.291$ ), or chlorophyll *a* ( $p = 0.7518$ ) were found between the windward and leeward side of the wave barrier (Table 1).

Time was a significant factor for light extinction ( $p < 0.0001$ ), wave velocity ( $p < 0.0001$ ), total suspended solids ( $p < 0.0001$ ), total volatile solids ( $p < 0.0001$ ), and chlorophyll *a* ( $p < 0.0001$ ).

Light extinction ( $p = 0.0027$ ), wave velocity ( $p < 0.0001$ ), total suspended solids ( $p = 0.0027$ ), volatile suspended solids ( $p = 0.0114$ ), and chlorophyll *a* ( $p < 0.0001$ ) also had a significant time-site interaction, meaning the effect of time on each variable was significantly different for each site. Importantly, the significance of the time-site interaction complicates the interpretation of the effect from the barrier. Significant interaction terms in a repeated measures ANOVA limit the ability to interpret main effects. The results, however, do indicate that the effect of the barrier on the measured water quality and wave velocity variables changed over time. Average water quality, light extinction, and wave velocity values per site are found in Appendix A. Changes in these variables over time can be found in Appendix B. A review of these figures shows that, for all variables, average windward and leeward values across the sampling period were similar. Changes in variables from one sampling date to the next, however, were sometimes dramatic, with the windward side having higher values on some dates and the leeward side having higher values on others.

Stepwise regression analyses determined that light extinction on the windward side of the CIC was significantly related to wave velocity ( $p = 0.0213$ ), while chlorophyll *a* was nearly significant ( $p = 0.0665$ ). Ashed solids and detritus were also not significant variables for the

**Table 1:** Repeated Measures Analysis of Variance (ANOVA) of water quality, light extinction, and wave velocity variables. Light extinction, wave velocity, total suspended solids, volatile suspended solids, and chlorophyll *a* were tested between windward and leeward sites, over time, and time by site. \* indicates a significant relationship (p-value < 0.05).

VARIABLE	BETWEEN SITES	WITHIN SUBJECTS (TIME)	WITHIN SUBJECTS (TIME*SITE)
Light Extinction	0.5797	<.0001*	0.0027*
Wave Velocity	0.7313	<.0001*	<.0001*
Total Suspended Solids	0.9207	<.0001*	0.0027*
Volatile Suspended Solids	0.291	<.0001*	0.0114*
Chlorophyll <i>a</i>	0.7518	<.0001*	<.0001*

**Table 2:** Stepwise regression tests for light extinction. Significant variables for stepwise regression tests of the relationship between light extinction and ashed solids, chlorophyll *a*, detritus, and wave velocity on each side of the CIC wave barrier.

SITE	DEPENDENT	INDEPENDENT	P-VALUE	R-SQUARE	PARAMETER ESTIMATE
Windward	Light Extinction	Wave Velocity	0.0213	0.1877	13.05717
Leeward	Light Extinction	Ashed Solids	0.0002	0.7257	0.04089
		Chlorophyll <i>a</i>	0.0351	0.1217	0.1865
		Wave Velocity	0.0001	0.0168	14.70525

windward site and, like chlorophyll *a*, were not included in the final model. On the leeward side, chlorophyll *a* ( $p = 0.0351$ ), ashed solids ( $p = 0.0002$ ), and wave velocity ( $p = 0.0001$ ) were significant predictors of light extinction (Table 2), while detritus was not. Scatterplots of all relationships between light extinction and the independent variables can be found in Appendix C. The final stepwise regression equations for the windward and leeward were the following:

#### Windward

Light Extinction =  $1.87183 + 13.05717$  (Wave Velocity); ( $R^2=0.1877$ ,  $p=0.0213$ )

#### Leeward

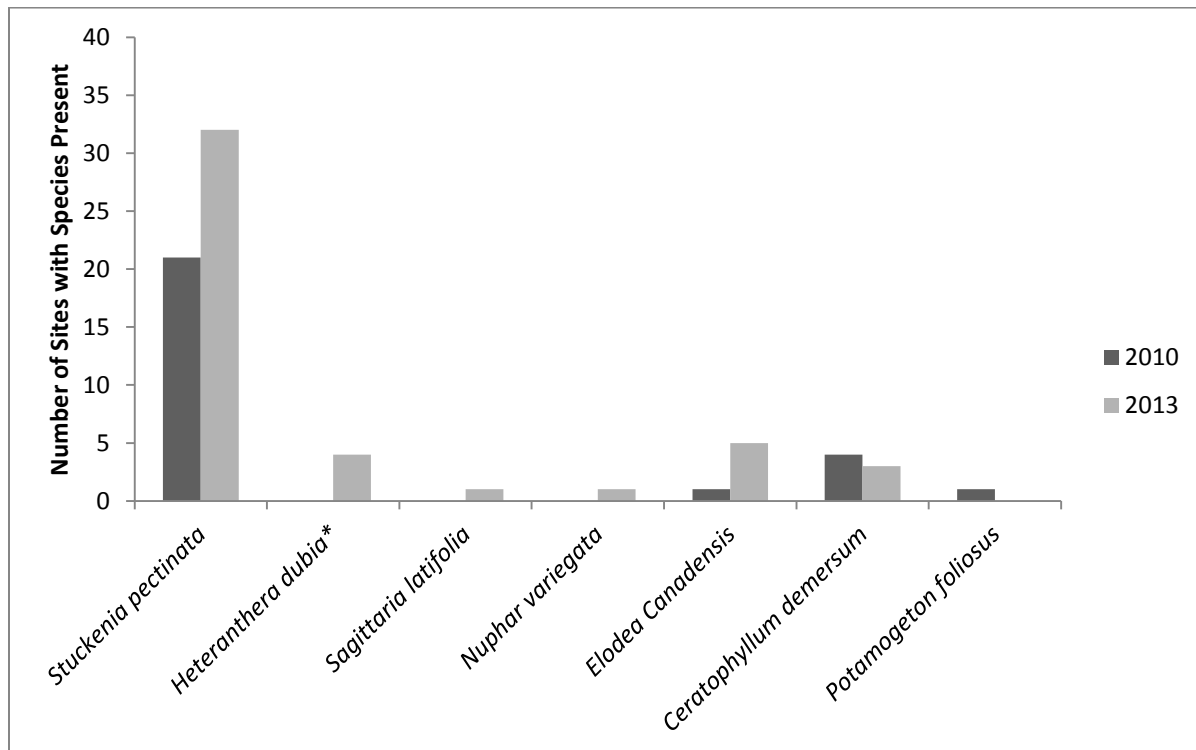
Light Extinction =  $0.80872 + 0.04089$  (Ashed Solids) +  $0.18650$  (Chlorophyll *a*) +  $14.70525$  (Wave Velocity); ( $R^2=0.8736$ ,  $p<.0001$ ).

### Vegetation Analyses

The chi-square distribution test for the leeward sample points found a significant difference between expected and observed counts of *Hederanthera dubia* (water stargrass) ( $p = 0.044$ ) between 2010 and 2013 (Figure 8). *Stuckenia pectinata* (sago pondweed) was found in 11 more survey locations than 2010, but was not significant ( $p = 0.106$ ). *Sagittaria latifolia* (broad-leaved arrowhead) and *Nuphar variegatum* (bull-head pond-lily) were also present, but were not found in the pre-treatment survey. *Potamogeton foliosus* (leafy pondweed) was the only AV species sampled at the leeward sites in 2010 and not found in 2013. The only species found in Dead Horse Bay in 2010, *S. pectinata*, was not observed in the 2013 survey. *S. pectinata* was the most encountered AV species, sampled at 32 different locations in the Duck Creek delta (i.e., 15% of the 207 sampled points). Spatial distribution of submergent vegetation from 2010 and

2013 can be found in Figure 9 and 10. Distributions of individual species for 2010 and 2013 can be found in Appendix D.

*S. acutus* stems averaged 17.3 stems greater per square-meter plot on the leeward side of the wave barrier on August 22, 2013, the last recording period before senescence started. *S. acutus* stem counts were significantly greater in the leeward site plots than windward plots ( $p < 0.0001$ ) (Figure 11). By the time of the first survey (July 11, which was 2 weeks after placement in the bay), four plots on the windward side had zero stems remaining.



**Figure 8:** Number of sites with species present for vegetation at Duck Creek Delta (2010 & 2013). \* indicates a significant change in species density ( $p$ -value  $< 0.05$ ).

## Duck Creek Delta Vegetation Survey

Submergent Vegetation 2010



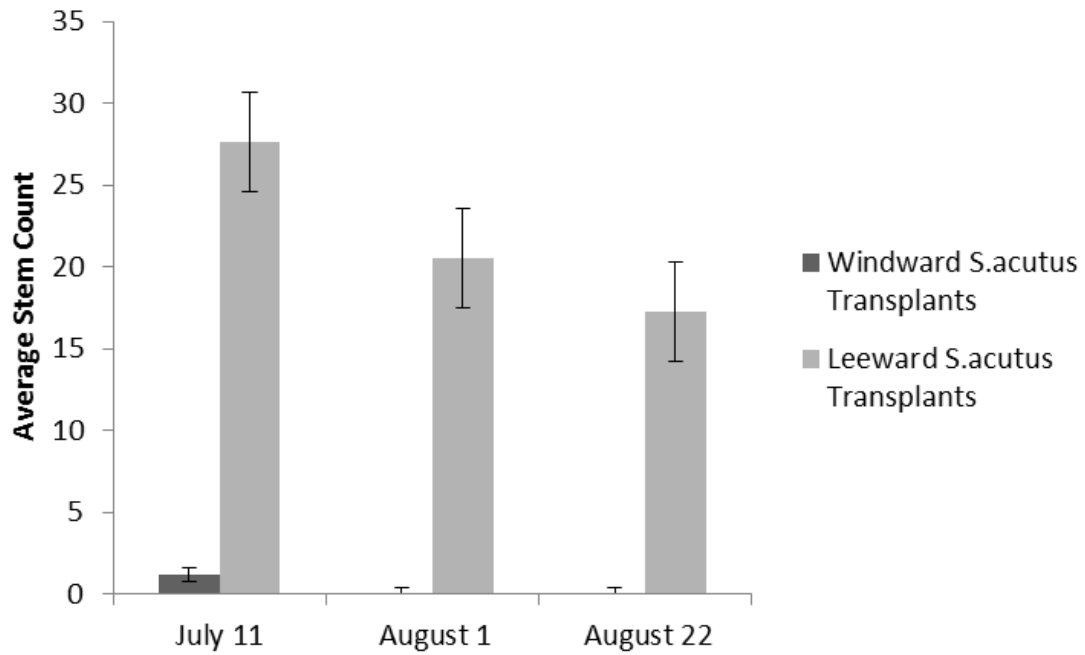
**Figure 9:** Spatial distribution of submergent vegetation at Duck Creek Delta (2010).

## Duck Creek Delta Vegetation Survey

Submergent Vegetation 2013



**Figure 10:** Spatial distribution of submergent vegetation at Duck Creek Delta (2013).

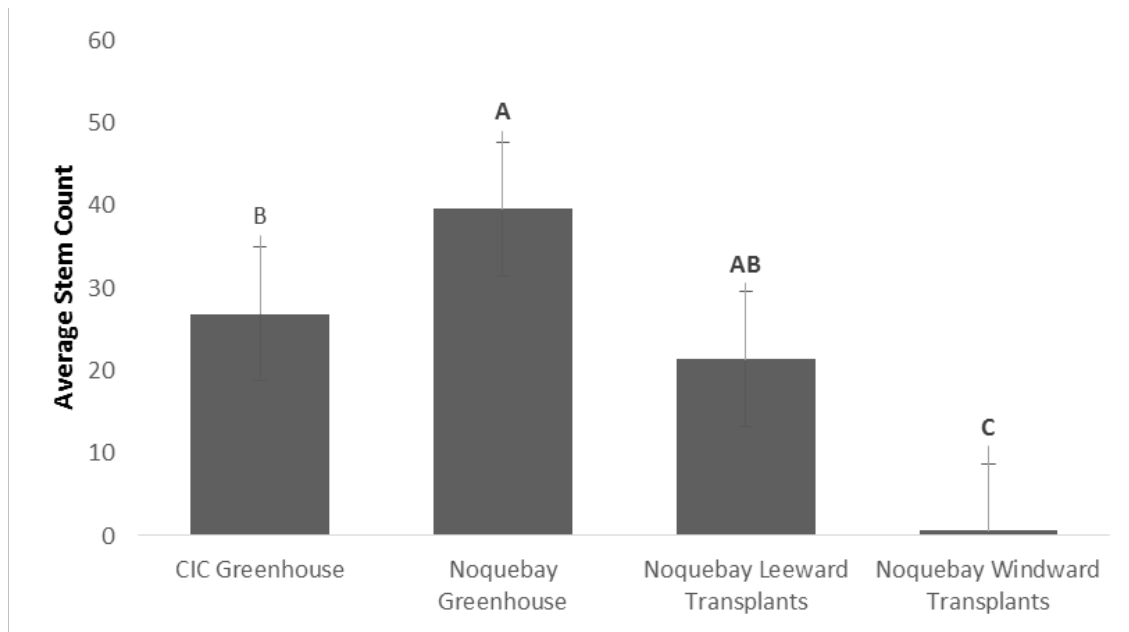


**Figure 11:** Average stem counts of *S. acutus* (hard-stem bulrush) transplants on the windward and leeward side of the CIC barrier.

Significant differences in average stem counts were also found across the Lake Noquebay sediment leeward transplants, Lake Noquebay sediment windward transplants, Lake Noquebay greenhouse sediment, and CIC greenhouse sediment ( $p < 0.0001$ ) (Figure 12). Lake Noquebay sediment windward transplants had significantly lower stem densities than CIC greenhouse sediment, Noquebay greenhouse sediment, and Noquebay sediment leeward transplants. Lake Noquebay sediment leeward transplants averaged 20.8 stems greater than Noquebay sediment windward transplants. Lake Noquebay greenhouse sediment was significantly greater than CIC greenhouse sediment and Noquebay sediment windward transplants, but were grouped with Noquebay sediment leeward transplants when Fisher's LSD method was used to examine pairwise differences. Lake Noquebay greenhouse sediment had the most stems, averaging 49.4 stems per tray.

Only three species were surveyed in the twenty CIC sediment germination trays in the greenhouse: *Phragmites australis* (common reed grass), *Populus tremuloides* (quaking aspen), and *Typha* species (cattail). *Typha* was the most abundant species in the CIC sediment, averaging over 23 stems per tray and was found in all twenty greenhouse germination trays. *Typha* accounted for 86.4% of the total stems in CIC trays. The *Typha* specimens did not mature enough to be distinguished between *Typha latifolia*, *Typha angustifolia*, and the hybrid *Typha xglauca*. The Lake Noquebay greenhouse sediment had the highest diversity of vegetation, containing *Alisma plantago-aquatica* (Eurasian waterplantain), *Bidens frondosus* (common beggar-ticks), *Ceratophyllum demersum* (coon's-tail), *Cyperus odoratus* (Flat Sedge), *Eleocharis intermedia* (matted spike-rush), *Leersia oryzoides* (rice cut grass), *Myriophyllum spicatum* (Eurasian watermilfoil), *N. variegatum*, *S. latifolia*, *Spirodela polyrrhiza* (giant duckweed), and *S. acutus*. Among these species, only *A. plantago-aquatica*, *C. demersum*, and *N. variegatum*





**Figure 12:** Average stem counts of greenhouse and transplant propagule trays. Cat Island Chain (CIC) greenhouse sediment, Lake Noquebay greenhouse sediment, Lake Noquebay sediment leeward transplants, and Lake Noquebay sediment windward transplants were tested for analysis of variance. Different letters indicate significant differences between germination trays. Stem counts were taken on August 22, 2013.

were found in the transplanted sediment placed in Green Bay. Two species that were not surveyed in the greenhouse, *H. dubia* and *S. pectinata*, were also surveyed in the transplant trays.

Average stem counts by species for each set of sediment trays can be found in Table 3.

**Table 3:** Average stem counts for each species found in sediment trays (August 22, 2013).

SPECIES (SCIENTIFIC NAME)	CIC GREENHOUSE	NOQUEBAY GREENHOUSE	LEEWARD TRANSPLANTS	WINDWARD TRANSPLANTS
<i>Alisma plantago-aquatica</i>	0	9.65	3.17	0.56
<i>Bidens frondosus</i>	0	0.35	0	0
<i>Ceratophyllum demersum</i>	0	0.15	31.83	0
<i>Cyperus odoratus</i>	0	1.85	0	0
<i>Eleocharis intermedia</i>	0	13.80	0	0
<i>Leersia oryzoides</i>	0	2.85	0	0
<i>Myriophyllum spicatum</i>	0	1.35	0	0
<i>Nuphar variegatum</i>	0	0.65	0	0
<i>Phragmites australis</i>	3.20	0	0	0
<i>Populus tremuloides</i>	0.45	0	0	0
<i>Sagittaria latifolia</i>	0	1.45	0	0
<i>Schoenoplectus acutus</i>	0	7.40	0	0
<i>Spirodela polyrrhiza</i>	0	0.05	0	0
<i>Stuckenia pectinata</i>	0	0	0.67	0.11
<i>Typha</i> spp.	23.20	0	0	0

## DISCUSSION

McAllister (1991) and Robinson (1996) both investigated water quality parameters and their effects on lower Green Bay. McAllister found the Duck Creek Delta area to have higher levels of turbidity, total phosphorous, and chlorophyll *a* compared to other sites located along a northern gradient in the bay. Robinson (1996) found chlorophyll *a*, detritus and ashed solids to be significant factors affecting light extinction near the Duck Creek Delta. Similarly, stepwise regression tests found chlorophyll *a*, ashed solids, and wave velocity to have a significant influence on light extinction on the leeward side of the wave barrier when all variables were considered in a stepwise procedure. Comparison with past research suggests that, on average, the abiotic and biotic factors affecting leeward light extinction have not changed substantially as a result of the wave barrier.

Wave velocity was the only significant predictor of light extinction on the windward side of the barrier. One of the limitations of this study was the relatively limited number of water quality samples collected and the lack of samples across a variety of climatic events. Relationships between windward light extinction and chlorophyll *a*, ashed solids, and detritus should be further explored with a more expansive data collection over a wider variety of precipitation and wind events.

Repeated measures ANOVA results indicated that the time-site interaction was significant for each measured variable, which further suggests that water quality data for each site was heavily influenced by weather conditions. The data collection from August 21, 2013, provides an example of how time affected the variables measured at each site. During the sampling effort on that day, wind conditions changed with a very noticeable increase in wind speeds between the time when the windward and leeward samples were collected. Average wind

speeds on August 21 were 9.5 mph, with the highest gust speeds reaching 62 mph (NWS, 2013). Wind speed increased as the day progressed, and windward samples were collected during calmer conditions while the leeward samples were collected during windier conditions. Samples that were taken on the leeside appeared to be heavily influenced by the increased wind speed, and showed substantially higher light extinction, wave velocities, total suspended solids, chlorophyll *a*, light extinction, and volatile suspended solids (Appendix A). This type of phenomenon is likely responsible for the significant time-site interactions, where the effect of time on each water quality variable was significantly different on each side of the wave barrier due to short-term temporal influences. This finding highlights how rapidly weather can change water quality conditions on site. As expected with stronger winds, the wave velocity, total suspended solids, volatile suspended solids, and light extinction coefficient on the leeside recorded their highest values during the August 21 wind event. Resuspension of sediment by wave action can greatly affect water quality, because it increases turbidity and enhances nutrient cycling by bringing sedimentary nutrients back into the water column (Kristensen *et al.* 1992; Søndergaard *et al.* 1992; De Vicente *et al.* 2006).

A review of the tables in Appendix A further reveals that it was not uncommon for water quality variable concentrations to fluctuate between higher on the windward side and higher on the leeward side depending upon site conditions during the day of sampling. For example, the leeward site had substantially higher concentrations of total suspended solids than the windward site on three dates, about equal concentrations on three dates, and substantially lower concentrations on five dates. The effect of the barrier was not consistent across the sampling dates.

Despite the installation of the wave barrier, wind and wave energy appear to continue to substantially influence the biotic and abiotic environment. We expected reductions in total suspended solids, ashed solids, light extinction, and wave velocity in areas leeward of the wave barrier. Collected water quality data instead showed fluctuations throughout the field season for both windward and leeward variables. An additional factor that could be affecting leeward water quality is the sediment load carried by Duck Creek. The mouth of the creek is at the southern end of the bay and the creek empties into the leeside of the barrier. Precipitation events contribute sediment loading from Duck Creek, a watershed influenced by agricultural activities. A USGS monitoring station on Duck Creek recorded events where total suspended solids concentrations exceeded 900 mg/L between 1988 and 2008 (Cibulka *et al.*, 2010). Agriculture-related contaminants, such as sediment, nutrients, and pesticides, constitute one of the largest diffuse sources of water quality degradation in the United States (Maas *et al.*, 1984; U.S. Department of Agriculture, 1985; Baker 1985), and precipitation events cause loading to lower Green Bay via Duck Creek, thus potentially obscuring the impact of the CIC wave barrier.

Sediment collected from the CIC site was examined under greenhouse conditions. The CIC sediment produced lower stem densities than the Lake Noquebay sediment kept in the greenhouse. Only three species germinated in the CIC sediment: *Typha*, *P. australis*, and *P. tremuloides*. Cattail appeared to be dominant in nearly all germination trays. *Typha* from this experiment are likely a combination of *Typha angustifolia* and *Typha xglauca*, which both are known to interfere with wetland communities by forming large mono-specific stands, out-competing native species, and altering substrate characteristics (Finklestein, 2003). Historically, the emergent marsh area of Green Bay's coastal wetlands were dominated by native *Typha latifolia* (Frieswyk and Zedler, 2007), but invasive species *T. xglauca* and *T. angustifolia* have

been expanding throughout the Great Lakes (Chow-Fraser *et al.*, 1998). Substrate occurring at the restoration site appears to be propagule limited and contains primarily invasive species. Lake Noquebay sediment trays transplanted in the leeward locations had stem counts statistically comparable to both greenhouse sediment groups, potentially indicating improved germination conditions for AV on the leeward side. Transplanted trays contained five aquatic plants: *A. plantago-aquatica*, *C. demersum*, *N. variegatum*, *H. dubia*, and *S. pectinata*. *A. plantago-aquatica*, *C. demersum*, and *N. variegatum* represent three of the 11 species found in the Noquebay greenhouse sediment. *H. dubia* and *S. pectinata* were not surveyed in the sediment at the greenhouse, but were in the vegetation rake pulls. These two species occur at the CIC site and likely were introduced from nearby vegetation communities after the transplant trays were anchored.

*S. acutus* plugs transplanted to the CIC site had an immediate response to the surrounding environment. Transplants occurring windward of the barrier had high mortality rates within two weeks of planting. Transplants on the leeward side had significantly higher survival rates. The repeated measures ANOVA suggested no consistent difference in wave velocity due to the constructed barrier, but limited water quality or wave velocity data was recorded during high wind or storm conditions. Differences in *S. acutus* survival rates may indicate that the wave barrier is having some effect on wave velocity during high energy events, especially those with northerly winds. Habitats with intense exposure to wind and wave stress are suboptimal for macrophytes because seedlings may be uprooted, mature plants damaged, and fine sediment and litter eroded (Wilson and Keddy, 1986). Our findings suggest that wind and wave energy continue to have a daily influence on the light environment both windward and leeward of the wave barrier. The “sheltered” area south of the barrier is still quite large, approximately 495

hectares, with a long fetch that can produce relatively high energy wave events during southerly wind events; however, the wave barrier may be offering protection from high energy wave events caused by strong northerly storms, as evidenced by the vegetation results. Our research highlights the need for further research into the influence of wave energy across a variety of wind events.

This study identified three aquatic plants that were not sampled or observed from the 2010 vegetation survey, including *H. dubia*, *S. latifolia*, and *N. variegata*. *Heteranthera dubia* has significantly increased since the construction of the wave barrier. Our findings with the transplanted *S. acutus* and germination trays suggest that this increase in AV may be a result of the wave barrier; however, water depths may also be partially responsible for vegetation changes. The overall water depth of Lake Michigan has decreased since the initial 2010 AV survey by approximately 20 cm (GLERL, 2014). *S. latifolia*, an emergent species commonly found in water depths of 30 cm or less, was present in the post-treatment survey but absent in 2010, suggesting that new aquatic species may be taking advantage of low water levels.

Lower Green Bay is currently listed as an Area of Concern (AOC), a geographic area that fails to meet general or specific objectives of the U.S.-Canada Great Lakes Water Quality Agreement, where such failures have caused or are likely to cause impairment of beneficial use of the area's ability to support aquatic life (Last, 2013). Of the 14 possible Beneficial Use Impairments (BUIs) listed in the 1987 Great Lakes Water Quality Agreement amendment, the Lower Green Bay and Fox River AOC is confirmed or suspected of having thirteen, including loss of fish and wildlife habitat and degradation of fish and wildlife populations (Last, 2013). Our results from the vegetation analyses suggest that the wave barrier has some potential to positively affect AV establishment and growth, potentially due to reductions in severe wave

energy resulting from the CIC wave barrier. Increases in AV abundance can lead to greater populations of fish and wildlife, reverse BUIs, and contribute to AOC delisting.



## CONCLUSIONS

The re-establishment of the historic Cat Island Chain, along with the installation of a wave barrier, aims to improve wetland habitat for waterfowl and fish species. Our study found differences in water quality conditions between the windward and leeward sides of the wave barrier changed over time, with poorer water quality conditions varying between the windward and leeward sites based upon temporal changes in climatic variables. Influences from wind and precipitation events need to be further examined. For example, water discharge from Duck Creek may carry sediment and nutrient loads that could confound the wave barrier's effect on water quality. Future research should consider monitoring water quality conditions and wave energy during varying wind and precipitation events, including extreme events. Further examination of the key biotic and abiotic influences affecting the CIC target restoration area can help mold future fish and wildlife habitat restoration efforts.

Importantly, our research suggests the need for further investigation of the potential for targeted re-introduction of AV on the leeward side of the barrier. The leeward area appears to be propagule limited. In addition, our research demonstrated that transplanted propagules and planted *S. acutus* plugs were more successful on the leeward side of the barrier. The reintroduction of AV could have tremendous ecological benefits for lower Green Bay, improve fish habitat, and increase migratory stopover sites for shorebirds and waterbirds. Increases in AV density could improve the site by reducing wave energy, allowing sediment deposition, reducing sediment resuspension, and improving water clarity. Uptake of carbon and excess nutrients by AV could also reduce algal blooms and improve water conditions.

Restoration of wetland habitat for fish and wildlife species is frequently a priority for Great Lakes Areas of Concern, such as the lower Green Bay and Fox River. Big problems

sometimes require big solutions, and large-scale landscape alterations like the CIC project may hold the key to restoration of coastal wetland habitat in highly altered and/or degraded systems. However, it is imperative that these large-scale projects are effectively monitored and examined to ensure that we learn from our restoration efforts in order to promote effective solutions. This study provides a contribution to that ongoing process.

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## APPENDIX A

### Average Values for Water Quality, Light Extinction, and Wave Velocity Variables by Site

DATE	WINDWARD TOTAL SUSPENDED SOLIDS (MG/L)	LEEWARD TOTAL SUSPENDED SOLIDS (MG/L)
20-Jun	17.78	31.70
27-Jun	32.30	31.78
3-Jul	26.68	24.38
10-Jul	22.60	9.62
17-Jul	29.13	19.70
24-Jul	23.90	12.50
31-Jul	32.13	25.13
13-Aug	38.50	29.25
21-Aug	29.75	59.83
29-Aug	19.00	24.25
5-Sep	31.50	30.00
	27.57	27.10

DATE	WINDWARD VOLATILE SUSPENDED SOLIDS (MG/L)	LEEWARD VOLATILE SUSPENDED SOLIDS (MG/L)
20-Jun	7.75	9.79
27-Jun	18.60	18.70
3-Jul	13.75	7.15
10-Jul	10.60	4.42
17-Jul	13.65	7.70
24-Jul	11.25	6.43
31-Jul	14.50	10.25
13-Aug	19.00	14.67
21-Aug	14.75	24.33
29-Aug	13.00	12.50
5-Sep	17.00	18.50
	13.99	12.22

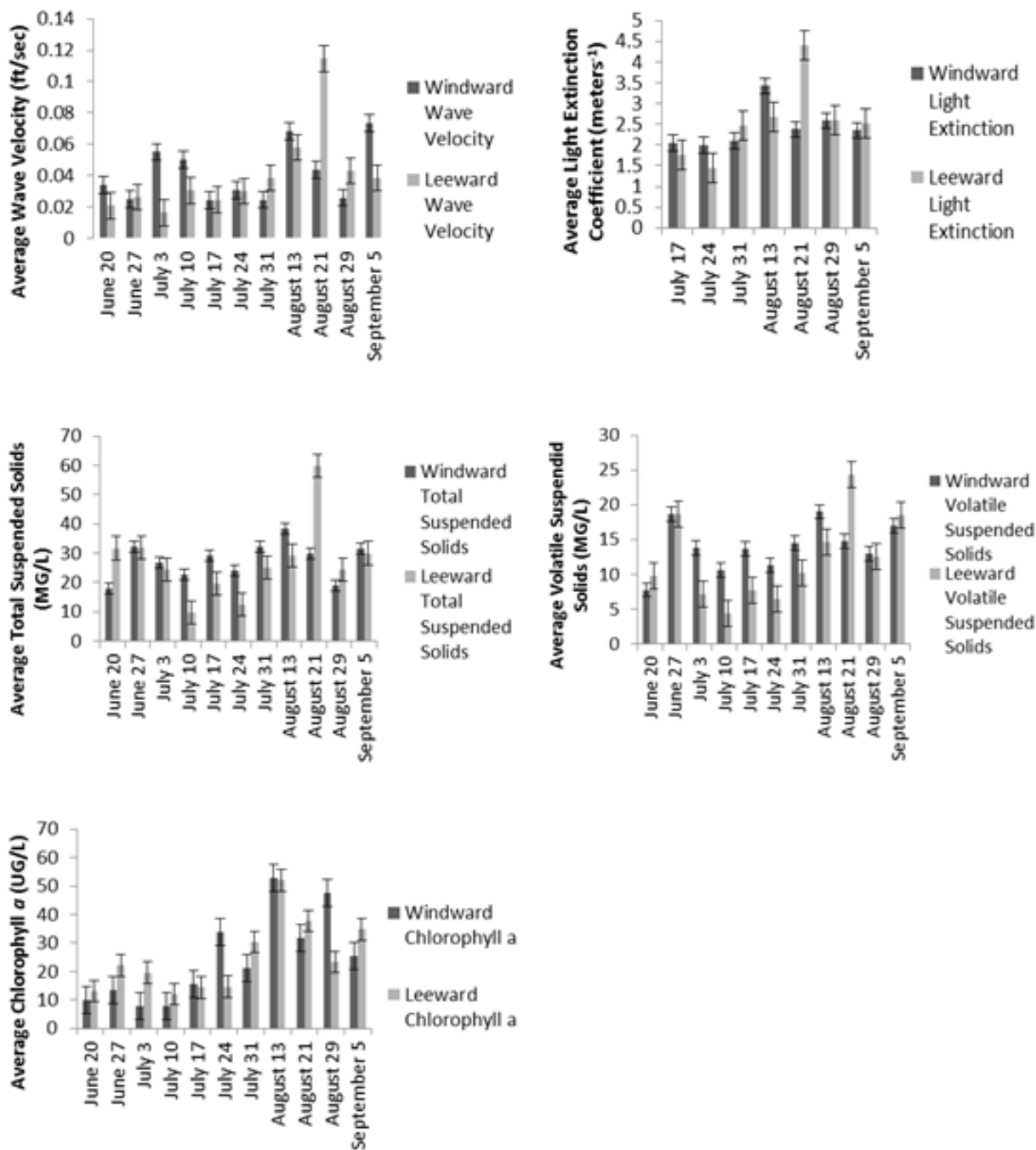
DATE	WINDWARD CHLOROPHYLL $\alpha$ (UG/L)	LEEWARD CHLOROPHYLL $\alpha$ (UG/L)
20-Jun	9.89	13.12
27-Jun	13.60	22.13
3-Jul	7.85	19.58
10-Jul	7.75	12.03
17-Jul	15.58	14.37
24-Jul	33.88	14.68
31-Jul	21.23	30.33
13-Aug	52.93	52.05
21-Aug	31.83	37.75
29-Aug	47.60	23.30
5-Sep	25.38	34.75
	24.32	24.92

DATE	WINDWARD WAVE VELOCITY (ft/sec)	LEEWARD WAVE VELOCITY (ft/sec)
20-Jun	0.03	0.02
27-Jun	0.03	0.03
3-Jul	0.06	0.02
10-Jul	0.05	0.03
17-Jul	0.02	0.02
24-Jul	0.03	0.03
31-Jul	0.02	0.04
13-Aug	0.07	0.06
21-Aug	0.04	0.11
29-Aug	0.03	0.04
5-Sep	0.07	0.04
	0.04	0.04

DATE	WINDWARD LIGHT EXTINCTION (meters <sup>-1</sup> )	LEEWARD LIGHT EXTINCTION (meters <sup>-1</sup> )
17-Jul	2.05	1.76
24-Jul	2.00	1.44
31-Jul	2.10	2.46
13-Aug	3.43	2.67
21-Aug	2.38	4.40
29-Aug	2.59	2.59
5-Sep	2.36	2.52
	2.41	2.55

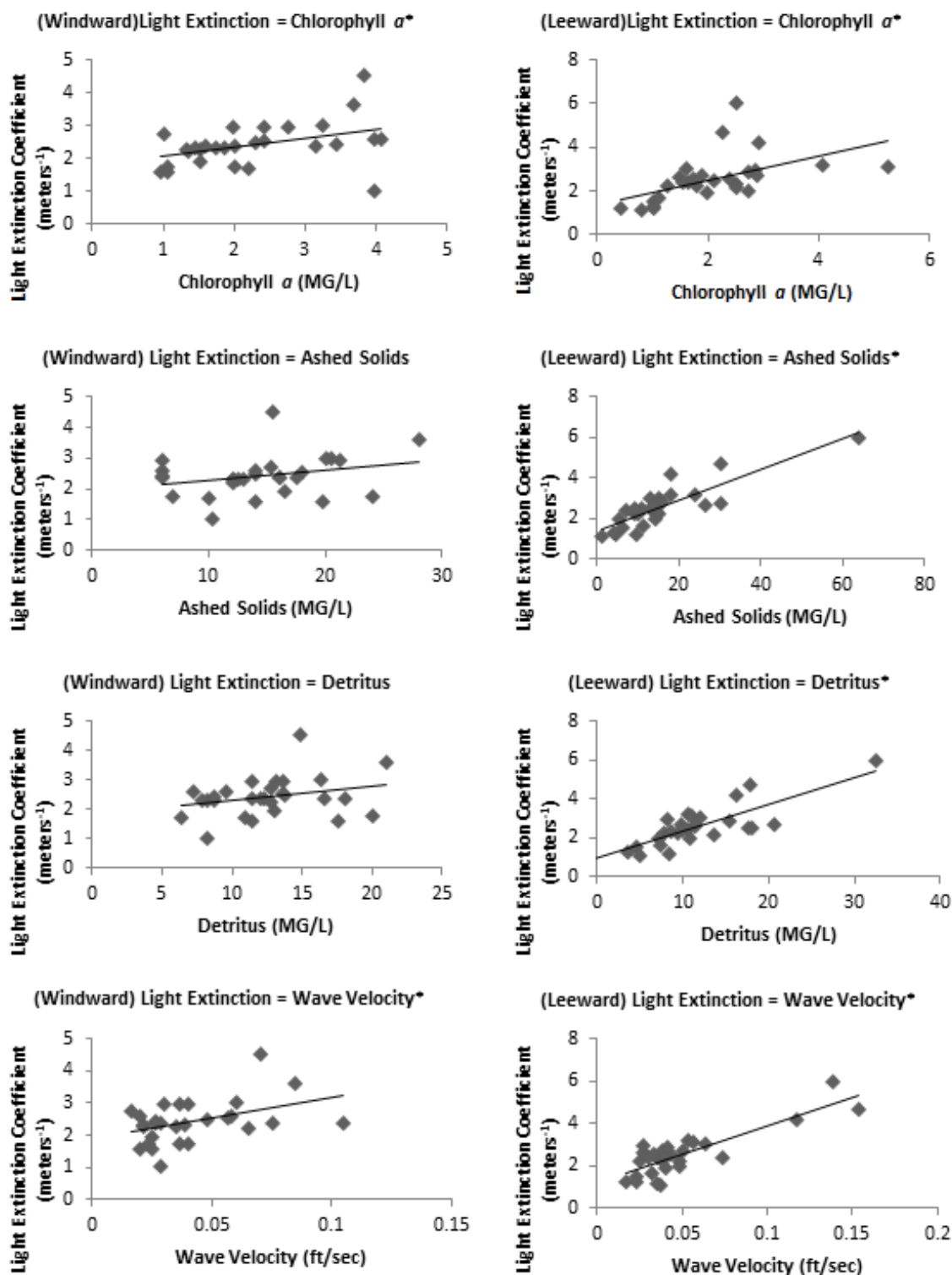
## APPENDIX B

### Changes in Variables over Time for Leeward and Windward Sites



## APPENDIX C

## Light Extinction Scatter Plots Relationships for Leeward and Windward Sites



## APPENDIX D

Species Distribution Maps for 2010 and 2013 Aquatic Vegetation Surveys

### Duck Creek Delta Vegetation Survey

*Ceratophyllum Demersum* 2010



## Duck Creek Delta Vegetation Survey

*Ceratophyllum demersum* 2013



## Duck Creek Delta Vegetation Survey

*Elodea Canadensis* 2010



## Duck Creek Delta Vegetation Survey

*Elodea Canadensis* 2013





## Duck Creek Delta Vegetation Survey

*Heteranthera Dubia* 2013





## Duck Creek Delta Vegetation Survey

Nuphar Variegata 2013



## Duck Creek Delta Vegetation Survey

Potamogeton Foliosus 2010



# Duck Creek Delta Vegetation Survey

*Sagittaria latifolia* 2013



0 0.5 1 2 Kilometers

○ Species Presence  
■ Approximate Distribution

## Duck Creek Delta Vegetation Survey

*Stuckenia pectinata* 2010



## Duck Creek Delta Vegetation Survey

*Stuckenia pectinata* 2013



## Dead Horse Bay Vegetation Survey

*Stuckenia pectinata* 2010



