Extent of Sedge/Grass Meadow in a Lake Michigan Drowned-River-Mouth Wetland Dictated by Topography/Bathymetry and Lake Level

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Research Article

Keywords: Great Lakes wetlands, water-level fluctuations, plant communities, sedge/grass meadow, photointerpretation, topography/bathymetry

Posted Date: October 18th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-980219/v1

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Abstract

Water-level fluctuations are critical in maintaining the diversity of plant communities in Great Lakes wetlands. Sedge/grass meadows are especially sensitive to such fluctuations. We conducted vegetation sampling in a sedge/grass-dominated Lake Michigan drowned-river-mouth wetland in 1995, 2002, and 2010 that followed high lake levels in 1986 and 1997. We also conducted photointerpretation studies in 16 years dating back to 1965 to include responses to high lake level in 1952 and 1974. Topographic/bathymetric data were collected to assess their influence on areal extent of sedge/grass meadow. Dominant species in short emergent and submersed/float plant communities changed with water availability from 1995 to extreme low lake levels in 2002 and 2010. Sedge/grass meadow was dominated by Calamagrostis canadensis and Carex stricta in all years sampled, but Importance Values differed among years partly due to sampling in newly exposed areas. Photointerpretation studies showed a significant relation between percent of wetland in sedge/grass meadow and summer lake level, as well as the number of years since an extreme high lake level. From the topographic/bathymetric map created, we calculated the cumulative area above each 0.2-m contour to determine the percent of wetland dewatered in select years following extreme high lake levels. When compared with percent sedge/grass meadow in those years, relative changes in both predicted land surface and sedge/grass meadow demonstrated that accuracy of lake level as a predictor of areal extent of sedge/grass meadow is dependent on topography/bathymetry. Our results regarding relations of plant-community response to hydrology are applicable to other Great Lakes wetlands.

Introduction

The relations between water-level fluctuations and plant communities of Great Lakes wetlands have been extolled for decades (e.g., Keddy and Reznicek 1986; Hudon 1997; Wilcox 2004; Wilcox and Nichols 2008; Keddy and Campbell 2020; Smith et al. 2021). High lake levels cause die-back of upland canopy-dominating wetland species, and succeeding low lake-level period exposes sediments and allows regrowth of smaller-statured wetland plants from seeds or propagules. Over the past nearly 5000 years, water levels on Lake Michigan-Huron (one lake hydrologically) have fluctuated on a quasi-periodic cycle (Baedke and Thompson 2000; Argyilan et al. 2018). Large, longer-term fluctuations from high to low lake levels recur about every 160 years, with fluctuations of about 30-33 years riding on them. The latter fluctuation pattern is responsible for much of the vegetation change (Wilcox 2004).

Models have been created that demonstrate the relation of such hydrology on vegetation. Wilcox and Nichols (2008) modeled the response of a bulrush marsh in Saginaw Bay of Lake Huron to the reduction of water levels following an extreme high in 1986. The model made use of plant community data collected along transects that followed elevation contours with specific water-level histories to make predictions of plant-community change as a function of meters above water vs. number of years out of water. Keddy and Campbell (2020) made use of literature knowledge to model relative marsh area vs. duration of dewatering in relation to invasion by and flooding-out of woody species.

The plant community most affected by water-level fluctuations is sedge/grass meadow (SGM), which occurs along the higher elevation fringe of the wetlands and, in relation to flooding and dewatering, is in competition with emergent vegetation at the lower extent and woody vegetation at the upper extent (Keddy and Reznicek 1986; Wilcox et al. 2008; Keddy and Campbell 2020). Gathman et al. (2005) sampled wetland plant communities in northern Lake Huron in 1996 when water levels were above average, 1997 with high water levels, and 1998 when levels were back near those of 1996. Stem counts of dominant sedge and grass species in the wet meadow decreased by >70% from 1996 to 1997 and increased in 1998, but only by 16%. Their study did not capture changes that would have occurred by 1999, when lake levels decreased an additional half meter, but we expect that increases were much greater. They also did not collect data on areal extent of SGM nor on elevations. Werner and Zedler (2002) and Peach and Zedler (2006) addressed microtopographic surface area in SGM provided by Carex stricta tussocks but not wetland topography or surface area.

On Lake Ontario, Wilcox et al. (2008) and Wilcox and Bateman (2018) assessed changes in SGM in relation to water levels using photointerpretation of aerial photographs. Wilcox and Xie (2007) brought in topographic relief data to model response of SGM to water-level fluctuations. However, Lake Ontario water levels have been regulated since about 1960 when the St. Lawrence Seaway began operation (Hudon et al. 2006; Wilcox and Xie 2007), so the results do not necessarily reflect natural Great Lakes processes. Although the Keddy and Campbell (2020) model imposed the concept of areal extent, it did not contain numerical area data, which they acknowledged would require site-specific topography/bathymetry.

As part of three studies at Arcadia Marsh on the eastern shore of Lake Michigan, we had the opportunity to sample changes in SGM and other plant communities in 1995, 2002, and 2010 related to water-level decreases from extreme lake-level highs in 1986 and 1997 (Fig. 1). Observations made prior to the last study in 2010 led us to recognize that area of SGM in various years was likely determined by the relation between topography/bathymetry and lake levels, which was not yet quantified. Thus, we added collection of elevation data to the study, as well as photointerpretation analyses, which allowed us to include decreases from extreme lake-level highs in 1952 and 1974 to the study also (Fig. 1). Our overall study objectives were to assess changes in composition of plant communities across the three study years that had different water-level histories and to draw correlations between topography/bathymetry and lake level in determining areal extent of SGM, which had previously not been made.

Methods

Study Area

Arcadia Marsh is a 170-ha drowned-river-mouth wetland (Albert et al. 2005) near the village of Arcadia in Manistee County, Michigan, USA (Fig. 2). The wetland follows the corridor of a stream formed by the confluence of Bowens, Tondu, and Lucker Creeks crossing a wide basin upstream from Arcadia Lake, which is connected to the eastern shore of Lake Michigan by a channel. The wetland is separated from Arcadia Lake by a 1.0-km-long road-crossing (M-22) with two large culverts that restrict flow during high flow periods. Surface sediments in the aquatic zone are largely decomposed peat, with some sand and silt. Numerous ditches were constructed through much of the wetland in an attempt to drain it for agriculture, which was unsuccessful because water levels...
are controlled by Lake Michigan levels. The adjacent land is used for agriculture. The most prominent vegetation type is sedge/grass meadow dominated by *Calamagrostis canadensis* and *Carex stricta*, although some areas have been invaded by species such as *Phalaris arundinacea*, *Typha angustifolia*, *Typha × glauca*, and more recently *Phragmites australis*.

### Vegetation Sampling

Initial vegetation mapping and plant sampling were conducted during 27-28 July 1995 (Wilcox et al. 2002). Major vegetation types clearly definable on aerial images, which were photographed in 1994 in anticipation of their need, were identified and ground-truthed in the field with photographs in hand. Vegetation types were categorized as interior sedge/grass meadow, invaded sedge/grass meadow, short emergent, cattail, and submersed/ floating. We then sampled ten 1-m x 1-m quadrats in each vegetation type according to a randomly dispersed, haphazard design (blind toss over shoulder). All taxa in each quadrat were identified to species, if possible, and estimates of percent cover were assigned to each taxon in the quadrats at one-percent increments to 10, then at five-percent increments. Data on *T. angustifolia* and *T. × glauca* were combined due to the tedious task of identifying each plant individually. Similar sampling was conducted during 13-16 August 2002 and 20-22 July 2010, with 20 quadrats sampled in interior sedge/grass meadow and submersed/ floating.

### Photointerpretation

New 1:5000 CIR photos in 1994 and 1:6000 CIR photos in 2002 and 2010 were contracted through private vendors. Following an extensive search, we selected the best available imagery from 1965 through 2010 for analysis (Table 1). Available orthophotos were loaded into ArcMap GIS (ESRI) such that each site had a layer file projected to UTM zone 16N. Heads-up digitizing was used to identify the boundaries of plant community types and delineate them with polygon features. Due to variation of photo resolution and quality, the resolution at which vegetation was delineated differed across years, although a scale of 1:1500 or better was used when drawing polygons. The border extent followed the description provided below for topographic data collection.

### Topographic Data Collection

We identified and quantified nine vegetation types, although not all of them were present in all years: sedge/grass meadow, short emergent, submersed aquatic, cattail, common reed, shrub, tree, open water, and upland. Initial ground-truthing of the mapped 1994 photos was conducted in 1995, and follow-up ground-truthing was done in 2002 and 2010. Although the sedge/grass meadow vegetation type was broken into two categories for field vegetation sampling, that subdivision could not be recognized in most photos, so it was not used in photointerpretation. Ground-truthing for other years was not possible, so the location of existing community boundaries in the 1994, 2002, and 2010 photos, as well their spectral signatures, helped identify the extent to which borders had expanded or contracted in the other years.

We used auto-complete polygons within the editor toolbar in ArcMap to produce polygon features around vegetation stands identified in each year (e.g., 2010: Fig. 3). To ensure that the extent of wetland delineated was the same in each year, the clip feature in ArcMap was used so that only the delineated polygons within the wetland border were used in the analyses. Total area was determined and compared to ensure that they matched.

### Table 1

Aerial photograph details for 1965-2010 imagery used in photointerpretation of Arcadia Marsh along the eastern shore of Lake Michigan.

| Date       | Photo Source         | Photo Type         | Resolution |
|------------|----------------------|--------------------|------------|
| 1965-07-26 | FSA                  | Black & White     | 1:20000    |
| 1973-07-07 | FSA                  | Black & White     | 1:40000    |
| 1978-06-29 | MDNR                 | Color Infrared    | 1:24000    |
| 1981-05-18 | USGS                 | Black & White     | 1:80000    |
| 1986-06-03 | USGS                 | Color Infrared    | 1:58000    |
| 1987-06-04 | MDNR                 | Black & White IR  | 1:15840    |
| 1988-06-23 | USGS                 | Black & White     | 1:80000    |
| 1992-09-24 | Corps of Engineers   | Color Infrared    | 1:24000    |
| 1993-04-23 | FSA                  | Black & White     | 1:40000    |
| 1994-07-07 | Abrams Aerial Survey | Color Infrared    | 1:5000     |
| 1998-06-27 | MDNR                 | Black & White IR  | 1:15840    |
| 2002-07-12 | Air-Land Surveys     | Color Infrared    | 1:6000     |
| 2004-07-19 | USGS                 | Natural Color     | 1:40000    |
| 2006-06-02 | FSA                  | Natural Color     | 1:40000    |
| 2009-07-13 | FSA                  | Natural Color     | 1:40000    |
| 2010-07-09 | Air-Land Surveys     | Color Infrared    | 1:6000     |
Topographic/bathymetric survey data were collected during July 2010 sampling using two methods. A Trimble RTK GPS was used for real-time, differentially-corrected elevations in areas above water, totaling 647 points with estimated elevation accuracy of 3 cm. A Garmin hand-held GPS in combination with water-depth measurements from a boat and a benchmark on the bridge culvert that was surveyed by RTK GPS was used for below water areas, totaling 381 points (Appendix Fig. 1).

All Digital Elevation Models (DEMs) used the International Great Lakes Datum 1985 (IGLD85) for reference. All spatial data sets were created based on the Universal Transverse Mercator Zone 16 North coordinate system, the North American Datum of 1983, and used internal units of the SI (metric) system.

Processing Methods

Extent. Prior to processing survey data to generate a DEM, we needed to establish an extent polygon for subsequent processing steps. We began by constructing a polygon within a Geographic Information System (GIS) based on the outermost points from the July 2010 topographic surveys. The polygon boundaries were then adjusted to limit the number of seemingly extraneous surveyed data points.

Merging hand-held GPS boat-based and RTK GPS data sets. GPS data were merged by selecting point features from each set, copying those features with the select tool in Arcmap’s editor tool bar, and pasting them into a new shape file with the same tool. Horizontal positional accuracy, vertical elevation values, and naming conventions were used to cross-validate the independent attribute fields with the input data that were used to produce the merged shape file.

Adjusting elevations to the IGLD85 datum. Vdatum (version 2.3.0) produced by the National Oceanic and Atmospheric Administration was used to convert North American Vertical Datum of 1988 (NAVD88) elevation values to the IGLD85 system.

Interpolation. An Inverse Distance Weighted (IDW) interpolation method was applied to the survey point data within Arcmap’s Spatial Analyst extension using the default settings. These settings included a second power weighting function combined with a variable search radius that required twelve points to estimate grid cell values.

Clipping. The resulting DEM was clipped based on the extent polygon we created. This eliminated unrealistic data from beyond the July 2010 survey extent that may have led to a poor depiction of actual ground surface and/or bathymetric elevation values.

LIDAR DEMs were provided by the United States Army Corps of Engineers Joint Airborne LIDAR Bathymetry Technical Center of Expertise (USACE JLBTCX) from flights conducted in 2008. Portions of these data were clipped and included to supplement the products produced as described above.

The interpolated DEM was used to create a topographic/bathymetric map with 20-cm contour intervals. Using the contour tool within ArcPro, the contour interval was set to 0.2m, and the base contour was set to an elevation of 175m, with a Z factor of 1. The contour type was “contour polygon” to enable summarizing the area between the contours. The contour polygon layer was then clipped to the extent of the study area, and using the summarize-within tool, the area between each contour was calculated in square meters.

Data Analyses

Plant community data from field sampling were sorted by vegetation type and year. For evaluation, Importance Values (IV) for all taxa were then calculated by vegetation type in each year as relative mean percent cover + relative frequency x 100.

We determined the area of wetland mapped in each vegetation type in each photo year and converted data to percent of wetland. To assess the relations of the prominent sedge/grass meadow with variable Lake Michigan water levels, we ran regressions of %SGM in each photo year from the photointerpretation data against the mean, three-month, growing season lake levels (June, July, August) in photo years and against the number of years since each photo year had an extreme high lake level (> 177m IGLD85).

To assess the effects of lake-level reductions following extreme highs (> 177m), we made comparisons between %SGM from photointerpretation results and topographic/bathymetric data. We calculated the cumulative area above each 0.2-m contour and interpolated to 0.01m levels to determine the percent of wetland that would be predicted to dewater when Lake Michigan water levels receded from extreme highs to those for specific photo years.

Results

Vegetation Sampling

The interior sedge/grass meadow was dominated by *C. canadensis* and *C. stricta* in all years sampled, with other prominent taxa including *Impatiens capensis* and *Persicaria amphibia* in 1995, *Campanula aparinoides* in 2002, and *Carex aquatilis* and *Carex lacustris* in 2010 (Table 2). The decrease in summertime peak water levels in 2002 was accompanied by an increase in *C. canadensis*, but it was not maintained in 2010 sampling. *Carex stricta* decreased in 2002 and even more in 2010.
Table 2

Importance Values (IV) for taxa identified during haphazard field sampling of interior sedge/grass meadow, invaded sedge/grass meadow, short emergent submersed/floating, and cattail vegetation types at Arcadia Marsh in 1995, 2002, and 2010.

| Species                        | Interior SGM | Invaded SGM | Short Emergent | Subm./Floating | Cattail |
|--------------------------------|--------------|-------------|----------------|----------------|---------|
|                                | 1995 | 2002 | 2010 | 1995 | 2002 | 2010 | 1995 | 2002 | 2010 | 1995 | 2002 |
| Bidens sp.                     | -    | -    | -    | 18   | -    | -    | -    | -    | -    | 2    | -    |
| Calamagrostis canadensis       | 72   | 104  | 82   | 27   | 45   | 24   | 2    | 1    | -    | 11   | 25   |
| (Michx.) P. Beauv.             |      |      |      |      |      |      |      |      |      |      |      |
| Campanula aparinoides Pursh    | 8    | 13   | 6    | 2    | 8    | 18   | -    | -    | -    | 2    | -    |
| Carex aquatilis Wahlenb.       | 5    | -    | 19   | -    | -    | -    | 6    | -    | -    | -    | -    |
| Carex robbinsii Fern.          | 2    | -    | 3    | 2    | -    | 1    | -    | -    | -    | -    | -    |
| Carex comosa Boott             | -    | -    | 4    | -    | -    | -    | 2    | -    | -    | -    | -    |
| Carex jacquish Wild.           | 5    | -    | 37   | -    | 12   | 31   | -    | -    | -    | -    | 3    |
| Carex rostrata Stokes          | 2    | -    | 3    | 2    | -    | 1    | -    | -    | -    | -    | -    |
| Carex stricta Lam.             | 43   | 37   | 24   | 53   | 13   | 13   | -    | -    | -    | -    | -    |
| Ceratophyllum demersum L.      | -    | -    | -    | -    | -    | -    | 25   | 16   | 8    | 5    | 27   |
| Chara vulgaris L.              | -    | -    | -    | -    | -    | -    | 2    | 1    | -    | 5    | 2    |
| Cicuta bulbifera L.            | -    | -    | -    | 4    | 2    | 2    | 4    | -    | -    | -    | -    |
| Cirium arvense (L.) Scop.      | -    | 4    | 3    | -    | -    | -    | -    | -    | -    | -    | -    |
| Decodon verticillatus (L.) Elliott | -    | -    | -    | 2    | 5    | -    | -    | -    | -    | -    | -    |
| Eleocharis palustris L.        | -    | -    | -    | 2    | -    | 9    | 21   | 2    | -    | 2    | -    |
| Elodea canadensis Michx.       | -    | -    | -    | -    | -    | -    | 2    | -    | 4    | -    | 15   |
| Epilobium coloratum Biehler    | -    | -    | -    | 1    | -    | 4    | -    | -    | -    | -    | -    |
| Eupatorium perfoliatum L.      | -    | 6    | -    | -    | -    | -    | 1    | -    | -    | -    | -    |
| Eutrochium maculatum (L.) E.E. Lamont | 6    | 4    | -    | -    | 8    | -    | -    | -    | -    | -    | -    |
| Galium trifidum L.             | 2    | -    | 4    | 5    | -    | -    | 1    | -    | -    | -    | 5    |
| Impatiens capensis Meerb.      | 13   | 6    | -    | 4    | -    | -    | -    | -    | -    | 4    | 3    |
| Leersia oryzoides (L.) Swartz  | -    | 2    | -    | 3    | -    | 3    | 36   | -    | -    | 3    | -    |
| Lemna minor L.                 | -    | -    | 3    | -    | -    | -    | 36   | 14   | 31   | 25   | 18   |
|                               |      |      |      |      |      |      |      |      |      |      |      |

|                      | Interior SGM | Invaded SGM | Short Emergent | Subm./Floating | Cattail |
|----------------------|--------------|-------------|----------------|---------------|---------|
| *Lycopus uniflorus*  | 2            | -           | -              | -             | -       |
| *Lycopus thyrsiflora*| -            | -           | 2              | -             | -       |
| *Myriophyllum sp.*   | -            | -           | -              | 2             | 9       |
| *Najas flexilis*     | -            | -           | -              | -             | 2       |
| *Nuphar variegata*   | 106          | -           | -              | -             | -       |
| Species                          | Interior SGM | Invaded SGM | Short Emergent | Subm./Floating | Cattail |
|---------------------------------|--------------|-------------|----------------|----------------|---------|
|                                 | 1995 | 2002 | 2010 | 1995 | 2002 | 2010 | 1995 | 2002 | 2010 | 1995 | 2002 | 2010 |
| Persicaria amphibia (L.) Gray p.p. | 10   | 8    | 5    | 5    | 2    | 5    | -    | -    | -    | -    | -    | -    | 7    |
| Persicaria punctata (Elliott) Small | -    | 3    | -    | -    | 1    | -    | -    | -    | -    | -    | -    | -    | -    |
| Phalaris arundinacea L.         | 2    | 2    | 2    | -    | 57   | 86   | -    | 7    | 8    | -    | -    | -    | 37   |
| Phragmites australis (Cav.) Trin. | -    | -    | 2    | -    | -    | -    | -    | 1    | 2    | -    | -    | -    | -    |
| Potamogeton crispus L.          | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2    | 23   | 12   | -    |
| Potamogeton foliosus Raf.       | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2    | -    | 4    | 18   |
| Ricciocarpus natans (L.) Corda  | -    | -    | 3    | -    | -    | -    | -    | -    | 32   | -    | -    | -    | -    |
| Sagittaria latifolia Willd.     | 4    | -    | -    | 9    | 3    | -    | 21   | 26   | 2    | -    | 4    | -    | 5    |
| Salix exigua Nutt.              | -    | -    | 12   | -    | -    | -    | 1    | -    | -    | -    | -    | -    | -    |
| Schoenoplectus tabernaemontani (C.C. Gmel.) Palla | -    | -    | -    | -    | -    | 7    | 27   | -    | -    | 1    | -    | -    | -    |
| Scirpus atrovirens Willd.       | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2    | -    | -    | -    |
| Scutellaria galericulata L.     | -    | 5    | 2    | 2    | 3    | 4    | -    | 1    | -    | -    | -    | -    | 2    |
| Solidago canadensis L.          | -    | 5    | -    | -    | -    | 5    | -    | -    | -    | -    | -    | -    | -    |
| Sparganium eurycarpum Engelm.   | -    | -    | 2    | 8    | 1    | -    | 38   | 19   | 72   | -    | 2    | 1    | -    |
| Spirodela polyrhiza (L.) Schleiden. | -    | -    | 3    | -    | -    | -    | 6    | 2    | 17   | 19   | -    | -    | 5    |
| Stuckenia pectinata (L.) Börner  | -    | -    | -    | -    | -    | -    | 4    | 80   | 95   | -    | -    | -    | -    |
| Symphyotrichum puniceum (L.) A. Löve & D. Löve | -    | 2    | -    | -    | 2    | -    | -    | 1    | -    | -    | -    | -    | -    |
| Typha sp.                       | -    | -    | -    | 36   | 6    | -    | -    | 3    | 2    | -    | -    | 78   | 72   |
| Typha latifolia L.              | -    | -    | -    | -    | -    | -    | -    | 3    | 2    | -    | -    | -    | -    |
| Urtica dioica L.                | 2    | -    | -    | -    | 7    | -    | -    | -    | -    | -    | -    | -    | -    |
| Utricularia macrorhiza Leconte   | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 2    | -    |

The invaded sedge/grass meadow was dominated by *Carex stricta*, *C. canadensis*, and *Typha* in 1995 (Table 2). However, sampling of this vegetation type was largely in a different area in 2002 and 2010 because lower water levels exposed areas of previously flooded sedge/grass meadow. *Carex stricta* and *Typha* then decreased in sampling, with *Phragmites arundinacea*, *C. lacustris*, and *C. canadensis* becoming the dominant species.
Areas sampled for short emergents also changed with changes in water level. During higher water levels in 1995, dominant species were *Sparganium eurycarpum* and *Lemna minor*, with *Ceratophyllum demersum* and *Sagittaria latifolia* prominent (Table 2). In drier 2002, dominants included *Leersia oryzoides*, *Schoenoplectus tabernaemontani*, and *S. latifolia*, with *Eleocharis palustris* and *S. eurycarpum* prominent. *Sparganium eurycarpum* was very dominant in 2010 sampling, joined by *Ricciocarpus natans* and *L. minor*.

The submersed/floating vegetation type decreased greatly in both area and water depth from 1995 to 2002 and 2010. Overwhelming dominance by *Nuphar variegata* in 1995 decreased substantially in 2002, and it was not sampled in 2010 (Table 2). Other prominent species across sampling years included *L. minor*, *C. demersum*, and *Potamogeton crispus*. The most dominant species in 2002 and 2010 was *Stuckenia pectinata*.

The cattail vegetation type was dominated by *Typha* sp. in all years sampled (Table 2). *Phalaris arundinacea* and *C. canadensis* were also prevalent in 2002 and 2010.

**Photointerpretation**

Three-month summer water levels were extremely low in 1965 (176.02m), with 84.4% of the mapped wetland in SGM and small areas of short emergent (SE) and submersed/floating vegetation (S/F) (Table 3). High waters returned in 1973 (177.29m), with 68.4% S/F, 27.3% SGM, and a small area of cattail (C). Water levels were reduced in 1978 (176.67m), but S/F remained high, SGM decreased to 24.4%, and SE became prominent. SGM increased to 44.0% in 1981 when lake level was 176.80m.

During extreme high three-month summer water levels in 1986 (177.37m), 94.0% of the mapped wetland was in S/F, with little SGM remaining (4.8%) (Table 3). However, as water levels receded in 1987 (177.04m) and further by 1988 (176.63m), S/F was reduced to 77.9% and SGM increased to 20.6%. Continuation of low water levels in 1992 (176.54m) resulted in an increase in SGM (27.3%), a decrease in S/F vegetation, and a return of SE and small areas of C. Water levels increased more than 35 cm in 1993 (176.86m), resulting in increased SF and a slight increase in SGM (28.8%) at the expense of SE. Water levels decreased slightly in 1994, with a reduction in SF and SE, while SGM increased to 35.2%.

High three-month summer water levels returned in 1997 (177.16m), and photointerpretation of 1998 photos (176.87m) showed another increase in S/F to 66.3% and a reduction in SGM to 20.6% (Table 3). A long period of low water levels began in 1999, with photos from 2002 (176.31m) showing SGM at 61.0%, SE at 20.6%, and S/F reduced to 12.1%. Changes in SGM and S/F were minor during continued low water levels in 2004, 2006, 2009, and 2010 (range 176.15 – 176.44m), while SE decreased and C increased. Common reed (CR) was mapped in 2004 and increased from 5.9–11.3% by 2010.

**Topography/Bathymetry**

The topographic/bathymetric map showed little variation in elevation across much of the study area (Fig. 4). Elevations from 175.8m to 176.8m (IGLD85) contained 89.8% of the total study area, which ranged in elevation from 175.0m to 178.0m (Table 4). Elevations from 176.0m to 176.4m accounted for 47.3%
of the total study area. For later analyses, the cumulative area of wetland above each contour interval was also calculated, which confirmed that much of the wetland area had little relief.

Table 4
Percent of delineated Arcadia Marsh between 0.2-meter contour intervals and calculated percent of area above each minimum contour elevation (IGLD85).

| Contour Minimum (m) | Contour Maximum (m) | Percent Total Area | Percent Area Above Minimum |
|---------------------|---------------------|-------------------|---------------------------|
| 175.0               | 175.2               | 0.03              | 99.99                     |
| 175.2               | 175.4               | 0.19              | 99.96                     |
| 175.4               | 175.6               | 0.99              | 99.77                     |
| 175.6               | 175.8               | 5.72              | 98.78                     |
| 175.8               | 176.0               | 14.84             | 93.06                     |
| 176.0               | 176.2               | 20.56             | 78.23                     |
| 176.2               | 176.4               | 26.77             | 57.66                     |
| 176.4               | 176.6               | 15.18             | 30.89                     |
| 176.6               | 176.8               | 12.43             | 15.71                     |
| 176.8               | 177.0               | 2.7               | 3.28                      |
| 177.0               | 177.2               | 0.36              | 0.58                      |
| 177.2               | 177.4               | 0.12              | 0.22                      |
| 177.4               | 177.6               | 0.05              | 0.1                       |
| 177.6               | 177.8               | 0.05              | 0.05                      |

Discussion

Plant Community Changes and Lake Levels

Sedge/Grass Meadow

The large increase in IV of *C. canadensis* in both interior and invaded sedge/grass meadow in response to the reduction in growing season water levels from 176.62m in 1995 to 176.31m in 2002 (Table 2) follows its known habitat preference for moist soil vs. standing water (Costello 1936; Voss and Reznicek 2012). Return to 1995 IV levels in 2010, when water levels dropped further to 176.25m, may have been related to competition from *C. lacustris*, which has a spreading growth form and can be quite productive (Bernard 1974; Yetka and Galatowitsch 1999). *Calamagrostis* can occur on *C. stricta* tussocks (Costello 1936; Peach and Zedler 2006) but is often found in slightly higher and drier elevations in wetlands (Costello 1936; Keddy and Reznicek 1982; Keddy 1984; Kercher and Zedler 2004). Both species can grow vegetatively by tillering and can expand readily into open areas, especially when water levels are lower (Costello 1936; Budelsky and Galatowitsch 2004). *Carex stricta* was quite prominent in both interior and invaded sedge/grass meadow in 1995, likely because it forms tussocks and can tolerate deeper water (Costello 1936; Peach and Zedler 2006). In the invaded sedge/grass meadow, increased competition from *C. lacustris* may have caused reductions in *C. stricta* by 2010, but the great increase in *P. arundinacea*, which has been shown to out-compete *C. stricta* (Wetzel and van der Valk 1998; Budelsky and Galatowitsch 2004; Kercher and Zedler 2004), was more likely responsible for the decrease in IV from 53 in 1995 to 13 in 2002 and 2010. The substantial decrease in *Typha* from 1995 to later years with lower lake levels is likely explained by its requirement for water, as demonstrated in studies of cattail invasion in sedge/grass meadows elsewhere (Wilcox et al. 1984, 2008).

Short Emergents

Many changes in IV in the short emergent community from 1995 to 2002 to 2010 (Table 2) were likely related to decreases in growing season water levels across years, resulting in changes in locations of areas that were sampled -- the short emergents were in different places. However, species typical of more shallow waters (Swink and Wilhelm 1979; Chadde 2012; Voss and Reznicek 2012), such as *E. palustris*, *L. oryzoides*, and *S. tabernaemontani*, increased substantially with lower lake levels in 2002.

Submersed/Floting

The most striking change in IV in the submersed/floating vegetation type was the great reduction in *N. variegata* from 1995 to 2002 and absence in 2010 sampling (Table 2). By 2002, lower lake levels reduced standing water to a relatively narrow channel that previously contained no *Nuphar*. The channel was rather turbid in 2002 and 2010, which explains dominance by turbidity-tolerant *C. demersum*, *P. crispus*, and *S. pectinata* (Adamus and Brandt 1990).

Sedge/Grass Meadow and Lake Levels
One of our objectives in this publication was to assess the responses of sedge/grass meadow to fluctuations in Great Lakes water levels, as SGM is an important habitat for wetland fauna (e.g., Wilcox 1995; Farrell 2001; Riffell et al. 2001; Farrell et al. 2006; Cooper et al. 2008), and it has faced losses in many Great Lakes wetlands (e.g., Albert 2003; Stanley et al. 2005; Frieswyk and Zedler 2007; Wilcox et al. 2008; Wilcox and Bateman 2018). We took several approaches for this assessment, including using our dataset to making comparisons of %SGM mapped in each photo year with mean three-month growing season lake level and number of years since the last extreme high summer lake level defined as >177m (1952:177.26m; 1974:177.27m; 1986:177.37m; 1997:177.16m). Percent SGM vs. mean three-month lake level, which is biologically important because it represents much of the growing season, showed a significant relation ($R^2 = 0.756, p = 0.000$) (Fig. 5A). The relation of %SGM vs. years since high lake level was also significant ($R^2 = 0.703, p = 0.000$) (Fig. 5B) and has importance because sedge/grass meadow may be reduced or even eliminated by extreme flooding, as will be addressed in our next assessment.

The percent of Arcadia Marsh returning to SGM when water levels decreased from high lake-level years differed among years. A 1.24-m reduction in three-month summer lake level from 1952 to photo year 1965 (Fig. 1) resulted in an increase of SGM from an unmeasured but likely low percentage to 84.4% in 13 years, despite an intervening higher lake level of 176.73m in 1960. Although there was a 0.60 decrease in lake level from the 1974 high to 1978, summertime water levels in 1976 were still at 177.12m, and the two-year lag time was not sufficient to allow regeneration of SGM (Wilcox and Xie 2007). The 0.83-m lake-level reduction from 1986 to 1992 resulted in SGM increasing from 4.8–27.3% in six years, while the nearly identical 0.85-m reduction from 1997 to 2002 resulted in an increase from 20.6% (photo year 1998) to 61.0% in five years. In a period of five to 13 years following a reduction in growing season water levels by 0.83m or more from an extreme high lake level, the increases in %SGM, as could be measured from available photos, ranged widely. Each of those time periods had lag times of five or more years, suggested as critical by Wilcox and Xie (2007). The disparity in response comes from the starting and ending elevations of lake level in these comparisons combined with the topography/bathymetry of the wetland. Growing season water levels were 176.02m in 1965, 176.54m in 1992, and 176.31m in 2002. Simply, lower lake levels may expose more of the underlying soils and create more habitat for sedge/grass meadow.

To assess this relationship, we made comparisons between %SGM from photointerpretation results and the topographic/bathymetric data from Arcadia Marsh, which were developed with 0.2-m contour intervals (Table 4). We calculated the cumulative area above each contour and interpolated to 0.01m levels to determine the percent of wetland that would be predicted to dewater when Lake Michigan water levels receded from extreme highs for comparison with %SGM in specific photo years. Exposure of the land surface would be expected to promote development/reestablishment of sedge/grass meadow (Wilcox 2004; Keddy and Campbell 2020).

The topographic/bathymetric data predicted 76.2% exposure of the wetland land surface in 1965, while %SGM was 84.4% (Fig. 6). The three-month summer lake level was very low (176.02m), and despite an intervening moderate, single-year high in 1960 (Fig. 1), there was a lengthy time lag following the 1952 extreme high lake level that would promote growth of sedge/grass meadow. Following the 1974 extreme high, predicted exposure of land surface was 11.4% in 1978, with lake levels at 176.67m, and %SGM was 24.4%. Although percent land cover was less than %SGM in 1978, both values were much less than for 1965.

Following the 1986 extreme high lake level, predicted land surface exposed was 13.9% in 1988 (176.63m) and 20.3% in 1992 (176.54m), with %SGM at 20.6% and 27.3%, respectively (Fig. 6). Following the 1997 extreme high, predicted exposure of the land surface was 42.9% in 2002 (176.31m), 38.9% in 2004 (176.34m), 62.9% in 2006 (176.15m), 27.9% in 2009 (176.44m), and 51.0% in 2010 (176.25m). Mapped %SGM was 61.0%, 61.3%, 67.1%, 61.7%, and 60.8% in those years, respectively. Only low-water 1965 had greater predicted land exposure and %SGM than the post-1997 low-water years. Once sedge/grass meadow was established, likely beginning in 1999 (176.37m), few drivers could alter %SGM other than increased land exposure in 2006 when lake levels were lowest and predicted land exposure was greater. Thus, %SGM was quite similar in those years, although closer to predicted land cover in 2006 and 2010.

Following all post-extreme years, percent land-surface exposure was always less than corresponding %SGM, likely due to accuracy of topographic/bathymetric mapping based on a finite number of RTK-GPS and water-depth data points and LIDAR DEM data from a relatively flat area. However, relative changes in both predicted land surface and %SGM shown in our results demonstrate that accuracy of lake level as a predictor of area of sedge/grass meadow is dependent on topography/bathymetry. Lake Michigan water levels increased again beginning in 2014 and extended to a three-month extreme high of 177.44m in 2020 (Fig. 1). When water levels decrease dramatically again, as expected based on historical data and paleo-lake-level studies (Baedke and Thompson 2000, Argyljan et al. 2018), the response of SGM in Arcadia Marsh and other Lake Michigan/Huron wetlands will depend on the duration and amplitude of the low lake-level period but also on topography/bathymetry.

**Relation to Other Great Lakes Wetlands**

These relations of plant-community response to hydrology are most applicable to other drowned-river-mouth wetlands along the eastern shore of Lake Michigan (Wilcox et al. 2002; Albert 2003; Albert and Minc 2004), which generally have large expanses of sedge/grass meadow subject to the same lake-level fluctuations. However, some Green Bay wetlands on the western shore of Lake Michigan contain sedge/grass meadow (Albert and Minc 2004; Frieswyk and Zedler 2007), and wetlands in northern lakes Michigan and Huron often have broad expanses of sedge/grass meadow also (e.g., Albert 2003; Albert and Minc 2004; Gathman et al. 2005). Historically, the shores of Saginaw Bay on Lake Huron contained sedge/grass meadow (Stanley et al. 2000; 2005; Albert 2003; Albert and Minc 2004), although invasion by *Phragmites* has likely replaced much of it (Albert 2005; Albert and Brown 2008). Such may also be the case on downstream Lake St. Clair (Jaworski et al. 1979; Albert 2003; Albert and Minc 2004; Wilcox 2012) and Lake Erie (Albert 2003; Wilcox et al. 2003; Albert and Minc 2004), where lake-level fluctuations are similar to Lake Michigan but with different amplitudes. Sedge/grass meadows of Lake Superior are found primarily on floating peatland mats (Albert 2003; Albert and Minc 2004) and may respond differently to lake-level changes.

As a result of water-level regulation that began in about 1960, sedge/grass meadows of Lake Ontario have been most-affected by lake levels. Unlike Arcadia Marsh on Lake Michigan, periods of low lake levels have not occurred there since the mid-1960s, and sedge/grass meadow species lost their competitive advantage over moisture-requiring cattails in years with drier soils, thus allowing cattail invasion (Wilcox et al. 2008). A new regulation plan for the Lake
Ontario/St. Lawrence River system (i.e., Plan 2014) was enacted in January 2017 (IJC 2014) that restores potential for some of the natural variability in water-level fluctuations, but could the response seen at Arcadia Marsh potentially take place there? Site-preemption by cattails (Grace 1987) at upper elevations suitable for sedge/grass meadow may negate that possibility without human intervention (Wilcox et al. 2018). In addition, Plan 2014 only allows for the required low lake levels when water supplies to the basin are low. Ironically, shortly after the new regulation plan was put in place, high water levels in the upper Great Lakes and large flows from the Ottawa River into the St. Lawrence River upstream from Montreal resulted in extreme high lake levels on Lake Ontario in both 2017 and 2019 that could not be prevented by any regulation plan. Smith et al. (2021) found a reduced elevation range for sedge/grass meadow in those years. The low lake-level period of Lake Michigan from 1999 to 2013 was missed on Lake Ontario, and the next period of lows may be 30 years in the future (Baedke and Thompson 2000; Argyilan et al. 2018).

Declarations

All manuscripts must contain the following sections under the heading ‘Declarations’, to be placed before ‘References’.

If any of the sections are not relevant to your manuscript, please include the heading and write ‘Not applicable’ for that section.

Funding (information that explains whether and by whom the research was supported)

Funding was provided by the U. S. Environmental Protection Agency–Mid-Continent Ecology Division Interagency Agreement DW14936071-01-0 in 1995, Great Lakes Commission Grant GL-97547301-0 in 2002, and International Joint Commission through U.S. Army Corps of Engineers SOI 0016-0024 in 2010.

Conflicts of interest/Competing interests (include appropriate disclosures) Not applicable

Ethics approval (include appropriate approvals or waivers) Not applicable

Consent to participate (include appropriate statements) Not applicable

Consent for publication (include appropriate statements) Not applicable

Availability of data and material (data transparency) not available

Code availability (software application or custom code) Not applicable

Authors’ contributions (optional: please review the submission guidelines from the journal whether statements are mandatory) Wilcox, Bateman, Kowalski, and Meeker conducted data collection and did data analyses. Dunn conducted topographic/bathymetric data analysis and mapping. Wilcox wrote much of the manuscript with assistance from other authors on selected parts.

Please see the relevant sections in the submission guidelines for further information as well as various examples of wording. Please revise/customize the sample statements according to your own needs.

Here are some examples of statements to be included in the manuscript:

Ethics Approval: Ethics approval was not required for this study

Consent to Participate: No patients.

Consent for publication: All authors consent to publish.

Availability of data and materials: All data produced from this study are provided in this manuscript.

Acknowledgments

Funding was provided by the U. S. Environmental Protection Agency–Mid-Continent Ecology Division Interagency Agreement DW14936071-01-0 in 1995, Great Lakes Commission Grant GL-97547301-0 in 2002, and International Joint Commission through U.S. Army Corps of Engineers SOI 0016-0024 in 2010. Field data collection in various years was assisted by Ben Meyer, Casey Kochanski, and Martha Carlson Mazur.

References

1. Adamus PR, Brandt K (1990) Impacts on quality of inland wetlands of the United States: a survey of indicators, techniques, and applications of community-level biomonitoring data. U. S. Environmental Protection Agency Report EPA/600/3-90/073
2. Albert DA (2003) Between Land and Lake: Michigan's Great Lakes Coastal Wetlands. Michigan Natural Features Inventory, East Lansing
3. Albert DA (2005) The impacts of various types of vegetation removal on Great Lakes wetlands of Saginaw Bay and Grand Traverse Bay. Michigan Natural Features Inventory Report to Michigan Department of Environmental Quality, Lansing
4. Albert DA, Brown P (2008) Coastal wetlands in Michigan: effect of isolation on Phragmites australis expansion. Michigan Natural Features Inventory Report 2008-14
5. Albert DA, Minc LD (2004) Plants as regional indicators of Great Lakes coastal wetland health. Aquatic Ecosystem Health and Management 7:233–247
6. Albert DA, Wilcox DA, Ingram JW, Thompson TA (2005) Hydrogeomorphic classification for Great Lakes coastal wetlands. Journal of Great Lakes Research 31 (Supplement 1):129–146

7. Argyilan EP, Johnston JW, Lepper K, Monaghan GW, Thompson TA (2018) Lake-level, shoreline, and dune behavior along the Indiana southern shore of Lake Michigan. In: Florea LJ (ed) Ancient oceans, orogenic uplifts, and glacial ice: geologic crossroads in America's heartland. Geological Society of America Field Guide 51:181–203

8. Baedke SJ, Thompson TA (2000) A 4,700-year record of lake level and isostasy for Lake Michigan. Journal of Great Lakes Research 26:416–426

9. Bernard JM, MacDonald JG Jr (1974) Primary production and life history of Carex lacustris. Canadian Journal of Botany 52:117–123

10. Budelsky RA, Galatowitsch SM (2004) Establishment of Carex stricta Lam. seedlings in experimental wetlands with implications for restoration. Plant Ecology 175:91–106

11. Chadde SW (2012) A Great Lakes Wetland Flora: a Complete Guide to the Wetland and Aquatic Plants of the Midwest, 4th ed. Steve W, Chadde

12. Cooper JE, Mead JV, Farrell JM, Werner RG (2008) Coexistence of pike (Esox lucius) and muskellunge (E. masquinongy) during early life and the implications of habitat change. Hydrobiologia 601:41–53

13. Costello DF (1936) Tussock meadows in southeastern Wisconsin. Botanical Gazette 97:610–648

14. Farrell JM (2001) Reproductive success of sympatric northern pike and muskellunge in an Upper St. Lawrence River bay. Transactions of the American Fisheries Society 130:796–808

15. Farrell JM, Mead JV, Murry BA (2006) Protracted spawning of St. Lawrence River northern pike (Esox lucius): simulated effects on survival, growth, and production. Ecology of Freshwater Fish 15:169–179

16. Frieswyk CB, Zedler JB (2007) Vegetation change in Great Lakes coastal wetlands: deviation from the historical cycle. Journal of Great Lakes Research 33:366–380

17. Gathman JR Albert DA, Burton TM (2005) Rapid plant community response to a water level peak in northern Lake Huron coastal wetlands. Journal of Great Lakes Research 31(Supplement 1):160–170

18. Grace JB (1987) The impact of preemption on competitive displacement between two Typha species along a water-depth gradient. Ecological Monographs 57:283–303

19. Hudon C (1997) Impacts of water-level fluctuations on St. Lawrence River aquatic vegetation. Canadian Journal of Fisheries and Aquatic Sciences 54:2853–2865

20. Hudon C, Wilcox DA, Ingram JW (2006) Modeling wetland plant community response to assess water-level regulation scenarios in the Lake Ontario-St. Lawrence River basin. Environmental Monitoring and Assessment 113:303–328

21. IJC (2014) Lake Ontario-St. Lawrence River Plan 2014: protecting against extreme water levels, restoring wetlands, and preparing for climate change. International Joint Commission, Washington, DC and Ottawa, ON

22. Jaworski E, Raphael CN, Mansfield PJ, Williamson BB (1979) Impact of Great Lakes water level fluctuations on coastal wetlands. Department of Geography-Geology, Eastern Michigan University, Ypsilanti

23. Keddy PA, Reznicek AA (1982) The role of seed banks in the persistence of Ontario's coastalplain flora. American Journal of Botany 69:13–22

24. Keddy PA, Campbell D (2020) The Twin Limit Marsh Model: a non-equilibrium approach to predicting marsh vegetation on shorelines and in floodplains. Wetlands 40:667–680

25. Keddy PA, Reznicek AA (1986) Great Lakes vegetation dynamics: the role of fluctuating water levels and buried seeds. Journal of Great Lakes Research 12:25–36

26. Kercher SM, Zedler JB (2004) Flood tolerance in wetland angiosperms: a comparison of invasive and noninvasive species. Aquatic Botany 80:89–102

27. Peach M, Zedler JB (2006) How tussocks structure sedge meadow vegetation. Wetlands 26:322–335

28. Riffell SK, Keas BE, Burton TM (2001) Area and habitat relationships of birds in Great Lakes coastal wet meadows. Wetlands 21:492–507

29. Smith IM, Fiorino GE, Grabas GP, Wilcox DA (2021) Wetland vegetation response to record-high Lake Ontario water levels. Journal of Great Lakes Research 47:160–167

30. Stanley KE, Murphy PG, Prince HH, Burton TM (2000) Above-ground biomass and productivity of the vegetation in coastal wet meadows bordering Saginaw Bay (Lake Huron). Verhandlungen des Internationalen Verein Limnologie 27:1962–1972

31. Stanley KE, Murphy PG, Prince HH, Burton TM (2005) Long-term ecological consequences of anthropogenic disturbance on Saginaw Bay coastal wet meadow vegetation. Journal of Great Lakes Research 31(Supplement 1):147–159

32. Swink F, Wilhelm G (1979) Plants of the Chicago Region. The Morton Arboretum, Lisle, IL

33. Voss EG, Reznicek AA (2012) Field Manual of Michigan Flora. University of Michigan Press, Ann Arbor

34. Werner KJ, Zedler JB (2002) How sedge meadow soils, microtopography, and vegetation respond to sedimentation. Wetlands 22:451–466

35. Wetzel PR, van der Valk AG (1998) Effects of nutrients and soil moisture on competition between Carex stricta, Phalaris arundinacea, and Typha latifolia. Plant Ecology 138:179–190

36. Wilcox DA (1995) The role of wetlands as nearshore habitat in Lake Huron. In: Munawar M, Edsall T, Leach J (eds) The Lake Huron Ecosystem: Ecology, Fisheries and Management. Ecosvision World Monograph Series. S.P.B. Academic Publishing, The Netherlands. pp. 223–245

37. Wilcox DA (2004) Implications of hydrologic variability on the succession of plants in Great Lakes wetlands. Aquatic Ecosystem Health and Management 7:223–232
39. Wilcox DA (2012) Response of wetland vegetation to the post-1986 decrease in Lake St. Clair water levels: seed-bank emergence and beginnings of the *Phragmites australis* invasion. Journal of Great Lakes Research 38:270–277

40. Wilcox DA, Apfelbaum SI, Hiebert RD (1984) Cattail invasion of sedge meadows following hydrologic disturbance in the Cowles Bog Wetland Complex, Indiana Dunes National Lakeshore. Wetlands 4:115–128

41. Wilcox DA, Bateman JA (2018) Photointerpretation analysis of plant communities in Lake Ontario wetlands following 65 years of lake-level regulation. Journal of Great Lakes Research 44:1306–1313

42. Wilcox DA, Kowalski KP, Hoare HL, Carlson ML, Morgan, HN (2008) Cattail invasion of sedge/grass meadows in Lake Ontario: photointerpretation analysis of sixteen wetlands over five decades. Journal of Great Lakes Research 34:301–323

43. Wilcox DA, Meeker JE, Hudson PL, Armitage BJ, Black MG, Uzarski DG (2002) Hydrologic variability and the application of index of biotic integrity metrics to wetlands: a Great Lakes evaluation. Wetlands 22:588–615

44. Wilcox DA, Nichols SJ (2008) The effect of water-level fluctuations on plant zonation in a Saginaw Bay, Lake Huron wetland. Wetlands 28:487–501

45. Wilcox DA, Xie Y (2007) Predicting wetland plant responses to proposed water-level-regulation plans for Lake Ontario: GIS-based modeling. Journal of Great Lakes Research 33:751–773

46. Wilcox KL, Petrie SA, Maynard LA, Meyer SW (2003) Historical distribution and abundance of *Phragmites australis* at Long Point, Lake Erie, Ontario. Journal of Great Lakes Research 29:664–680

47. Yetka LA, Galatowitsch SM (1999) Factors affecting revegetation of *Carex lacustris* and *Carex stricta* from rhizomes. Restoration Ecology 7:162–171

### Figures

**Figure 1**

Hydrograph showing historical water levels for Lake Michigan-Huron, 1940 to 2020.
Figure 2

Map showing the Arcadia Marsh study site along the eastern shore of Lake Michigan in Manistee County, MI.
Figure 3

Example map of photointerpreted vegetation types in Arcadia Marsh study area in 2010 derived from color infrared photographs.

Figure 4
Topographic/bathymetric map of the Arcadia Marsh study area showing elevations at 20-cm contour intervals.

**Figure 5**

Percent of Arcadia Marsh study area mapped as sedge/grass meadow (SGM) A) vs. mean three-month summer water levels of Lake Michigan (June-August) in photointerpretation study years (\( y = 177 - 0.0147x \), \( R^2 = 0.756, p = 0.000 \)), B) vs. number of years since extreme high lake level exceeding 177m (IGLD85) (\( y = -149 + 0.16x \), \( R^2 = 0.703, p = 0.000 \)).

**Figure 6**

Percent of Arcadia Marsh study area (blue) with elevation greater than three-month summer water levels of Lake Michigan (June-August) and (red) mapped as sedge/grass meadow (SGM) in years with low lake levels following extreme highs in 1952, 1974, 1986, and 1997.

**Supplementary Files**

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- AppendixFig1.eps