Digitizing Great Lakes Coastal Wetlands: A Case Study of GIS Data Integration

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Abstract

Great Lakes coastal wetlands have a huge impact on Michigan's economy and yet since the Europeans settled the area these wetlands have had a history of decline. In order to adequately manage Michigan coastal wetlands the current locations, sizes, and geometries need to be recorded. The Great Lakes Coastal Wetland Inventory was created in 2004. The objective of this project is to update the Great Lakes Coastal Wetland Inventory using newly available data like true-color and false-color air photos, detailed land cover classification, and LiDAR bathymetry. Area, perimeter length, and fragmentation statistics were calculated and analyzed to determine changes since 2004. The preliminary results show that the updated Great Lakes Coastal Wetland decreases wetland area and increased perimeter length and fragmentation. While natural and anthropogenic factors may have contributed to the change, differences in mapping methods are likely a major contributor.

Introduction

The degradation of Great Lakes coastal wetlands could have large impacts on the entire upper Midwest region of the United States. The combined Great Lakes shoreline is roughly equal in length to the U.S. Atlantic shoreline plus the U.S. Gulf of Mexico (Mitsch & Wang, 2000). Coastal wetlands used to be plentiful along the Great Lakes shoreline (Mitsch & Wang, 2000), but now more than 90% of the colossally long shoreline is devoid of wetlands (Wetzel, 1990). Great Lakes coastal wetlands have been deteriorating since European settlers arrived, and the decline is not stopping (Brazner, 1997). Currently, over half of the world's population lives within 100 km of the coastline and that number could continue to climb (Zhenghua, 2010). According to Joan Ehrenfeld (2000), "coastal regions are among the most rapidly urbanizing places on Earth" (p.253). Due to this urban growth, coastal wetlands have been filled, dredged, drained, and fragmented (Mazzotta et al., 2002; Brazner, 1997) for farming and development. Unlike tidal wetlands, which are partially protected due to the returning tide, Great Lakes wetlands are extremely susceptible to filling during low lake level periods, mostly because the water levels of the Great

Lakes can fluctuate over 1.5 meters from a wet year to a dry year (Mitsch & Wang, 2000). The western Basin of Lake Erie, for example, has lost an estimated 95% of its wetlands (Mitsch & Wang, 2000). Michigan alone has lost a large portion (as much as 50 percent) of coastal wetlands due to agriculture and urban development (Xie et al., 2015). Many of the remaining coastal wetlands are being permanently fragmented and altered by dams and other exogenous factors.

Habitat fragmentation occurs when a specific habitat is divided into two or more parts. This process occurs both naturally and through human land use activities (Tomaselli et al., 2011). Biogeographical factors like the area of habitats and how isolated each habitat is can greatly influence species diversity in plants and animals (Wettstein and Schmid, 1999). The likelihood of genetic drift occurring can increase in smaller populations which leads to decreased genetic diversity and increases the likelihood of inbreeding (Hooftman et al., 2003). Genetic drift is a mechanism of evolution that describes the occurrence of some organisms creating more offspring purely by chance. Additionally, smaller populations are more vulnerable to natural events such as tornadoes or flooding. This study will focus on the number of fragments and the area of the largest patch in each coastal wetland.

The main research question of this project is: **does the utilization of the latest GIS tools and remote sensing products change how coastal wetlands are mapped?** This project's main goal was to update Great Lakes coastal wetland boundaries in the southeast part of Michigan's Lower Peninsula to reflect a change in digitizing processes. The original Great Lakes Coastal Wetland Inventory file from 2004 combined existing wetland boundaries from a plethora of different data sources. If deemed necessary, former wetland boundary updates were performed by field scientists who used personal knowledge of wetland sites and air photos.

Findings from this project can be combined with all the existing data to gain a better understanding of coastal wetlands in the Great Lakes basin and help aid the decisions of managers. This project constitutes only the first part of the final study. Estimated IBI scores, alpha diversity values, land ownership percentages, surrounding human population densities, and surrounding linear road distances will be calculated in the future and comparative analysis will be used on each wetland to discover where statistically significant high and low values cluster. Once high and low clusters are identified, all the information gathered can be used to better understand the wetlands.

Background

Great Lakes coastal wetlands have some hydrologic connection to at least one of the five Great Lakes (i.e. Erie, Huron, Michigan, Ontario, and Superior). Members of the Great Lakes Coastal Wetland Consortium developed a systematic way to classify Great Lakes coastal wetlands based on hydrogeomorphology in 2002 (Albert et al., 2005). Hydrogeomorphology is an emerging discipline that focuses on links between hydrologic and geomorphic processes (Sidle & Onda, 2004). This classification system recognizes three different Great Lakes coastal wetland systems: lacustrine, riverine, and barrier-protected (Figure 1) each of which can be further classified into classes and subclasses (Albert et al., 2005). This study includes a mix of all three systems: 32 lacustrine, 30 riverine, and 11 barrier-protected wetlands.

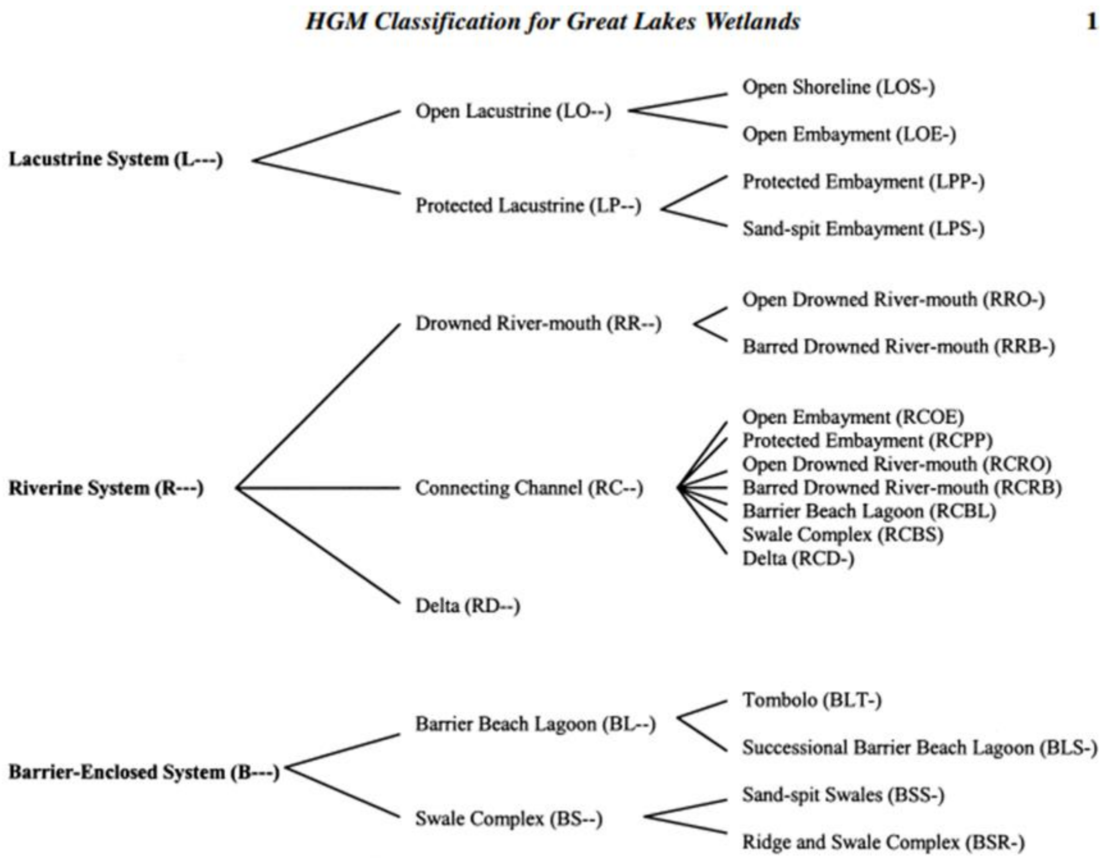

Figure 1. Great Lakes coastal wetland classification hierarchy (Albert et al., 2005).

Lacustrine wetlands are greatly affected by lake depth fluctuations because they are directly controlled by the Great Lakes. Some of these systems are protected from shoreline processes by various geomorphic features. Lacustrine systems can further be broken down into open lacustrine and protected lacustrine classes. Open lacustrine systems have little to no protection from nearshore processes and include open shoreline wetlands and open embayment wetlands. Protected lacustrine systems are sheltered by: offshore bars, sand-spits, or bedrock-enclosed bays. These systems, which include protected embayment and sand-spit embayment subclasses are quite shallow and have more extensive aquatic vegetation than open lacustrine systems (Albert et al., 2005).

Riverine wetlands spatially exist in or along rivers and creeks that flow between or into the Great Lakes. These systems are effected not only by upland drainage but also by flooding lake waters. Due to the presence of bars and channels these systems are protected from coastal processes like waves. There are three classes of riverine systems in the Great Lakes: delta, drowned river-mouth, and connecting channel. Deltas are created by the transportation of alluvial materials and are often extensive wetlands that include deep organic materials in wet meadow zones. Drowned river-mouth wetlands, which include open drowned river-mouth and barred drowned river-mouth subclasses, are commonly referred to as estuarines. They are mostly protected from coastal processes but still receive heavy silt loads from a combination of river and coastal water interactions. Connecting channel wetlands are very similar to other riverine systems except they don't have deep organic soils due to strong river currents. These wetlands are so large that they include seven different subclasses: open embayment, protected embayment, open drowned river-mouth, barred drowned river-mouth, barrier beach lagoon, swale complex, and connecting channel delta (Albert et al., 2005).

Barrier-protected wetlands are originally formed from coastal or river processes, but sediment buildups eventually separate these systems. These wetlands are only connected to the Great Lakes through channels, which decreases water level fluctuations. Barrier beach lagoon and swale complex are the two different classes of barrier-protected wetland. Sand barriers enclose barrier beach lagoons, which include the tombolo and successional barrier beach lagoon subclasses. Since these systems are cut off from Great Lakes waters, discharge from upland areas and ground water contribute heavily to the water supply. Swale complexes form between sand spits (sand-spit swales) and old beach ridges (ridge and swale complexes). Both subclasses of swale complexes are heavy in herbaceous material due to minimal water level fluctuations and protection from open water sources (Albert et al., 2005).

The Laurentian Great Lakes system currently has over 2000 coastal wetlands (Cvetkovic & Chow-Fraser, 2011), which cover over 1200 square kilometers (Mitsch & Wang, 2000; Jude & Pappas, 1992). They are biologically diverse ecosystems that play an vital role in water quality improvement of the Great Lakes (Canadian Wildlife Service, 2002), and provide a plethora of ecological goods and services including but not limited to: 1) essential spawning grounds for many species of fish (Watchorn et al., 2015) that are important for tourism and the economy, 2) crucial habitat for fish, birds, reptiles, and amphibians (Cvetkovic & Chow-Fraser, 2011), 3) sinks/storage areas for various nutrients and sediments (Watchorn et al., 2015), and 4) soil erosion buffers along exposed shorelines (Canadian Wildlife Service, 2002). These wetlands provide critical habitat to many different types of fish, reptiles, amphibians, and birds. According to Cvetkovic and Chow-Fraser (2011), approximately 80% of all Great Lakes fish species use coastal wetlands for spawning or nursery habitat, and sport fishing adds 4 billion dollars to the economy (NOAA) so the degradation of Great Lakes coastal wetlands is not only a biological issue, it is also a political and economic concern.

Methods

1. Study Area

The extent for this project will be the United States portions of: southwest Lake Huron including the Saginaw Bay area, western Lake St. Clair, and eastern Lake Erie. The Saginaw Bay watershed encompasses the largest adjoining freshwater coastal wetland system in the United States. Its ties can be traced to 22 different counties which makes it the largest drainage basin in the state of Michigan at approximately 14,000 square kilometers (Selzer et al., 2014). Both the Saginaw Bay watershed and the Western Edge of Lake Erie are unique due to their shallow basins. The Saginaw Bay itself is almost 1,700 square kilometers and is comprised of two distinctive regions: an inner bay with an average depth of 5 meters and an outer bay with an average depth of 14 meters (Selzer et al., 2014). Meanwhile, the water depth of the western basin of Lake Erie averages between 7 and 10 meters (Herdendorf, 1992). These long shallow basins create a great environment for coastal wetlands and as a result they are heavy in them, but coastal wetlands are threatened in these areas.

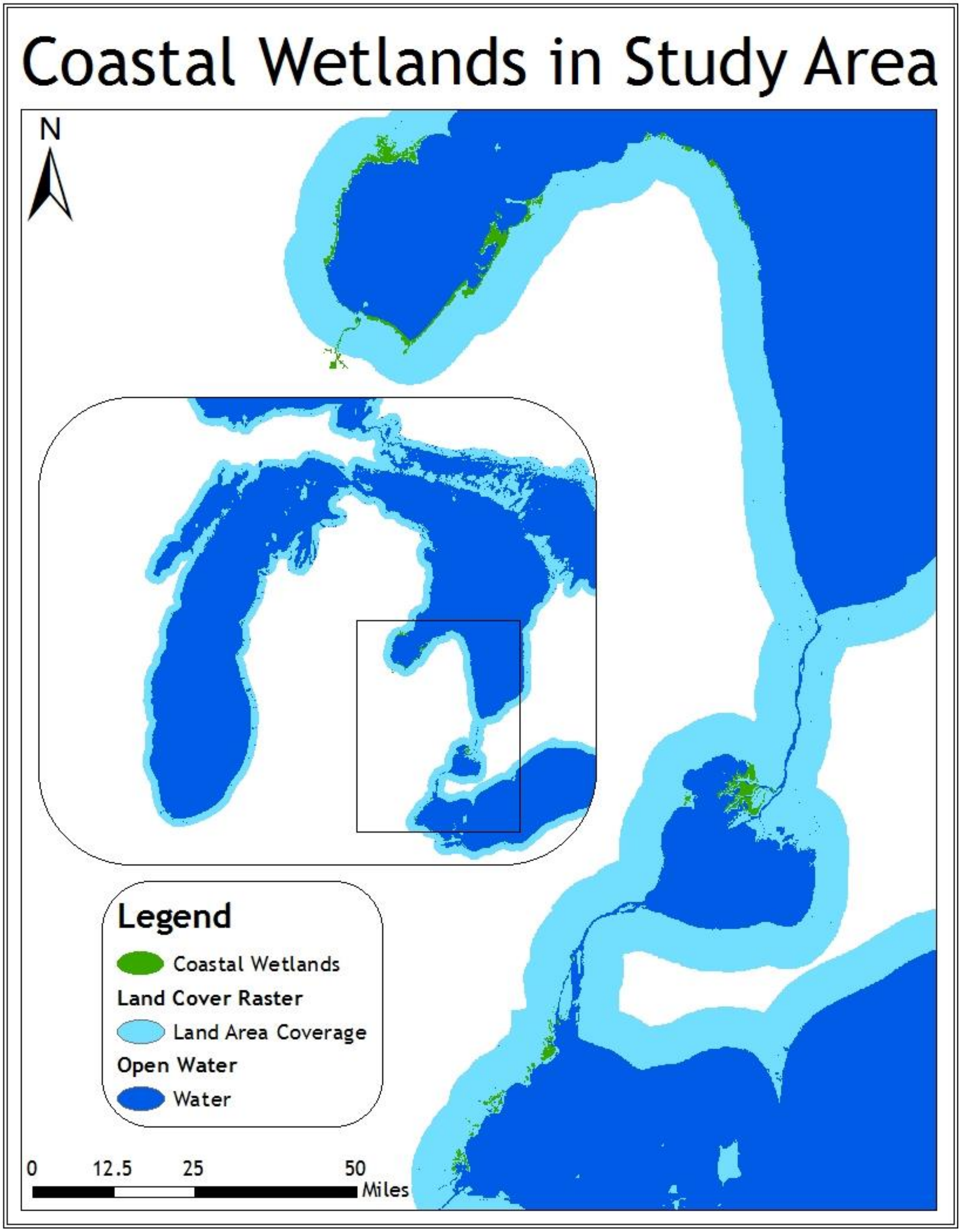

Figure 2. Study Area – Green Areas are Coastal Wetlands.

2. Datasets

Table 1. Datasets

Dataset Name	Format	Resolution (m)	Source
Great Lakes Total Updated Land Cover	TIF	12.5	Environmental Protection Agency, Michigan Technological Research Institute, 2011
Great Lakes Coastal Wetland Inventory	SHP	N/A	Environment Canada, Canadian Wildlife Service - Ontario Region, U.S. Geological Service, Michigan Natural Features Inventory, Ontario Ministry of Natural Resources, 2004
Aerial Imagery (NAIP)	SID	1	National Agricultural Imagery Program, 2014
Michigan All Roads	SHP	N/A	Michigan Department of Transportation, 2010
(MI) Statewide County Layer	SHP	N/A	Center for Shared Solutions, 2014
Great Lakes Bathymetry	TIF	~90	National Geophysical Data Center, NOAA, 1999
Lake Huron & Lake Erie Bathy-topo	TIF	~2.7	National Geophysical Data Center, NOAA, 2014

3. Data Preparation - Managing and Updating Wetland Boundary File

Coastal wetlands naturally change in size and composition from year to year due to hydrological processes and because coastal regions are rapidly urbanizing (Ehrenfeld, 2000). The current Coastal Wetland Inventory file is 12 years old. Additionally, new data has become available to assist with wetland digitization. Wetland boundary updates were done by using the following: one meter true color imagery from 2014 (NAIP, 2014), a land cover classification including select wetland communities

(MTRI & EPA, 2011), and a LiDAR-based data (NOAA, 2014). While the land cover data includes wetland classes, the resolution of this data is relatively coarse and does contain some error (about 93 percent for Lake Huron and 92 percent for Lake Erie in this layer).

NAIP air photos from 2014 have a 1 meter resolution and cover all 9 counties in the study area. The land cover layer has a 12.5 meter resolution and includes the classification of land and water for a couple of miles along the entire basin coastline. The classification recognizes 23 different land cover classes from urban areas to regions with high densities of plants from the genus Schoenoplectus to Typha. Bathymetry is essentially underwater topography because it shows the depth from water's surface to the floor.

Each of the datasets were added under one dataframe in ArcGIS 10.2. All of the data was georeferenced to a logical coordinate system, North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) zone 16N. A transparency of 70 percent was applied to the land cover layer so it could be visualized with the other layers. The bathymetry was classified to show areas with elevations corresponding to water depths of 2 meters or less, all deeper areas were blacked out. The dataframe layer order was as follows: wetland shapefile on top, land cover TIF, bathemetry, aerial imagery on bottom. Each wetland over four hectares in area, existing in or between Saginaw Bay and the southwestern basin of Lake was selected. A scale of 1:3000 was used for each wetland to maintain consistency and polygon vertices were added, deleted, and moved based on a set of rules. Figure 2 shows an updated coastal wetland in comparison to the original wetland and all the different data used to perform the update. Below is a simplified list of rules followed in the current digitizing process.

4. List of Digitizing Rules

- Do not adjust polygon boundary unless it conflicts with one or more of the other datasets
    - If it does conflict:
        - Use Land Cover layer to adjust the boundary

- Consult air photos before adjusting (Land Cover Classifications are not 100 percent accurate due to averaging of multiple classes within single pixels)
- Land Cover classes to omit from wetlands:
    - Urban
    - Suburban
    - Urban Grass
    - Urban Road
    - Fallow Field
        - Sensor confuses this with *Phragmites* sometimes, consult the Aerial Imagery.
    - Orchard
    - Agriculture
    - Sensor confuses this with *Phragmites* sometimes, consult the Aerial Imagery.
    - Pine Plantation
    - Shrub
    - Open Water
        - Only open water regions of roughly 15 pixels or more should be removed.
    - Forest
        - Only forest regions of roughly 15 pixels or more should be removed.
- Land Cover classes for expanding:
    - Aquatic Bed

            - Most of the time can't be observed on Aerial Imagery so consult Bathymetry layer for this.
            - Aquatic bed that appears deeper than 2 meters should not be included.
            - Otherwise, trust the Land Cover layer's classification.
        - Emergent Wetland
        - *Schoenoplectus*
        - *Typha*
        - *Phragmites*

- Compare polygons to Air Photos
    - Great at pointing out obvious regions to omit: cities, buildings, farms, forests, etc.
    - Imagery and roads layer should be used to fragment.
        - To make this process less tedious, just omit roads that are paved with 2 or more lanes.
- Bathymetry should be used to omit rivers or water channels that are deeper than 2 meters.
- In order to obtain the highest accuracy, create "holes" inside polygons to omit non-wetland areas.
- Segment polygons into smaller fragments whenever necessary.
- If two or more wetlands overlap then separate based on nearest observable separating feature.
    - Examples: roads, rivers, channels, ditches, forested region or other upland boundary.

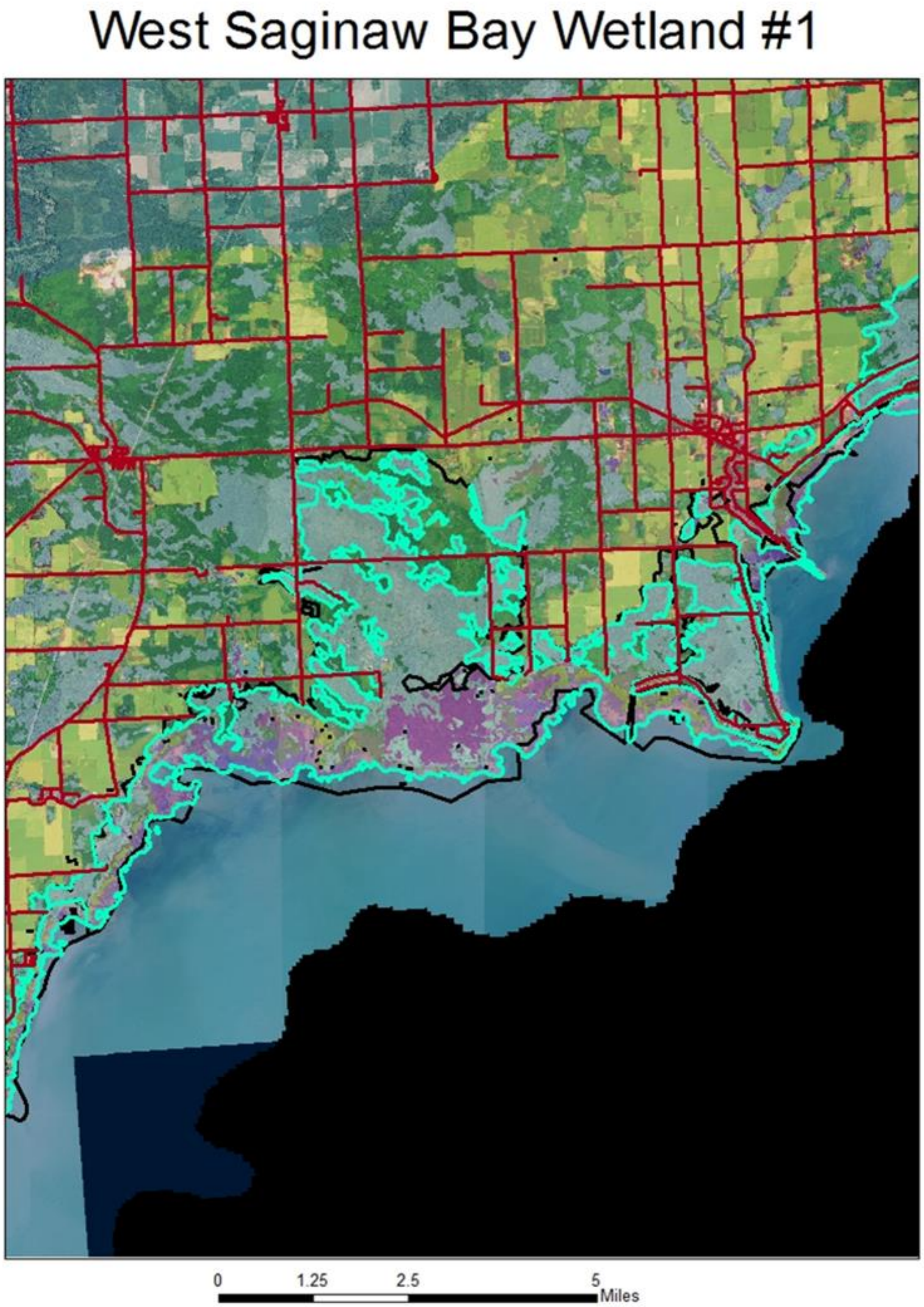

Figure 3. Image showing the original coastal wetland boundary (thin black line) and the updated coastal wetland (outlined in light blue). Updated performed by using a roads layer (red), semi-transparent land cover layer, air photo, and bathymetry (black area).

5. Data Analysis - Calculate Geometry and Fragmentation Data

The area and perimeter of each wetland was updated by manually adding, deleting, and moving the vertices that constitute the shape of each wetland polygon. Each vertex was placed in accordance with the rules described above. Coastal wetland fragmentation was determined by using the Michigan roads layer with the updated polygon layer. There were three metrics for fragmentation: the number of wetland fragments, the area of the largest existing fragment of each wetland, and the perimeter of each wetland divided by its area. If a wetland was not fragmented it received a value of 1 and the area reflects the entire area of the wetland. While most fragmentation is due to roads, some is caused by the creation of deep boating channels or natural phenomena like the formation of natural barriers (ridges, spits, streams, etc.). Fragmentation numbers in this study do not distinguish between different causes.

6. Data Analysis - Statistical Analysis of Area

Summary statistics were performed in Microsoft Excel to determine normality. Levene's test was used in Minitab 17 to test the variances of wetland area and perimeters before and after updates. A Mann-Whitney test was used to test the null hypothesis that there is no statistically significant different between pre and post updated wetland areas.

Results

Figure 3 shows the area change for all 73 coastal wetlands in the study area. Most wetlands showed a change greater than 10% but the largest wetlands showed the most consistent decline in area. Original wetlands ranged from just over 4 hectares to 5515 hectares (Appendix A), after updates the range decreased 3.5 hectares to 4301 hectares. Figure 4 shows that the average wetland area was 383 hectares in 2004 and in 2015 the average area is down to 341 hectares. There is a statistically significant difference between original and updated wetland areas (Figure 8). Based on the histogram in figure 6 and the high kurtosis and skewness values in table 2, there is a non-normal distribution in area values. Figure 7 shows that there was a P-value of 0.633 for Levene's test of equal variance so there is no statistical difference in variances between 2004 and 2015. A Mann-Whitney test was performed and it was determined that there is a statistically significant difference between wetland areas (Figure 8).

Figure 4 shows that 42 of the 73 wetlands experienced positive growth, while the other 31 shrank in size. Coastal wetland growth percentages range from -45.7 percent to 458.7 percent (Appendix A). All of the wetlands combined covered an area of 27,933.4 hectares before updates and dropped to 24,864.2 hectares after. That is a loss of 3,129.2 hectares which is an 11.2 percent decline. However, West Saginaw Bay Wetland #1 and East Saginaw Bay Coastal Wetland #14, formerly the largest and third largest wetlands, account for about 70 percent of the loss in area over the entire region.

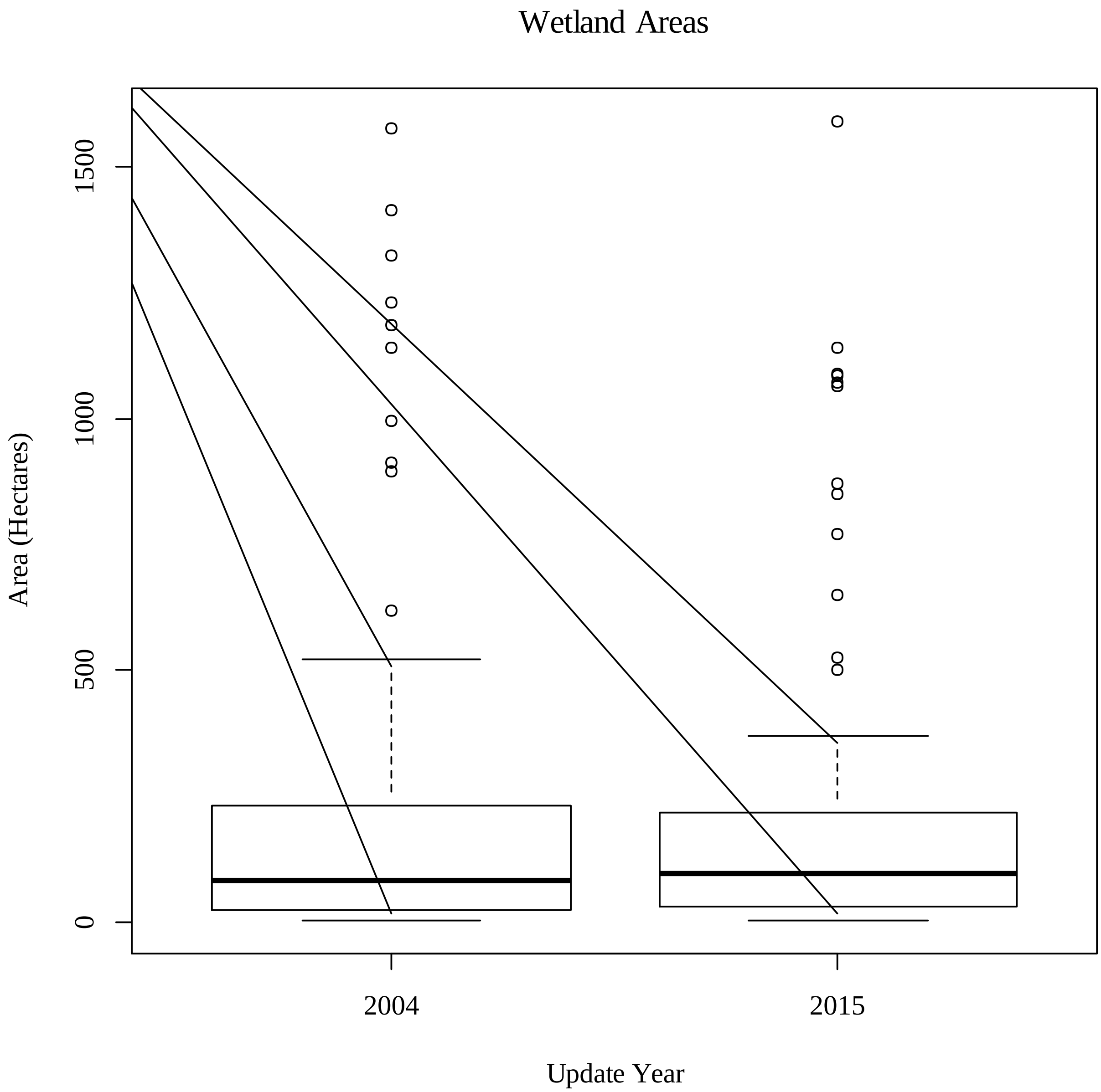

Figure 4. Box plot of the area of each wetland based on the update year. To enhance display, original areas greater than 2,000 hectares and their corresponding 2015 values were omitted.

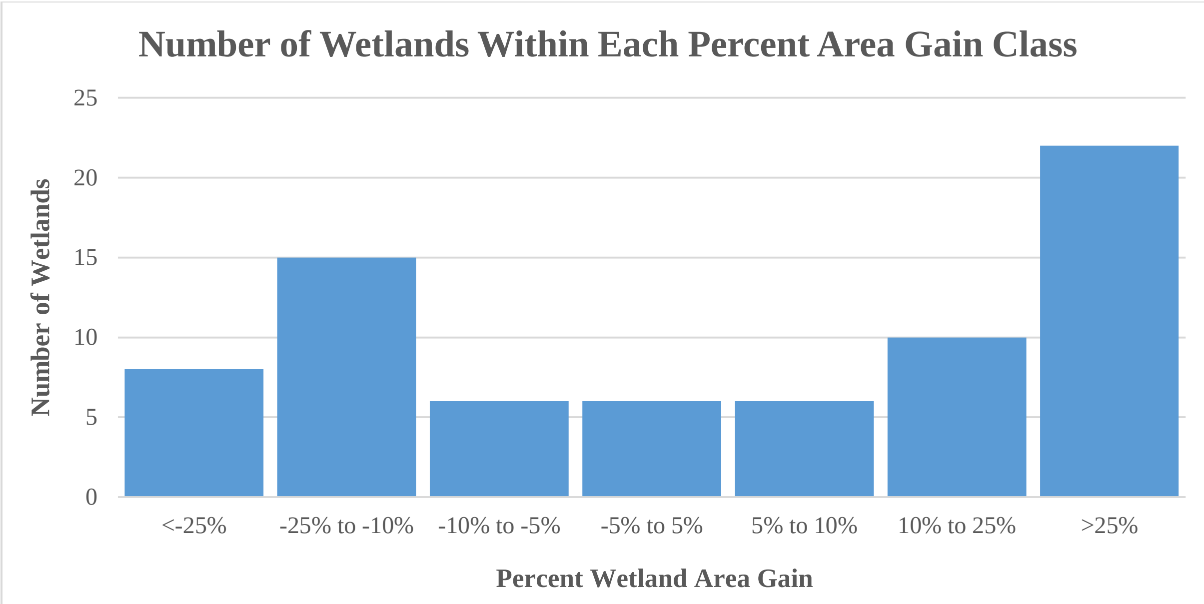

Figure 5. Number of wetlands belonging to each of 6 different wetland area loss classes. Negative loss means positive growth.

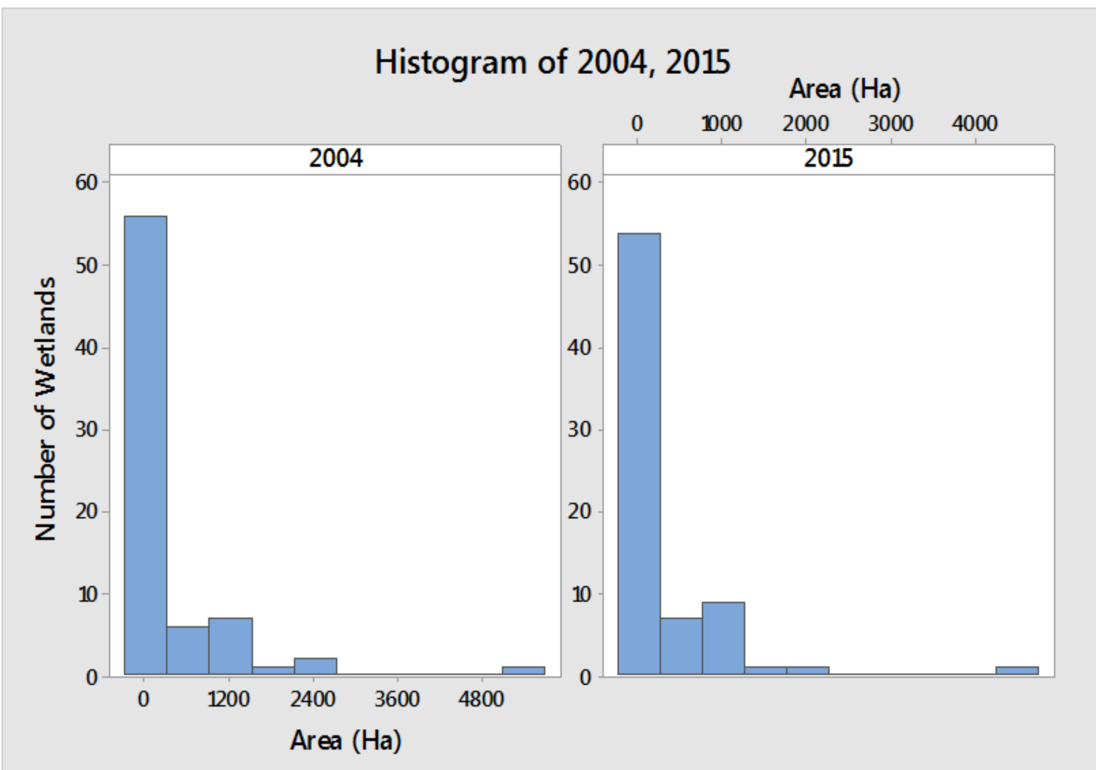

Figure 6. Histogram showing area distributions pre and post updates. X-axis units are hectares.

Table 2. Summary statistics including kurtosis and skewness for pre and post wetland areas.

Original Area (Ha)		*Updated Area (Ha)*	
Mean	383.47	Mean	340.61
Standard Error	93.06	Standard Error	74.17
Median	94.37	Median	104.83
Standard Deviation	795.08	Standard Deviation	633.70
Sample Variance	632156.62	Sample Variance	401578.80
Kurtosis	24.38	Kurtosis	21.46
Skewness	4.37	Skewness	4.07
Range	5511.30	Range	4297.49
Minimum	4.05	Minimum	3.48
Maximum	5515.35	Maximum	4300.97
Sum	27993.43	Sum	24864.24
Count	73.00	Count	73.00
Confidence Level(95.0%)	185.51	Confidence Level(95.0%)	147.85

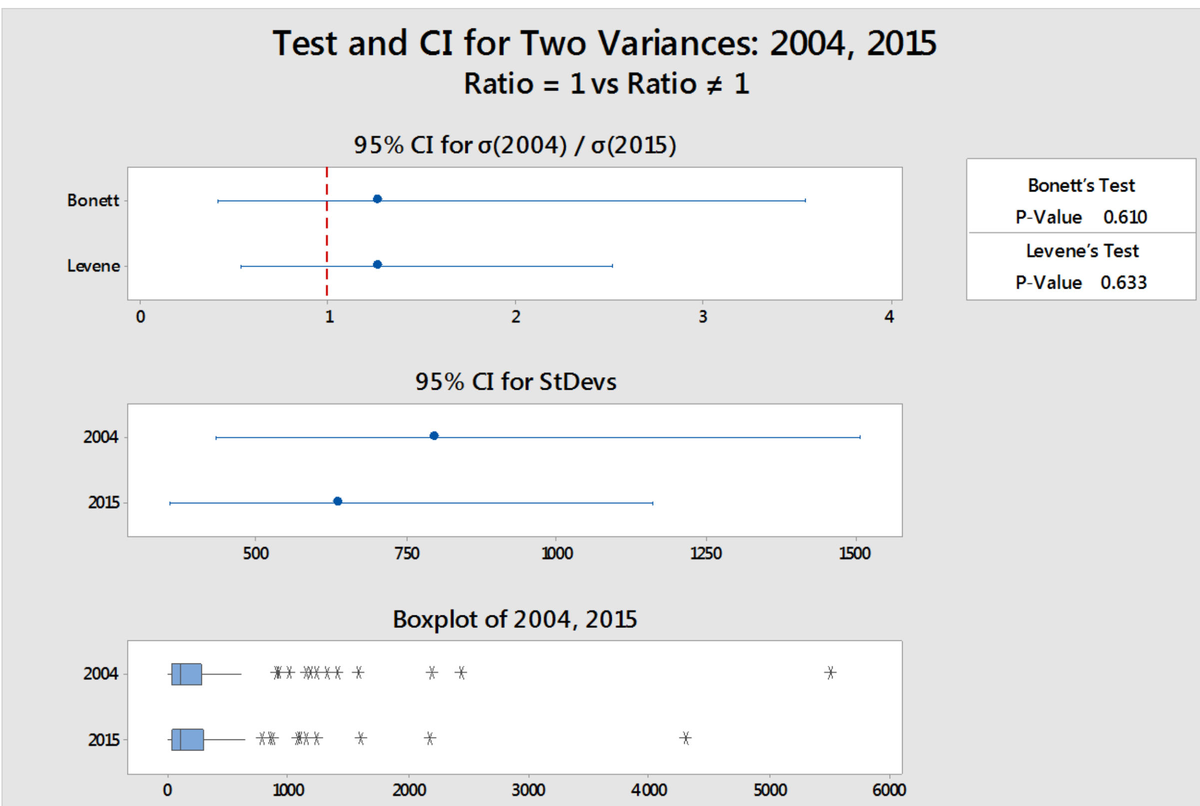

Figure 7. Output from Levene's test of equal variance for area changes.

Mann-Whitney Test and CI: 2004, 2015

```
       N  Median
2004  73    94.4
2015  73   104.8


Point estimate for η1 - η2 is -7.1
95.0 Percent CI for η1 - η2 is (-43.4,24.0)
W = 5227.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.5891
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Figure 8. Output from Mann-Whitney test for area changes.

Most of the largest wetlands increased in perimeter length while very few wetlands decreased in perimeter length. Original wetland boundaries ranged from just over 1 kilometer to over 135 (Appendix B), while the updated boundary changed to a 1.34 kilometers to 220 range. Only 9 of the 73 wetland perimeters decreased in length. Percent growth rates range from -20.65 to 117.67, with an average growth of almost 15 percent. The combined perimeter length of all 73 coastal wetlands was 1327.69 kilometers before updates and increased by 262.8 kilometers to equal a grand total of 1590.49 km. That's an average increase of 3.6 kilometers per wetland which can be seen in figure 9.

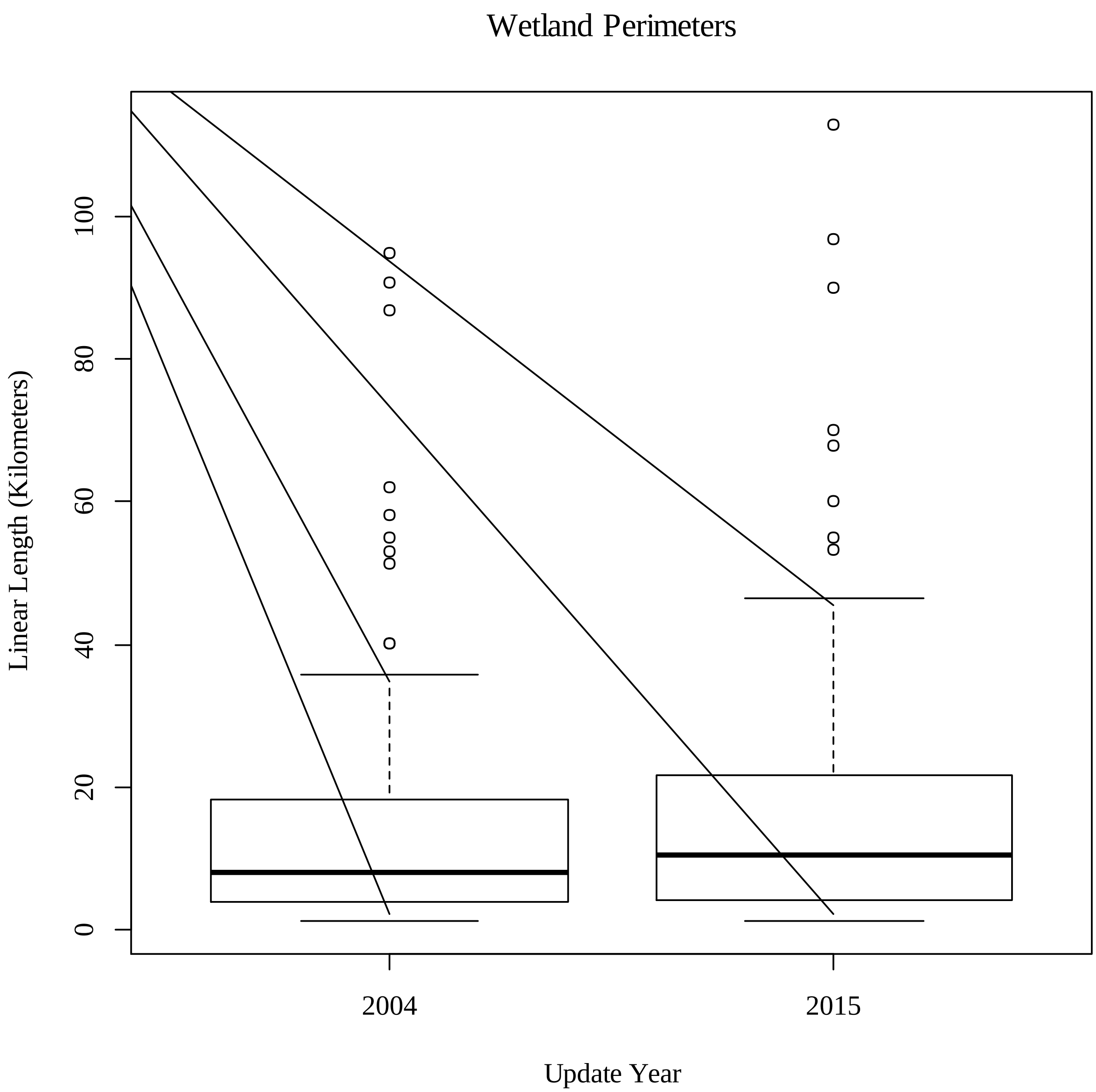

Figure 9. Box plot of the perimeter of each wetland based on the update year. To enhance display, the largest pair of perimeter values were removed.

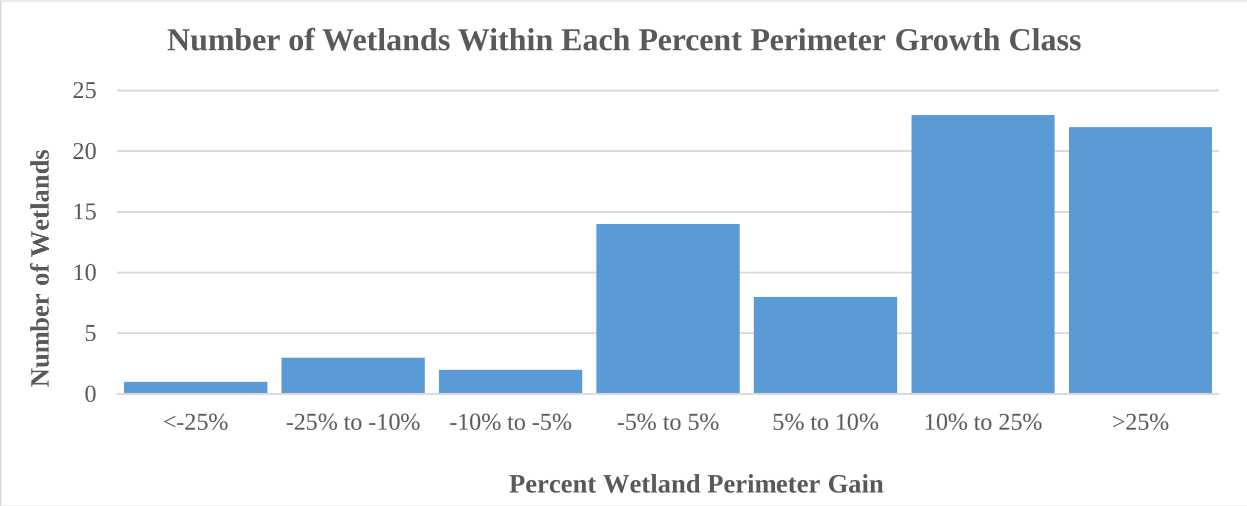

Figure 10. Number of wetlands belonging to each of 6 different wetland perimeter loss classes. Negative loss means positive growth.

Out of the 73 wetlands, 34 of the original wetlands were fully intact without any fragmentation. Using the new mapping methods, 1 additional wetland was found to be fragmented, making a total of 33 single piece wetlands. Another 33 updated wetlands are split between 2 and 10 pieces. The remaining 7 updated wetlands are split into 13 to 34 fragments. Area values range from 3.5 to just shy of 3,000 hectares but it may be important to note that single piece wetlands range from 3.5 to 1086 hectares while the largest fragment of separated wetlands range from 7.8 to 2993 hectares. Table 3 shows that the average wetland is split into 4 pieces and the largest piece averages 252.6 hectares in area, which is about 74% of the total average area of each wetland (340.6 hectares).

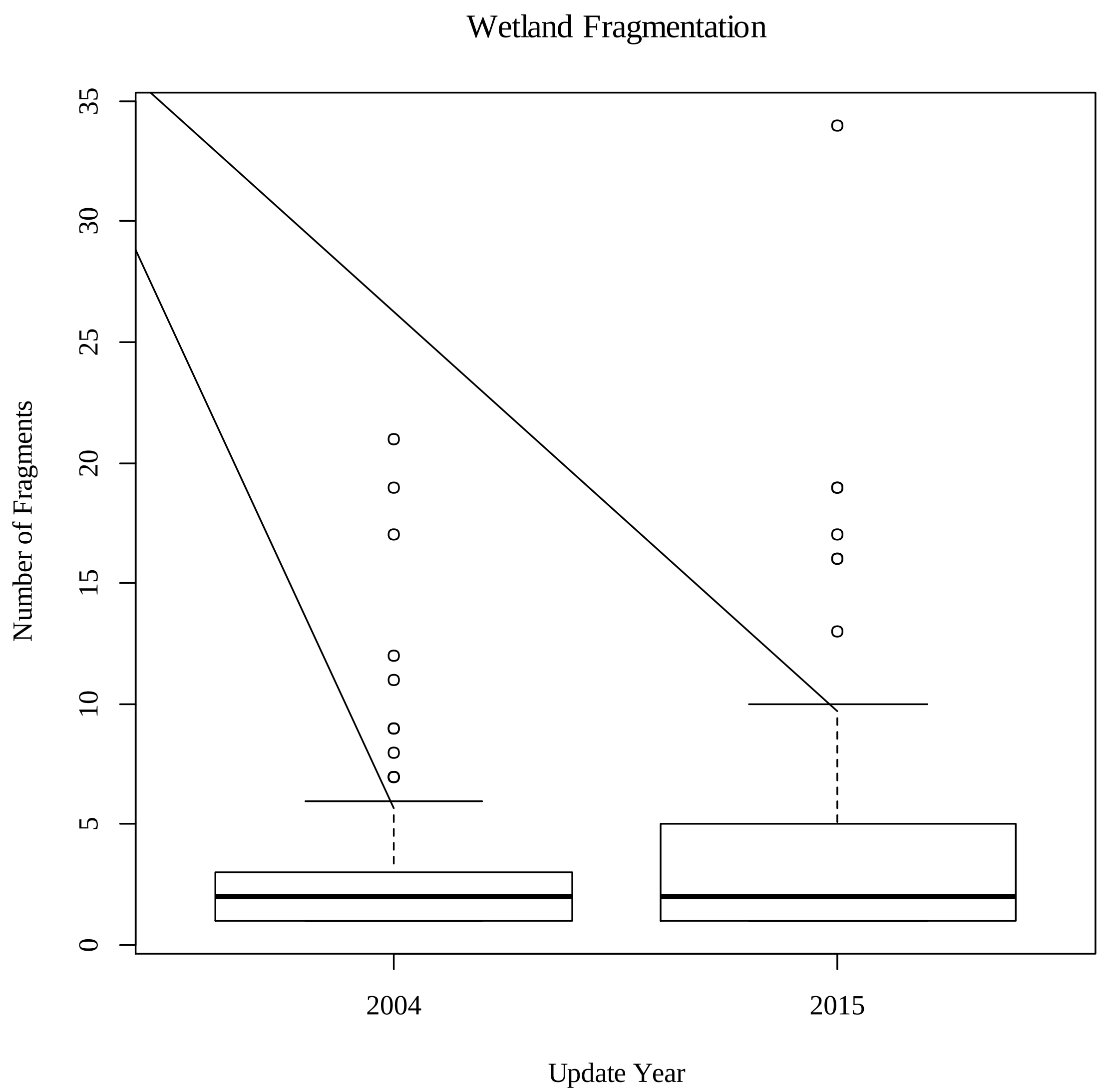

Figure 11. Box plot of the number of fragments of each wetland based on the update year. To enhance display, the two largest pairs of fragments were omitted.

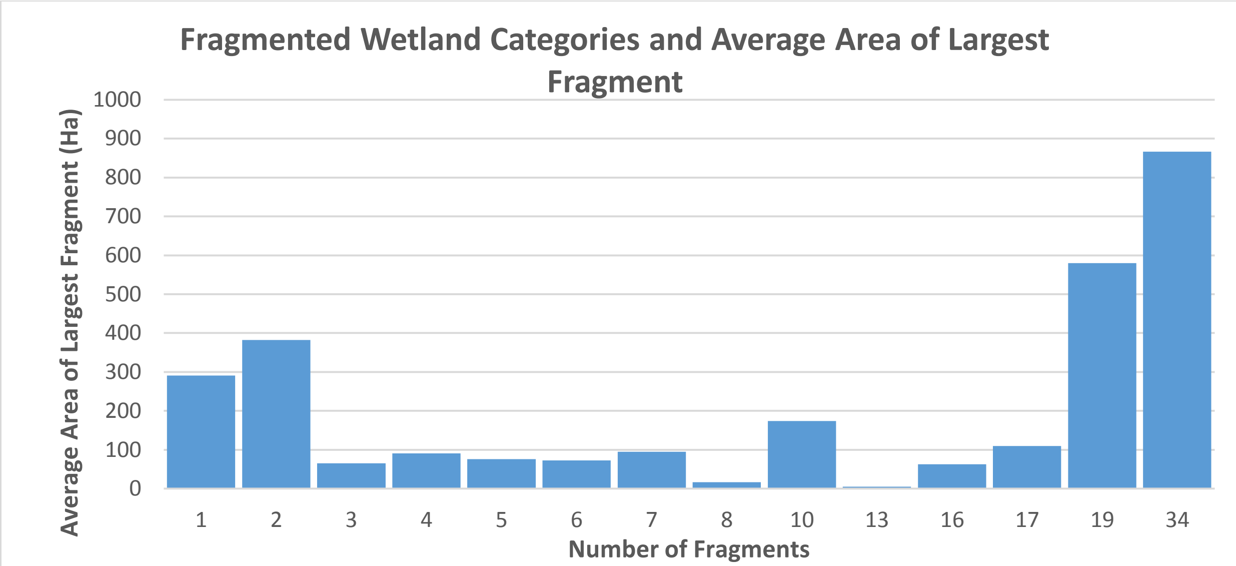

Figure 12. Number of wetland fragments and the corresponding average area of the largest fragment in hectares for each class.

Table 3. The total and average: number of fragments, area of largest fragment, and area of entire wetland in hectares.

	Original Fragments	Updated Fragments
Total	239.00	296.00
Average	3.27	4.05

Table 4. The total and average: number of updated fragments, area of largest fragment, and area of entire wetland in hectares.

	Updated Fragments	Area (Hectares)	Whole Wetland Area (Hectares)
Total	296.00	18436.30	24864.24
Average	4.05	252.55	340.61

Discussion

The results show an 11% decrease in the area of the coastal wetlands, a 20% increase in perimeter and a 24% increase in fragmentation. These changes could be caused by several different factors. As Mitsch and Wang (2000) note, Great Lakes wetlands are extremely susceptible to filling during low lake level periods, mostly because the water levels of the Great Lakes can fluctuate over 1.5 meters from a wet year to a dry year. Human impact aside, these wetlands can shift and fragment naturally. Both the Saginaw Bay and the western basin of Lake Erie are extremely shallow areas. A 1.5 meter change in water level can drastically effect where emergent vegetation can grow and result in a vastly different wetland distribution based on wetland classification systems. If the water level drops then small pockets of deeper areas will still hold water and support wetland vegetation which results in fragments.

While natural fluctuation in area, perimeter, and fragmentation is occurring, most of the new fragmentation in this study was due to the presence of roads, although some urban areas also contributed. However, it is important to note that numerous state (Ex. Natural Resources and Environmental Protection Act 451 of 1994) and federal laws (Ex. Section 404 of the Clean Water Act) now protect these coastal wetlands. Most of the road and urban reductions can likely be explained by the change in mapping methodology. Some of the changes in fragmentation, area, and perimeter between the former digitized file and the file created in this project can be explained by the use of multiple detailed GIS data sources previously unavailable: color air photos, remote sensing-based land cover, LiDAR bathymetry, and a roads layer.

Future Work

An updated Great Lakes coastal wetland file that reflects the current shape, size, and spatial distribution of the wetlands enables the calculation and collection of a series of different attributes that could aid in coastal wetland management. We are currently calculating and compiling information on:

wetland accessibility, land ownership, watershed land cover, biodiversity, and nearby human population. Human population metrics are almost complete and Appendix C shows a sneak peak of values.

Census blocks from the 2010 census with attributed population data were used with the updated wetland polygon layer. This produced three different criteria: total population within a 1km buffer of each wetland, total population within a 5 km buffer of each wetland, and total population within a 10 km buffer of each wetland. The population of each census block that is entirely encompassed by a wetland buffer was added together. In the event that only part(s) of one or more census block was covered by a wetland, the percentage of overlap between the two layers was calculated and only that percentage of the population was used towards the total population sum. A hydrology layer was used to calculate and remove areas of land covered by lakes and rivers where people cannot live to obtain updated area values and more accurately calculate human population densities for each buffer size. A script was developed in Python to perform these processes. While much of these analysis has been completed, it has not been included in this paper due to space constraints.

Conclusions

Great Lakes coastal wetlands from Saginaw Bay to the Western Basin of Lake Erie are changing. The updated wetland polygons showed that there was a loss in area of 3,129.2 hectares over the entire study area, which is an 11.2 percent decline and it is a statistically significant change (Figure 8). Additionally, perimeter length of wetlands in the study area increased by almost 15 percent. In fact 64 of the 73 wetlands experienced perimeter growth of 3.6 kilometers on average. Also the number of wetland fragments increased from 239 to 296 over the entire region. Based on these evidences one could easily conclude that Great Lakes coastal wetlands are being separated into pieces and decreasing in size, but it is important to point out that just 2 wetlands account for 70 percent of the decline and 42 of the 73 wetlands experienced small amounts of positive growth.

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Appendix A

Original area in hectares, updated area, overall change in area, and percent growth of each coastal wetland in the study area.

Name	Original Area (Ha)	Updated Area (Ha)	Change	Percent Growth
Tobico Lagoon Area Wetland	4.05	3.48	-0.57	-14.08
Trenton Channel Wetland	5.01	14.92	9.90	197.47
Elba Island Wetland	5.29	20.36	15.07	284.85
Russel Island Area Wetland	6.29	9.28	2.99	47.58
Russel Island Wetland	8.26	8.96	0.70	8.47
Stony Creek Wetland	10.08	5.48	-4.60	-45.66
Old Shore Road Area Wetland #1	10.18	56.88	46.70	458.70
Tobico Lagoon Wetland	11.29	12.37	1.08	9.55
BENCHMARK:Linwood Area Wetland #2	12.47	18.86	6.38	51.16
Round Island Wetland	13.73	25.56	11.82	86.09
Lagoon Beach Wetland	13.95	25.29	11.34	81.27
No. 2 Drain Wetland	16.96	21.09	4.13	24.36
Purdy Bay Wetland	17.76	31.17	13.41	75.50
Enrico Feral Wetland	19.35	80.39	61.04	315.41
Camp Farewell Area Wetland	19.41	21.06	1.65	8.50
Sandy Creek Wetland #1	23.03	59.89	36.86	160.04
Point aux Chenes Wetland	23.27	21.87	-1.40	-6.02
St. Margaret Mission Wetland	23.37	66.71	43.35	185.52
Caseville Township Wetland #2	23.64	31.02	7.37	31.18
Grassy Island Wetland	24.18	39.26	15.08	62.36
Linwood Area Wetland #1	25.59	17.87	-7.73	-30.19

Stony Point Wetland	25.82	33.52	7.70	29.84
Cherry Isle Wetland	27.41	85.31	57.90	211.21
Caseville Township Wetland	34.06	65.59	31.53	92.58
Whiskey Harbor Wetland	34.15	26.78	-7.38	-21.60
Point aux Tremble Wetland	36.88	30.85	-6.03	-16.36
Au Sable Point Wetland	43.46	43.41	-0.05	-0.12
Celeron Island Wetland	46.52	54.38	7.86	16.89
Old Shore Road Area Wetland	48.08	39.36	-8.72	-18.13
BENCHMARK:Monroe Dikes A	52.87	75.41	22.54	42.63
Aplin Beach Wetland	62.10	38.11	-23.99	-38.63
North Island Wetland	69.90	98.59	28.69	41.05
Halfway Creek Wetland	72.16	121.94	49.78	68.99
BENCHMARK:Monroe Dikes B	75.22	78.39	3.16	4.21
Nayanguing Point Wildlife Area Wetland #2	78.45	93.41	14.96	19.08
Rockwood Road Wetland	86.27	95.18	8.91	10.33
Otter Creek Wetland	94.37	95.86	1.49	1.58
BENCHMARK:Nayanguing Point Wildlife Area Wetland #5	102.63	109.17	6.54	6.37
Gore Township Wetland	107.44	169.48	62.04	57.75
BENCHMARK:Nayanguing Point Wildlife Area Wetland #3	116.32	104.83	-11.48	-9.87
Toledo Beach Wetland	119.87	128.00	8.13	6.78
Hardwood Point Wetland	119.97	194.18	74.21	61.85
Swan Creek Wetland	152.90	177.85	24.95	16.32
BENCHMARK:Woodtick Penninsula Wetland	174.75	213.29	38.55	22.06
BENCHMARK:North Maumee Bay Area	179.42	143.26	-36.16	-20.15

Wetland				
East Saginaw Bay Coastal Wetland #11	181.46	162.13	-19.32	-10.65
Willow Creek Wetland	188.27	170.84	-17.43	-9.26
East Saginaw Bay Coastal Wetland #9	188.35	126.70	-61.65	-32.73
BENCHMARK:Wildfowl Bay Wetland	209.37	216.43	7.06	3.37
Nayanguing Point Wildlife Area Wetland #1	219.31	248.40	29.08	13.26
Black Creek Area Wetland	222.13	209.65	-12.48	-5.62
West Saginaw Bay Wetland	230.62	156.83	-73.79	-32.00
North Gore Township Wetland	231.67	260.24	28.58	12.33
Pointe aux Barques	256.23	182.15	-74.08	-28.91
Burnt Cabin Point Wetland	259.13	218.38	-40.74	-15.72
Bay Creek Area Wetland	280.37	341.48	61.11	21.79
Nayanguing Point Wildlife Area Wetland #4	404.07	361.91	-42.16	-10.43
East Saginaw Bay Coastal Wetland #8	416.78	503.09	86.31	20.71
East Saginaw Bay Coastal Wetland #2	466.26	371.62	-94.64	-20.30
Monroe City Area Wetland	520.80	651.58	130.78	25.11
Nayanguing Point Wildlife Area Wetland	617.35	524.32	-93.03	-15.07
Caseville Township Wetland #1	895.73	769.93	-125.81	-14.05
East Saginaw Bay Coastal Wetland #15	912.19	850.40	-61.80	-6.77
Mouillee Marsh	996.87	1064.94	68.07	6.83
East Saginaw Bay Coastal Wetland	1139.67	1085.54	-54.13	-4.75
Bouvier Bay Wetland	1184.39	1087.36	-97.04	-8.19
East Saginaw Bay Coastal Wetland #10	1229.65	870.11	-359.54	-29.24
Saginaw Bay River	1325.38	1141.88	-183.50	-13.84
BENCHMARK:East Saginaw Bay Coastal Wetland #5	1412.58	1070.67	-341.91	-24.20
Harsens Island Area Wetland	1577.07	1591.01	13.94	0.88

East Saginaw Bay Coastal Wetland #14	2195.91	1237.55	-958.36	-43.64
Dickenson Island Area Wetland	2438.26	2180.21	-258.05	-10.58
West Saginaw Bay Wetland #1	5515.35	4300.97	-1214.38	-22.02

Appendix B

Original perimeter length in kilometers, updated perimeter length, overall change in perimeter length, and percent growth of each coastal wetland in the study area.

Name	**Original Perimeter (KM)**	**Updated Perimeter (KM)**	**Change**	**Percent Growth**
Round Island Wetland	2.20	2.24	0.04	1.95
Elba Island Wetland	2.07	4.09	2.01	97.04
No. 2 Drain Wetland	4.22	4.33	0.11	2.67
Trenton Channel Wetland	2.05	3.13	1.08	52.81
Grassy Island Wetland	2.68	3.33	0.65	24.23
Black Creek Area Wetland	18.49	13.42	-5.07	-27.43
Bouvier Bay Wetland	40.20	46.20	6.00	14.93
Point aux Tremble Wetland	6.76	7.48	0.72	10.64
Dickenson Island Area Wetland	94.90	113.06	18.16	19.14
Harsens Island Area Wetland	86.97	90.12	3.15	3.62
Point aux Chenes Wetland	3.90	4.59	0.69	17.78
Russel Island Wetland	1.27	1.35	0.07	5.75
Purdy Bay Wetland	5.16	6.62	1.46	28.33
Old Shore Road Area Wetland #1	3.04	5.62	2.58	84.87
Old Shore Road Area Wetland	4.38	5.38	1.00	22.93
Hardwood Point Wetland	14.91	19.26	4.36	29.21
St. Margaret Mission Wetland	4.48	5.52	1.03	23.03
Gore Township Wetland	16.36	19.29	2.93	17.90
Whiskey Harbor Wetland	2.31	3.03	0.72	31.16
North Gore Township Wetland	12.65	19.55	6.91	54.61
Willow Creek Wetland	15.11	14.89	-0.22	-1.47
Burnt Cabin Point Wetland	21.34	26.55	5.21	24.40

Pointe aux Barques	19.56	25.78	6.22	31.80
Caseville Township Wetland #2	3.60	3.87	0.28	7.73
Caseville Township Wetland #1	58.14	60.03	1.89	3.25
Caseville Township Wetland	4.32	5.57	1.25	28.82
BENCHMARK:Wildfowl Bay Wetland	15.43	17.78	2.36	15.27
North Island Wetland	4.79	10.42	5.63	117.67
Celeron Island Wetland	3.88	4.03	0.15	3.99
Camp Farewell Area Wetland	3.70	3.83	0.13	3.44
Russel Island Area Wetland	1.11	1.34	0.23	20.70
Aplin Beach Wetland	6.56	7.76	1.20	18.27
Lagoon Beach Wetland	3.33	3.49	0.16	4.65
Tobico Lagoon Area Wetland	1.34	1.42	0.08	5.65
Tobico Lagoon Wetland	2.60	2.82	0.22	8.42
Linwood Area Wetland #1	3.54	4.10	0.56	15.94
Nayanguing Point Wildlife Area Wetland	19.27	22.74	3.47	18.00
Nayanguing Point Wildlife Area Wetland #2	7.91	10.43	2.52	31.91
Nayanguing Point Wildlife Area Wetland #4	22.08	23.34	1.26	5.71
BENCHMARK:Nayanguing Point Wildlife Area Wetland #5	7.03	8.68	1.65	23.52
West Saginaw Bay Wetland	14.40	15.45	1.04	7.24
West Saginaw Bay Wetland #1	135.30	220.16	84.85	62.71
East Saginaw Bay Coastal Wetland #15	28.49	36.36	7.87	27.63

East Saginaw Bay Coastal Wetland #11	9.38	13.06	3.67	39.13
East Saginaw Bay Coastal Wetland #8	9.95	13.21	3.26	32.76
BENCHMARK:East Saginaw Bay Coastal Wetland #5	53.07	53.20	0.13	0.25
East Saginaw Bay Coastal Wetland #2	22.62	28.77	6.15	27.17
East Saginaw Bay Coastal Wetland	35.82	39.87	4.05	11.31
East Saginaw Bay Coastal Wetland #9	7.87	14.61	6.73	85.56
BENCHMARK:Linwood Area Wetland #2	2.11	2.87	0.76	35.78
Nayanguing Point Wildlife Area Wetland #1	15.18	15.12	-0.06	-0.40
BENCHMARK:Nayanguing Point Wildlife Area Wetland #3	7.71	9.30	1.60	20.71
Saginaw Bay River	90.71	96.92	6.22	6.85
East Saginaw Bay Coastal Wetland #10	55.02	67.94	12.91	23.47
East Saginaw Bay Coastal Wetland #14	62.01	70.11	8.10	13.07
Halfway Creek Wetland	11.80	10.32	-1.48	-12.56
BENCHMARK:Woodtick Penninsula Wetland	10.76	10.93	0.17	1.59
Bay Creek Area Wetland	17.99	21.95	3.97	22.05
Toledo Beach Wetland	10.98	12.74	1.76	16.00
Otter Creek Wetland	11.35	14.78	3.43	30.26
Sandy Creek Wetland #1	5.03	4.75	-0.28	-5.61
Stony Creek Wetland	1.58	1.25	-0.33	-20.65
Stony Point Wetland	2.96	3.66	0.70	23.49

Enrico Feral Wetland	5.52	4.44	-1.08	-19.50
Swan Creek Wetland	9.77	12.54	2.77	28.30
Mouillee Marsh	40.07	55.04	14.97	37.37
Rockwood Road Wetland	10.72	13.36	2.65	24.69
Cherry Isle Wetland	7.99	7.75	-0.24	-3.03
Monroe City Area Wetland	51.41	46.51	-4.89	-9.52
BENCHMARK:North Maumee Bay Area Wetland	11.65	21.51	9.85	84.54
BENCHMARK:Monroe Dikes A	3.91	4.20	0.29	7.33
BENCHMARK:Monroe Dikes B	3.76	3.87	0.11	2.97
Au Sable Point Wetland	7.15	7.46	0.31	4.29

Appendix C

Table 1. Total human population estimates within a 1, 5, and 10 kilometer buffer distance of each coastal wetland.

Wetland Name	Total Population 1KM	Total Population 5KM	Total Population 10KM
North Island Wetland	0	630	2008
East Saginaw Bay Coastal Wetland #15	2	852	4494
BENCHMARK:Woodtick Penninsula Wetland	3	8040	41698
East Saginaw Bay Coastal Wetland #10	4	1070	4915
Whiskey Harbor Wetland	16	262	1155
North Gore Township Wetland	36	343	1298
St. Margaret Mission Wetland	45	2325	3742
East Saginaw Bay Coastal Wetland #9	45	2527	3817
Willow Creek Wetland	50	418	1331
East Saginaw Bay Coastal Wetland #8	66	2300	4807
Old Shore Road Area Wetland	77	2458	3697
Old Shore Road Area Wetland #1	112	2487	3740
Purdy Bay Wetland	112	658	3758
East Saginaw Bay Coastal Wetland #11	124	2158	4187
Grassy Island Wetland	124	87031	251144
Burnt Cabin Point Wetland	135	870	2031
BENCHMARK:North Maumee Bay Area	147	12900	77959

Wetland			
Au Sable Point Wetland	161	837	3802
Caseville Township Wetland	165	1690	5047
Nayanguing Point Wildlife Area Wetland #2	179	3298	6811
BENCHMARK:Nayanguing Point Wildlife Area Wetland #3	182	3185	6646
BENCHMARK:Monroe Dikes B	185	27959	58998
Nayanguing Point Wildlife Area Wetland #1	202	3995	8851
Nayanguing Point Wildlife Area Wetland #4	223	3928	9084
BENCHMARK:Nayanguing Point Wildlife Area Wetland #5	231	1476	7858
Gore Township Wetland	240	724	1467
East Saginaw Bay Coastal Wetland #2	245	1555	8644
BENCHMARK:Monroe Dikes A	246	34271	57495
Hardwood Point Wetland	253	1029	3766
West Saginaw Bay Wetland	282	1504	8019
Linwood Area Wetland #1	337	3662	14889
Bay Creek Area Wetland	354	10295	63417
Tobico Lagoon Area Wetland	358	11497	59777
Nayanguing Point Wildlife Area Wetland	363	4360	11224
BENCHMARK:Linwood Area Wetland #2	396	3517	10709
BENCHMARK:East Saginaw Bay Coastal Wetland #5	423	1988	8264
Tobico Lagoon Wetland	434	11690	59930
BENCHMARK:Wildfowl Bay Wetland	447	2137	5546

Trenton Channel Wetland	553	66270	216451
Russel Island Area Wetland	557	8373	15091
Pointe aux Barques	566	1395	2020
Celeron Island Wetland	623	18922	86447
East Saginaw Bay Coastal Wetland	666	16798	69663
Otter Creek Wetland	686	12425	49285
Swan Creek Wetland	693	7699	30406
Round Island Wetland	782	19717	90422
Caseville Township Wetland #2	797	2138	3697
Mouillee Marsh	830	15145	68028
Toledo Beach Wetland	843	6473	36531
Camp Farewell Area Wetland	889	9291	15462
Elba Island Wetland	915	15586	89782
Russel Island Wetland	996	8538	15338
Enrico Feral Wetland	1258	7251	23148
West Saginaw Bay Wetland #1	1259	4281	9557
Aplin Beach Wetland	1305	21820	73993
Lagoon Beach Wetland	1320	15130	70347
East Saginaw Bay Coastal Wetland #14	1369	3913	8509
No. 2 Drain Wetland	1378	46437	127151
Caseville Township Wetland #1	1422	3303	6102
Stony Creek Wetland	1499	9359	45819
Stony Point Wetland	1538	7942	28112
Harsens Island Area Wetland	1708	11749	18883
Halfway Creek Wetland	1787	18060	109337

Point aux Chenes Wetland	2014	9510	15775
Sandy Creek Wetland #1	2037	20290	59684
Point aux Tremble Wetland	2039	12595	18397
Dickenson Island Area Wetland	2076	12216	55967
Rockwood Road Wetland	2746	29728	97794
Cherry Isle Wetland	2824	28930	95699
Monroe City Area Wetland	3318	44019	65381
Bouvier Bay Wetland	4253	18146	60803
Black Creek Area Wetland	6386	32221	177789
Saginaw Bay River	26031	78228	116190

Table 2. Human population density estimates (people per hectare) within a 1, 5, and 10 kilometer buffer distance of each coastal wetland.

Wetland Name	**Population Density 1KM**	**Population Density 5KM**	**Population Density 10KM**
North Island Wetland	0.00	0.65	0.23
East Saginaw Bay Coastal Wetland #15	0.01	0.21	0.27
BENCHMARK:Woodtick Penninsula Wetland	0.01	1.80	1.88
East Saginaw Bay Coastal Wetland #10	0.01	0.21	0.29
Whiskey Harbor Wetland	0.06	0.06	0.08
North Gore Township Wetland	0.06	0.07	0.08
St. Margaret Mission Wetland	0.07	0.32	0.21
East Saginaw Bay Coastal Wetland #9	0.08	0.07	0.07

Willow Creek Wetland	0.11	0.43	0.20
East Saginaw Bay Coastal Wetland #8	0.15	0.13	0.25
Old Shore Road Area Wetland	0.17	0.16	0.12
Purdy Bay Wetland	0.20	0.14	0.20
Old Shore Road Area Wetland #1	0.21	0.36	0.21
Grassy Island Wetland	0.21	0.50	0.21
East Saginaw Bay Coastal Wetland #11	0.21	2.12	3.41
Burnt Cabin Point Wetland	0.23	0.12	0.21
BENCHMARK:North Maumee Bay Area Wetland	0.25	0.50	0.37
Au Sable Point Wetland	0.27	0.63	0.42
Caseville Township Wetland	0.29	0.11	0.08
Nayanguing Point Wildlife Area Wetland #2	0.29	1.34	2.52
BENCHMARK:Nayanguing Point Wildlife Area Wetland #3	0.30	0.50	0.21
BENCHMARK:Monroe Dikes B	0.31	0.24	0.22
Nayanguing Point Wildlife Area Wetland #1	0.33	0.15	0.18
Nayanguing Point Wildlife Area Wetland #4	0.35	0.56	0.34
BENCHMARK:Nayanguing Point Wildlife Area Wetland #5	0.36	5.03	2.96
Gore Township Wetland	0.37	0.59	0.36
East Saginaw Bay Coastal Wetland #2	0.37	1.35	1.91

BENCHMARK:Monroe Dikes A	0.38	0.22	0.34
Hardwood Point Wetland	0.41	0.56	0.46
West Saginaw Bay Wetland	0.41	0.38	0.30
Linwood Area Wetland #1	0.43	0.64	0.22
Bay Creek Area Wetland	0.45	5.78	2.78
Tobico Lagoon Area Wetland	0.48	0.26	0.38
Nayanguing Point Wildlife Area Wetland	0.48	0.27	0.24
BENCHMARK:Linwood Area Wetland #2	0.50	0.26	0.31
BENCHMARK:East Saginaw Bay Coastal Wetland #5	0.56	0.29	0.21
Tobico Lagoon Wetland	0.64	0.26	0.22
BENCHMARK:Wildfowl Bay Wetland	0.65	2.12	3.14
Trenton Channel Wetland	0.66	1.61	2.06
Russel Island Area Wetland	0.68	1.57	1.41
Pointe aux Barques	0.85	0.25	0.13
Celeron Island Wetland	0.87	1.15	1.58
East Saginaw Bay Coastal Wetland	1.22	0.75	0.74
Otter Creek Wetland	1.25	1.07	1.76
Swan Creek Wetland	1.35	19.92	14.04
Round Island Wetland	1.43	2.34	3.01
Caseville Township Wetland #2	1.45	2.44	3.10
Mouillee Marsh	1.60	0.70	0.54
Toledo Beach Wetland	1.74	13.07	12.02
Camp Farewell Area Wetland	1.96	1.71	2.68

Elba Island Wetland	2.14	4.95	2.50
Russel Island Wetland	2.22	0.40	0.22
Enrico Feral Wetland	2.30	2.06	1.26
West Saginaw Bay Wetland #1	2.64	1.49	2.07
Aplin Beach Wetland	2.65	4.73	6.48
Lagoon Beach Wetland	2.78	1.82	1.49
East Saginaw Bay Coastal Wetland #14	2.88	3.82	3.52
No. 2 Drain Wetland	2.88	1.61	1.16
Caseville Township Wetland #1	3.05	6.62	6.05
Stony Creek Wetland	3.43	4.96	5.85
Stony Point Wetland	3.45	4.28	4.47
Harsens Island Area Wetland	3.53	2.84	4.53
Halfway Creek Wetland	3.61	2.49	1.32
Point aux Chenes Wetland	4.47	2.98	3.52
Sandy Creek Wetland #1	4.55	2.33	1.91
Point aux Tremble Wetland	4.56	3.02	2.02
Dickenson Island Area Wetland	4.67	3.64	3.05
Rockwood Road Wetland	5.11	2.01	1.23
Cherry Isle Wetland	5.13	1.84	2.55
Monroe City Area Wetland	5.34	2.43	1.30
Bouvier Bay Wetland	5.69	4.73	4.65
Black Creek Area Wetland	7.85	7.56	10.28
Saginaw Bay River	10.09	4.59	5.22