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MODELING COASTAL WETLAND CHANGE DUE TO LAKE LEVEL FLUCTUATIONS

Justin D. Cole, MS, GISP, Monroe County DES GIS Services Division
Karl F. Korfmacher, pHD. Rochester Institute of Technology

Introduction:

An essential component to the health and stability of the Great Lakes ecosystems are the coastal wetlands. Coastal wetlands are significant ecological features with ecologic and economic values. Ecologically, wetlands provide important habitat and play a critical role in natural and chemical cycles, such as the hydrologic and nitrogen cycles. Economically, wetlands, in particular coastal wetlands, provide many functions such as water retention, pollution control, and coastline protection (Keough et al. 1999). Coastal vegetation also aids in removing pollutants from entering the larger water bodies. Acting as a filter, wetlands reduce stream velocity and wave action, allowing suspended sediments to settle out. Wetland plants, such as cattails, remove other pollutants, including heavy metals such as mercury, storing pollutants in their biomass until the plants decompose. The removal rates of heavy metals by the Cattails are on the order of 47% uptake from the water body (Coon and Bernard, 2000). Often this biomass is buried in the sediments, becoming trapped by the wetland and trapping the pollutants as well. Wetland plants also stabilize the shorelines by creating a matrix of roots, which hold the soil in place during storm events. The soils of a wetland are essential for water storage and for pollution control. The soil is usually high in clay and organic matter, which have high water and nutrient retention capacities. The soils allow for both water storage and the slow discharge of storm water back into the system, so rainfall from an intense storm may not enter a stream network until long after the storm has passed.

Despite their ecological value, wetlands have historically been considered agricultural economic resources because of their fertile soils and more recently as development resources because of their locations adjacent to major water bodies. Coastal wetlands are drained and crops, such as fruit, vegetables and tobacco, can be grown on them (EPA and Environment Canada 2006). This conversion from wetland to cropland has been encouraged and subsidized by Federal agriculture policy. In the United States, wetlands were considered to be of little value in their natural state, and Congress determined that they were not public domain because they could not be used for development. Thus, Congress passed the Swamp acts of 1849, 1850, and 1860 to aid in the draining of these lands to make them "productive" (USGS, 2005). The USDA classified this land alteration as “improved” land, and provided incentives in the form of grants or tax credits to drain a wetland to convert it into farmland.

More recently, areas adjacent to the Great Lakes have accrued high economic value because of their location (Ball 2003). Many people want lake front property, and with the controlling of water levels and new ways to harden shorelines, people were able to move into and/or remove the wetlands. There are many ways of hardening a shoreline, but the most prevalent way is to create a concrete barrier that dissipates wave energy and keeps the natural shoreline contained but isolated from the lake. Figure 1 shows the same stretch of land along the coast of Lake Ontario in Greece, NY, from 1930, 1961, and 2005. In the 1930 photo, there are no houses on the edge and the edge is actually smaller than the 1960 and 2005. Both the 1960 and 2005 images show residential encroachment and shore hardening devices such as retaining walls.

Figure 1- Shoreline Analysis of Lake Ontario on Edgemere Dr in Greece,NY. Looking at the lake shore, more people started to move out due to possible shore hardening and improved lake level management.

Shoreline erosion was a major concern during the first plan of the Saint Lawrence River control Board to control water levels on Lake Ontario. As the lakeshore developed, shoreline loss due to wave action increased. Thus this economic development created concerns for property loss, but not concerns over lost ecological functions. While not directly mentioned in the original lake level program, consistent lake levels favored less erosion and that led to less property loss (IJC, 1961). Additionally, the loss of lake level fluctuation altered the periodic flooding needed to maintain certain types of coastal wetlands. Yet coastal wetlands are easily impacted by hydrologic changes, both natural and human induced, which likely lead to cascading impacts in the Great Lakes ecosystem though vegetative changes. Periodic lower water levels will allow wetland plants to germinate and periodic high water levels are often needed to maintain wetlands (Assel, 2004). Lower water levels provide areas where oxygen can penetrate and high water levels are associated with primarily anaerobic respiration within the soil column, helping suppress non-wetland plant species. These fluctuating water levels are key hydrologic parameters for maintaining the health of wetland soils.

In the Lake Ontario system, lake level fluctuations are caused by many different factors. The natural causes for lake level fluctuations are events such as spring thaw and seasonal precipitation cycles. The water levels of the other Great Lakes also affect Lake Ontario because of the drainage patterns, with Lake Ontario receiving flow from all the other Great Lakes. Human diversions to the Mississippi Basin have lowered the supply in Lake Superior, so there is less contributing flow into Lake Ontario (IJC, 1961). These divisions were started in 1848 and have varied impacts on the Lake Ontario basin.

The main reasons for these diversions were to provide irrigation water to the country's growing agriculture lands. These farms are located primarily in the 5midwestern states. While the US and Canadian governments agreed to keep the water in the Great Lakes watershed, diversions to locations outside the Great Lakes watershed still occur. Looking at the diversion averages, however, there is only a 0.09 foot (2.74 cm) change in Lake Ontario due to the diversions (IJC, 1973). While this does not appear to be a large impact by itself, compounded with other uses of the lake system this could potentially contribute to significant change in the lake and coastal ecosystems. However, the regulation on the other Great Lakes did not affect the lake levels on Lake Ontario as much as its own regulation did when the dams were placed in the Saint Lawrence (IJC, 1973). Because of the natural variability of the water level fluctuations, due primarily to precipitation cycles and other natural processes, the water levels of Lake Ontario have been stabilized by human engineering to facilitate human use of the resource.

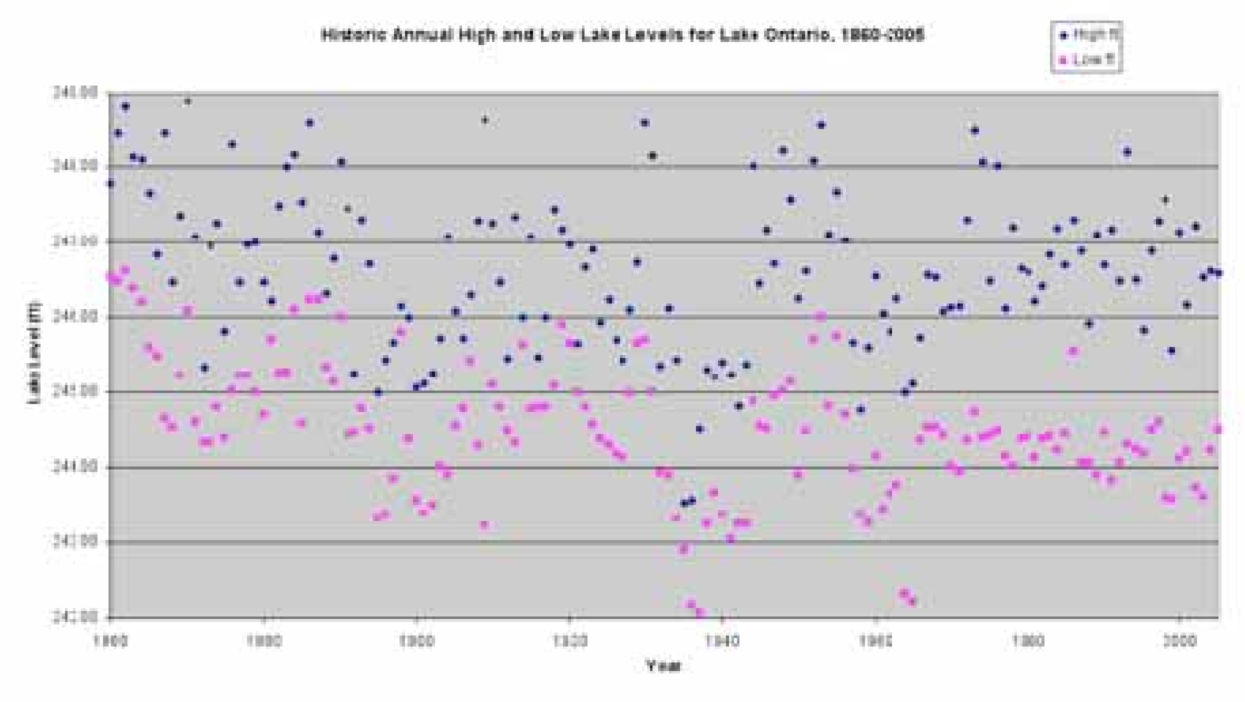


Figure 2- A Graph of the Historic High and Low Lake Levels taken from the Rochester, NY Gauge Station

Stable water levels are maintained for three primary uses, shipping, hydropower, and shore protection. To maintain stable water levels, the Robert Moses Dam was constructed in 1951. The water stabilization plan developed with the dam had very little consideration for non-human factors, such as environmental impacts. Starting in the 1950s and 1960s, citizens, managers, and scientists began to notice unforeseen ecological impacts due to lake level management. These include decreased water quality and flood increases (United States Government 1972-2006). Left unaddressed, these impacts could potentially affect the human population in regards to both health and economic loss.

Methods:

This project produced a GIS model for Lake Ontario that estimated potential change in coastal inundated areas due to lake level stabilization resulting from the construction of the Robert Moses Dam in 1951. The model was created using lake level data from the Rochester Sewer Department, United States Geologic Survey (USGS), and the United States Army Corps of Engineers (USACE), dating from 1866 to present, and an integrated DEM/bathymetry model from National Oceanographic and Atmosphere Administration (NOAA). The lake level data were used to create annual lake level high and low layers, which were used with the DEM/bathymetry to calculate and spatially locate areas of inundation and exposure, referenced to the published average lake level of 74.76 meters (245.26 feet) (IOC 1971). Results were compared to historic aerial photography of Lake Ontario's shore for wetlands delineation, producing a model about the different long-term changes to lake levels on the Great Lakes. The project used ArcGIS and the 3-D Analyst extension with raster functionality (Environmental Systems Research Institute, 1999-2006). Using bathymetry data from NOAA, a three dimensional model of Lake Ontario, including a two kilometer inshore buffer, was constructed.

The two-kilometer terrestrial buffer was derived to create a manageable dataset, as the full dataset (over 500 megabytes in size) did not allow for multiple processes due to current memory capability. Data from the City of Rochester Department of Engineering and City of Rochester Sewer Department were used for determining the seasonal lake levels from 1860 to 1930. These data are in a large blueprint graph, and highs and lows for each year were measured using the graph scale and entered into a spreadsheet. For the remaining years (1931-present), the USGS and USACE water monitoring data for the Rochester, NY area, already in a digital spreadsheet, were used to compute annual lake levels. Both datasets were combined and used to create an average lake elevation, calculated to be 245.57 feet (74.849736meters), which can be compared to annual highs and lows, raising or lowering the lake surface in the three dimensional model. These surfaces were converted to Boolean images and used to determine volume of water change and areas of inundation and/or exposure on an annual basis. This in turn allowed for estimates of wetland loss due to changes in inundation or exposure. Comparisons against the average lake level were conducted over three time periods. The first was an analysis all of the years (1860-present) to estimate generally if there is a potential long-term change in wetlands via shoreline inundation or exposure. The other two analyses were used to estimate how the dam operation impacted the average shoreline elevation by looking at areas of inundation/exposure pre and post dam. These data were checked against historical photos, available for Monroe County New York, in order to estimate accuracy. The complete conceptual model for the project is provided in Figure 3. The model consists of two primary steps. Figure 4 provides a graphical representation of the modeling process as generated by the ESRI Model Builder module.

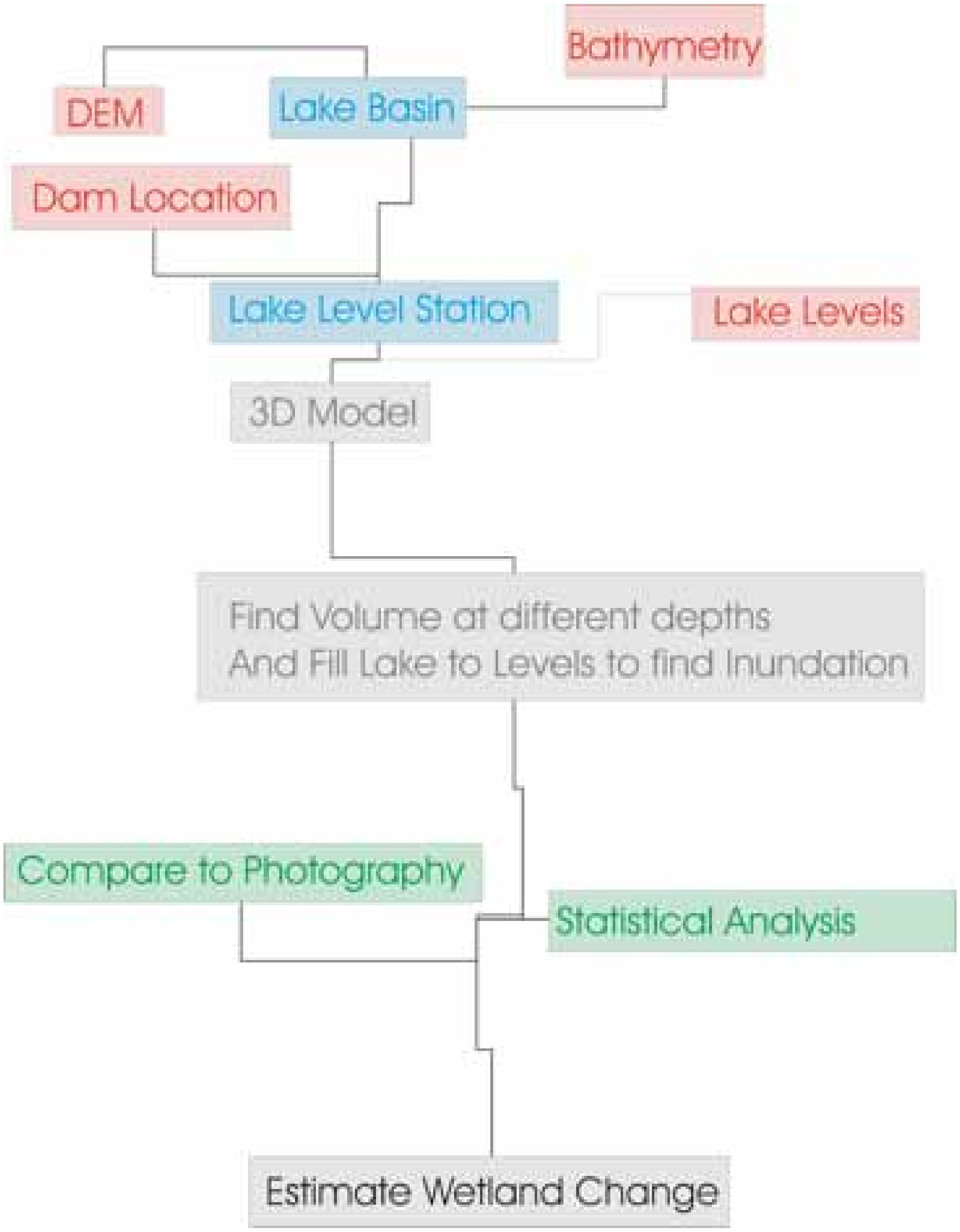


Figure 3 – The conceptual model for the analysis

The first step takes the Lake Ontario bathymetry model and reclassifies it, based on a given year's high or low lake level, to show what would be inundated as a "1" (less than or equal to the lake surface elevation) and exposed land as a "2" (greater than the lake surface elevation). Ideally, this analysis would have used "1" and "0" to generate a true Boolean image, but due to a limitation in the ESRI Geodatabase format, the "0" value generated errors in Model Builder. Step one is symbolized by the blue circle (Project_Lake1.tif), which served as the input for the reclassification routine (the first gold box), which outputs a raster file (e.g. 1860L.tif). The second converts the raster (e.g.1860L.tif) into a polygon feature to simplify the overlay process and to focus on the boundary of the lake alone. Step two is symbolized by the second gold box in the model (raster to feature class). This routine generates a Geodatabase, which automatically calculates the area of the lake surface polygon as an attribute, but unlike the shape file a geodatabase stores true curves, which is useful in area calculations. These steps were repeated semi-automatically 191 more times, done by copying step one and then altering the initial input values and names of the results to generate annual high and low files. The model represented in Figure 3 is a good graphical representation of the process, but the ESRI model builder module (Figure 4) used to build this graphic is an efficient method for inputting all the variables at once.

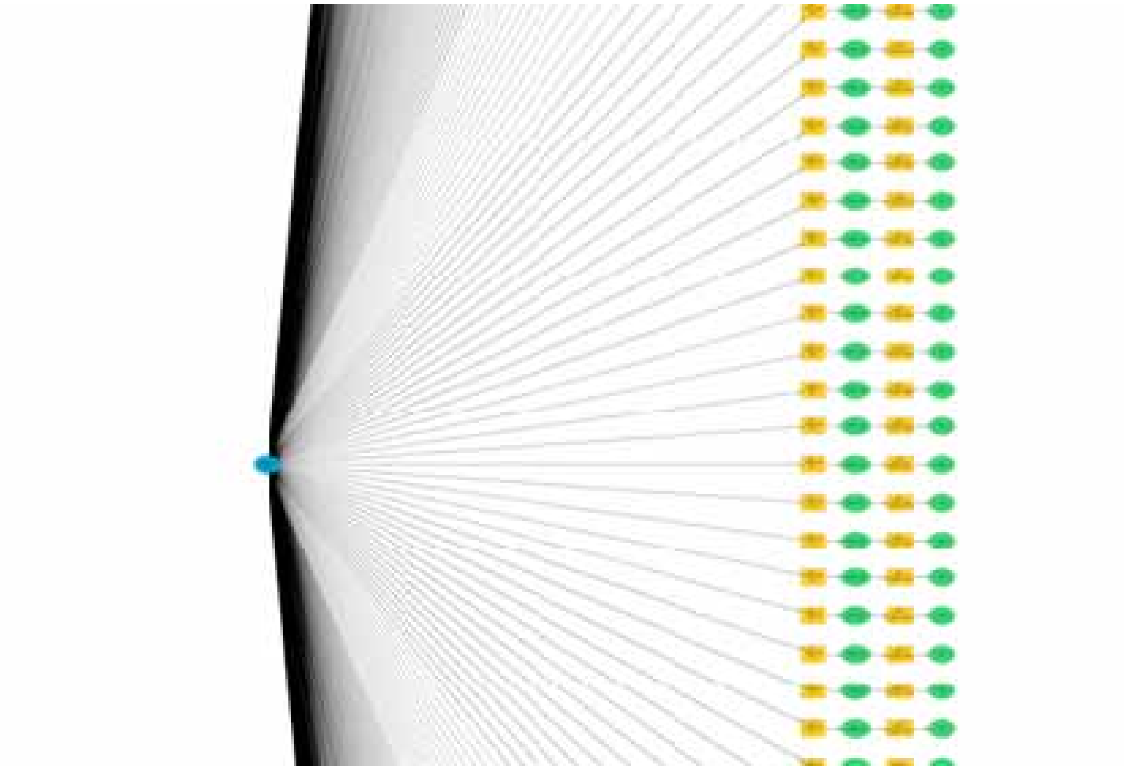
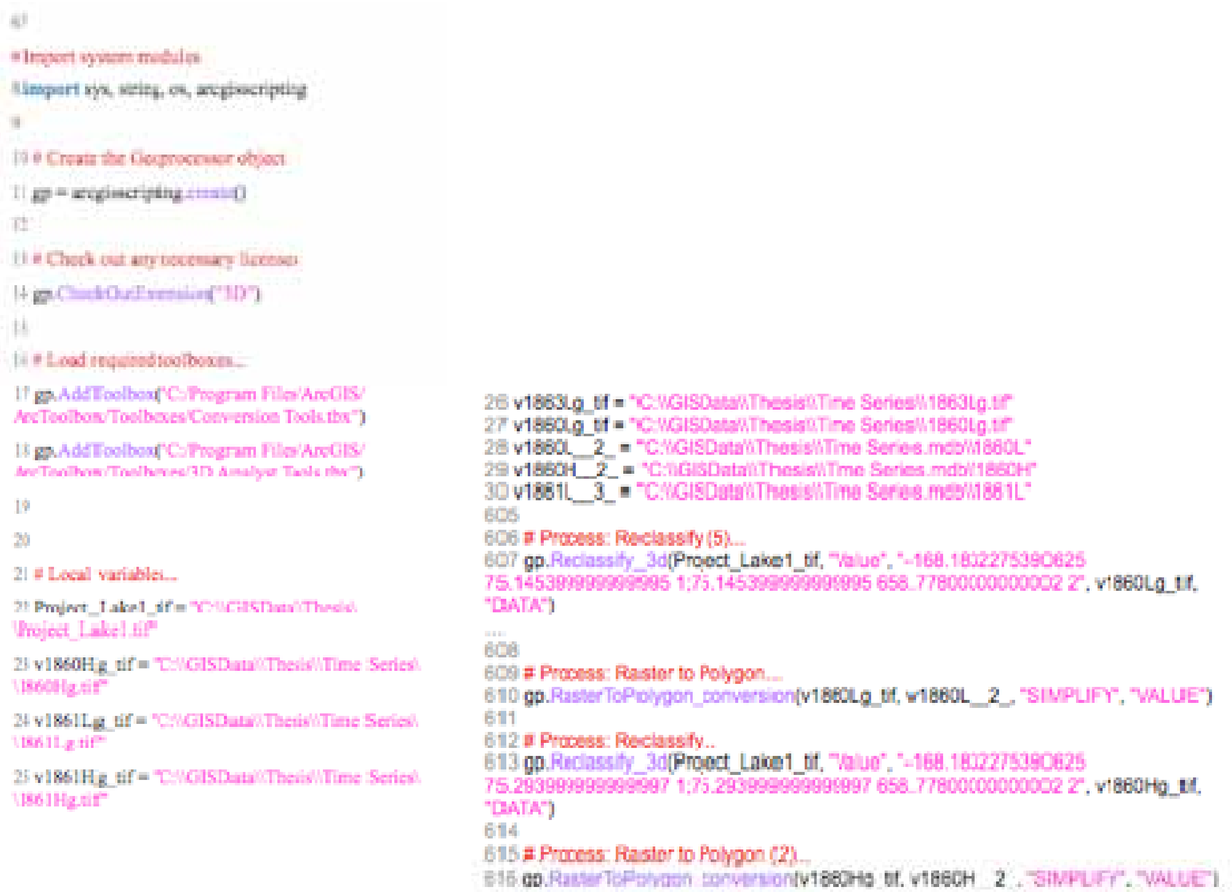


Figure 4 – A small piece of the ESRI Model Builder Model



```
# Import system modules
import sys, string, os, arcgisscripting

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Check out any necessary licenses
gp.CheckOutExtension("3D")

# Load required toolboxes...
gp.AddToolbox("C:/Program Files/ArcGIS/
ArcToolbox/Toolboxes/Conversion Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/
ArcToolbox/Toolboxes/3D Analyst Tools.tbx")


# Local variables...
Project_Lake1_tif = "C:\\GISData\\Thesis\
\Project_Lake1.tif"
v1860Hg_tif = "C:\\GISData\\Thesis\\Time Series\
\1860Hg.tif"
v1861Lg_tif = "C:\\GISData\\Thesis\\Time Series\
\1861Lg.tif"
v1861Hg_tif = "C:\\GISData\\Thesis\\Time Series\
\1861Hg.tif"
```

```
v1863Lg_tif = "C:\\GISData\\Thesis\\Time Series\\1863Lg.tif"
v1860Lg_tif = "C:\\GISData\\Thesis\\Time Series\\1860Lg.tif"
v1860L__2_ = "C:\\GISData\\Thesis\\Time Series.mdb\\1860L"
v1860H__2_ = "C:\\GISData\\Thesis\\Time Series.mdb\\1860H"
v1861L__3_ = "C:\\GISData\\Thesis\\Time Series.mdb\\1861L"

# Process: Reclassify (5)...
gp.Reclassify_3d(Project_Lake1_tif, "Value", "-168.1832275390625
75.145399999999995 1;75.145399999999995 658.77800000000002 2", v1860Lg_tif,
"DATA")

....

# Process: Raster to Polygon...
gp.RasterToPolygon_conversion(v1860Lg_tif, v1860L__2_, "SIMPLIFY", "VALUE")

# Process: Reclassify...
gp.Reclassify_3d(Project_Lake1_tif, "Value", "-168.1832275390625
75.293999999999997 1;75.293999999999997 658.77800000000002 2", v1860Hg_tif,
"DATA")

# Process: Raster to Polygon (2)...
gp.RasterToPolygon_conversion(v1860Hg_tif, v1860H__2_, "SIMPLIFY", "VALUE")
```

Figure 5- Sample of the python code for the analysis

To automate the process, the model was converted in to a python script (see snippet in Figure 5). This provides the ability to see all of the steps at one time and to input values using find and replace. Scripting in python is not really difficult, and it is highly recommended that an existing script act as a template to avoid programming errors. The python script also ran much faster than the model builder script. Ultimately, the python model took about two days to program / modify and three hours to run using an IBM workstation with a 3.4gigahertz Pentium IV^{HT} processor computer and 1.5 gigabytes of ram.

Results and Discussion:

The model did not work as envisioned the first time it was run. Problems stemmed from the software not recognizing the extreme value extents for the annual lake level data, which were programmed into the model. As a result, instead of simply producing Boolean images (0's and 1's) as part of a reclassify operation, the output images included pixels with values representing the programmed lake level extremes. The model was then adjusted by providing artificially extreme values (-168.1832275390625 for the low values and 658.77800000000002 for the high values, see python snippet) to reset the lake level data extents, which produced the Boolean image for lake and upland.

The working model results of the entire Lake Ontario shoreline suggest major changes in inundated area extents due to limiting lake level fluctuation ranges. The highs are represented in red and the lows are represented in yellow. The samples that are shown are only part of the 292 different results that were generated. The earliest recorded Lake Ontario level that was on record for this project was in 1860 and there was not a lot of change in lake level, resulting in minimal changes in the shorelines. Highs and lows that year only varied by 0.4 meters from the long-term average lake level (245.26 feet). Figure 6 (representing 1923) is one of the most extreme examples of the difference of shorelines in the analysis. This image suggests that the St. Lawrence was non-navigable for large ships during the low period. Issues like the disappearing St. Lawrence Seaway prompted a closer look at the DEM/bathymetry database and the lake level high and low database. Figure 7, like Figure 6, shows a similar occurrence of the "disappearing" St. Lawrence Seaway during an extreme low lake level, which certainly did not happen in 2005. Figure 8 shows a portion of modern NOAA chart, produced in 2005, including bathymetric data, illustrating the narrow, deep channel of the St. Lawrence Seaway. This channel has been maintained since 1824 (Great Lakes St. Lawrence Seaway System, 2007), when it was dredged from an original depth of 1.5 meters (5 ft) deep to the current depth of 8 meters (26 ft) deep. These examples point out the limitations of the DEM/Bathymetry model's resolution and issues concerning the data's ability to accurately reflect changes in shoreline and potential wetland changes.

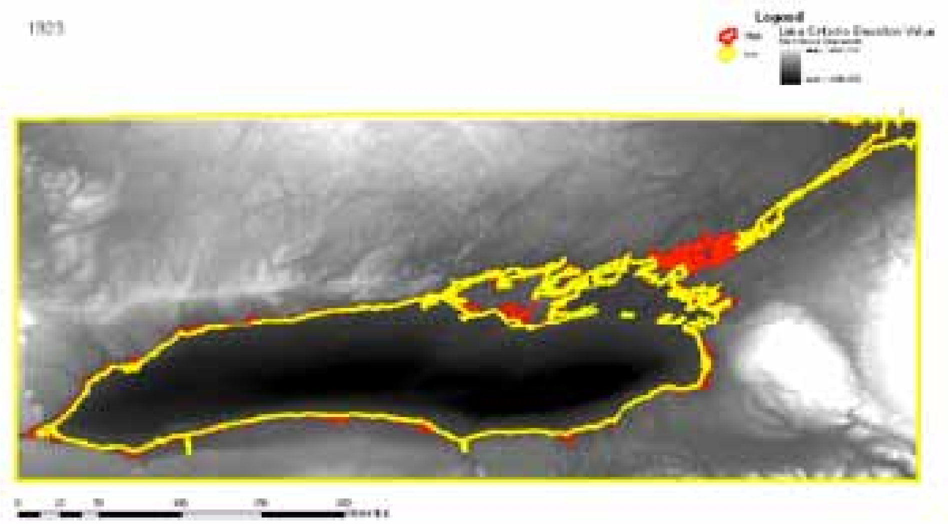


Figure 6- The 1923 analysis which started the question of why was the St. Lawrence River Drying Up

When specific areas were analyzed and verified close up, such as the St. Lawrence Seaway, problems with the raster DEM/Bathymetry layer resolution became apparent. These best available data have a resolution of 100 meters per pixel, and this level of detail does not allow for the accuracy that is needed to fully distinguish inundation and exposure changes due to the lake level, resulting in potential wetland changes. The reason that 100 meters is not accurate enough is that when dealing with coastal systems there could be a change as small a few meters of shoreline from a change in lake level of .01 meters. In general, the model appears to overestimate both the extent of inundation and exposure due to the large pixel size, which generalizes subtle changes in elevation and shoreline curves.

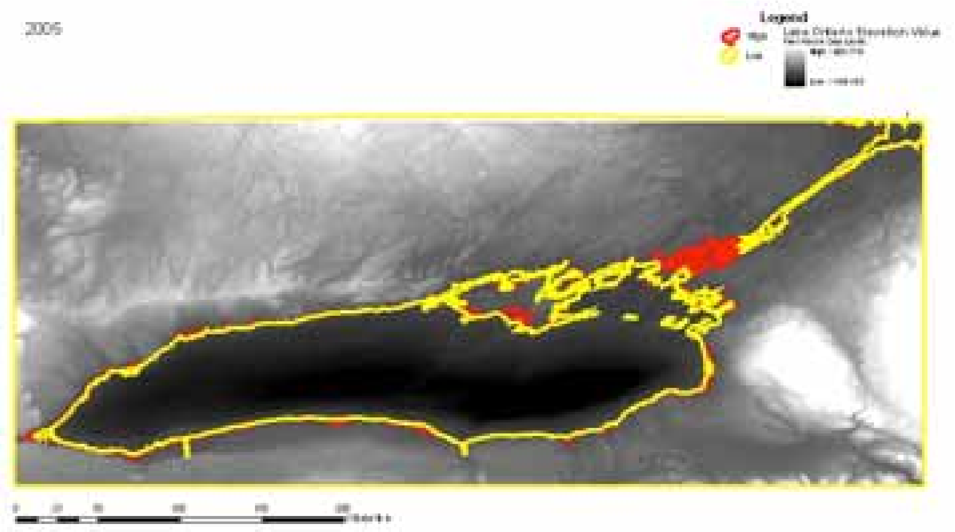


*Figure 7 - The 2005 Analysis also showing the same iss*ue with the St. Lawrence River

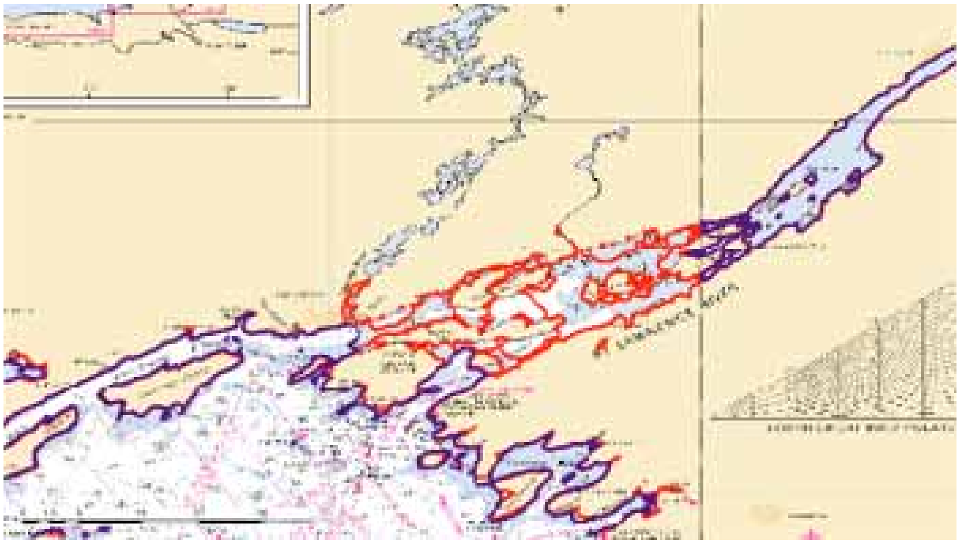


Figure 8- A sample from the 2005 NOAA Navigation Chart showing a navigable channel of the St Lawrence River during the entire year

Figure 9 - The 2005 analysis overlaid on the 2005 New York State Orthoimagery. As you can see large portions of the shoreline are supposed to be inundated and while there is problems with erosion, there is not a problem with complete flooding.

Because of this, large areas, such as the St Lawrence Seaway, show relatively large areas of change. Smaller bays along the Lake Ontario shoreline that were visible in the vector shoreline layer for Lake Ontario, however, were likely removed from the generalized lake surface raster images in most simulations. An example of this is Braddock's Bay (Figure 9), where high water inundation predicted in 2005 would have flooded that the Lake Ontario Parkway. This parkway is slightly elevated, and a more detailed elevation model would have picked this up, thus preventing the inundation. The low water level extents would also move the shoreline between 10-90 meters from where they should be. This limitation may be rectified when the more precise data model for the bathymetry and elevations are available from current LiDAR and bathymetry initiatives (Lopez-Torrijos 2005), slated for completion in 2012.

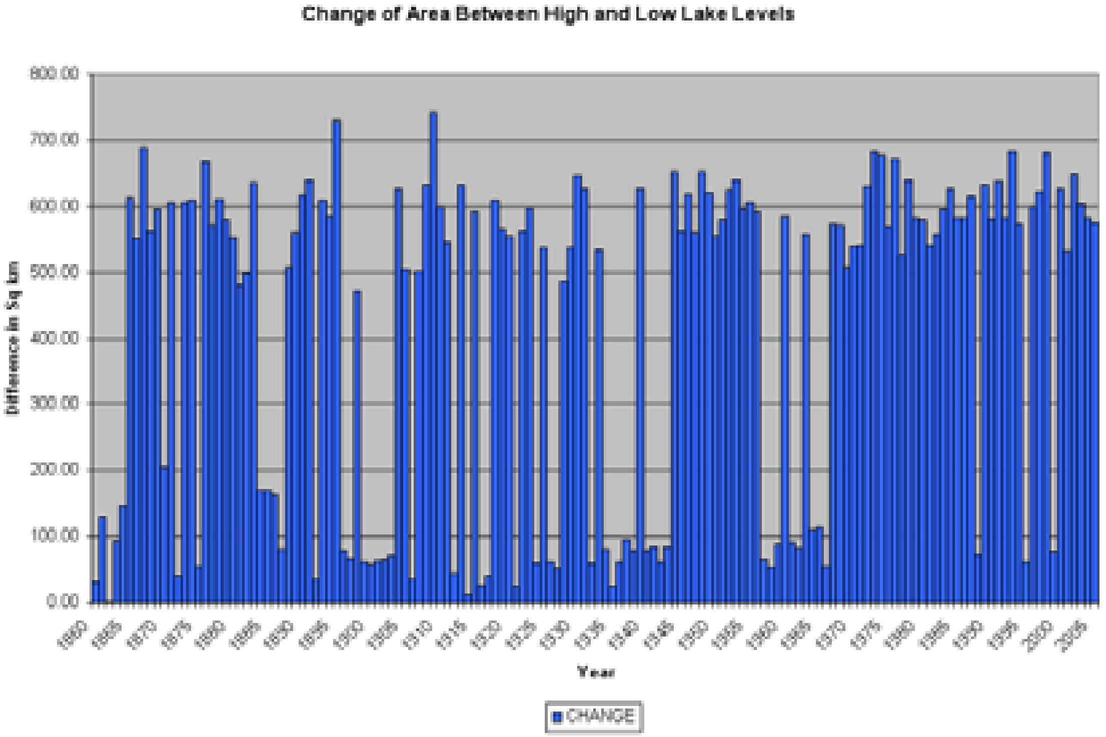


Figure 10 - A graph showing the changes in area between the high and low lake level. From the installation of the Robert Morse Dam on you can see there has been a consistency in the difference of the areas.

	Water Level	**Average Height (m)**	**Standard Deviation Height (m)**	**Area (km^2)**	**Change in Area km^2 between high and low**	**Standard Deviation Area (km^2)**
Pre Dam	High	75.18	1.18	19,505	498	294.41
	Low	74.58	0.97	19,007		37.78
		Difference 0.60				
Post Dam	High	75.17	0.74	19,454	376	220.72
	Low	74.40	0.54	19,079		21.07
		Difference: 0.77				
Totals					Difference: 123	

Figure 11 - A summary table of the results.

Another temporal problem encountered was not being able to model the duration of the seasonal highs and lows. The model generates extents for annual peak highs and lows, but extended periods of inundation are needed to influence wetland extent. A more accurate model would incorporate the lake levels for each day, allowing for an analysis of long-term inundation and potential alteration to wetland biogeochemical functions. Looking at detailed (daily) temporal patterns of lake level changes can be used to determine if the hydrology of a wetland is present for a given area, even if the area is not mapped as a current wetland (Tiner 2002).

Conclusions:

As a proof of concept, this model successfully generates annual lake areas based on annual extreme lake level data and illustrates where those areas of change may occur in Lake Ontario, indicating both changes in shoreline and potentially coastal wetland area. It also illustrates the stabilizing impact the dam has had on lake levels. The model was able to show the potential high and low areas of inundation and an estimation of loss or gain of shoreline. The estimation of shoreline loss or gain can be related to the loss or gain of coastal wetlands because of their relationship to the hydrology of the Lake Ontario system. Due to the resolution of the original data, the results produce areas of significant over or under estimation, resulting in generalized areas of interest. The uncertainty cannot be reliably calculated because the model was based on a 100 meter per pixel elevation model, and when dealing with significant, but localized, changes in elevation, such as a raised highway, subtleties of the landscape cannot be captured. A small area within a pixel's size would be lost to the average pixel value (10,000 m^2).

Even with the data resolution limitations, however, there are noticeable areas of repeated shoreline impacts, which would suggest areas of major wetland loss over time (123 km2 in the current model). Areas of greatest change in the model results appear to be in the St. Lawrence Seaway, the Buffalo, NY area, and in some of the smaller bays around the Lake (Figures 9). These would be the primary areas to focus on when the more precise data model for the bathymetry and elevations become available in 2012. Also, since the current model only looks at a few factors, some of the potential wetland loss may have been attributed to a change in wetland type. In order to more accurately predict this, we would have to look at a large time scale as well as both historical photos and ground surveys.

Conceptually, the model could work with any water body that had accurate bathymetry and digital elevation data. This model could aid in historical monitoring and studies to aid future research. This model could also help in determining human impact studies on certain bodies of water. Finally, this model fills a gap of information for Lake Ontario. There have been small studies of lake level fluctuation impacts on bays and rivers, but there has not been a complete Lake Ontario fluctuation model that dealt with the entire historical record. This hopefully will be added to the knowledge of the lake system and aid in future projects for years to come.

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Author Information

Justin D. Cole, MS, GISP
Senior GIS Analyst
Monroe County Department of Environmental Services
GIS Division
50 W Main St Suite 7100
Rochester, NY 14614
Phone 585-753-7504
Jcole@monroecounty.gov

Dr Karl Korfmacher
Environmental Science Program Director

Rochester Institute of Technology
85 Lomb Memorial Dr
Gosnell 08 Rm 2102
Rochester, New York 14623