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Methods For Estimating Sediment Yield And Dam Capacity In The Great Lakes Watershed

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METHODS FOR ESTIMATING SEDIMENT YIELD AND DAM CAPACITY IN THE GREAT LAKES WATERSHED

by

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INTRODUCTION

Background

Dams can store large volumes of sediment and greatly alter the geomorphology of a river. Different from natural lakes, sedimentation in reservoirs present a unique chronological record of sedimentation accumulation from the dam's construction to present day. Damming can result in increased flooding as the channels lose their flow capacity and impoundments lose storage (Csiki and Rhoads 2013, Baxter 1977).

It is estimated that sediment yield has increased by nearly an order of magnitude since European settlement. The U.S. Army Corps of Engineers (USACE) currently spends $40 million annually removing 2 to 4 million cubic yards of sediment from 100 federal harbors in order to maintain navigation channels. Much of the precipitation from the Great Lakes Basin enters streams and rivers and then eventually passes through these federal harbors carrying sediment and contaminants (Creech 2010). Increases in sediment production in the Great Lakes Watershed can be related back to the historical changes in landuse and development in the region. Changes in forestry from the logging industry were accompanied with the construction of many dams. After deforestation, many watersheds experienced major changes in landuse for agricultural development. Anthropogenic activities such as these have led to the incision of rivers with bank erosion and thus an increase in sedimentation in reservoirs (Creech 2010). While many of these watershed remain predominately agricultural, others have been converted back to a forested watersheds or converted into an urban watersheds, thus presenting an interesting case of sediment production differences based on landuse (Baxter 1977).

While there is massive amount of sediment production from these human activities, much of it remains behind dams and very little is actually delivered to the harbors and then out to the Great Lakes. As the dams lose storage capacity, flooding occurs and sediments overwhelm natural habitats and channels.

Problem Statement

Various studies have been conducted to try to understand sedimentation and quantify sediment transport (Hans-Einstein Equation 1942, Bagnold 1966, Advers and White 1973, Yang Method 1973, Flow Sediment/Power Sediment 2006). However, no one study holds the exact theoretical quantification of sediment transport. A recent study by Syvitski and Milliman created a long-term sediment flux model called BQART that was created to incorporate the many contributing factors to coastal zones which includes basin area and relief, geography, geology and human activities. The model pulled data from over 480 rivers which represented over half of earth's land surface (Syvitski and Milliman 2013). Studies that try to understand the hydrology are also being examined which can help assess the nature as well as vulnerability of the system (Pastore 2012).

This study seeks to further the current understanding and knowledge of sedimentation in the Great Lakes Watershed and understand the magnitude of the contributing anthropogenic factors. Twelve reservoirs throughout the Great Lakes watershed were selected and analyzed for this study. Both historic and new data were collected on these dams to determine how the storage capacity has changed over time and to estimate the remaining life-span of the impoundments. Different methods were used to estimate the sediment yield and dam capacity including (1) bathymetric subtraction, (2) USGS (United States Geological Survey) sediment gages, (3) the application of trend lines, and (4) radionuclide dating. Past studies such as the USACE regression equation and the RESSED equation will be used to compare the results of this study with. The USACE regression equation quantifies a sediment yield based on the watershed drainage area in tons per year. This equation was developed from USACE 516e studies in the Great Lakes Watershed. The RESSED equation is developed from a sedimentation survey database for selected reservoirs across the United States.

Because little is known about the remaining storage capacity in the dams on the Great Lakes, an improved understanding of the mechanisms influencing sediment production and storage in the watershed will provide insight regarding potential control of this process.

SITE SELECTION

Introduction of Sites

This study selected 12 reservoirs throughout the Great Lakes watershed (Figure 1) to represent different land cover types across the Great Lakes to understand the scope of sedimentation in this region. The field data from these 12 reservoirs was collected between the summer of 2010 and the winter of 2011. There was emphasis was on studying reservoirs that drained agricultural land and as well as urban land or forested land (Table 1) below.

Figure 1: Map of All Selected Reservoir Sites

Historical analyses were conducted on the twelve sites to identify and understand any anthropogenic influences that may have influenced sedimentation accumulation rates. Likewise, information on non-anthropogenic factors such as flooding and forest fires were also collected and analyzed. While it is difficult to piece together a complete reconstruction, understanding historical contributing factors is vital to proper interpretation of this sort of data.

Table 1: All Dams in Study

Dam Name	Location	Construction Year	Land-use Type	Drainage Area (sq. mi)	River
Lake Rockwell	Kent, OH	1914	Forested	208	Cuyahoga
Riley	Sherwood, MI	1923	Agricultural	518	Saint Joseph
Upper Green Lake	Green Lake, WI	1869	Agricultural	115	Puchyan
Mio	Comins Flats, MI	1917	Forested	1100	Au Sable
Alcona	Oscoda, MI	1923	Forested	1469	Au Sable
Brown Bridge Pond	Traverse City, MI	1922	Forested	153	Boardman
Goshen Pond	Goshen, IN	1866	Agricultural	554	Elkhart
Potters Falls	Ithaca, NY	1911	Forested	45.5	Six-mile
Independence	Columbus, OH	1924	Agricultural	5545	Maumee
Ballville	Fremont, OH	1911	Agricultural	1254	Sandusky
Ford Lake	Belleville, MI	1932	Urban	810	Huron
Webber	Lyons, MI	1907	Agricultural	1750	Grand

Lake Rockwell Dam

Lake Rockwell Dam is located in Kent, Ohio and is part of the Upper Cuyahoga watershed. It was constructed as the primary water supply for the City of Akron and it remains so. Based on GIS landuse maps created for this study, the drainage area primarily consists of forested land cover as well as some agricultural and developed use. The growth in industry and population led to the pollution of the downstream river and the infamous burnings of the Cuyahoga River. According to the Akron Water Supply, the area surrounding the dam has never had any recorded dam failures or forest fires. Likewise, there has never been any dredging done in Lake Rockwell although there had been discussion of it in the past. In the 1980s, there was an alum feeding program in place for a few years where aluminum sulfate was fed into the Cuyahoga River just upstream of Lake Rockwell. (Glowczewski, 2013). The drainage area is 208 square miles (= 539 km^2) and when built, had an estimated storage volume of 7,422.8 acre-feet (= 9.16 x 10^6 m^3) (National Inventory of Dams, 2010)

Riley Dam

Riley Dam impounds Union Lake in Branch County, Michigan and is located in the St. Joseph River basin on the main branch of the St. Joseph River which just downstream of Union City, Michigan. The Riley Dam sub watershed area consisted primarily of forest as well as wetland and savanna prior to the construction of the dam (Comer and Albert, 1998). Currently, over half the land use is an agricultural type as determined by GIS mapping calculations. Population increases to the surrounding counties (Calhoun, Hillsdale and Branch) also suggest significant changes in land use as the population has grown by 81% from 1920 to 2000 (Creech et al., 2010). The impounded lake has a drainage area of 518 square miles (= 1342 km^2) and had a storage volume of 3,240 acre-feet (= 4.00 x 10^6 m^3) (National Inventory of Dams, 2010).

Upper Green Lake Dam

Upper Green Lake Dam, which impounds Green Lake, is downstream of the city of Ripon, Wisconsin. The dam is located on the Puchyan River which drains into the Fox River and ultimately into Lake Michigan at Green Bay. Green Lake existed prior to the construction of the dam. Prior to European settlement, the land cover for the area was heavily forested with some wetlands and grasslands as well (GIS). Currently, the land use is mainly agricultural with pockets of developed land particularly near the city of Ripon. The Green Lake area reported high water level that threatened the dam and so in 1987, the bulk head on the dam was replaced and water levels returned to normal levels. The dam was also modified in 1994 (Heiple and Heiple 1977). By comparison to the other sites investigated in this study, the watershed is relatively small being 115 square miles (= 298 km^2) with Ripon being not far upstream while the storage volume is 30,000 acre-feet. (National Inventory of Dams, 2010).

Mio and Alcona Dam

Both Mio and Alcona Dam are impoundments along the Au Sable River with Alcona Dam being roughly 20 miles downstream of Mio Dam. Alcona Dam is located in Alcona County, Michigan whereas Mio is located in Oscoda

County. Mio Dam was constructed in 1917 and while the Alcona dam began construction in 1916, it was not completed until 1923 (due to financial issues). Prior to the construction of both dams, the area surrounding was used heavily by lumbering industries and as logging railroads that surrounded the Au Sable River (Macdonald 1942) as the land cover was primarily forested. Cleared lands were used for agricultural practices. Currently, the drainage area for these dams are primarily forested as well. In August of 2009, the water level of Mio dam was drawn down by Consumers Energy. Mio Dam has drainage area is 1100 square miles (= 2840 square kilometers) and a storage volume of 6061 acre-feet (= 7.48 x 10^6 m^3) (National Inventory of Dams, 2010). Alcona Dam has a drainage area is 1469 square miles (= 3805 km^2) and had a storage volume of 25000 acre-feet (= 30.84 x 10^6 m^3) (National Inventory of Dams, 2010).

Brown Bridge Pond Dam

Brown Bridge Pond dam was located on the Boardman River and was part of the Boardman River watershed. Along with the Brown Bridge Dam, there was construction of many dams from 1867 to 1922 along the Boardman River. On October 7th, 2012, there was a breach on the Boardman River which emptied Brown Bridge Pond. This occurred due to the Brown Bridge Pond dam removal project (Puit et al., 2012). The dam has since been removed. (Ellison 2013). The land use of the present and past the contributing drainage area is and was largely forested. This dam had a drainage area of 153 square miles (= 396 km^2) and the storage volume is 1700 acre-feet (National Inventory of Dams, 2010).

Goshen Pond Dam

Goshen Pond Dam is located in Elkhart County, Indiana and sits on the Elkhart River which eventually drains into the St. Joseph River. The drainage area of Goshen Pond Dam is 554 square miles as calculated by GIS map. The Elkhart River Watershed comprises of Elkhart, LaGrange, Noble, and Kosciusko counties. In 1992, the original dam was replaced after having had to add supplementary draw down structure and other previous repairs. Throughout the twentieth century, a hydroelectric plant that fueled milling industry along the river started to fade out and ended by the mid-1960’s (Elkhart County Park Department, 2012). The drainage area of Goshen Pond dam is 554 square miles (= 1434.85 km^2) and the storage volume is 930 acre-feet (National Inventory of Dams, 2010).

POTTERS FALLS DAM

Potters Falls Dam is located on the Oswego River and is a part of the Six Mile Creek Watershed. Upstream of Cayuga Lake, the dam is the water supply for the city of Ithaca. In 1911, Potters Falls Dam was completed but due to the geography and geology of the area, a small silt dam was constructed upstream of Potters Falls Dam in 1925 to help slow the sediment accumulation to the main reservoir (Tompkins Historical Society, 2012). In 1936, the silt dam was repaired, cleaned and enlarged. The silt dam is drained and dredged every few years. However, Potters Falls Dam still has a lot of sediment accumulation. Full scale dredging of Potters Falls has not been done, but it was dredged by the opening of the low level outlet gate through the 1950s (Tompkins Historical Society, 2012). The drainage area of Potters Falls Dam is 45.5 square miles (= 117.84 km^2) and the storage volume is 800 acre-feet (National Inventory of Dams, 2010).

Independence Dam

Independence Dam is located near the city of Defiance, Ohio on the Maumee River. The River is located near Ft. Wayne, Indiana and flows towards Toledo, Ohio where the river spills into Lake Erie. The Independence Dam is a low head dam owned by the Ohio Department of Natural Resources. There are not many trees located along the Maumee River. According to documentation obtained on the U.S Fish and Wildlife website, only 3 to 5 % of the Maumee River Basin remains wooded, which is due to agricultural purposes. The existing dam on the Maumee River was completed in 1924. This cement dam replaced the original wooden dam which was built in the 1800s for the canal system (Evans et al., 2002). The drainage area of Independence dam is 5545 square miles (= 14,362 km^2) and the storage volume is 3270 acre-feet (National Inventory of Dams, 2010).

Ballville Dam

During a statewide flood of 1913, the original dam was heavily damaged and had to be enlarged to what it is presently. Ballville Dam is 15 miles from the mouth of the Sandusky River, which flows from South to North. Ballville Dam is located on the outskirts of the city of Fremont, Ohio and it also owned by the city. There was minor debris removal during the 1904s and 1950s near the penstock intakes. There was also a drawdown in 1969 to repair and modify the dam. Because the dam reservoir is long (3400 meters) and narrow (less than 490 meters), there is greater flooding and widening of the river upstream of the dam. Currently, the city is working with the US Army Corps to remove this dam. The drainage area of Ballville Dam is 1254 square miles (= 3,247.9 km^2) and the storage volume is 524 acre-feet (National Inventory of Dams, 2010).

Ford Lake Dam

Ford Lake Dam, which is in Ypsilanti Township, Michigan, is located on the Huron River and is a part of the Huron River Watershed. Ford Lake Dam was constructed by Henry Ford in 1932 as a part of his program to develop rural industry in Michigan (Benson Ford Research Center, 2012). As a result, the area surrounding the lake was bought out for agriculture as done by employees of the dam. The development of Interstate-94 in the late 1940's and early 1950's contributed to the current landuse of the area which is primarily urbanized. The drainage area of Ford Lake Dam is 814 square miles (= 2,098 km^2) and the storage volume is 17,770 acre-feet (National Inventory of Dams, 2010).

Webber Dam

Webber Dam is located on the Grand River in Ionia County, Michigan. Webber dam was constructed in 1907 and began operations on March, 12, 1907 (Hyde, 1976). The drainage area of Webber Dam is 1750 square miles (= 4,532 km^2) and the storage volume is 6,000 acre-feet (National Inventory of Dams, 2010

METHODS

Sediment Yield Using Bathymetric Subtraction

The first approach used in the estimation of sediment accumulation applied a post and pre dam construction bathymetric subtraction method across the reservoir. Current bathymetry data was collected using a SonTek M9 River Surveyor. Cross sections that were perpendicular to the flow were mapped at the smallest intervals as time allowed. In order to estimate sediment yield using bathymetric mapping, a historic bathymetry map of reservoir and river pre-dating the construction of the dam was used. Most of the dams used in this study were built approximately 80 to 100 years ago. Often due to changes in ownership of the dam, pre-construction maps could not be found for all sites. Therefore, the bathymetric subtraction method could not be applied to all reservoirs. For the reservoirs with historic maps, ArcGIS software was used to create a digital pre-dam construction bathymetry map. Landmarks that existed in both historic and present day were used to line up the historic map as an overlay to the present day. This method provided the study a total average sedimentation rate from pre-construction to current time.

Sediment Yield Estimation Using United States Geological Survey Sediment Gages

A second method for estimating sediment yield used collected data from USGS sediment gages. This technique is not applicable to all reservoirs because sediment gage data was either not available for a number of years or was not available at all. For this study, upstream impoundments were not considered. Each USGS sediment gage can have a different period of record and therefore needed to be interpreted in a way that represented all the data properly. The data, recorded in tons per day, was summarized over each year and averaged over all the years of data. In order to make comparisons, the data was normalized by the contributing drainage area. From these gages, 5 quantitative methods for sedimentation were developed.

The first application method in determining sediment accumulation used data collected from USGS sediment gages located upstream of the reservoir, as well as (in some cases) sediment gages downstream of the reservoir. Data from these gage locations were used to develop an estimated loading rate (tons/sq. mile/year) to the reservoir. This was done by extrapolating the gage data to fit the drainage area of reservoir. The loading rate was determined based on the stream mile associated with the gages. The second application then used the same sediment gages to calculate a loading rate by determining the un-weighted average value. The third application calculated the weighted average value. For the fourth application, the weighted average value was only applied to the un-gaged areas of the reservoir. The sediment load contributing from the other areas were calculated using the data reflected by the sediment gage. A summation was applied to incorporate all of these components. And finally, a fifth application was applied that interpolates the slope of the contributing watershed to the gages and the reservoir. For calculations for each method, please refer to Appendix I.

Sediment Yield Estimation Using Radionuclide Dating of Sediment Core Samples

The third technique in sediment yield estimation used radionuclide dating. Radionuclide dating of sediment yields a rate in centimeters per year. The methodology and results of this method were conducted by Dr. Mark Baskaran and Dr. Anupam Kumar.

A total of 112 sediment cores were taken from 12 of the study sites across the Great Lakes watershed, each having about 10-12 core samples. The cores were frozen and cut a 1 cm thick slices for the top 10 cm and 2 cm for the rest of the core. From the radionuclide dating results, more specific time frames can be correlated with certain mass depths. Therefore, this method serves as an important means of relating anthropogenic activity to certain time periods which the other methods do not. The radionuclide dating shows the quantification of sediments in a reservoir and their movement. The Constant Flux Constant Sedimentation model (CFCS) assumes system is in steady state with a constant accumulation of sediments and a constant supply of 210Pbxs (checked against Cs Peak) (Robbins 1978). The equation for the $^{210}Pb_{xs}$ activity (A_x) at depth x is calculated as shown below:

$$A_x = A_0 e\text{-}^{\lambda Pbt}$$

Where,

Ax = $^{210}Pb_{xs}$ activity at depth x

A0 = $^{210}Pb_{xs}$ activity at depth 0

t = age (years)

The natural log of $^{210}Pb_{xs}$ activities can be plotted against mean linear depth to calculate linear sedimentation. Aging a layer of sediment for ^{137}Cs can bit a difficult to date as precisely as ^{210}Pb. This is because the appearance of ^{137}Cs at the bottom of the core corresponds to the year 1952 when nuclear tests were first conducted after Nagasaki and Hiroshima in 1945. This can often be difficult to identify due to radioactive decay. Because of these difficulties, this study will not be using the ^{137}Cs data to associate an age with each layer. However, aging a layer of sediment is more feasible for ^{210}Pb. This is done by dividing cumulative mass depth (g cm^{-2}) by sediment mass accumulation rates (ω_{pb} g cm^{-2} yr^{-1}) which gives the sediment layer age in years based on the CFCS model (Robbins 1978). Sedimentation mass accumulation rates were calculated by plotting $\ln^{210}Pb_{xs}$ activities against cumulative mass depth and substitution ω_{pb} for slope (Baskaran et al 2014. *In Press*).

Human activities such as dredging were noted. For example, Potters Falls Reservoir has record of dredging right near the head of the dam, but nowhere else in the reservoir (Tompkins County Historical Society 2012). Therefore, sediment cores for dating were not selected near that area. The sedimentary record would not be well preserved. Radionuclide dating data and calculations can be found in Appendix II.

Core Length Method

Because not all the core samples the reservoir were dated due to costs, an alternate method was devised to get useful data from the core samples. It was assumed that the core sample ended at native soil and if not was noted otherwise. Each core sample represents the total amount of sediment accumulated at each point since the dam was constructed. This method does not work for reservoirs that were lakes prior to construction such as Upper Green Lake Dam and Ford Lake Dam. This alternative method assigned a contributing surface area and summed the results across the reservoir surface and divided the number of years since dam construction for each dam. Ballville Dam did not have core samples taken from the reservoir. Core length method calculations can be found in Appendix C.

STUDY RESULTS AND DISCUSSION

Sediment Yield Using Bathymetric Subtraction

The total amount of sediment deposition was converted to tons using the equation below and then the result was divided by the number of years between dam construction and current bathymetry. These calculations assumed the specific gravity of the sediment to be 2.65 and the assumed porosity of the sediment to be 0.58.

$$\frac{(2.65)(0.58)\left(62.4\ \frac{lbs}{ft^3}\right)\left(\frac{1\ ton}{2{,}000\ lbs}\right)(Total\ Amount\ of\ Sediment\ ft^3)}{\#\ of\ years\ since\ construction} = Sedimentation\ Rate\ {}^{tons}/_{year}$$

For Lake Rockwell, Upper Green Lake, Mio, and Potters Falls Dams, historic bathymetry maps were obtained and therefore the bathymetric subtraction process was applicable. All bathymetric models showed an accumulation of sediment or a positive sediment yield since pre-construction time periods. The results of Upper Green Lake Dam are higher than the other methods of calculation for this dam as well as other dams of similar landuse categorization, which may be due in part to the site having already been a lake prior to the dam's construction. Upper Green Lake is about 11.5 square miles in area and 240 feet at its deepest point. Upper Green Lake is also a natural lake with Upper Green Lake Dam only providing approximately 8 feet of head and therefore it was a unique challenge to map. While, the reservoir transects were mapped at a proper speed, the large lake allowed for spacing to be at 1,400 feet which is fairly large. Since the Green Lake was already a lake before it was a reservoir, the bottom of the lake was observed to be very smooth and with very gradual contours. This provides greater confidence in the bathymetric map as a smooth surface often correlates with very few areas improper interpolated data. The reservoirs where the relief is minor and the historic map contours are coarse leave much of the subtraction for interpolation. Of the four sites where the bathymetric subtraction method applied, Lake Rockwell Dam and Potters Falls Dam were reservoirs that were geometrically deeper and narrower compared to other sites in this study. Both were mapped with high resolution and could be geo-referenced very accurately to the pre-construction maps. Potters Falls Dam also had two different maps used in the subtraction process. Upper Green Lake Dam and Mio Dam however, had a lower level of resolution to the mapping process as the reservoir bottoms were very spread out.

Potters Falls Dam is another one of the reservoirs in this study that drains primarily agricultural land. This study site is unique in the fact that two different historic maps were used to estimate sediment yield. The first historic map used for bathymetric subtraction was dated and yielded 9,406 tons per year since then. The second historic map used for bathymetric subtraction was dated 1909 and was from before the dam was constructed in 1911. Subtracting this map from the current map yielded 12,885 tons per year. Subtracting the 1951 map from the 1909 map yielded 17,912 tons per year. Thus, the reservoir experienced a higher sedimentation rate during the first 41 years (17,912) after construction and slowed down from 1951 to current (9,406) but averaging 12,885 since construction. The table below (Table 2) shows the sediment yield results when using the bathymetric method. To see calculations and process of this method, please refer to Appendix IV.

Table 2: Results using Bathymetric Method (tons/yr.) and (tons/yr. /sq. mile)

Bathymetric Method	Sediment Yield (tons/yr.)	Sediment Yield (tons/yr. /sq. mile)
Lake Rockwell Dam	17,980	93.7
Upper Green Lake Dam	88,913	1,028
Mio Dam	18,546	16.5
Potters Falls Dam	12,885	305

Sediment Gage Data – Method 1 to 5

Sediment yield estimation using USGS sediment gages could only be applied to some of the dams in this study as other reservoirs either did not have sediment gages or watershed maps were not developed for those sites. The results were estimated for Lake Rockwell Dam, Riley Dam, Upper Green Lake Dam, Potters Falls Dam, Independence Dam and Ballville Dam.

Lake Rockwell Dam and Potters Falls Dam had sediment gages that were well distributed across the watershed. Lake Rockwell Dam, located on the Cuyahoga River which has three USGS sediment gages within its watershed is 208 square miles (not considering any impounded areas upstream). Potters Falls Dam, located on Six mile Creek which has two USGS sediment gages just upstream is 45.5 square miles (not considering any impounded areas upstream). When assessing slope as a sediment yield estimation method, it appears that sites that have well distributed sediment gages tend to output numbers that correspond to the other methods developed in this study better.

Contrarily, the numbers for the slope method for Riley Dam and Upper Green Lake Dam are lower than the rest of the numbers for the other methods. Riley Dam which located on the St. Joseph River and has four sediment gages upstream is 518 square miles (not considering any impounded areas upstream). The sediment gages within this watershed only drain a small part of total area. Gage Application Method 1 was not applied to Riley Dam as there an accurate estimation could not have been made using this method due to too many inputs. Similarly, Upper Green Lake Dam which is located on the Puchyan River and has three USGS sediment gages in its watershed is 103.2 square miles (not considering any impounded areas upstream). Gage Application Method 1 was not applied to this site because the sediment gages are on different rivers inputting to Green Lake in different areas. It is often difficult to have a perfect record of data.

Table 4) shows the results for each site using the 5 different sediment gage methods both in total sediment yield (tons/year) and sediment yield by drainage area (tons/sq. mi/year). While it is likely that upstream impoundments retain sediments, this study looked at the total drainage area for an impoundment for consistency across dams due to lack of equal information for all dams.

Table 3: Results of Sediment Gage Methods (tons/year)

Method	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Potters Falls Dam	Independence Dam	Ballville Dam
Sediment Gage App. 1	19,300	N/A	N/A	24,978	1,319,706	294,486
Sediment Gage App. 2	29,536	7,839	18,543	17,760	1,224,114	196,376
Sediment Gage App. 3	57,616	5,609	4,051	18,328	N/A	258,362
Sediment Gage App. 4	18,209	5,105	4,700	20,662	1,312,018	275,067
Sediment Gage App. 5	21,167	618	1,673	11,230	N/A	N/A

Table 4: Results of Sediment Gage Methods (tons/year/square mile)

Method	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Potters Falls Dam	Independence Dam	Ballville Dam
Sediment Gage App. 1	93	N/A	N/A	549	238	235
Sediment Gage App. 2	142	15	161	390	221	157
Sediment Gage App. 3	277	11	35	403	N/A	206
Sediment Gage App. 4	88	10	41	454	237	219
Sediment Gage App. 5	102	1	15	247	N/A	N/A

Sediment Yield Using Various Trendlines

Methods of this study were compared against the data from two trendlines from previous studies, the USACE Great Lakes Regional Sediment Curve and the Great Lakes Reservoirs from the Subcommittee on Reservoir Sedimentation (RESSED database). Applying this study's data to the two trend line applications developed from these previous studies, Tables 5 and 6 were developed.

United States Army Corps of Engineers Detroit District

This regression equation was developed by the United States Army Corps of Engineers Detroit District to relate watershed drainage area with sediment yield in tons per year (Creech et al., 2010). This equation uses 13 data points from other USACE 516(e) studies in the Great Lakes watersheds, and 48 other Great Lake Reservoirs from the Subcommittee on Reservoir Sedimentation database (Creech et al. 2010). The resulting equation is as follows:

$$Y=407.3*A^{0.77}$$

Where,

Y= Sediment yield in tons per year

A=Area of the watershed drainage area in square miles

The resulting curve is in Figure 2 below

Figure 2: United States Army Corps of Engineers Great Lakes Regional Curve

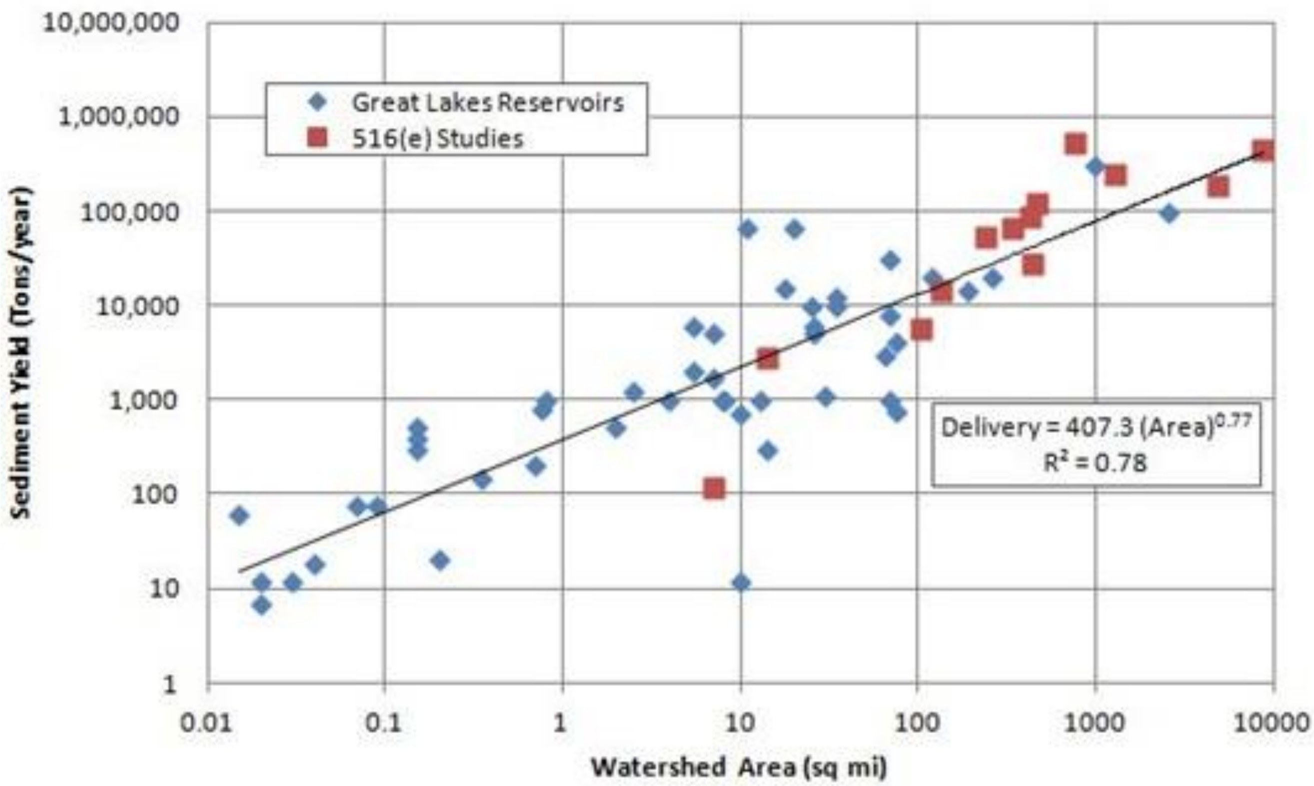

Figure 3: Sedimentation Trendline (as compared to USACE Great Lakes Regional Curve)

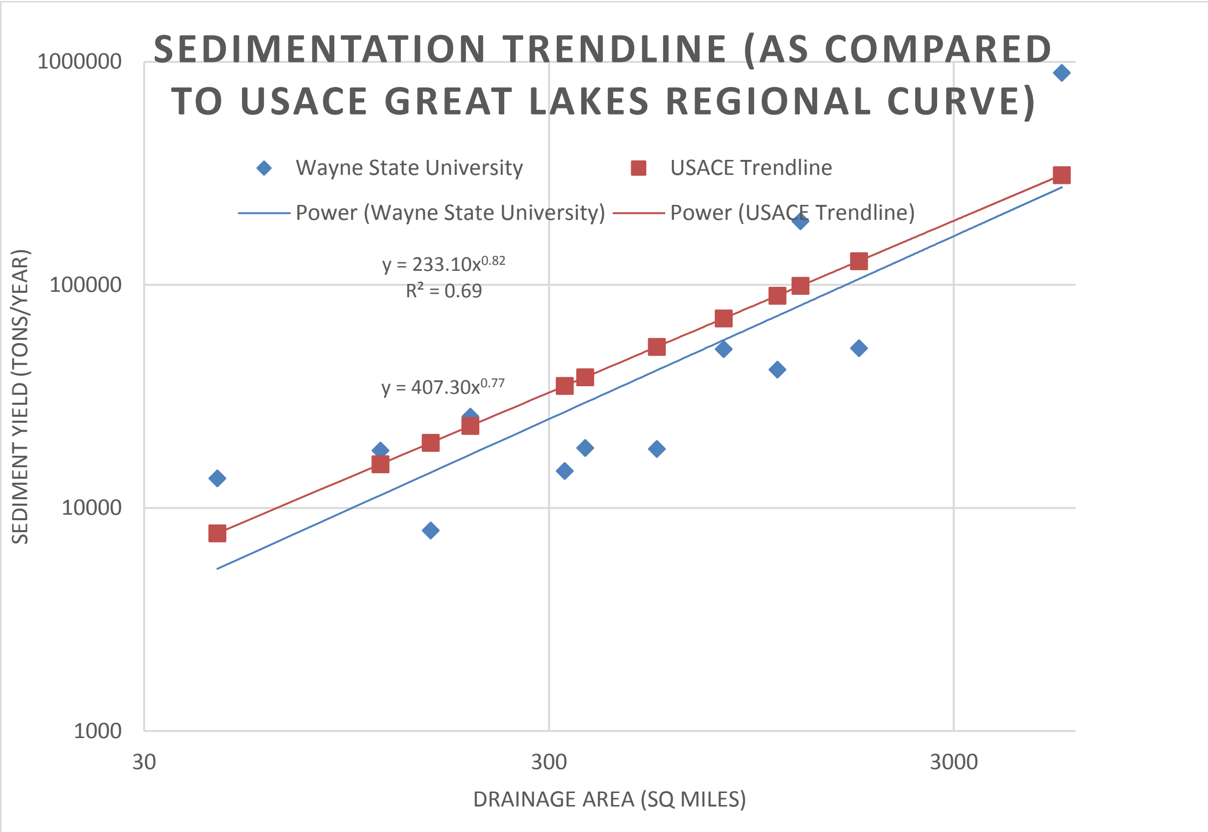

Figure 3 show the results of this study compared with USACE Great Lakes Regional Curve with the red points not indicating actual data points, but instead reflecting the trendline equation (points were created using the equation from the previous figure, Figure 2 to be able to plot the position of the trendline in comparison to this study's data). Overall, a similar positive correlation between drainage area (sq. miles) and sediment yield (tons/year). The r^2 values were similar as the USACE Great Lakes Regional was 0.78 and this study yielded 0.69 suggesting the data collected for this study is fairly acceptable. Results were more or less in the same order of magnitude suggesting the validity this study according to the USACE Great Lakes Regional Curve.

Great Lakes Reservoirs From the Subcommittee on Reservoir Sedimentation

RESSED is a database where sedimentation survey data is stored for select reservoirs in the United States. The units of cumulative suspended sediment load are a function of drainage area. The resulting graph with the RESSED data points and fit curve can be seen in Figure 4 below (Creech et al. 2010).

Figure 5 shows the results of this study compared with RESSED Curve with the red points not indicating actual data points, but instead reflecting the trendline equation (points were created using the equation from the previous figure, Figure 4 to be able to plot the position of the trendline in comparison to this study's data). Overall, a similar negative correlation between drainage area (sq. miles) and sediment yield (tons/year), however the r^2 values were both low as expected (such studies do not usually have high r^2 values). The RESSED Curve differs the USACE Curve in that the y-axis is sediment yield in tons/square mile/year. Given this difference, the r^2 values were both around 0.25. Results were more or less in the same order of magnitude suggesting the potential validity this study according to the RESSED Curve. Table 5 and 6 show the values constituting these graphs by each dam in this study.

Figure 4: RESSED Great Lakes Regional Curve (Creech et al. 2010)

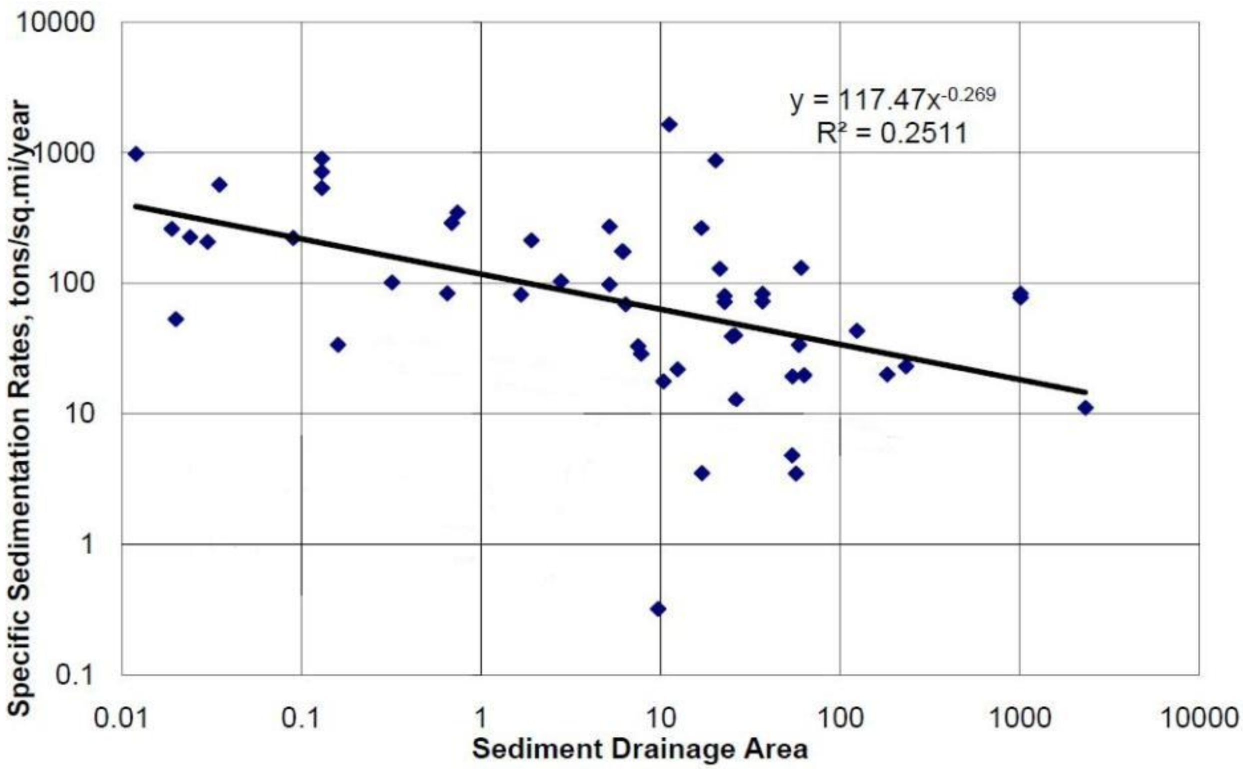

Figure 5: Sedimentation Trendline (as compared to RESSED Trendline equation)

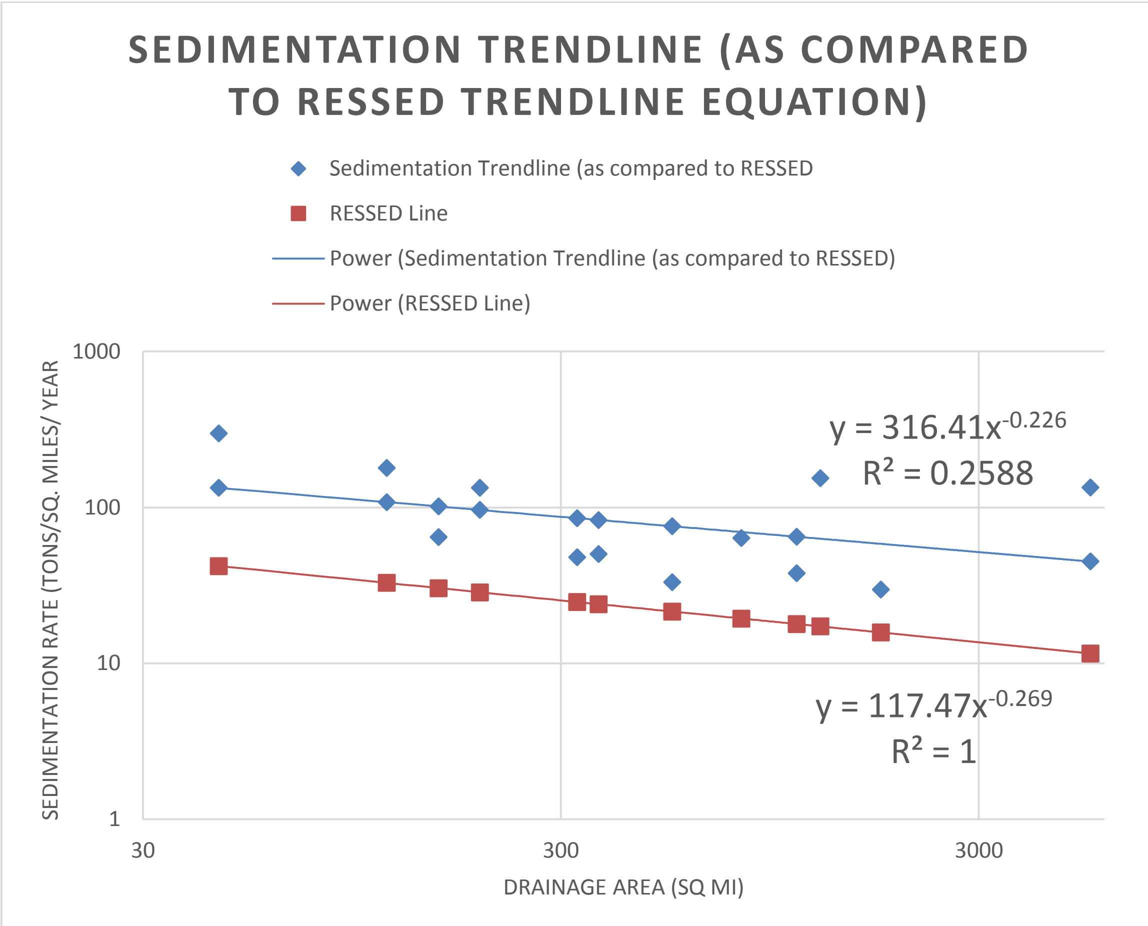

Table 5: Sediment Yield Estimation Trend Line Summary Table (tons/year)

Method	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Mio Dam	Alcona Dam	Brown Bridge Pond Dam	Goshen Pond Dam	Potters Falls Dam	Independence Dam	Ballville Dam	Ford Lake Dam	Webber Dam
USACE	24,821	50,410	14,473	105,375	24,821	19,545	52,787	7,699	310,970	98,993	70,973	127,954
RESSED	5,813	11,391	3,484	22,937	5,813	4,633	11,900	1,913	64,079	21,616	15,761	27,580

Table 6: Sediment Yield Estimation Trend Line Summary Table (tons/year/sq. mile)

Method	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Mio Dam	Alcona Dam	Brown Bridge Pond Dam	Goshen Pond Dam	Potters Falls Dam	Independence Dam	Ballville Dam	Ford Lake Dam	Webber Dam
USACE	129	154	126	96	67	128	95	169	56	79	88	73
RESSED	30	35	30	21	16	30	21	42	12	17	19	16

Radionuclide Dating Results

The radionuclide results were interpreted through multiple approaches. The first approach took the data as a whole for each dam and calculated an averaged dated core sedimentation rate based on the age of the dam and the per year sediment rate. The radionuclide dating results for this technique are summarized in the table below.

Table 7: Radionuclide Dating Analysis Summary Table (tons/year)

Dam Name	Dated Core Sample Method	Core Length Method
Lake Rockwell Dam	18,422	30,682
Riley Dam	18,795	20,703
Upper Green Lake Dam	395,067	N/A
Mio Dam	24,176	37,560
Alcona Dam	10,835	32,790
Brown Bridge Pond Dam	8,666	6,770
Goshen Pond Dam	3,817	5,043
Potters Falls Dam	N/A	4,718
Ford Lake Dam	N/A	67,966
Webber Dam	25,446	27,166

Reservoir sites that had many core samples dated correlated better with the core length estimation method. Of 15 total core samples were retrieved from Green Lake, only two of the core samples have been dated to obtain a sedimentation rate. This rate was averaged together and determined to yield 395,067 tons per year. Only having two data points across an eleven square mile lake is a very coarse estimate of sedimentation. The core length method makes use of the undated cores to provided further confidence in the results of this study. The core length method results are within the same order of magnitude and tend to be slightly higher than the dated method overall. Depending on the geological composition of the sediment sample and other factors, some data samples had larger excesses of $^{210}Pb_{xs}$ ^{resulting} in a more developed chronology. Other studies have indicated that silt and clay particles are dominant carriers of $^{210}Pb_x$ as opposed to coarser particles such as sand (Jweda and Baskaran 2011). In order to associate the core mass depth with a sedimentation age, different models can be applied including the CFCS model, the Constant Rate of Supply (CRS), and the Constant Initial Concentration (CIC) models. For this, only the CFCS model was used. The Constant Rate of Supply model assumes that there is a constant flux and an efficient transfer of 210Pbxs from the air–water interface to sediments that results in a constant rate of supply to the sedimentary layer even if the sediment accumulation rate varies over time. In the CRS model, the initial 210Pbxs activity varies inversely with the accumulation rate. The Constant Initial Concentration Model (CIC) assumes a constant initial activity at the sediment–water interface regardless of changes in net accumulation CIC model should be better suited than the CRS model for systems heavily influenced by erosional input. In a future study, these models were be applied.

CONCLUSION

Analysis across Reservoirs

From Table 8 and 9, it appears that on a rough average, agricultural watersheds deliver a higher sediment load per square mile than forested watersheds do. The urban watershed sediment load per square mile was quite high as well. This may be due to the fact that the urban watershed was rural before it was urban. Some of the sediment in the reservoir could be legacy sediment. It is likely that the data gaps in the different methods make it difficult to draw a definitive conclusion about sedimentation in the Great Lakes watershed. Likewise, other possible factors non related to urbanization and agricultural may also need to be taken into account when analyzing the estimations presented in this study.

After reviewing all of the sediment yield estimation techniques in this study it is clear that not all techniques could be applied to all reservoirs. Reasons for this included the fact that sometimes historic maps were not available for bathymetric subtraction. Likewise, there were no historic records of sediment gages in the watershed for certain sites. The sediment gages could also not be well distributed. Likewise, in some cases there were very few to none sediment cores were dated from the reservoir.

Most of the sites investigated in this study had surrounding agricultural landuse. The variation in the sediment yield per area amongst these agricultural sites should be examined further. For example, due to the geological and geographical nature of the area, Potters Falls Dam is known to have much sediment accumulation (Tompkins Historical Society 2012) thus explaining the very high sediment yield estimations. It is important to note that there is a small silt dam upstream of Potters Falls Dam that is dredged every few years to reduce the amount of sediment accumulation to Potters Falls Reservoir. Likewise, Upper Green Lake was a lake before being impounded and is rather deep. The method sediment core length method cannot be applied because it is unknown when the oldest sediment entered the reservoir since Green Lake was a lake before it was a reservoir.

In conclusion, from the different methods described in this study, it seems that there is correlation between anthropogenic activity and higher sediment yields. Likewise, other non-anthropogenic factors may have influenced the sedimentation rate including geological and geographical features. The urban watershed sediment load per square mile was quite high as well. This may be due to the fact that the urban watershed was rural before it was urban. Some of the sediment in the reservoir could be legacy sediment.

Further studies could include applying two additional sediment models to the radionuclide method. The CRS and CIC model are better suited than the CFCS model when mass accumulation rates are variable, which is very likely for many of the sites in this study (Jweda and Baskaran 2011). Such models could help associate a date with the sediment mass depths and better relate historic events with changes in mass sediment accumulation rates.

Additional dating of sediment cores will also help in establishing a clearer chronology of the past and will allow for a better analysis of the current data. Reservoirs including as Ford Lake Dam and Potters Falls Dam are currently being dated and will soon have radionuclide data available as well.

Table 8: Sediment Yield Estimation Summary Table (tons/year)

	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Mio Dam	Alcona dam	Brown Bridge Pond Dam	Goshen Pond Dam	Potters Falls Dam	Independence Dam	Ballville Dam	Ford Lake Dam	Webber Dam
Bathymetric Method	17,980		88,913	18,546				12,885				
Sediment Gage Application 1	19,300							24,978	1,319,706	294,486		
Sediment Gage Application 2	29,536	7,839	18,543					17,760	1,224,114	196,376		
Sediment Gage Application 3	57,616	5,609	4,051					18,328		258,362		
Sediment Gage Application 4	18,209	5,105	4,700					20,662	1,312,018	275,067		
Sediment Gage Application 5	21,167	618	1,673					11,230				
USACE Trend Line	22,054	27,624	11,250	80,651	119,193	14,149	35,623	6,900	310,970	98,993	70,973	
RESSED Trend Line	5,196	6,435	2,743	17,795	25,784	3,409	8,192	1,724	64,079	21,616	15,761	27,580
"Dated" Sediment Core Method	18,422	18,795		24,176	10,835	8,666	3,817					25,446
Sediment Core Length Method	30,682	20,703		37,560	32,790	6,770	5,043	4,718	1,461		67,966	27,166
Average Across Methods	24,016	11,591	18,839	35,746	47,151	8,249	13,169	13,243	705,391	190,817	51,567	26,731

Table 9: Sediment Yield (tons/year/sq. mile)

Method	Lake Rockwell Dam	Riley Dam	Upper Green Lake Dam	Mio Dam	Alcona dam	Brown Bridge Pond Dam	Goshen Pond Dam	Potters Falls Dam	Independence Dam	Ballville Dam	Ford Lake Dam	Webber Dam
Bathymetric Method	86		773	17				283				
Sediment Gage Application 1 (River Mile)	93							549	238	235		
Sediment Gage Application 2 (Raw Average)	142	15	161					390	221	157		
Sediment Gage Application 3 (Weighted Average)	277	11	35					403		206		
Sediment Gage Application 4 (filling in knowns)	88	10	41					454	237	219		
Sediment Gage Application 5 (Slope)	102	1	15					247				
USACE Trend Line	106	53	98	73	323	92	64	152	56	79	88	
RESSED Trend Line	25	12	24	16	70	22	15	38	12	17	19	16
"Dated" Sediment Core Method	89	36		22	29	57	7					15
Sediment Core Length Method	148	40		34	89	44	9	104	0		84	16
Average Across Methods	115	21	144	32	128	43	24	291	127	152	64	15

APPENDIX A

Appendix I describes the process for the calculations used in the method of Sediment Yield Estimation Using United States Geological Survey Sediment Gages using Lake Rockwell as an example. These calculations and calculation write ups were conducted and written by Eric Andersen and were later processed into this report.

Application 1

For application 1, there are two sediment gages along the Cuyahoga River. Sediment gage 04202000 is located sixteen river miles upstream of Lake Rockwell Dam and sediment gage 04206000 is located 16 river miles downstream of Lake Rockwell Dam. For this method the relationship between the two sediment gages was assumed to be linear with a change in sediment loading of 1056 tons per year per linear mile. This method yields approximately 19,300 tons per year at the reservoir.

Application 2

The second application took the sediment load in tons per year that was divided by the drainage area and average the 3 gages. This yields 142 tons per square mile per year considering the drainage area as un impounded and 227 tons per square mile per year considering areas as impounded. Multiplying these numbers by the drainage area yields 29,536.

$$\frac{(16)+(93)+(317)}{(3)} = \frac{142\,\frac{tons}{mi^2}}{yr} \rightarrow \frac{142\,\frac{tons}{mi^2}\ x\ 208\ sq.miles}{yr} = \mathbf{29,536\ tons/year}$$

Application 3

The third method took the drainage area of each gage and the sediment yield in tons per year and develop a weighted average.

Considering all areas as un impounded $\frac{(16)(151)+(93)(388)+(317)(691)}{(151+388+691)} = \frac{277\frac{tons}{mi^2}}{yr} \rightarrow \frac{277\,\frac{tons}{mi^2}\,x\ 208\ sq\ miles}{yr} =$ $\mathbf{57,616\ tons/year}$

Application 4

The fourth application used the weighted sediment yield number based on area and filled in areas in the watershed where sediment data was unknown, such as between USGS gage 04202000 which downstream of the sediment and Lake Rockwell. The average observed sediment load for sediment gage 04202000 is 2,420 tons of sediment per year and the unknown area is 57 square miles. Since the weighted average sediment load of 277 tons per square mile per year, the estimated yield is 15,789 tons per year. Summing these numbers up brings the total to 18,209 tons of sediment per year for Lake Rockwell using sediment data.

208 total square miles – 151 known square miles = 57 square miles

57 unknown square miles x 277 tons/sq. mi/year = 15,789 + 2,420 = **18,209 tons/year**

Application 5

The fifth method was to calculate a sediment loading rate based on the slope of each gage and apply it based on the slope of the drainage area of Lake Rockwell.

Table 10: Lake Rockwell Dam Method 5 Results

Watersheds	Sediment Load (tons/yr.)	% Rise	Degree
Gage 04208000	218,710	4.5927	2.8786
Gage 04206000	36,220	3.7937	2.1792
Gage 04202000	2,240	3.3346	1.9089
Lake Rockwell		3.6615	2.09796

The percent rise of each sediment gage drainage area was calculated using GIS. The percent rise of Lake Rockwell's drainage area was also calculated. This data was put into excel and a polynomial best fit equation was applied.

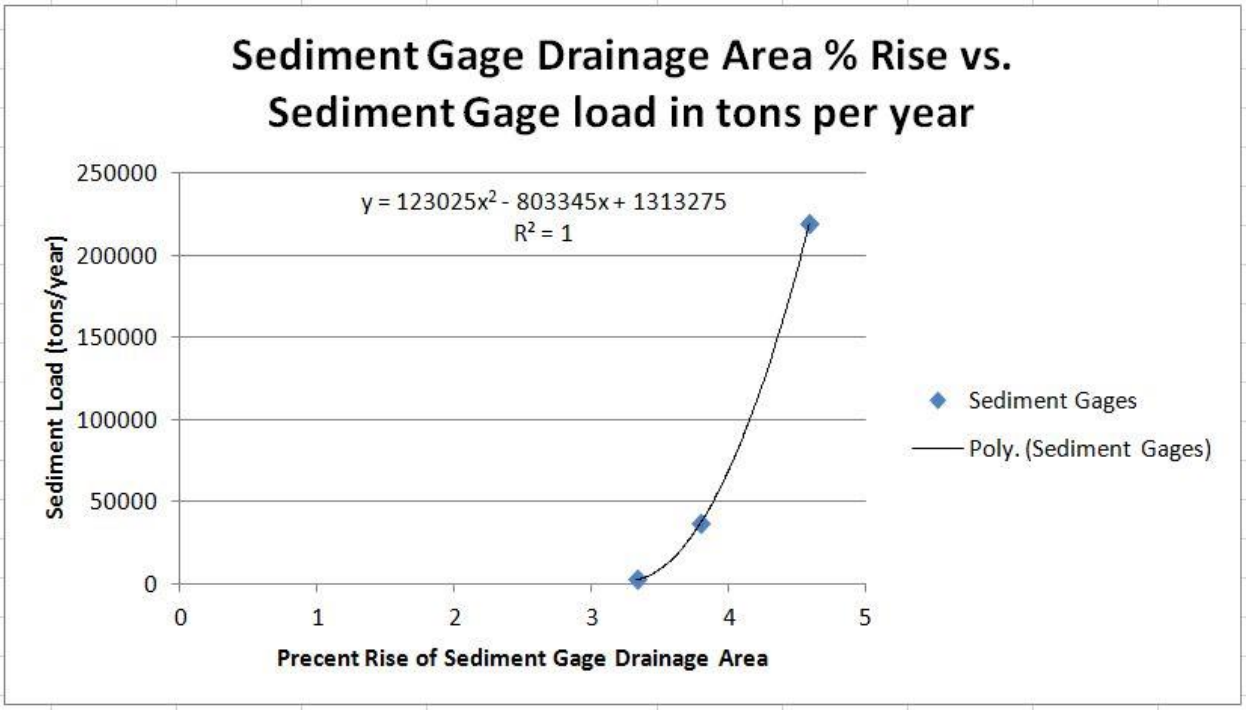

Figure 6: Sediment Gage Drainage Area % Rise vs. Sediment Gage Load in Tons Per Year

The percent rise of Lake Rockwell's drainage area was plugged into the equation a sediment load of 21,167 tons per year was outputted.

APPENDIX B

The following figures are maps of the bathymetric mapping process including pre-construction (historic), post-construction (current) and subtraction maps for all applicable reservoirs. These bathymetric maps were developed by Eric Andersen.

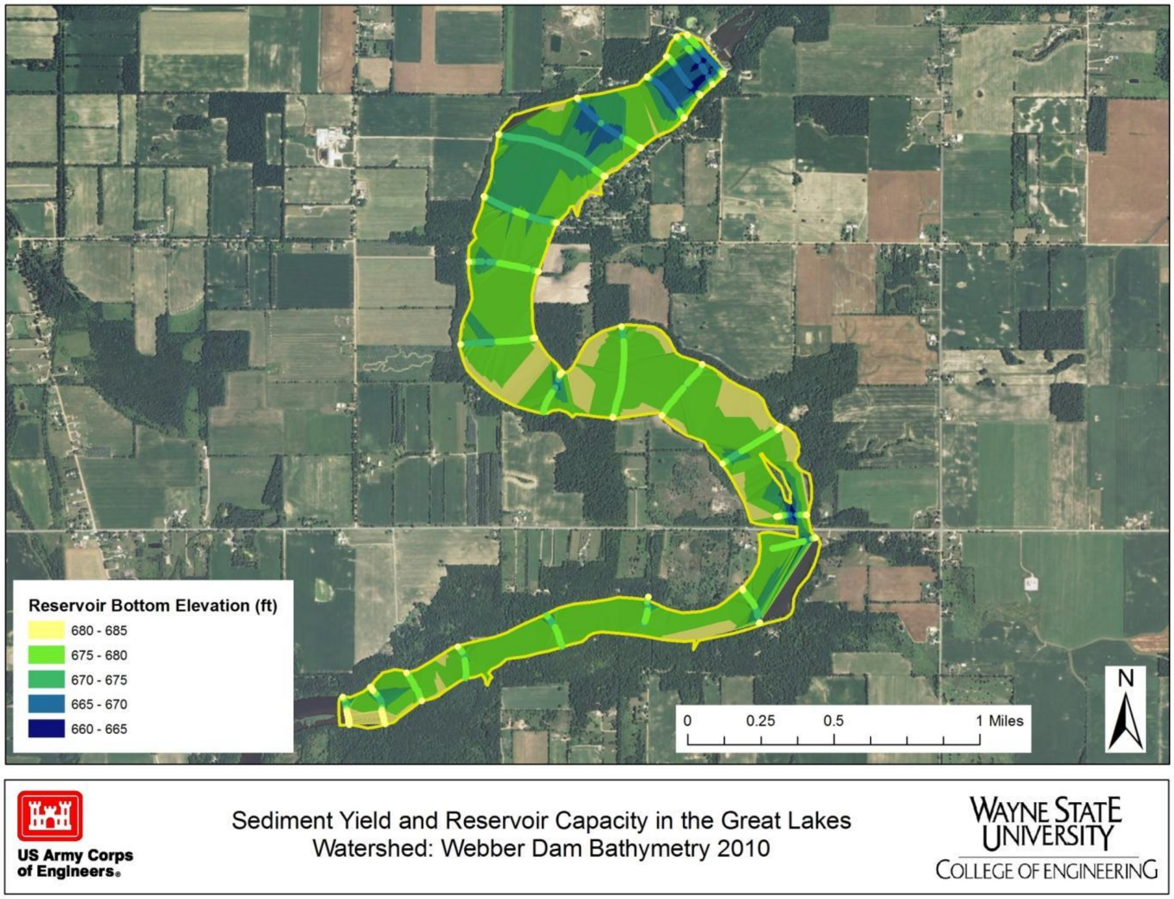

Figure 7: Webber Dam Current Bathymetry (2010)

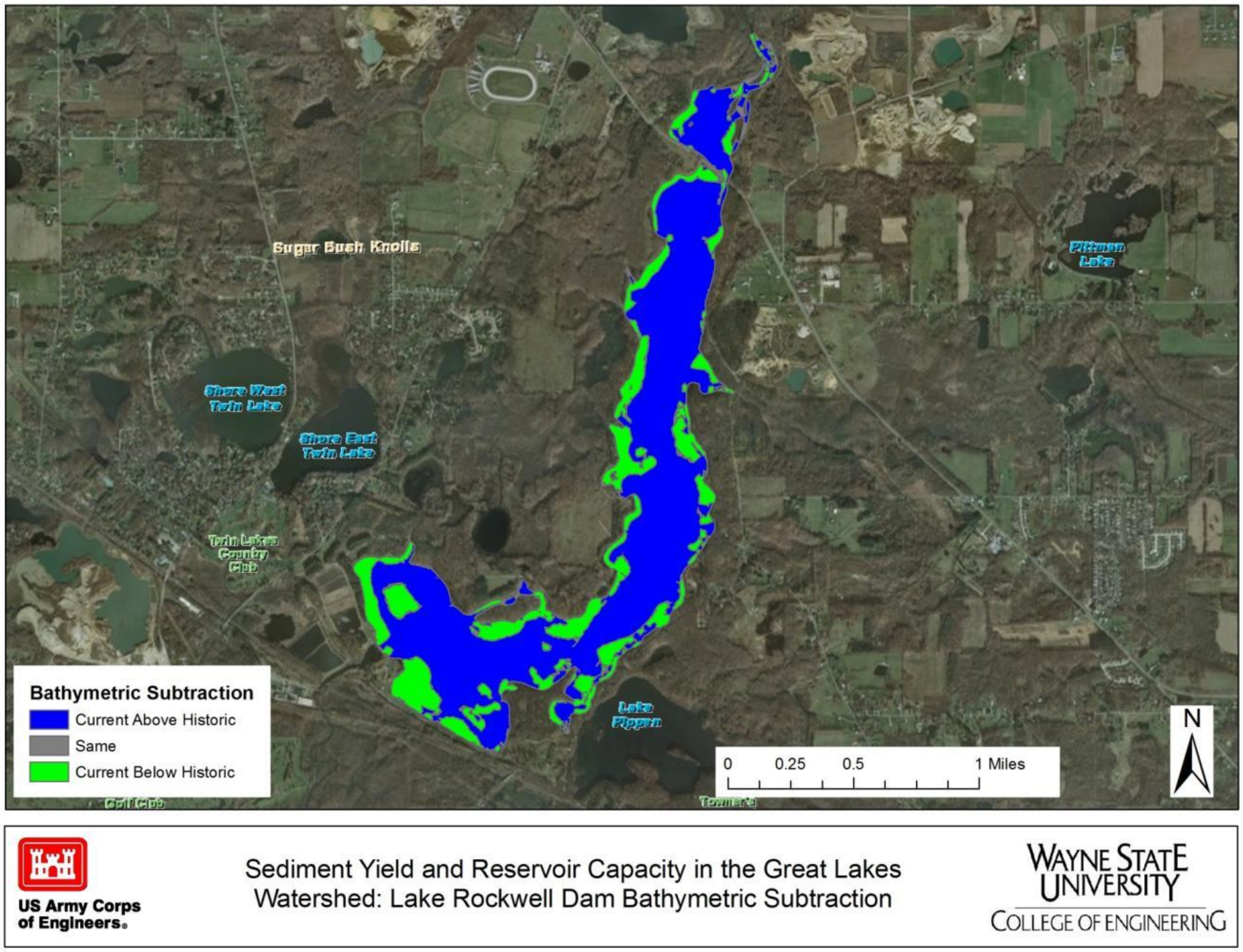

Figure 8: Lake Rockwell Dam Bathymetric Subtraction

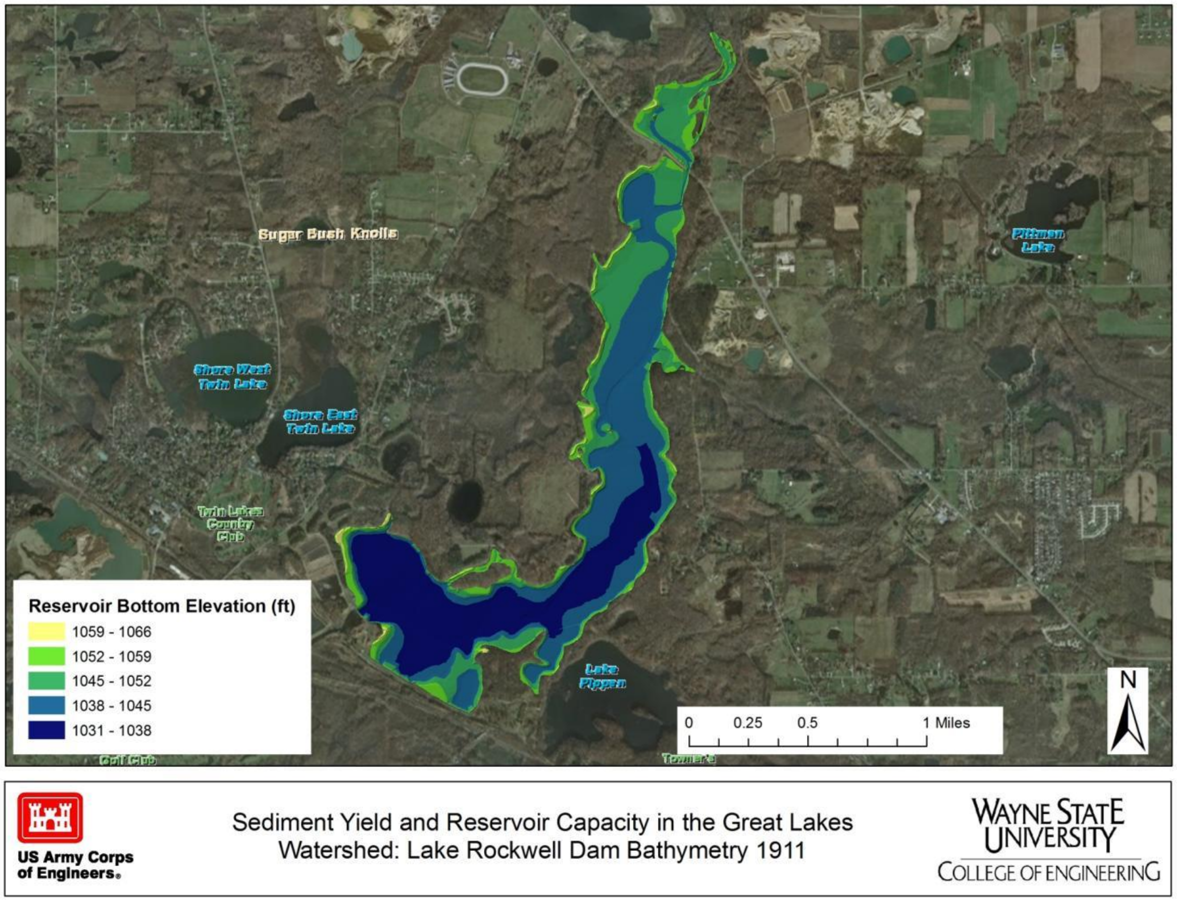

Figure 9: Lake Rockwell Dam Pre-Construction Bathymetry (1911)

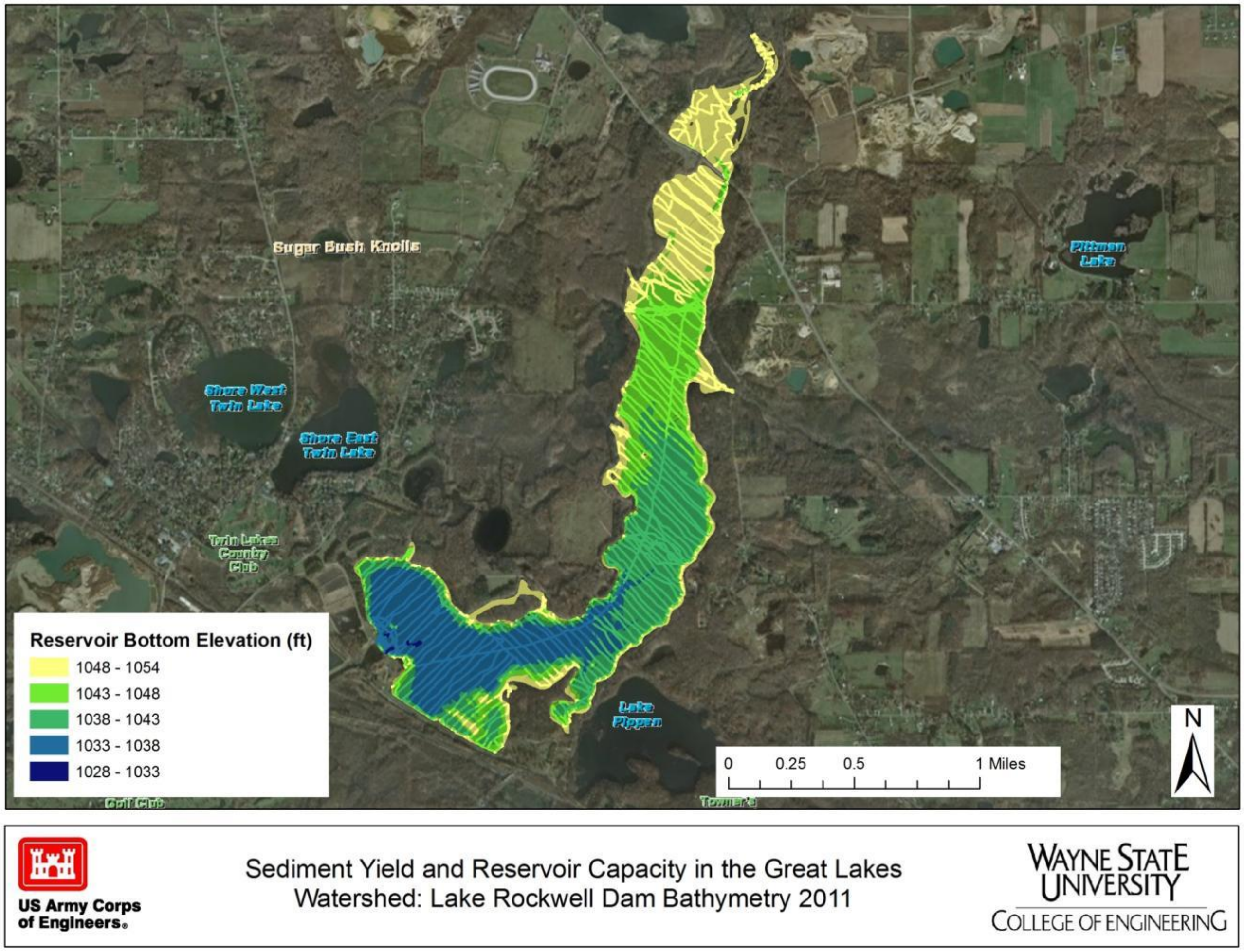

Figure 10: Lake Rockwell Dam Post-Construction Bathymetry (2011)

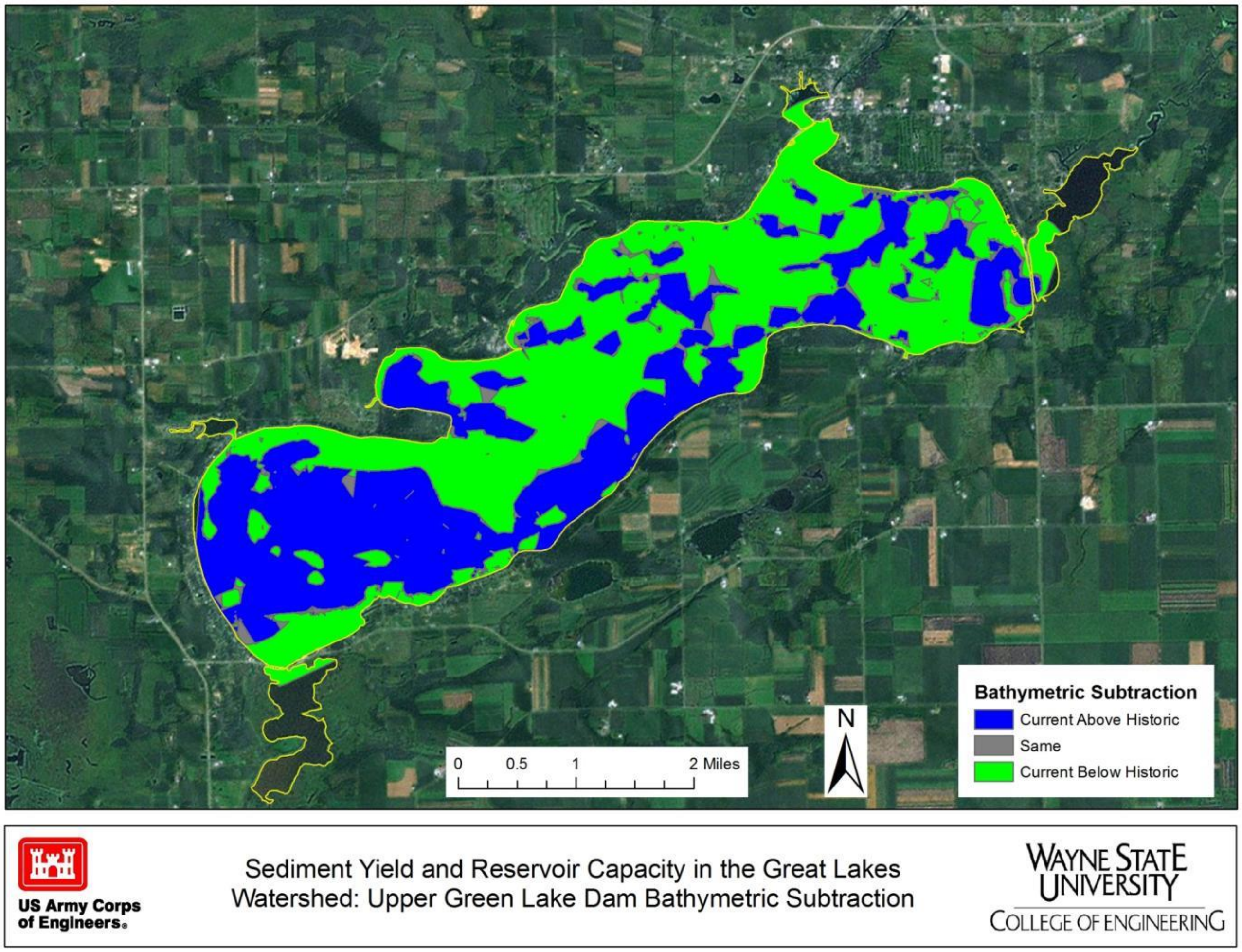

Figure 11: Upper Green Lake Bathymetric Subtraction

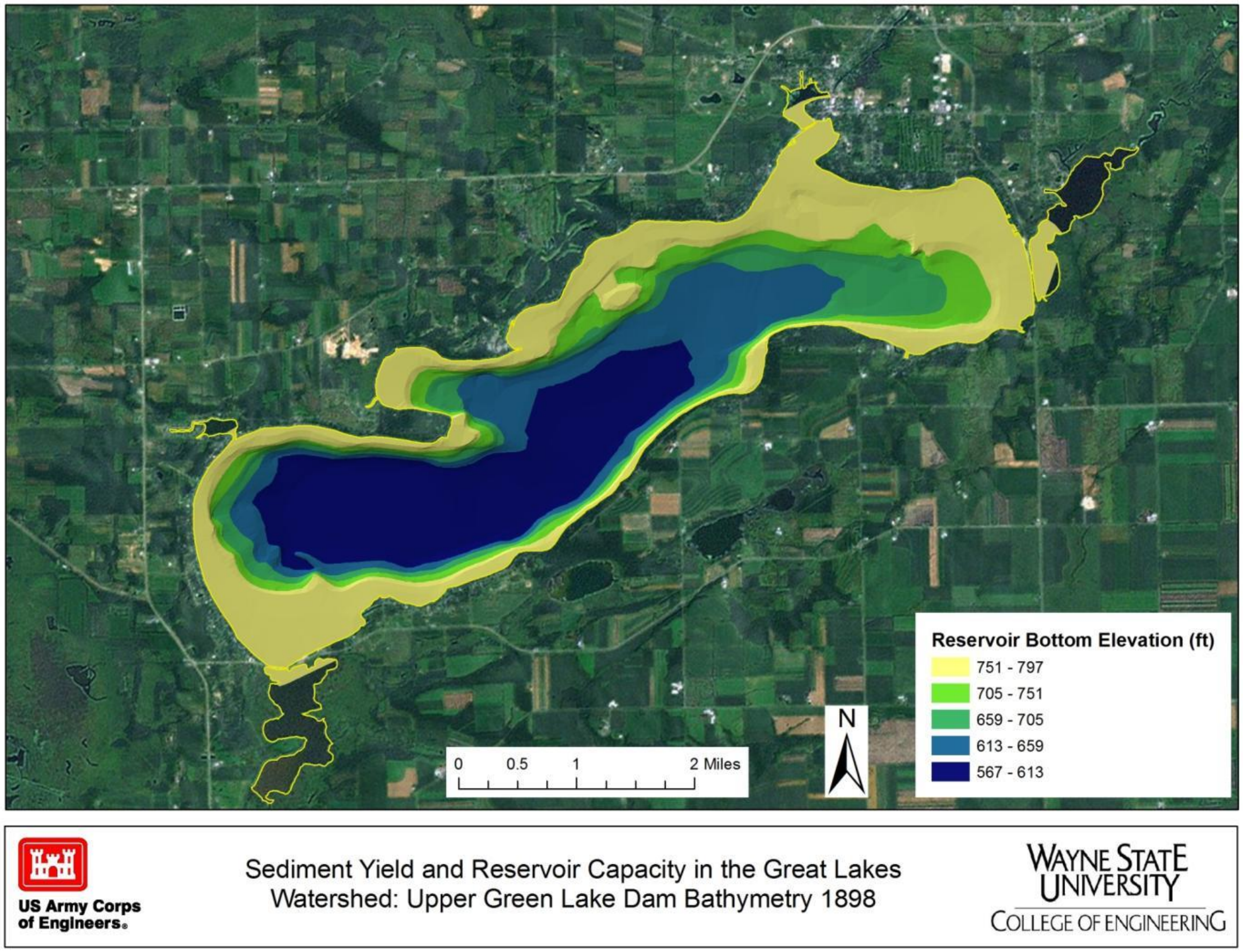

Figure 12: Upper Green Lake Dam Historic Bathymetry (1898)

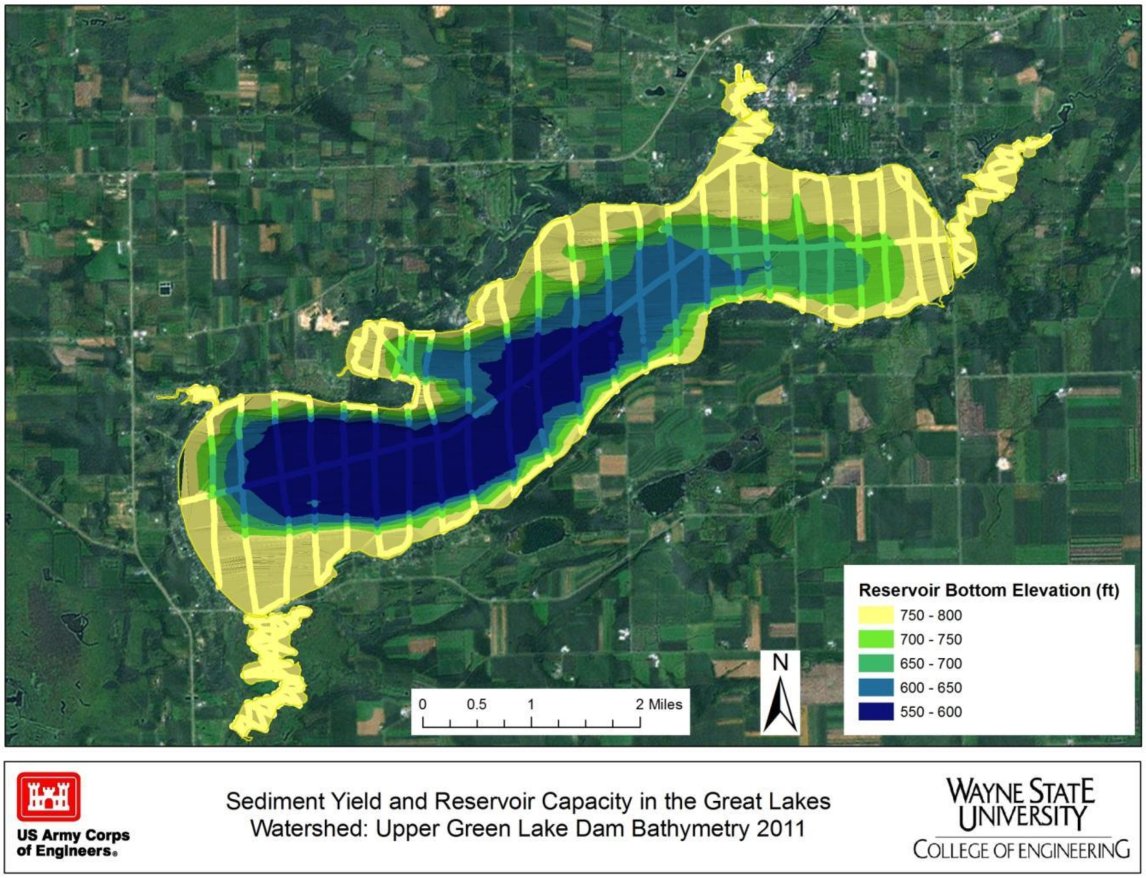

Figure 13: Upper Green Lake Dam Current Bathymetry (2011)

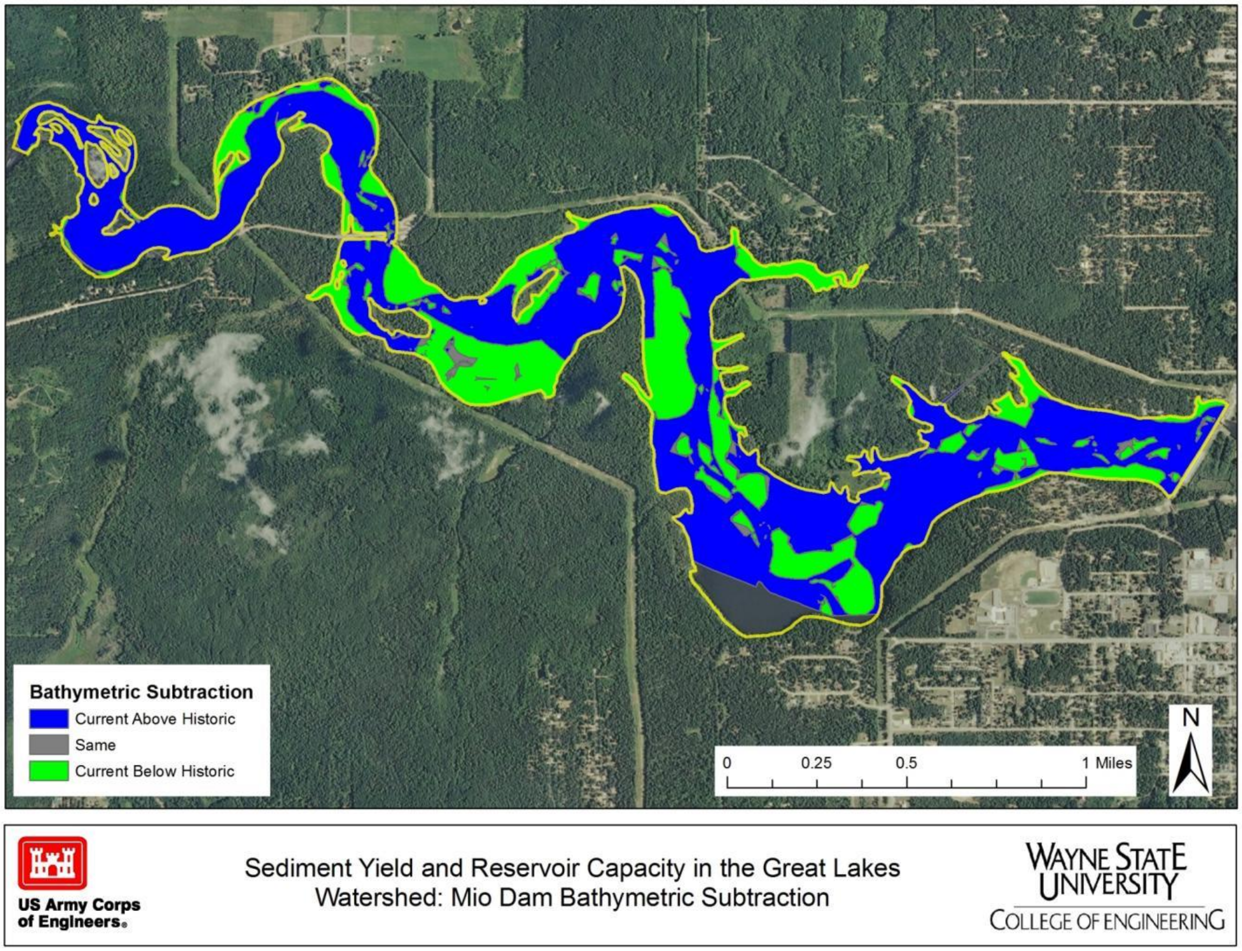

Figure 14: Mio Dam Bathymetric Subtraction

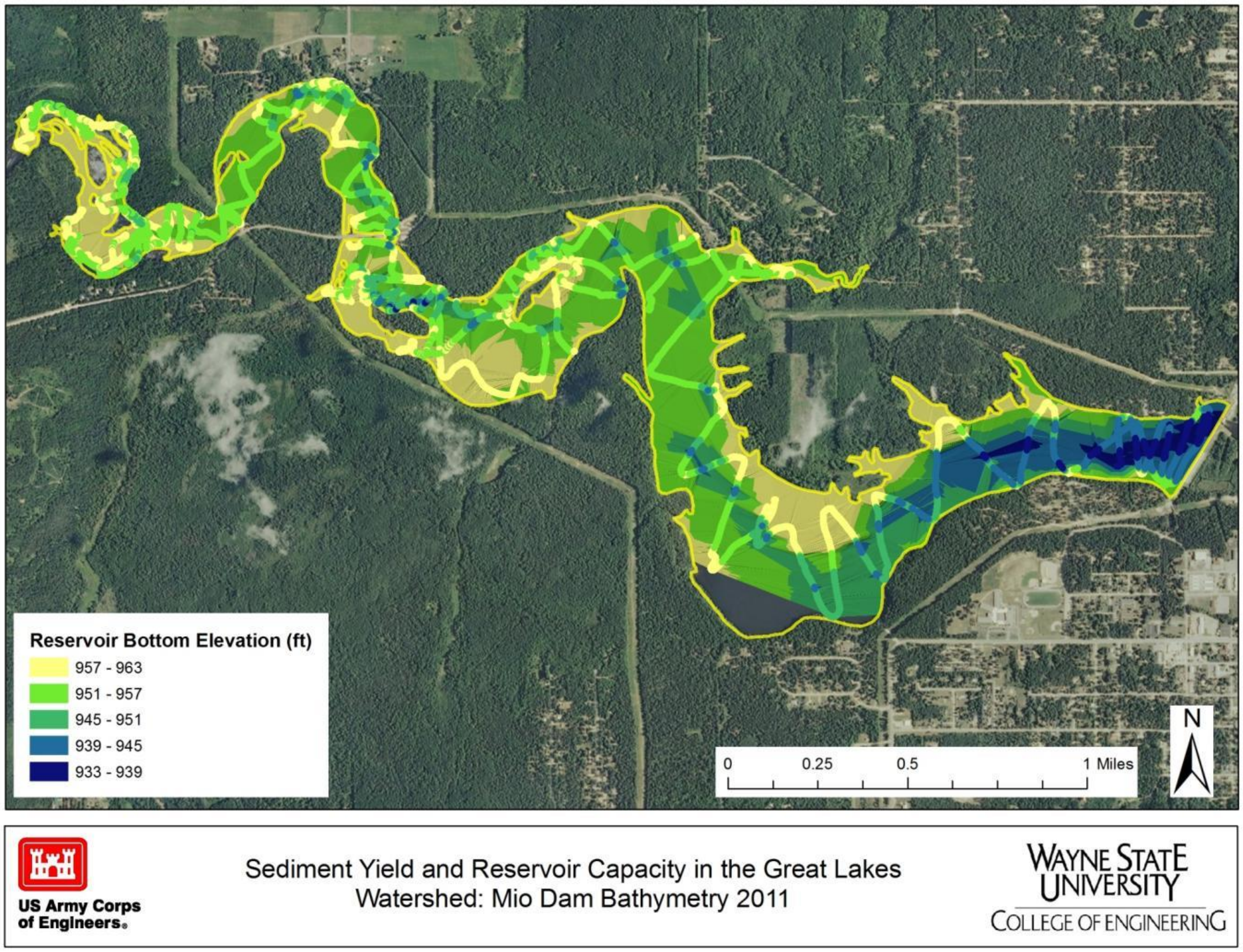

Figure 15: Mio Dam Current Bathymetry (2011)

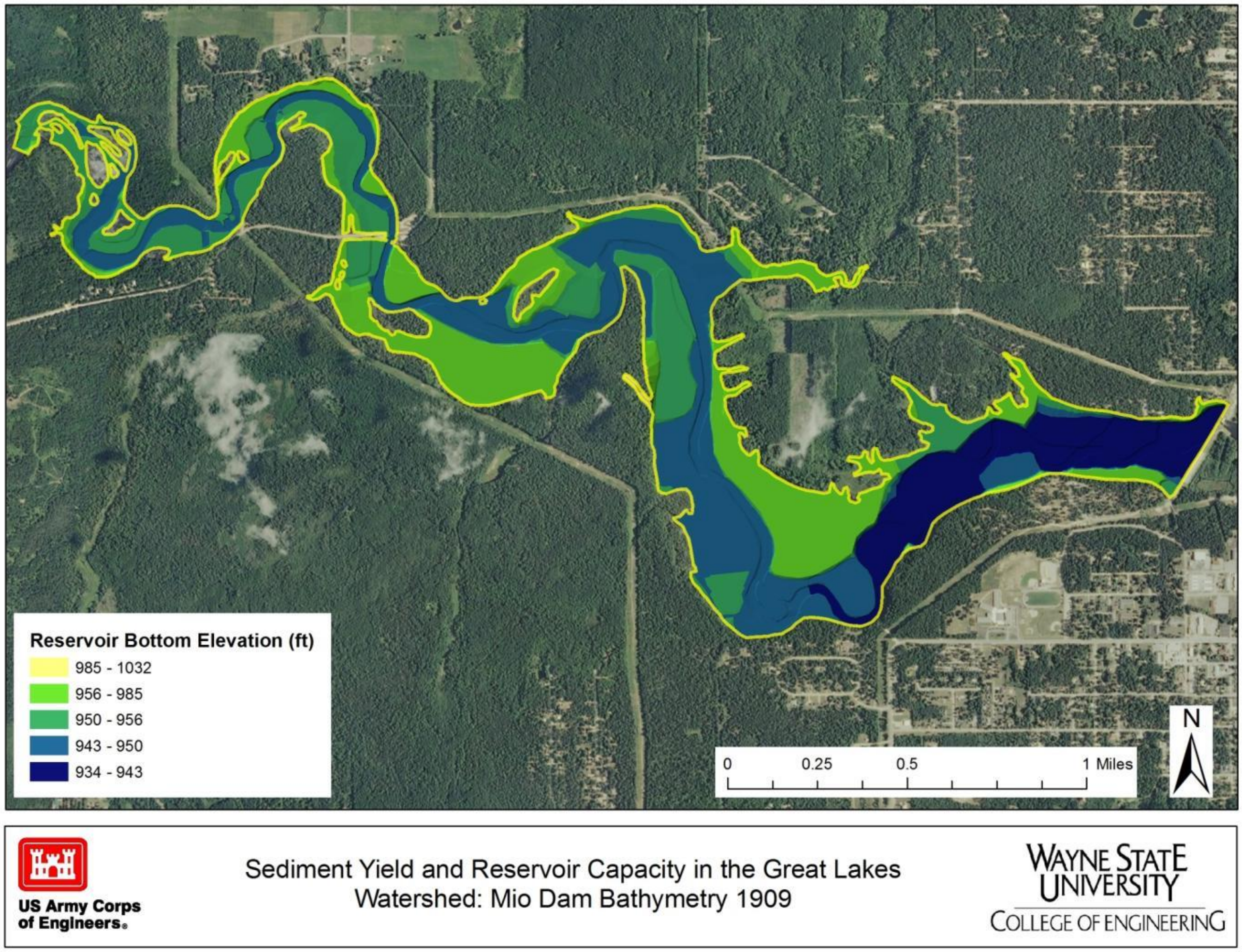

Figure I-J: Mio Dam Historic Bathymetry (1909)

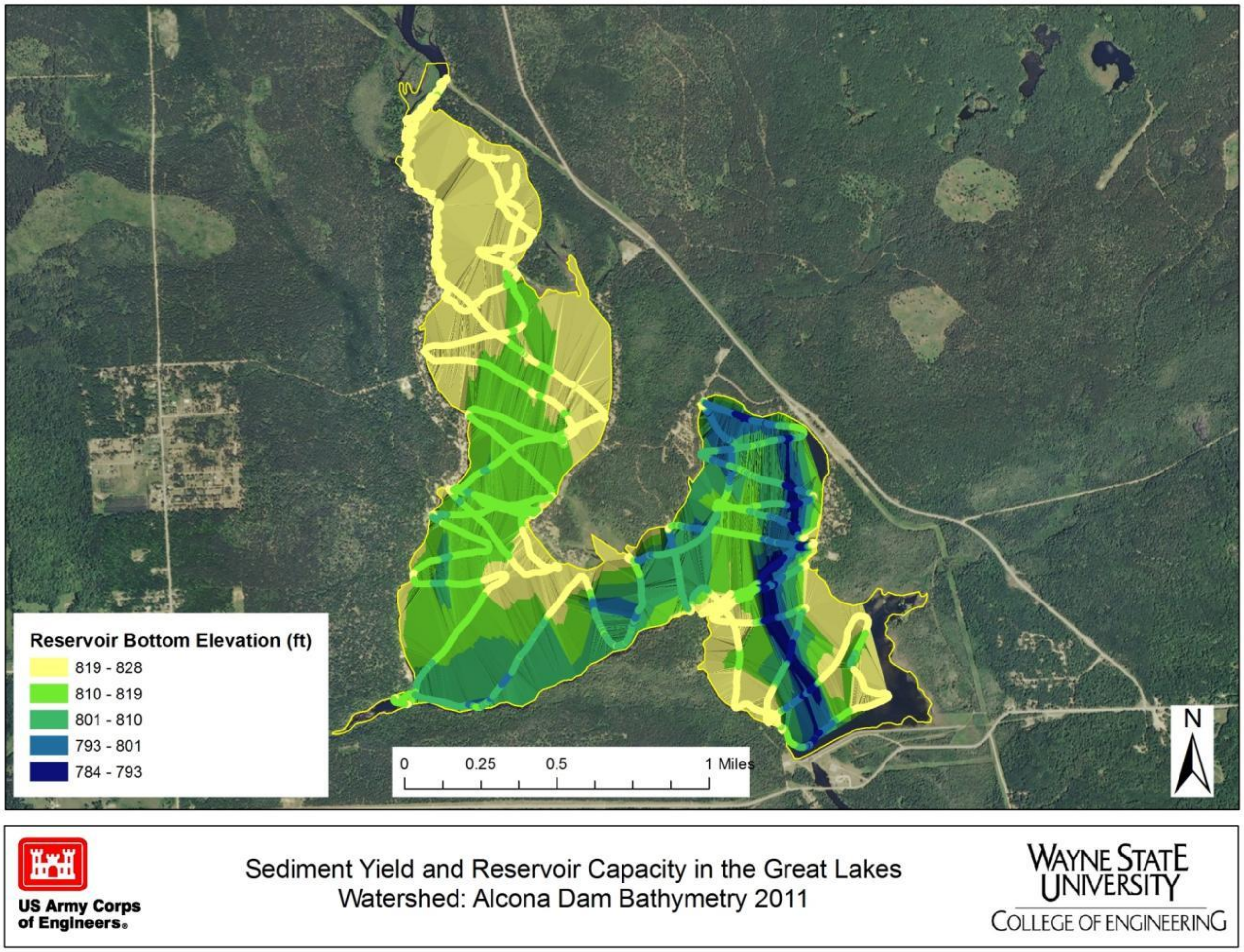

Figure 16: Alcona Dam Current Bathymetry 2011

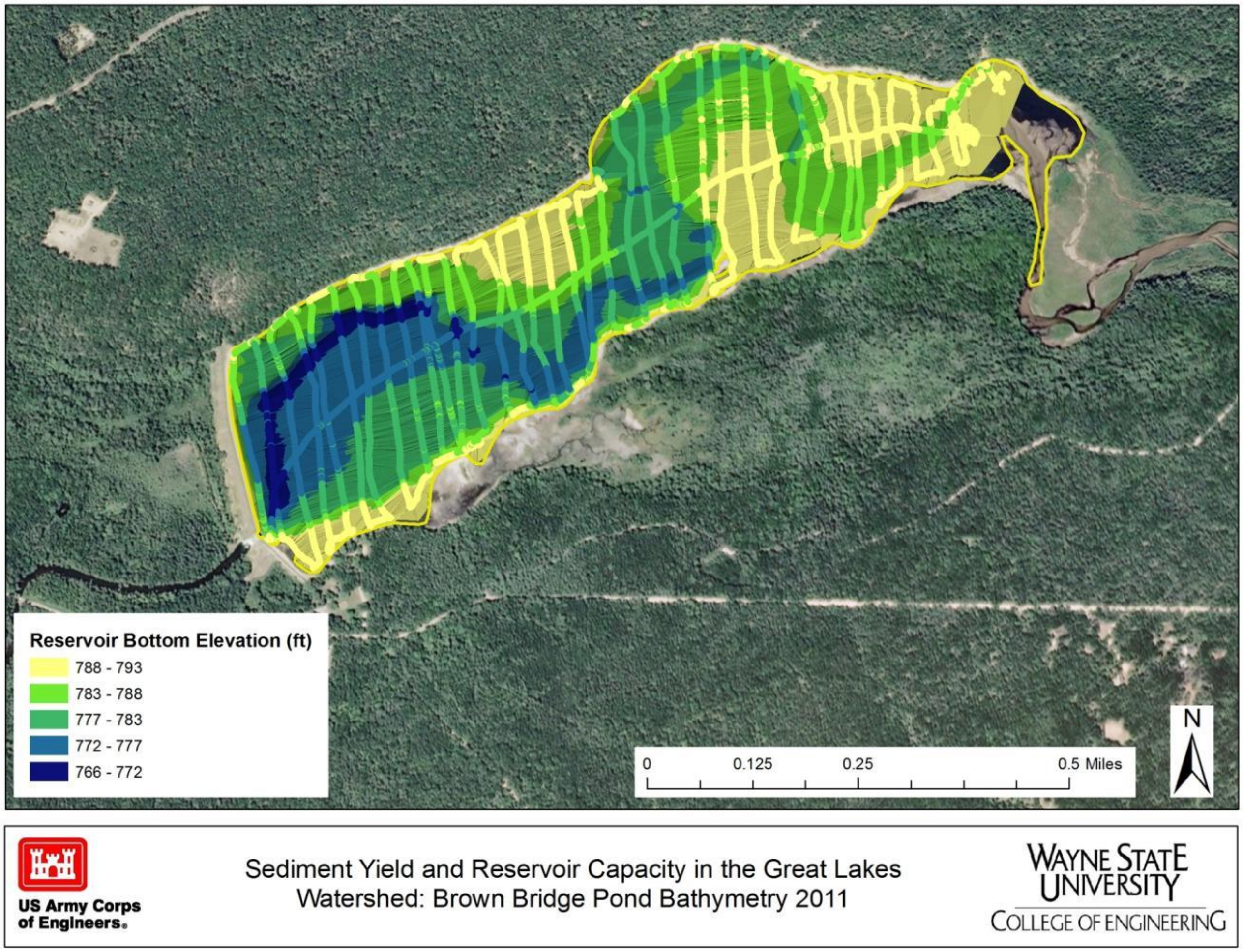

Figure 17: Brown Bridge Pond Current Bathymetry 2011

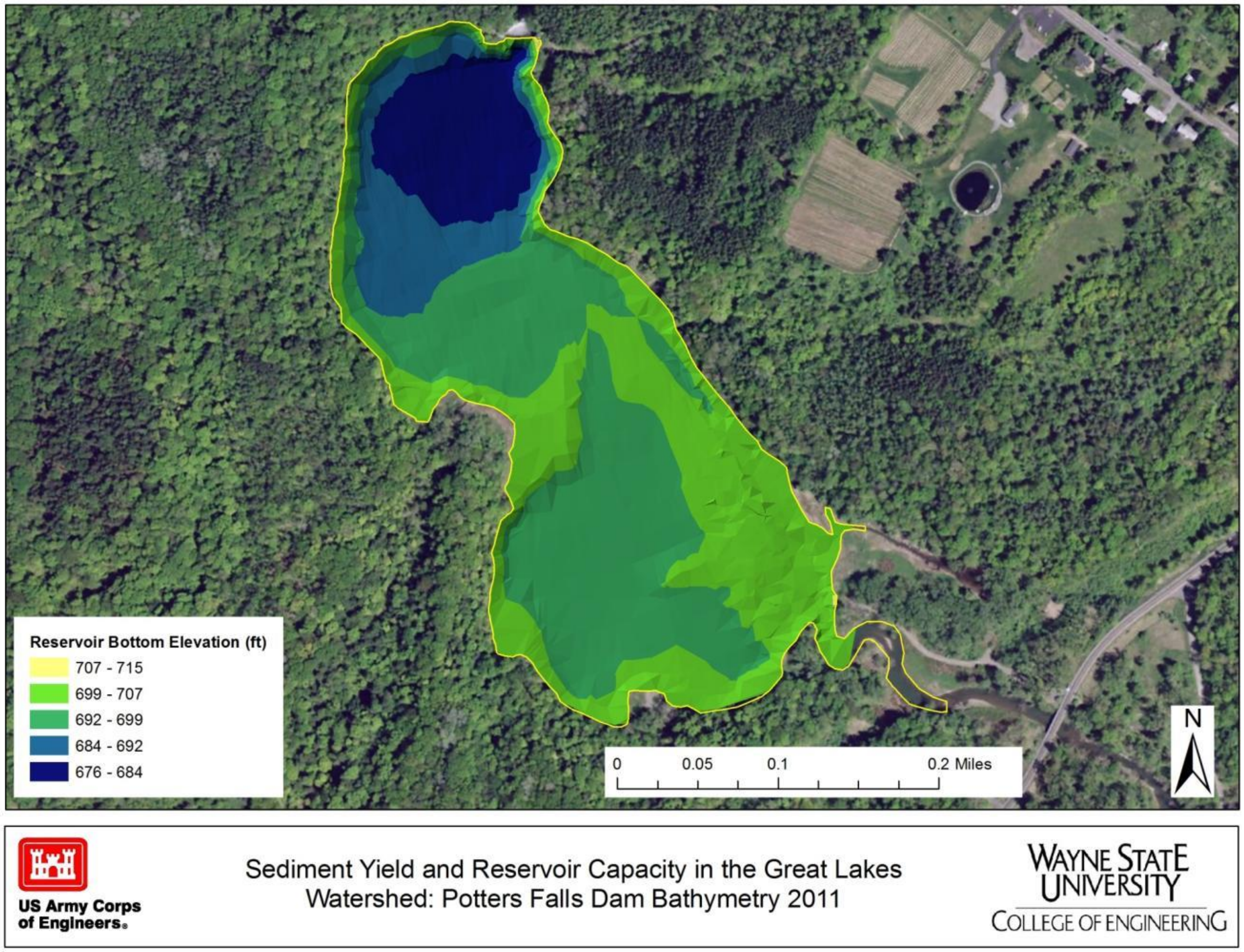

Figure 18: Potters Falls Dam Current Bathymetry 2011

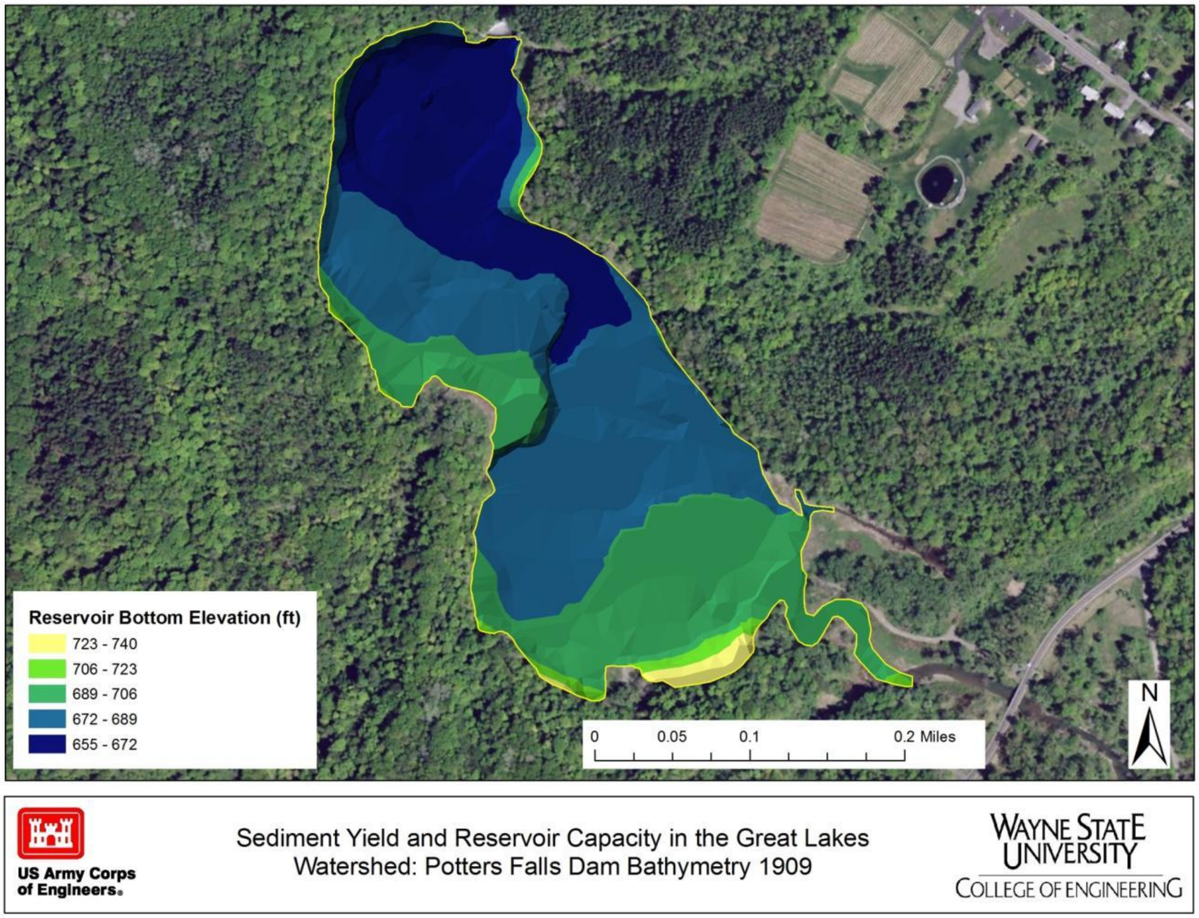

Figure 19: Potters Falls Dam Historic Bathymetry (1909)

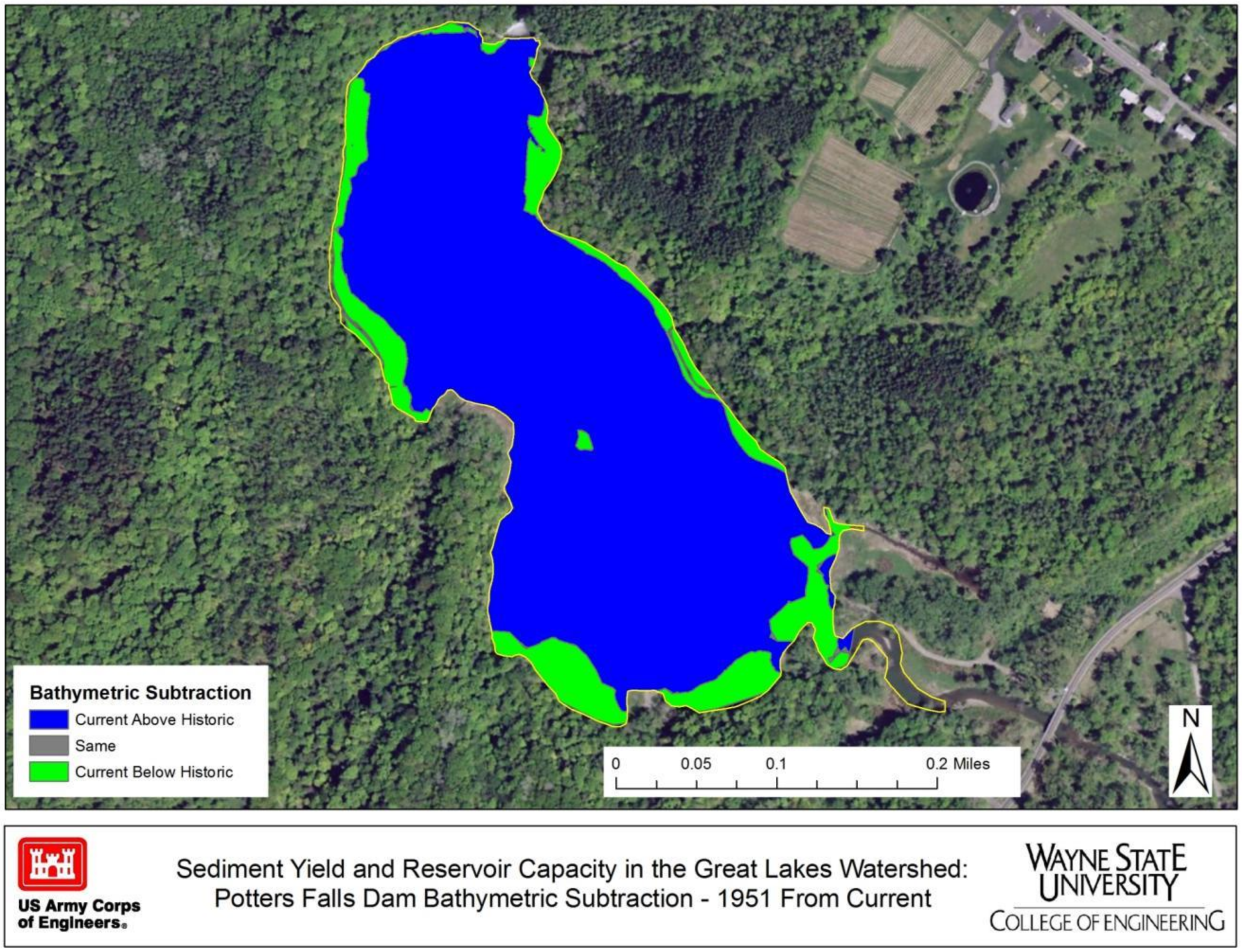

Figure 20: Potters Falls Dam Bathymetric Subtraction (1951 - Current)

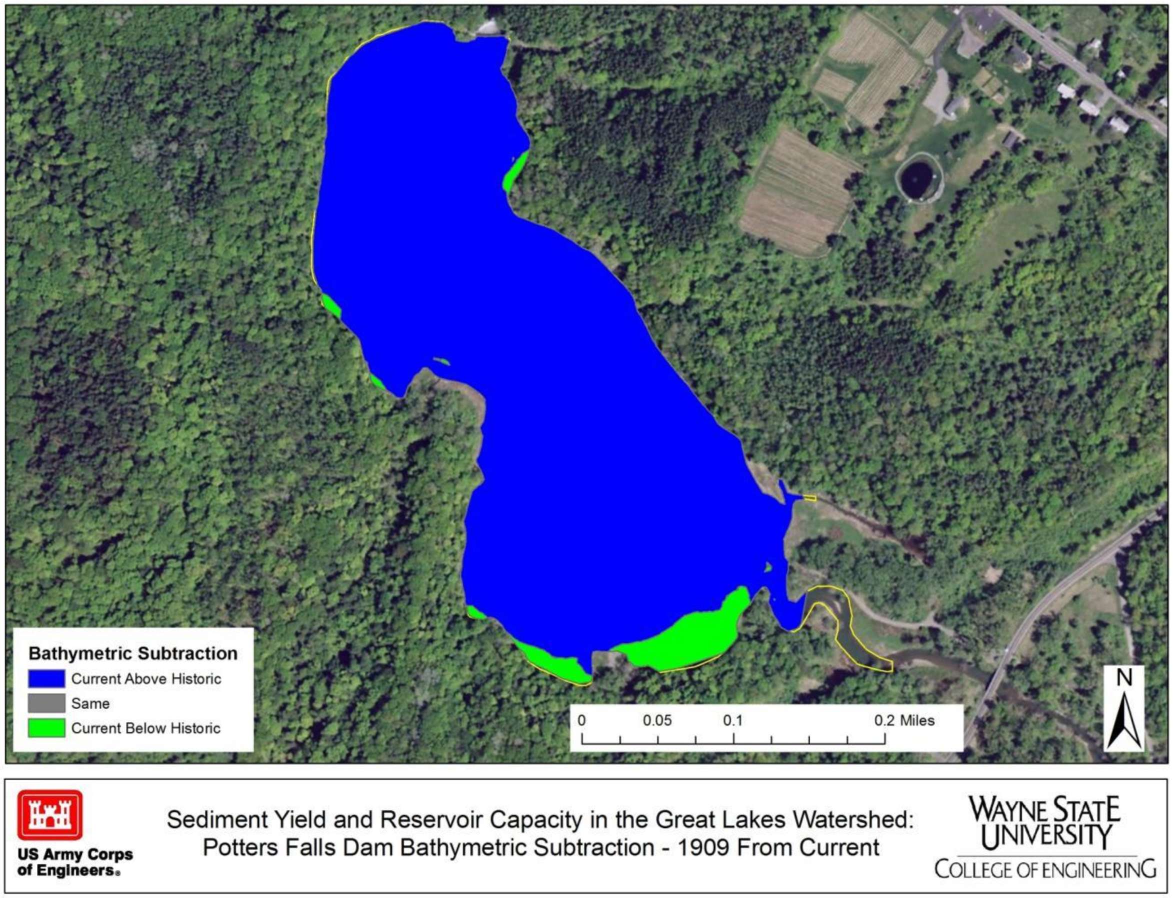

Figure I-P: Potters Falls Dam Bathymetric Subtraction (1909 - Current)

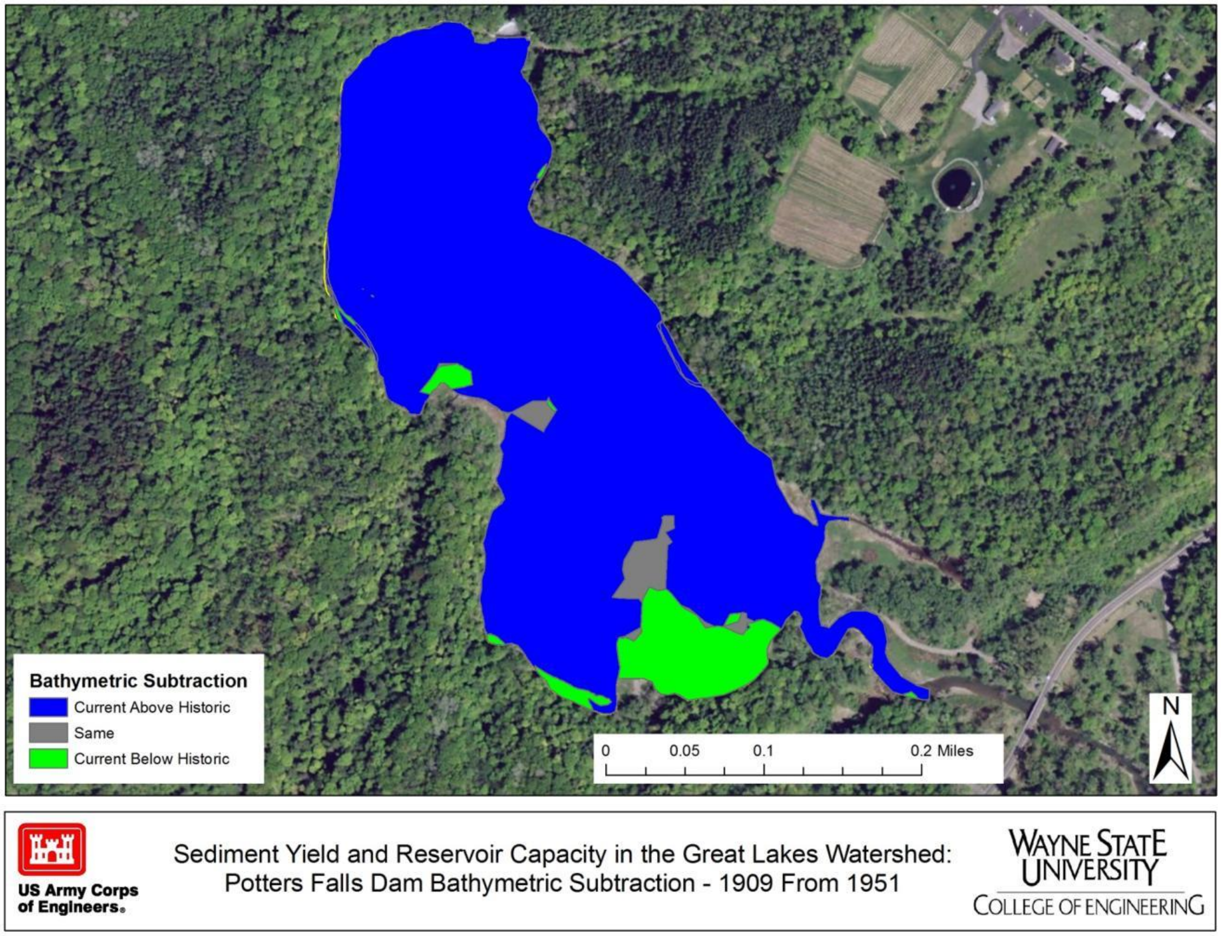

Figure 21: Potters Falls Dam Bathymetric Subtraction (1909 - 1951)

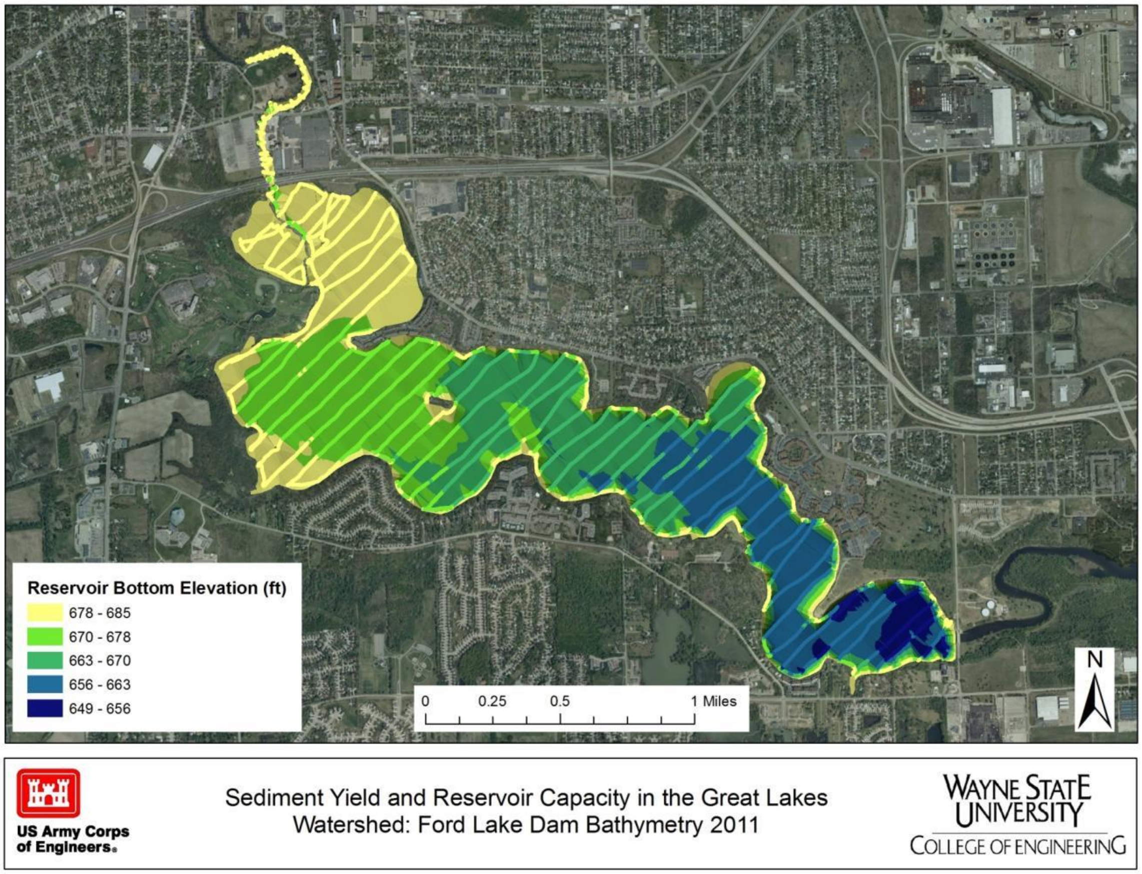

Figure 22: Ford Lake Dam Current Bathymetry (2011)

APPENDIX C

The following figures are visual mappings of the length of the sediment core retrieved from the various location across the reservoir. These individual core location values were averaged and weighted by interpolated area to get an average sedimentation rate for the entire reservoir. The equation used is as follows:

Sedimentation based on Core Length = (Core length 1)(Area 1) + (Core length 2)(Area 2) + (Core length 3)(Area 3) + …. (Core length n)(Area n)/ (Number of Cores)(Total Area)

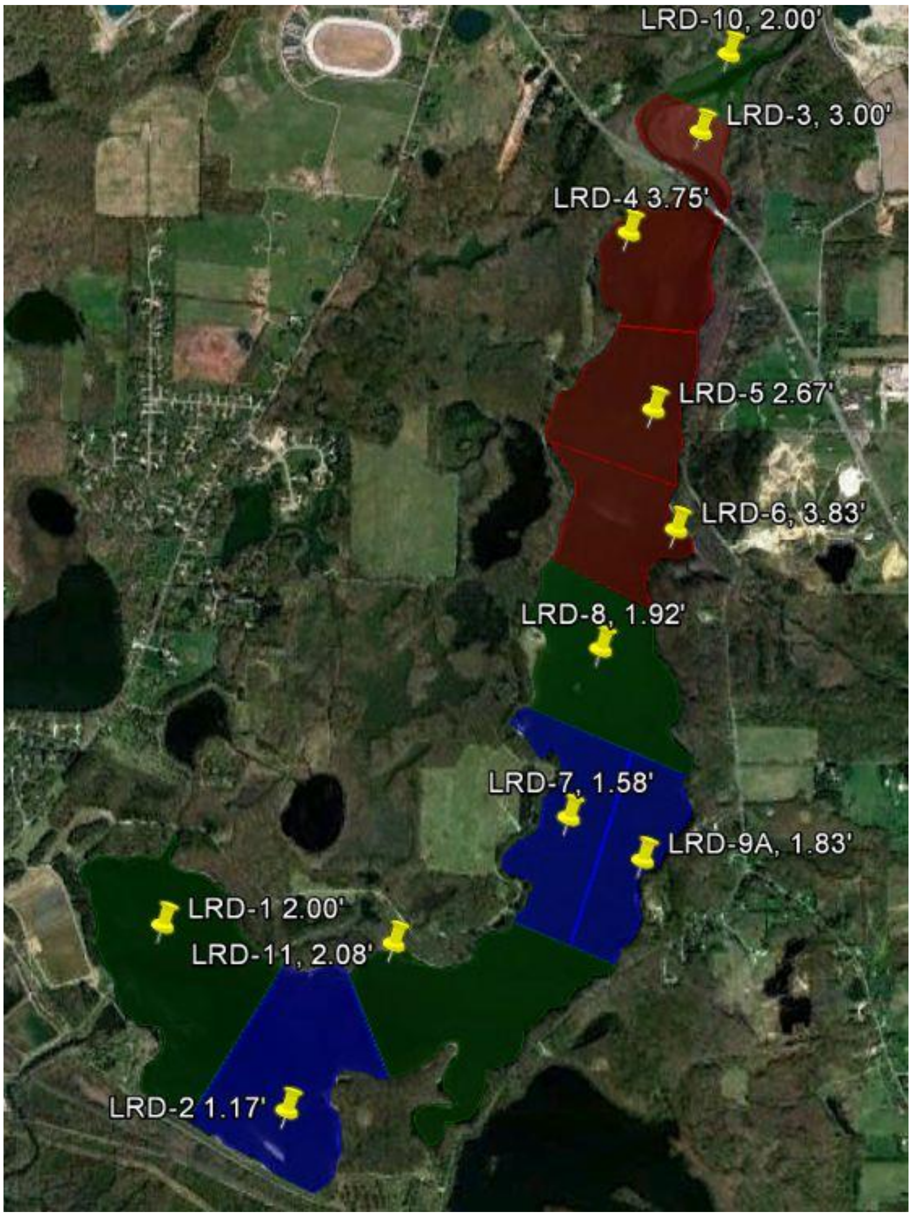

Figure 23: Lake Rockwell Dam Sediment Core Length Dating Method

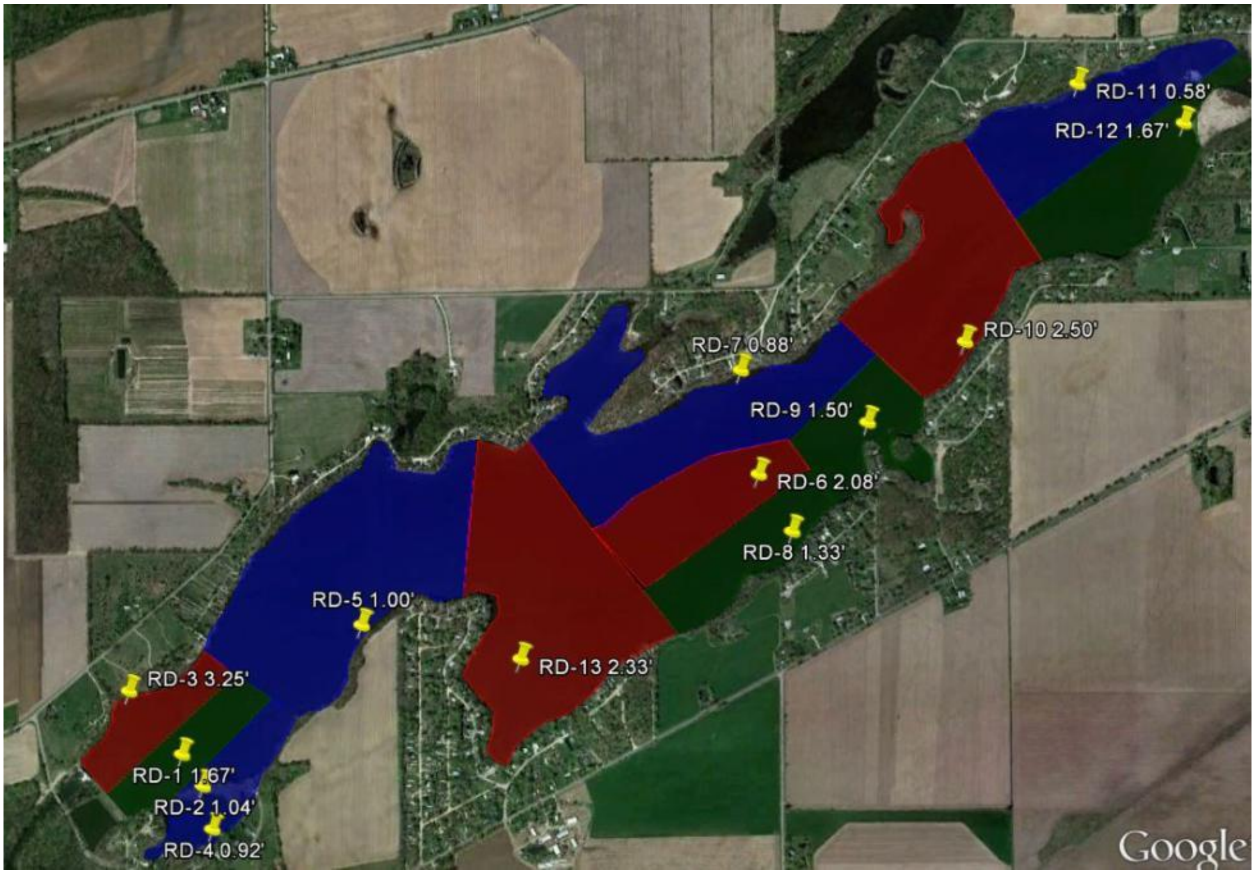

Figure 24: Riley Dam Sediment Dating Rate Applied Across Reservoir-Alternate

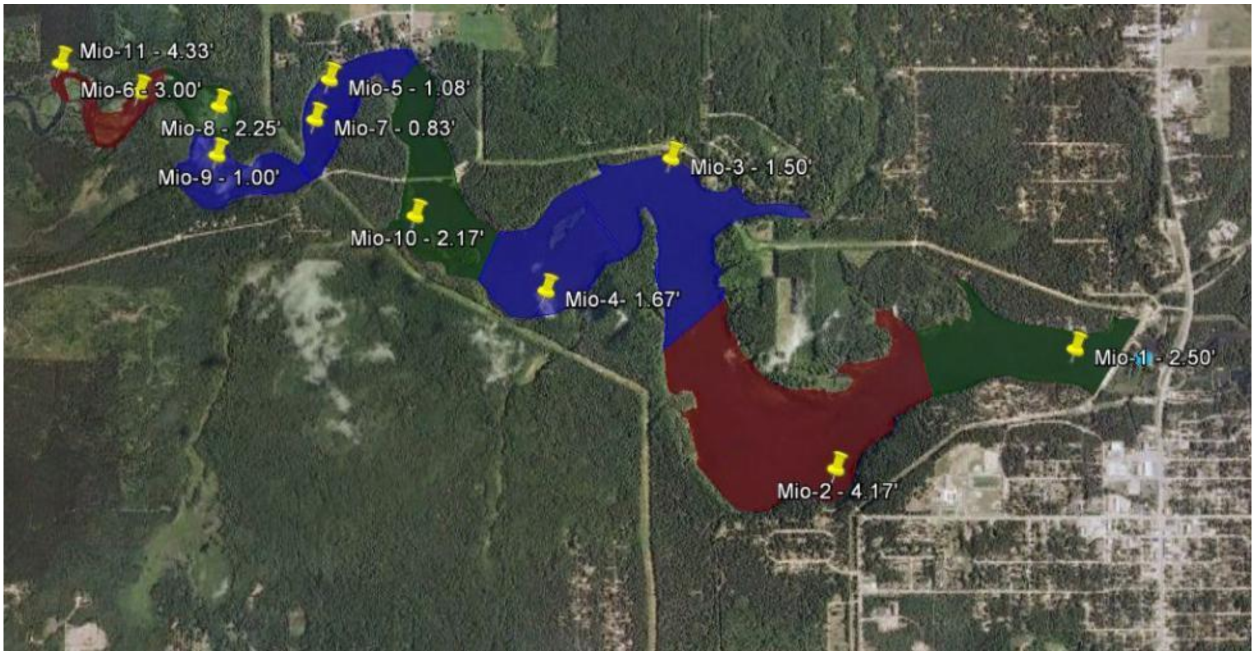

Figure 25: Mio Dam Sediment Dating Rate Applied Across Reservoir-Alternate

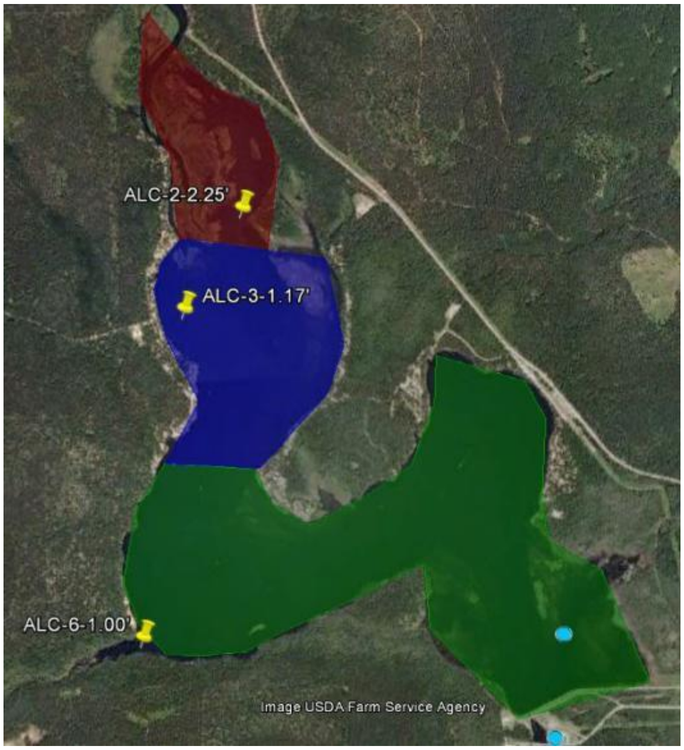

Figure 26: Alcona Dam Sediment Dating Rate Applied Across Reservoir

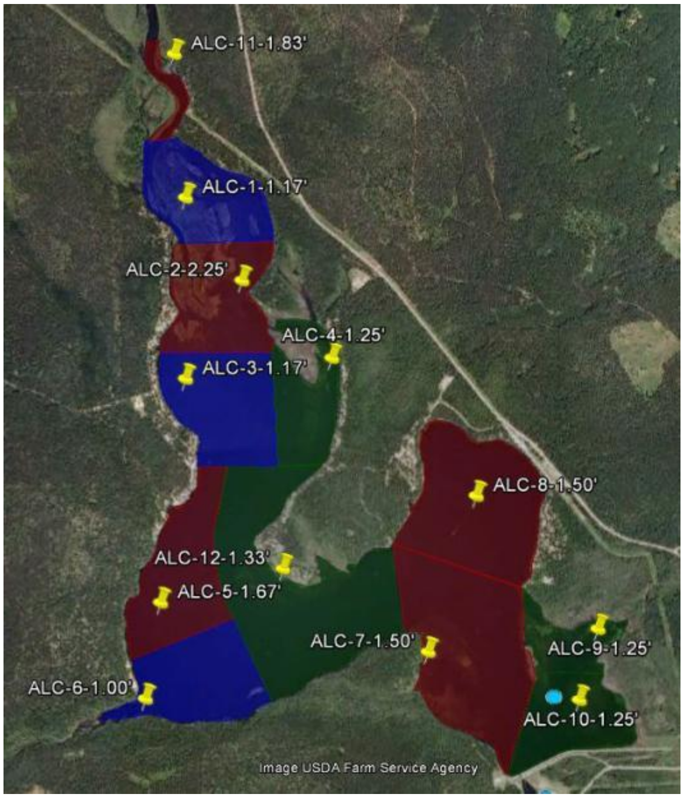

Figure 27: Alcona Dam Sediment Dating Rate Applied Across Reservoir-Alternate

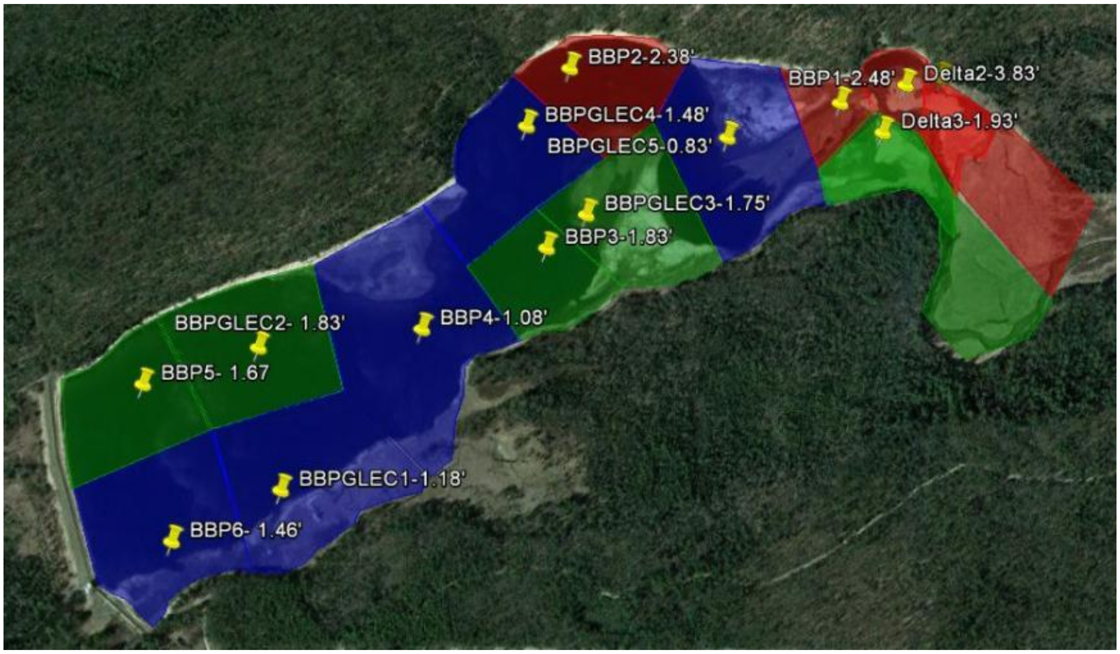

Figure 28: Brown Bridge Pond Sediment Dating Rate Applied Across Reservoir-Alternate

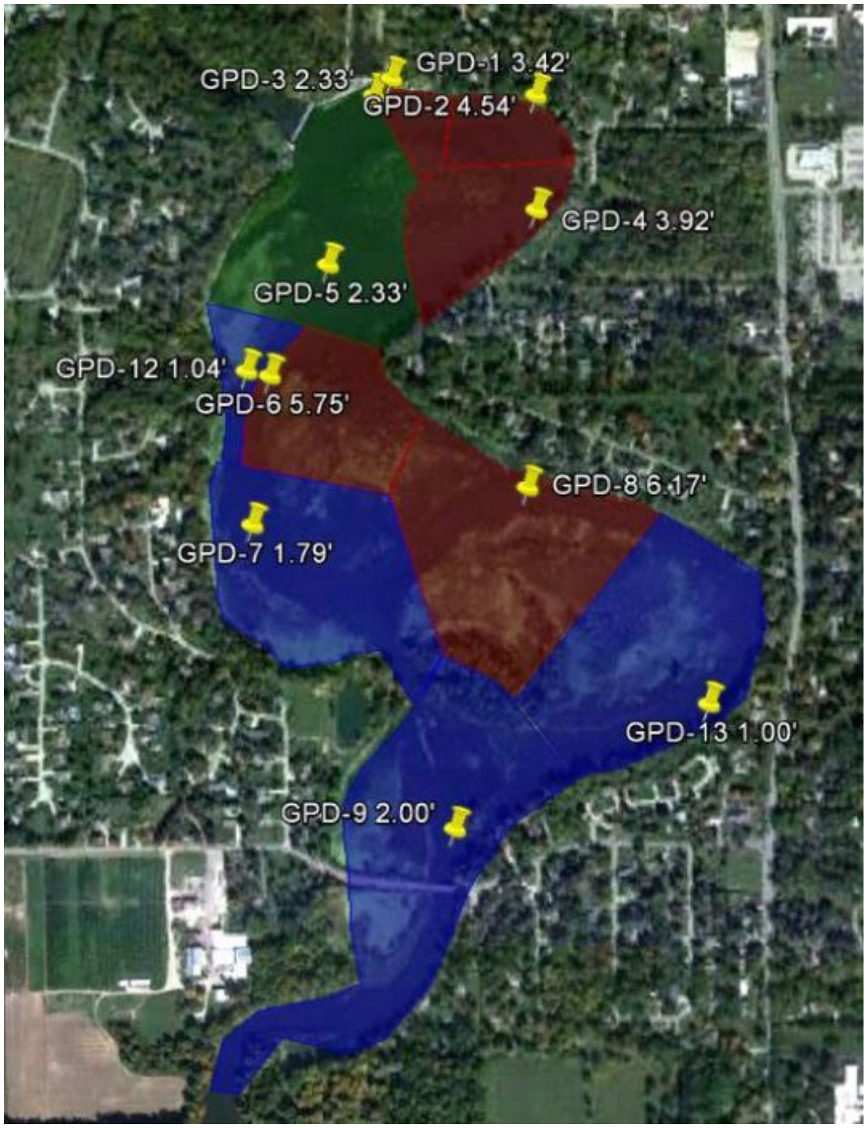

Figure 29: Goshen Pond Dam Sediment Dating Rate Applied Across Reservoir-Alternate

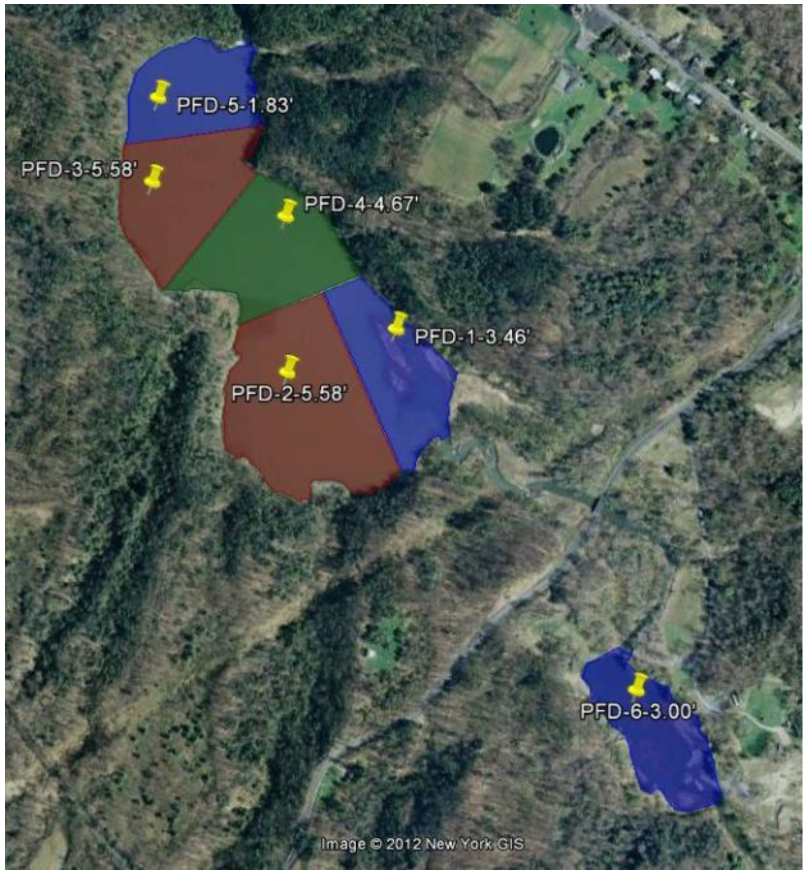

Figure 30: Potters Falls Dam Sediment Dating Rate Applied Across Reservoir-Alternate

Figure 31: Ford Lake Dam Sediment Dating Rate Applied Across Reservoir-Alternate

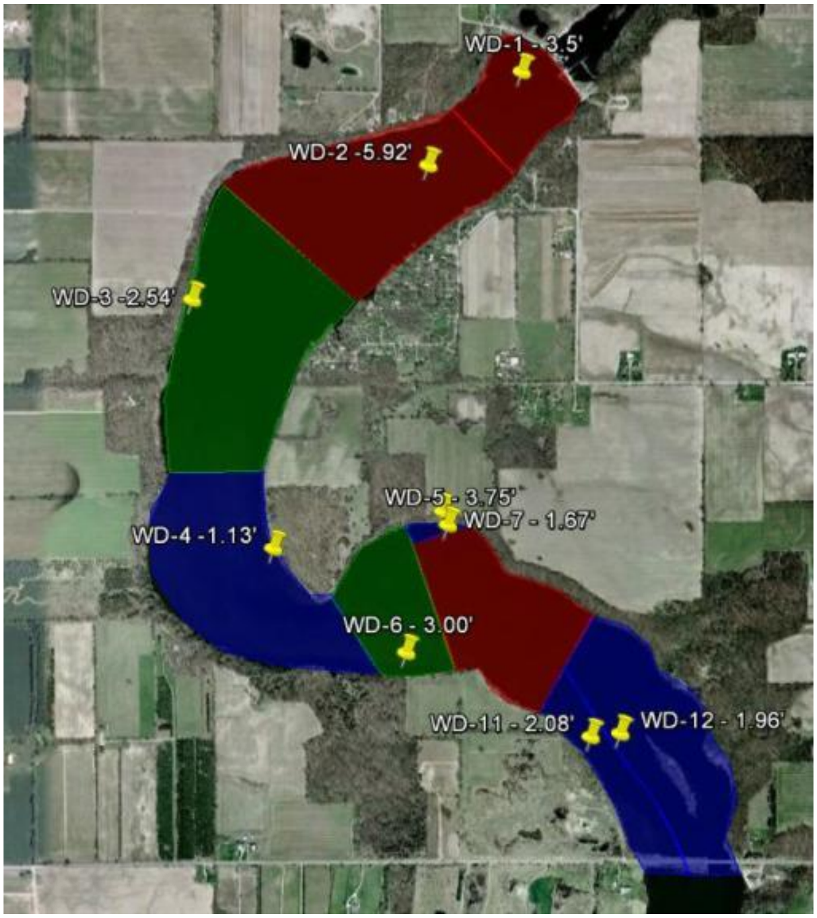

Figure 32: Webber Dam Sediment Dating Rate Applied Across Reservoir-Alternate

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ABSTRACT

METHODS FOR ESTIMATING SEDIMENT YIELD AND DAM CAPACITY IN THE GREAT LAKES WATERSHED

by

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Sedimentation is the most important factor in the longevity of dams built in the United States. As most dams are reaching their capacity for sediment storage, this study investigated the historical and predicted future rates of sediment accumulation as well as the remaining storage capacity. This study examined the mechanisms influencing sediment production and storage in the watershed to provide future insight regarding potential control of this process. Twelve reservoirs throughout the Great Lakes watershed were selected and analyzed for their greater applicability to the entire watershed. Both historic and new data were collected on these dams to determine how the storage capacity has changed over time and to forecast the remaining life-span of the impoundments. Different methods were used to estimate the sediment yield and dam capacity including (1) bathymetric subtraction, (2) USGS (United States Geological Survey) sediment gages, and (3) radionuclide dating. Some correlation was found between agricultural watersheds and a higher sediment load per square mile than forested watersheds do.

AUTOBIOGRAPHICAL STATEMENT

Jennifer Hui just got her Master of Science degree in Civil and Environmental Engineering researching under Dr. Carol Miller. She completed her bachelors of science in Civil and Environmental Engineering at Wayne State University in 2013.