KRBY Engineering
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500 Pillsbury Dr. SE
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December 12, 2017

North Oaks Home Owners' Association
100 Village Center Drive, Suite 240
North Oaks, MN 55127

Re: Pleasant Lake Sustainability Study for North Oaks Homeowners Association

Dear North Oaks Home Owner's Association,

We have concluded our study of Pleasant Lake. The attached report includes a detailed account of our work on the following requests: analyze lake level data for wet and dry years to ascertain what the system would look like if there were no artificial inputs into the lake, provide specific management recommendations for maintaining fluctuations consistent with a natural lake, offer suggestions for making the system resilient to both increased pumping needs and possible climate changes in the future.

Our work included: site visits and research to identify areas along the shoreline subject to erosion, statistical analysis of the existing water surface elevation fluctuations, analysis of water quality of Pleasant Lake and the river water being pumped from the Mississippi, a hydrologic model to assess the effects of pumping on natural water cycles.

Our recommendations for future work include: continue shoreline remediation projects, enforce existing land use ordinances, continue with the hydrologic model to optimize pumping to minimize lake level fluctuations, continue to collect data for pumping rates, surface elevation, water quality, and wind-wave energy, consider improving monitoring practices and equipment.

Thank you for your involvement in our capstone design course, it was a pleasure working with you!

Sincerely,

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Pleasant Lake Sustainability Study for North Oaks Homeowners' Association

Project: F17RH-011 Barr Drkg Water
November 7, 2017

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Certification Page

By signing below, the team members submit that this report was prepared by them and is their original work to the best of their ability.

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Executive Summary

A sustainability study was performed on Pleasant Lake at the request of North Oaks Home Owners Association (NOHOA). Decades of pumping Mississippi River water through Pleasant Lake to supply the Lake McCarrons Water Treatment Plant (WTP) with drinking water for the St. Paul metro area has disrupted the natural cycles of the lake. Fluctuating lake surface levels, shoreline erosion, and water quality are all of concern to the surrounding residents. KRBY Engineering was asked to: (1) analyze lake level data for wet and dry years to ascertain what the system would look like if there were no artificial inputs into the lake, (2) provide specific management recommendations for maintaining fluctuations consistent with a natural lake, (3) offer suggestions for making the system resilient to both increased pumping needs and possible climate changes in the future.

Pumping data, water surface level data, and precipitation data were analyzed for the years 2001 to 2017 to observe seasonal pumping trends, maximum surface level changes, event frequency, and pumping differences between wet and dry years. Lake surface levels appear to be driven by Mississippi River inputs rather than Lake McCarrons WTP pumping demands. A general decline in pumping volumes was observed in recent years most likely due to water conservation efforts. The fluctuations stay within the 3-foot agreement held between St. Paul Water Regional Water Services (SPRWS) and NOHOA.

There are many contributing factors to shoreline erosion. The soil types surrounding the lake are susceptible to erosion and the manmade alterations to the lake shore have most likely accelerated erosion in many areas. Wind driven energy may be the cause of some of the undercutting in locations where wind travels uninterrupted for long distances across the lake creating high energy waves.

Water quality in Pleasant Lake appears to be significantly affected by the Mississippi River inputs. Water clarity and dissolved oxygen levels are not of concern but phosphorous levels are slightly higher than found in other lakes in the same ecoregion. A relationship was observed in the phosphorous levels in the Mississippi River water entering the lake and within Pleasant Lake.

Watershed characteristics were identified (size, slope, shape, drainage density, land use, geology and soils, and vegetation) and used to model the watershed. The model was created using HEC-HMS software to try and determine what the lake would look like in its natural state, without the Mississippi River inputs and Lake McCarrons WTP outputs. The model calibration process was started but time constraints did not allow a complete calibration of the model; however, it was discovered that groundwater is a significant contributing input to Pleasant Lake

To make the system resilient to increased pumping and possible climate changes in the future, KRBY recommends the following: (1) continue shoreline restoration projects to make the shoreline more resistant to erosion, (2) wind and wave analysis to determine if additional shoreline protection from wind-wave energy is necessary, (3) complete the watershed model calibration process and use the model to determine optimal pumping rates for minimizing lake surface level fluctuations, (4) continue gathering data and consider updating monitoring methods and equipment.

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1. Introduction

Pleasant Lake and the surrounding chain of lakes is an old system that has been used to transfer water from the Mississippi River to the McCarrons Water Treatment Plant (WTP). Problems with lake level fluctuations, shoreline erosion, and water quality has prompted North Oaks Homeowners Association (NOHOA) to try to make the system more resilient to the effects of pumping into the lake. Background and site information found in section 2 includes: a brief examination of site history and land use, section 2.1 and relevant lake information, section 2.2. The methodology in section 3 includes: site assessments identifying areas along the shoreline subject to erosion, section 3.1, and data analysis and modeling of the lake surface levels and watershed, section 3.2. Results of the data analysis and watershed modeling are found in section 4 and followed by recommendations in section 5.

2. Background and Site Information

Pleasant Lake is located in North Oaks, a northern suburb of the city of St. Paul, Minnesota, see Figure A-1 in the Appendix. To better understand the problems pertaining to Pleasant Lake, a short history of land use and basic knowledge of the environmental setting of Pleasant Lake is provided.

2.1 Brief History of Land Use

The close proximity of Pleasant Lake to urban areas and the natural flow of gravity which carries water through the Vadnais Lake Area Watershed has made it a valuable drinking water resource for surrounding communities. For these reasons, the lake has experienced artificial influences since the mid 18th century. Beginning with St. Paul Water Company in the mid 1800's, the lake and the land surrounding it has experienced changes in ownership, management, and physical modifications to the natural environment in order to supply the residents of the greater St. Paul area with water.

2.1.1 St. Paul Water Company

Joan C. Brainard and Richard Leonard's book "Three Bold Ventures" presents a detailed history of Pleasant Lake. In the 1850's, the growing city of St. Paul, Minnesota, desperate for a reliable source of water, chartered Charles Gilfillan and the St. Paul Water Company to solve this problem. Plans were drawn and a complex network of pipes, gates, and canals powered by the force of gravity to transport water to the St. Paul Water Company. The original source waters included White Bear Lake and Goose Lake, however, resident complaints of varying water levels caused St. Paul Water Company to explore other options. In 1876, Gilfillan, purchased 3,000 acres of lakeshore property located in what is now the suburb of North Oaks. The acquired property surrounded Charley, Pleasant, Deep, and Wilkinson Lakes. Canals were dredged in the existing streams connecting the lakes in order to expedite the transport of water through the chain of lakes.

Once construction was finished, Gilfillan sold the St. Paul Water Company to the city of St. Paul and the land surrounding the lakes was sold to James J. Hill. The sale included a stipulation giving the water company the right to enter the land to construct conduits as well as complete control over water surface levels. The land was later passed on to NOHOA (Leonard 2007) .

To meet the increasing water demands of St. Paul, the Mississippi River was "tapped" in 1925. A pumping station was built along the river in Fridley. A 60 inch conduit was installed connecting the Fridley pumping station to lake Charley through which river water is pumped from Fridley emptying through a large culvert on the north side of Charley Lake. In 1959 a second conduit was also installed (Leonard 2007).

2.1.2 Saint Paul Regional Water Services

Today, Saint Paul Regional Water Services (SPRWS) operates the system that transports water from the Mississippi River to the McCarrons WTP. Two 60 inch conduits transport water from the pumping station in Fridley into Charley Lake. The pumping station controls the input of water into the system. Once water exits the conduit into Charley Lake, it flows by gravity through a channel on the east side of Charley into Pleasant Lake. A gatehouse on the south end of Pleasant Lake controls the flow into Sucker Lake. The water then flows through Sucker Lake into a second gatehouse on the south end of Sucker Lake and then into East Vadnais Lake where it flows to a pumping station which carries it to McCarrons WTP. See Figure 2.1.2.

The flow of water through the system is dependent mainly on the needs of the city of St. Paul. When water is in high demand, more water is pumped from the Mississippi River into Charley Lake. SPRWS releases water from the gatehouse depending on the surface water level in Pleasant Lake. The lake must not exceed a range of three feet according to an agreement between NOHOA and SPRWS.

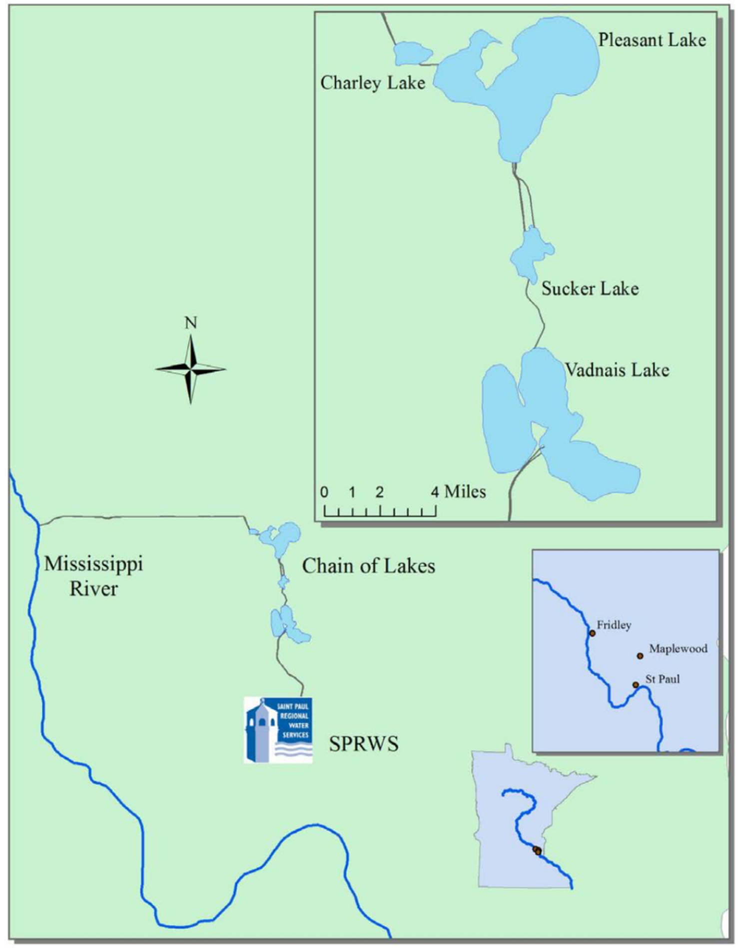

Figure 2.1.2 Map depicts the path of water transportation managed by SPRWS. The path begins at the Fridley pumping station and ends at the McCarrons treatment plant south of Vadnais Lake.(Map taken from project overview document)

2.1.3 North Oaks Community

Pleasant Lake is unique, while many lakes in Minnesota have a combination of private residential and public shoreline, Pleasant Lake shoreline is completely privately owned and managed. Pleasant Lake is located in North Oaks, a private community in the northern suburbs of St. Paul, Minnesota. Residential areas surround the lake, but NOHOA owns and maintains a buffer zone between the lake shore and the private properties that abut the lakeshore, which includes a gravel walking path that is 10 to 12 feet wide and circles almost the entire lake.

Evidence of shoreline erosion exists along much of the lakeshore. Erosion is a concern because as the shoreline erodes, it encroaches upon the walking trail. NOHOA has been working hard to understand the extent of the erosion and how to best reverse the effects. Great River Greening was hired by NOHOA in 2009 to conduct a shoreline study which analyzed the location and extent of erosion and provided remediation suggestions. Since 2009, NOHOA has prioritized shoreline restoration projects as suggested by this study to the best of their ability, but a limited budget makes this a difficult task.

2.2 Relevant Lake Information

To better understand the problems faced by Pleasant Lake, information was gathered about the watershed, shoreline erosion, and water quality.

2.2.1 Watershed

A watershed is an area of land that drains into a river or body of water. For the purpose of watershed analysis, watersheds are often divided into separate subcatchments to narrow the scope of drainage. The Vadnais Lake Area Watershed encompasses about thirteen square miles, and the Pleasant Lake subcatchment covers about three square miles within it. Refer to Figure A-2 in the Appendix for a map of the Vadnais Lake Area Watershed and the orientation of subcatchment flows with respect to Pleasant Lake.

Subcatchment characteristics that impact the amount of contributing runoff include size, slope, shape, land use, geology, soils, and vegetation cover. Soils surrounding the lake consist of primarily fine sands and loamy sands. The surrounding geology of the lake is clay-rich glacial till which acts as a confining unit that does not allow groundwater flow. The water table intersects the lake on the northeast and southeast corners. A buried glacial aquifer sits in the glacial till beneath the lake, the overlying geology applies pressure to the aquifer (Meyer 1992). This type of aquifer is described as "artesian" meaning that if there is an opening in the confining layer, water will rise through the opening until the pressure of the water is balanced with the pressure at the surface of the opening. See at Appendix 2 and 3 for maps and site information.

2.2.2 Shoreline Erosion

Figure 2.2.2 Example of shoreline erosion. Exposed roots and shelf like cut in the soil beneath the overlying vegetation is a sign of erosion (Walton 2009).

A shoreline evaluation conducted by Great River Greening in 2009 concluded that active erosion is prevalent along much of the shoreline including "exposed bare soil, sloughing of soil into the lake, undercutting/incision of shoreline toe, encroachment of bank upon the trail, and invasions of non-native plant species." (Walton 2009, 12), see Figure 2.2.2 for an example of erosion on Pleasant Lake. The study deduced that a major cause of the erosion is lack of vegetation along the buffer zone. However, the report also indicated other factors that likely play a role in shoreline alterations. One of these factors is the wind. Westerly and northwesterly winds are common and significant fetch is developed affecting the north east and southeast side of the shoreline as well as the southwest side of the peninsula. Another likely factor mentioned is the input of water from the Mississippi River and the rise and fall of the lake surface elevation (Walton 2009, 7-8). In the 2009 study, erosion points of interest were recorded and rated according to priority levels 1, 2, 3 or urgent, and 1 being lowest priority. Many remediation projects have been implemented since 2009, most of these projects were focused on the urgent priority areas which included the island peninsula, the southwest shore, the central portion of the east shore, and blue water lagoon, see Figure A-11 and A-13 for reach delineation and priority areas. Even though there are various factors that contribute to shoreline erosion, the full extent of the shoreline erosion suggests that the fluctuating lake levels most likely also play a significant role.

2.2.3 Water Quality

The addition of Mississippi River water into Pleasant Lake also effects water quality. In general, water quality of the Mississippi River is typically worse than that of a lake in this region. In the 1950's algal blooms threatened the lake causing problems for recreational activities and for the WTP downstream. Copper sulfate and iron treatments were attempted but failed (Leonard 2007). An oxygenation system was installed in recent years to increase oxygen levels at the bottom of the lake. The oxygenation system prevents the release of phosphorus from lake sediments, and limiting algae growth. Algae levels have improved but shoreline erosion and Mississippi River inputs are still of concern in regards to maintaining good water quality (Brainard 2007).

Three water quality parameters were examined to determine if a relationship exists between the Mississippi River inputs and the water quality of Pleasant Lake: turbidity, dissolved oxygen (DO) and total phosphorous (TP). Typical values for lakes in the ecoregion surrounding Pleasant Lake can be seen in Table A-5 in the Appendix. Turbidity is a measurement describing water clarity and represents the concentration of suspended solids in the water. Sediment from erosion, waste discharge, and algae growth all contribute to turbidity. High turbidity is of concern because it reduces sunlight entering the water and restricts biologic activity. Excess suspended sediments also provide attachment points for pollutants (USGS 2016). DO is an important indicator of the overall health of an ecosystem; levels below 5 mg/L can be harmful to aquatic life (Minnesota DNR n.d.). Phosphorous is a limiting nutrient in freshwater environments. High dissolved phosphorous often correlates with algal blooms. Phosphorus is transported to the lake from fertilizers and organic waste in sewage and industrial wastewaters (USGS 2016).

Invasive species are also a problem for the health of the lake because they disrupt the natural ecosystem. For Pleasant Lake, these invasive species are Zebra mussels and Asian carp. Asian carp are a problem in many Minnesota lakes and it is unknown if the carp have entered the lake thorough the conduit or by other means. These species do not have corresponding natural predators to keep their numbers in check, thus leading to a frenzied increase in population. These species can outcompete other animals and change the ecosystem. For the Zebra mussels in particular, the costs for maintaining the infrastructure are substantial. Zebra mussels attach to surfaces of the conduit as well as inside the gatehouse used to monitor lake levels and flow rates. Professionals are hired regularly to remove these invasive species.

2.2.4 Wind and Wave Energy

Energy of winds over water bodies results in development of waves which can have a significant effect on shoreline erosion. Undercutting, as shown by Figure 3.1 in the next section, is a typical sign of wave erosion. The southwest shoreline is one location that appears to exhibit significant undercutting.

The wind energy over water bodies is transferred to wave energy which can be represented by wave height and wave period. The wave height depends on wind speed, water depth and fetch. Fetch or fetch length is the undisrupted length over a water body where persistent winds blow. Local westerly winds and fetch may be a contributing cause to some of the erosion on the southwest shoreline of

Pleasant Lake. Data from a 2015 Saint Anthony Falls Laboratory (SAFL) study on Pleasant Lake was referenced to determine if wind is playing a significant role in shoreline erosion. The goal of the study was to determine a reliable method for quantifying wind-wave energy to "predict near-shore wave energy for small to medium sized lakes in Minnesota."(Herb et al. 2016).

According to the wind and wave data, nearly 35% of the waves counted in the study were in the southwest quadrant of the wind rose, see the Figure A-12 in the Appendix for wind rose figure. These data suggest that the southwest shoreline receives more constant wave action than other shorelines of the lake. The wind speed in the southwest direction is generally low, 0-4 m/s. The majority of the waves are low in height, 0-1 cm, according to the Herb et al. (2016) study. Slightly larger waves and higher wind speeds were experienced in the northeast and northwest directions, however, wave counts were lower. The observed significant wave height is defined as the highest third of all waves measured, the significant wave height measured on Pleasant Lake was 1.65 cm. The maximum wave height was 20 cm. This measurement is used in calculations for determining the amount of cover needed to protect the shoreline form wind driven wave energy. (Herb et al. 2016).

Though it is possible that wind-wave energy may be contributing to some shoreline erosion, the SAFL Wind and Wave study only monitored Pleasant Lake for one season providing a very limited data set. Observed wave height is also low making it difficult to determine if the undercutting on the southwest shoreline is caused solely by wind-wave erosion. The shoreline erosion may be a combination of water levels and waves.

3. Methodology

This section describes the methods that were used for the site assessment, the watershed model, the data analysis and the watershed evaluation.

3.1 Assessment

A brief site visit was conducted to examine the condition of the shoreline surrounding Pleasant Lake. Lakeshore undercutting is visible in many locations along the shoreline with many of these locations exhibiting a log like "bulge" of soil above the location of the undercutting, Figure 3.1. Since the shoreline evaluation conducted in 2009, many remediation projects have taken place to mitigate the erosion.

Figure 3.1 Undercutting and soil bulge found on North Shore.

3.2 Modeling

This section explains how water surface level data and a watershed model were used to try and understand the anthropogenic effects of pumping in Pleasant Lake.

3.2.1 Water Surface Level Evaluation

St. Paul Regional Water Services (SPRWS) provided the team with data pertaining to the surface elevation in Pleasant Lake. The members of SPRWS have an agreement with NOHOA that the surface elevation of the lake will not change by three feet inside of a year. It is for this reason, among others, that SPRWS monitors these lake levels and flow rates. Since 2001 the surface elevation in the lake has been recorded daily. SPRWS provided the flow rates in millions of gallons per day (MGD) of Mississippi River water influent to Charley Lake as well as the amount of water that flows out of Vadnais Lake and into the treatment facility. For analysis purposes, the input to Charley Lake was treated as if it were directly inputting to Pleasant Lake and the input to the treatment facility was observed as the local water demand for the region.

In performing the data analysis, the first task was to plot the raw data and observe broad trends. The team hypothesized that seasonal trends would be observed in the surface elevation, river water input, and drinking water demand. The results of this raw data evaluation can be found in the results section of this report.

After gross trends were observed, these data needed to be observed in a finer resolution. The 17 years of surface elevation data were separated into three sets of data, each approximately 5-years long. The flow rates were removed temporarily and the focus was put into observing the surface elevation changes in Pleasant Lake. Once separated into manageable time segments, it was easier to observe and remove outliers from the data. These outliers were identifiable as days with a sudden change in surface level that are followed by another sudden change of similar magnitude. For example, if three subsequent days read: 892.1, 895, 892, then the data point in the middle was removed because it would not be feasible for the lake level to change by three feet in a 24-hour period on back to back days. These points were removed from the dataset discreetly and recorded in Table A-6 in the Appendix.

The project team identified that it is important to note whether the lake surface levels remain within a delta of three feet annually, as per the agreement between SPRWS and NOHOA. To do this, the difference between surface elevation on any given day and the value n-days before was calculated. For example, if the surface elevation today is 892.5 feet above sea level and a week ago the reading was 892 feet above sea level, then the surface elevation fluctuation would be 0.5 feet in a 7-day period. Six figures were generated for each 5-year period. Fluctuations were observed over 1-day, 3-day, 7-day, 10-day, 2-week, and 4-week periods. Once these figures were generated, outliers showed up as vertical lines on the graph and more outliers were discreetly removed for the same reasons mentioned previously. These datasets were observed for their maximum fluctuations to see if the agreement between SPRWS and NOHOA had been kept. The team hypothesized that the 4-week fluctuation would exceed the three-foot agreement at some point. The results of this fluctuation analysis are in the results section of this report.

After each series of fluctuation graphs was generated, significant events in surface elevation were selected to look at more closely and also were compared with the flow rate data (i.e. river water input and treatment plant influent). These events were three to six month segments in which: surface elevations were relatively steady, surface elevation rates were changing rapidly (e.g. monthly), surface elevation values achieved a relatively high peak or relatively low valley. The team hypothesized that the surface elevation in Pleasant Lake would be highly dependent on drinking water demand (i.e. the influent to the treatment plant) and thus would possess a Seasonal trend. The results of this extreme event analysis can be found in the results section of this report.

The project team decided to investigate the frequency of severe lake level changes by quantifying the amount of large surface elevation fluctuations. A count was performed on the fluctuation dataset to count the number of days a delta greater than a foot was observed. A bar graph was generated to show the number of 1-day, 3-day, 7-day, 10-day, 2-week, and 4-week fluctuations were between 1.0-1.5 feet, 1.5-2.0 feet, 2.0-2.5 feet, and greater than 2.5 feet. As a gross estimate, the quantity of fluctuations in each category was divided by the ~17 years of data to determine the frequency of each fluctuation (e.g. a fluctuation greater than one foot over n-days happens x times each year). The results of this fluctuation frequency analysis can be found in the results section of this report.

The team sought to find a relationship between the volume of water added to the chain of lakes and the amount of annual precipitation. The total volume of water pumped annually from the Mississippi River was calculated as well as the total volume of water influent to the treatment plant. The team hypothesized that the ratio between the Mississippi River water and the amount of water influent to the treatment plant would be smaller for years that had high precipitation. The results of this precipitation analysis can be found in the results section of this report.

3.2.2 Watershed Evaluation

To quantify the effects of pumping water through the chain of lakes, the project team developed an HEC-HMS model which included each lake upstream of Pleasant Lake within the Vadnais Lakes Area Watershed.

Watershed delineations for each reservoir were provided by VLAWMO, but were adjusted slightly for modelling purposes. The impervious area percentage, saturated hydraulic conductivity, and lag time were calculated for each watershed using ArcGIS 10.3.1 software. Metropolitan Council land-use data were downloaded into ArcGIS. Using directly connected impervious area approximations based on land use, weighted average impervious percentages were computed for each watershed in the model. Soil data were downloaded from Natural Resources Conservation Service (NRCS), and the lowest saturated hydraulic conductivities within the provided six-foot depth profile were used to compute weighted averages for each watershed. To compute the lag time of each watershed, topographic data from Minnesota Geospatial Commons were used to approximate the most hydraulically remote flow paths for each watershed. The lengths and slopes of these paths were calculated, and using a figure developed by the U.S. Department of Agriculture Soil Conservation Service, the velocities for each flow path were approximated (Mays 2011). These velocities were used in Equation 8.8.5 (Mays, 2011) to compute times of concentration for each watershed. Finally, lag times were calculated using Equation 8.8.2 (Mays, 2011), allowing the NRCS Unit Hydrograph Transform Method to be used. Surface depression storages for each applicable watershed were estimated using the GIS topography maps. These equations are not included in this report but can be found in the Mays text.

The storages of each lake were modelled using bathymetry data provided by VLAWMO and Minnesota Geospatial Commons. Stage-area curves for each lake were developed using linear approximations between stages and input as reservoirs in the model. The outflows of each reservoir other than Pleasant were modelled as rectangular sharp-crested weirs, using GIS contour data to approximate weir dimensions. Using the equation for sharp-crested rectangular weir flow, stage-outflow curves were determined for these lakes. For Pleasant Lake, an outflow curve was calculated using an orifice outflow, with a method from Design of Small Dams (United States Bureau of Reclamation 1987). Refer to Figure A-10 in the Appendix for stage-area-outflow curves of each lake.

Flow paths between reservoirs were modelled as trapezoidal cross-section open channels, with dimensions approximated using satellite imagery and routing calculated by the Muskingum-Cunge method.

Temperature and precipitation data were downloaded from the U.S. National Climate Data Center (NCDC) and used in the model as a time series (National Centers for Environmental Information

2017). Evapotranspiration data were downloaded from the Minnesota Department of Natural Resources and was also used in the model as a time series (Minnesota Climate Summaries Publications 2017). To allow evapotranspiration to occur in the model, a canopy method was approximated using canopy interception values from a publication by Barr Engineering Company (Barr Engineering Company 2010). The provided pump flow data from the Mississippi River were input directly into the model as a source feeding Charley Lake.

To assess the effects of different pumping inflow or outflow scenarios, the model would need to be calibrated. This would entail testing many different parameter values within the soil moisture accounting method for each watershed, and trying to get the model to produce lake elevations over time that are as close to the data as possible.

4. Results

This section provides the results of the water surface elevation analysis, water quality analysis, and watershed evaluation.

4.1 Water Surface Elevation Evaluation Results

Topics discussed in this section: the seasonal trends observed in the water level elevation data, the relationship of pumping to extreme lake level fluctuations, and the maximum water surface elevation changes, frequency of significant changes in water surface elevation, and the relationship between annual precipitation and pumping amounts.

4.1.1 Water Surface Level Seasonal & Trends Results

The team hypothesized that regular seasonal trends would exist for the water surface elevation in Pleasant Lake as well as for the rate of influent river water and the rate of the treatment plant uptake. As one might observe below, this hypothesis was only partially true. Seasonal trends are not observable in the surface elevation or river water pumping rate data sets. However, there is an obvious seasonal trend in the amount of water demand (represented by the plant influent rate) shown in orange circles in Figure 4.1.1. Rates are higher at the end of the summer because drinking water demands are higher; the opposite goes for the winter months. Another gross trend to observe is the fact that peak water demand is decreasing over time despite a growing population. It is possible that this trend is attributable to the water conservation efforts in the area.

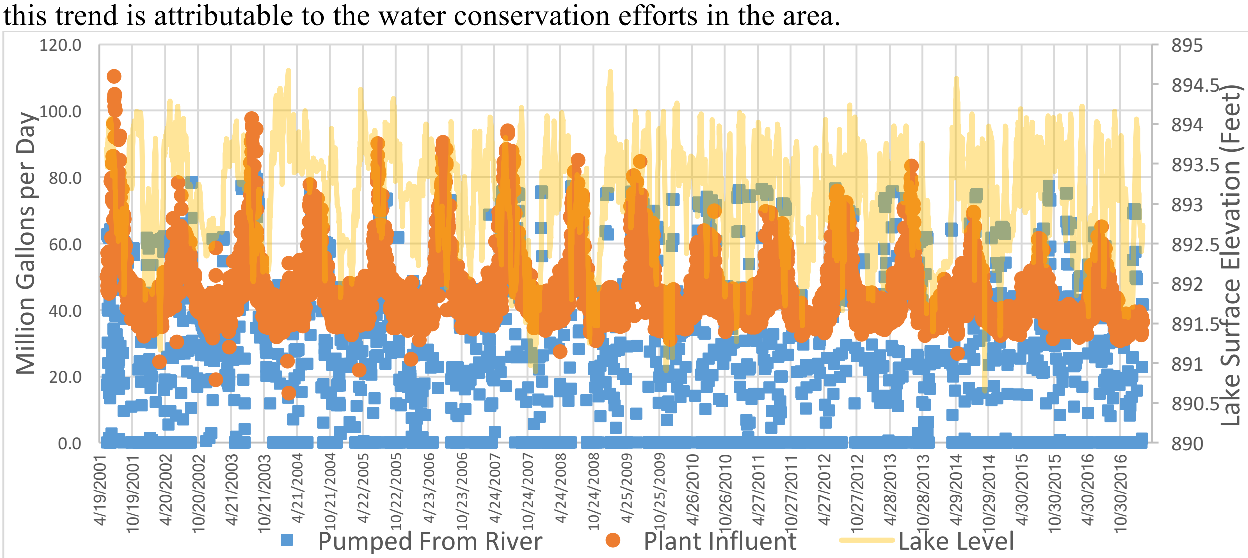

Figure 4.1.1 Pleasant Lake Surface Elevation and Pumping Rate Raw Data

4.1.2 Water Surface Level Fluctuation Trends Results

The fluctuation graphs were used to identify outliers and significant events to investigate further. This series of figures was selected due to the obvious nature of the event in early 2014. This event of little surface elevation fluctuation will be further investigated in Figure 4.1.3 below.

Figures A-18 through A-20 in Appendix 5 of this report were used to separate the data into more manageable pieces for investigation. Figure A-20 of this series of figures is part three of the three 5-year sets of figures showing fluctuations in surface elevation alongside the actual surface elevation level. Notice the lack of variation in surface elevation near the beginning of the year 2014; this is an example of an unusual event that was selected and investigated at a finer resolution alongside the pumping data. It is important to plot multiple variations in time; the reason can be observed in the spring of 2016. Notice that there is a peak in surface elevation (gold line) but that the 1-day fluctuation graph (top) shows that this is not a sudden change whereas the 4-week fluctuation graph (bottom) causes the change to seem sudden.

4.1.3 Extreme Surface Fluctuation Events & Relationship to Pumping

Figure 4.1.3a below shows an event of relatively steady elevation that can be observed. It is a rare occurrence that the input from the Mississippi River is as invariant as Figure 4.1.3a shows. When the pump is steady, however, the surface elevation in Pleasant Lake seems to increase gradually. To draw a conclusion from this event, it is important to look at a contrasting event for the same time period in a different year.

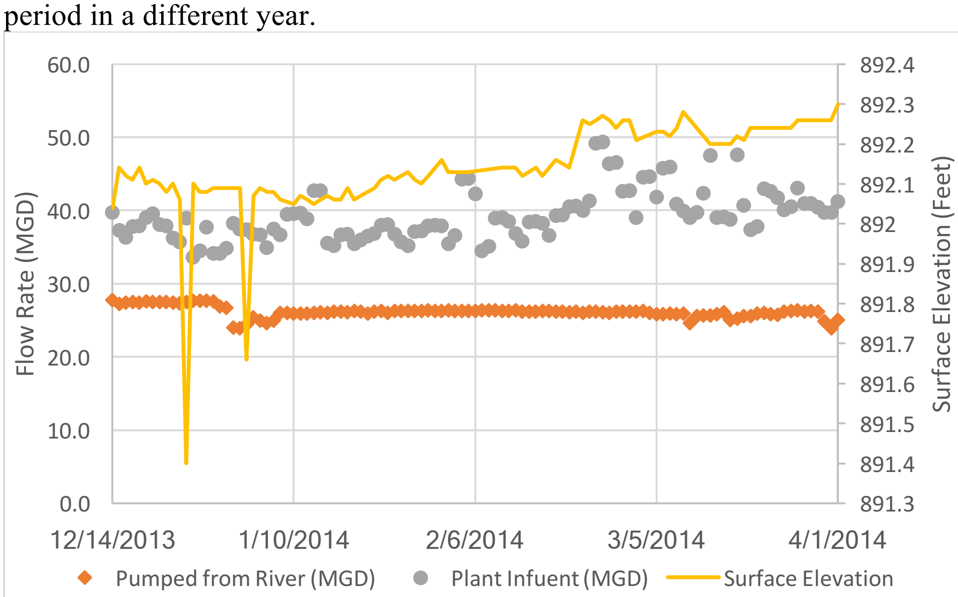

Figure 4.1.3a Trends in Pumping and Surface Elevation from December 14th 2013 through April 1st 2014

The spring of another year was investigated because it demonstrated relatively high amounts of fluctuation for the same season. Figure 4.1.3b below shows an event in early 2002. The important detail to observe in this figure is the relationship between the input from the river and the resulting surface elevation changes. When the pumping rate from the river is greater than the rate influent to the plant, the surface elevation increases; conversely when the pumps from the river are turned off or the rate is less than the demand, the surface elevation decreases dramatically. As a result, three rapid increases in surface elevation of 1.4 feet, 2 feet, and 2.6 feet are observed. It was hypothesized that the surface elevation fluctuations are caused by changes in water demand, this hypothesis seems incorrect. The events shown in Figure 4.1.3a and Figure 4.1.3b show a steady demand and an inconsistently changing river input rate. All of this points to the conclusion that the surface elevation in Pleasant Lake is more impacted by the input from the Mississippi River than the output to the drinking water treatment facility.

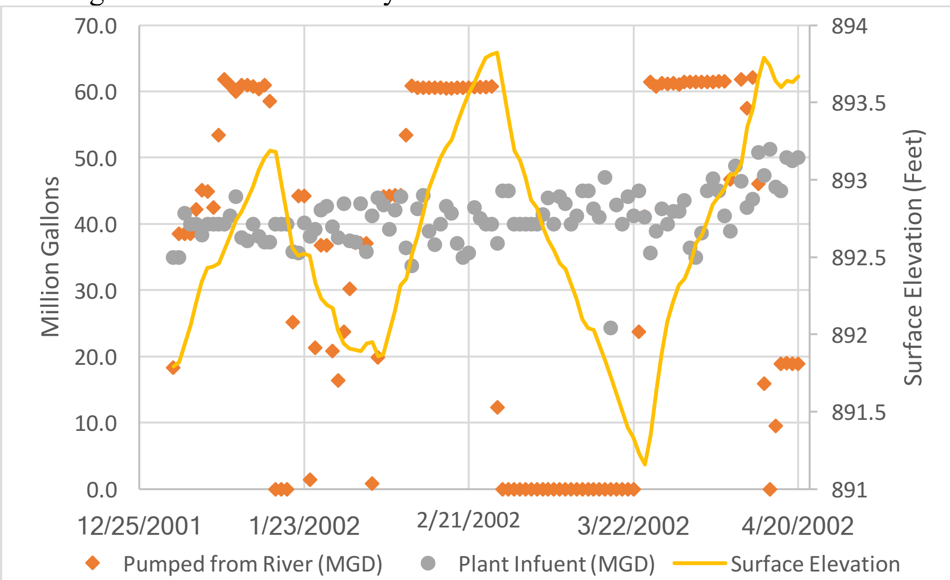

Figure 4.1.3b Trends in Pumping and Surface Elevation from December 31st 2001 through April 20th 2002

4.1.4 Maximum Changes in Surface Elevation

The maximum fluctuation values were observed for each time interval and are described in Table 4.1.4 below. To determine the maximum surface elevation change, the absolute value of the data, created for the fluctuation graphs above, were taken and the maximum delta was recorded. None of the fluctuations exceeded three feet over the intervals analyzed, fulfilling the agreement between SPRWS and NOHOA. The highest observed surface elevation fluctuation was 2.87 feet over a 2-week period.

Table 4.1.4 Maximum Change in Surface Elevation for Each Time Interval Observed

Time Interval	1-day	3-day	7-day	10-day	2-week	4-week
Max. Change in Surface Elevation (Feet)	1.24	1.42	1.98	2.37	2.87	2.77

4.1.5 Frequency of Significant Surface Elevation Fluctuations

It is important to note the frequency in which these large fluctuations take place. Figure 4.1.5 shows the quantities of significant changes respective to time interval. To develop a rate, the quantities above a certain threshold were summed and divided over the 17 years. For example, the number of monthly fluctuations greater than one foot in a given year can by calculated from the following:

$$(647+261+94+7 \text{ days}) / (17 \text{ years}) = 60 \text{ days per year}$$

This indicates that in any given year, based on this data, one should expect the lake level to increase or decrease by at least one foot over a 4-week duration 60 times. Calculations were performed for a few other extreme values:

Monthly fluctuations greater than 2 feet per year:
(7+94) / (17 years) = 6 days per year
Biweekly fluctuations greater than 1 foot per year:
(514+139+16+1 days) / (17 years) = 40 days per year
Biweekly fluctuations greater than 2 feet per year:
(16+1 days) / (17 years) = Once a year

The significance of these numbers is that despite remaining within the constraints of the agreement to avoid a change greater than three feet in a given year, significant fluctuations occur over a monthly or weekly time interval multiple times per year.

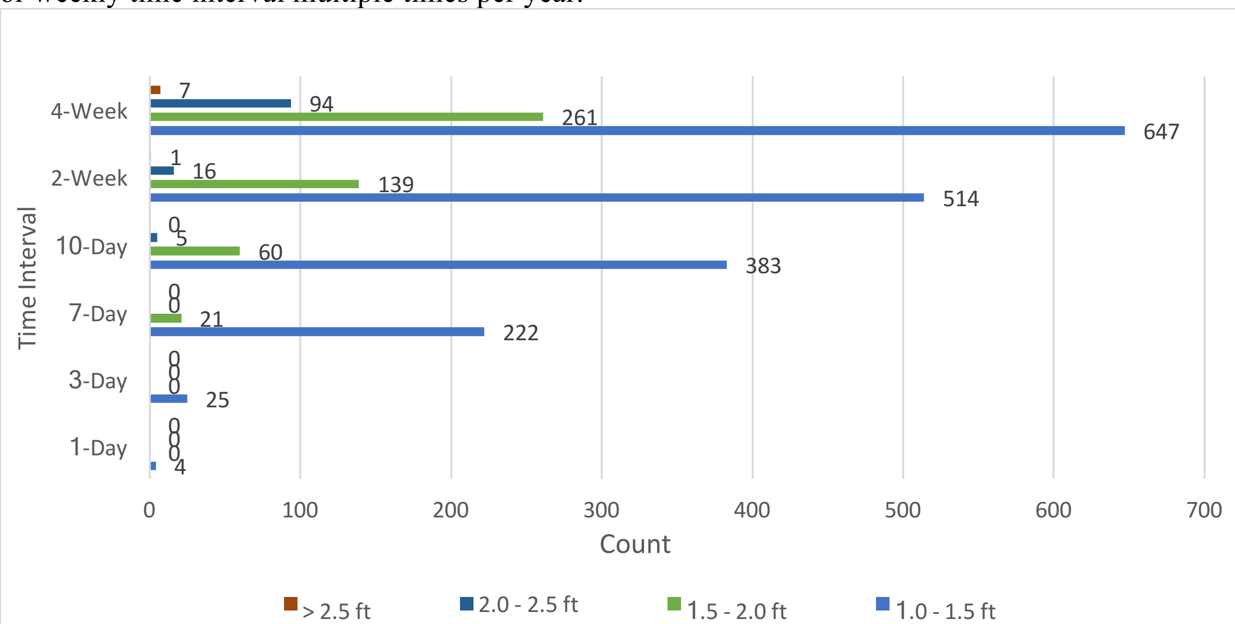

Figure 4.1.5. Number of Fluctuation Instances 2001-2017 Excluding Values Below 12"

4.1.6 Annual Precipitation Analysis

An analysis was performed to compare annual totals of both the river water input and the volume influent to the water treatment facility with the amount of annual precipitation. Table 4.1.6 shows a ratio between the volume of river water pumped annually and the volume of water influent to the treatment facility. The three highest ratios correlate with the three years of lowest precipitation, indicating that more water is added to the chain of lakes during dry years. While the table shows a correlation between dry years and an increase in river water added, the opposite relationship does not necessarily appear true. The two years with the lowest ratios correlate with relatively moderate amounts of precipitation. The table shows that years after 2013 have significantly lower ratios. The average ratio is 0.71 and the standard deviation is 0.11. The past three years have ratios that are more than a standard deviation lower than the mean. Therefore the low ratios, indicating a smaller annual contribution of river water to the system, likely have more to do with recent practices, as opposed to correlating with high annual precipitation.

Table 4.1.6 Comparison between Annual Totals of River Water Input and Total Volume Influent to the Water Treatment Facility with the Amount of Annual Precipitation

Input/Uptake Ratio	Annual Precip. (in.)	Year	Input Volume (Million Gallons)	Plant Uptake (Million Gallons)
0.87	23.9	2009	14690.6	16925.8
0.81	22.1	2008	13690.4	16848.8
0.80	17.6	2003	13989.6	17534.2
0.79	30.8	2012	12982.5	16471.3
0.76	27.6	2007	13788.3	18139.1
0.76	33.3	2010	11986.2	15798.8
0.75	33.7	2011	11912.9	15982.6
0.74	30.6	2004	12513.9	16983.4
0.73	30.7	2002	12200.3	16619.9
0.73	27.7	2013	11573.4	15921.1
0.71	26.4	2006	12254.9	17222.5
0.70	34.2	2005	11790.9	16775.6
0.58	39.6	2016	8545.3	14848.1
0.52	27.9	2014	8122.5	15623.1
0.42	31.2	2015	6241.0	14896.1

4.1.7 Water Surface Elevation Analysis Conclusion

Through this data analysis, much was learned about the relationship between pumping rates and the surface elevation in Pleasant Lake. First, it seems that only the drinking water demand (i.e. the amount of water influent to the treatment facility) possessed a seasonal pattern. In the middle of winter, demand was low and at the end of the summer water demand was high. A counterintuitive trend was observed in that despite a growing population, peak water demand is decreasing over time; this is likely due to water conservation efforts in the region. Second, the surface elevation changes in the lake seem to be more closely related to the input from the Mississippi than originally hypothesized. The figures showed that when the pumps from the river ran at a regular rate, the surface elevation stayed steady; they also showed that when the pumps from the river were shut off, the surface elevation decreased dramatically. Third, the data analysis confirmed that the agreement between SPRWS and NOHOA in terms of managing surface elevation changes in Pleasant Lake is being upheld. The maximum fluctuation observed was 2.87 feet over a period of two weeks which is less than 3 feet. An analysis regarding the frequency showed that significant changes in surface elevation occur multiple times each year when observed over a two-week and four-week period. The analysis of the amount of river water input compared with annual precipitation identified two key relationships. First, the analysis showed that years with relatively low precipitation have relatively high volumes of river water added to the chain of lakes. Second, the analysis showed a significant decrease in the total annual volume of river water inputted since 2013. Years of relatively low volumes of river water inputted to the chain of lakes correlate more with recent practices than any visible trend in annual precipitation.

4.2 Water Quality Analysis Results

There are three water quality parameters that were considered in this analysis: turbidity, DO, and total phosphorous. The Secchi depth and the DO data are shown in the appendix because results seemed normal and exhibited no significant trend. Figure 4.2.1 shows measurements of total phosphorous for the Mississippi River, Pleasant Lake, and Vadnais Lake. The blue box shows the typical range of values, see Table A-5 of typical water quality values in the Appendix. Figure 4.2.1 shows that the total phosphorous levels in Pleasant Lake are very similar to those the Mississippi River and slightly exceed the levels of phosphorous found in lakes in the same ecoregion.

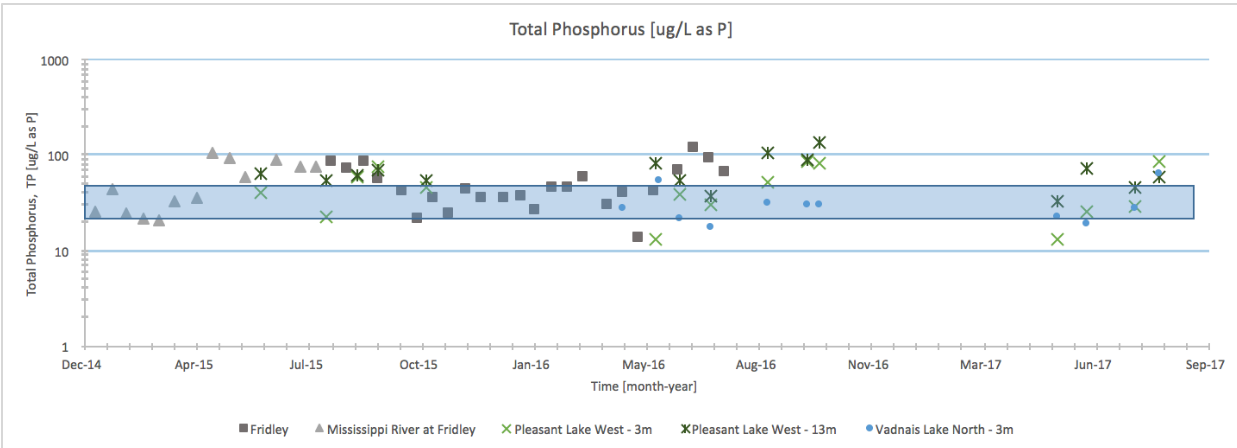

Figure 4.2.1 Phosphorus at Fridley, Pleasant Lake and Vadnais Lake

4.3 Watershed Evaluation Results

While the groundwater storage over time remains unknown due to the model not being calibrated, the surface runoff calculated from model runs is relatively accurate. The model was run with zero baseflow to quantify the effects of surface runoff, and runoff was determined to be an extremely small source to changes in lake surface elevations. To keep lake levels from falling unrealistically low or rising unrealistically high, a source of 2.5 cfs needed to be added to Pleasant Lake. This means that over long periods of time, the average groundwater contribution to Pleasant Lake is roughly 2.5 cfs. This suggests that the bottom of Pleasant Lake intersects with the groundwater table and is fed through a hydrostatic pressure balance. This quantity was calculated to be roughly 5% of the water intake in the McCarron's Treatment Plant. This information would be useful in further model development. Refer to the Appendix for the resulting parameters of watershed evaluation.

5. Recommendations

Although this study should be continued, the project team was able to draw many conclusions about the system and develop recommendations to further this investigation while maintaining Pleasant Lake in the meantime.

First, it is recommended that the shoreline remediation projects continue. Long fetch, soil composition, and the fluctuating surface elevation of the lake will continue to cause shoreline erosion; however, the severity of this erosion can be mitigated by implementing the shoreline remediation techniques outlined by the "Pleasant Lake Shoreline Evaluation" (Walton 2009). The second recommendation is to enforce ordinances and shoreline buffers. Areas of little to no vegetation and lawns that go right up to the lakeshore are extremely susceptible to erosion.

An extensive wind and wave analysis is also recommended to identify locations that may benefit from wind and wave protection. The wind analysis requires gathering data from nearby weather stations for analysis, a wave frequency analysis, and a cost analysis including maintenance costs to determine erosion counter measures. The winds with annual probability of exceedance should be used for the design of a shoreline counter measure.

Next, it is recommended that the watershed HEC-HMS model started in this project is followed through to completion. The fully developed model can be used to better predict the natural inputs to the system; in theory this would make the pumping rates easier to estimate and prevent a more reactive approach to selecting the input pumping rate. It is also recommended that the input driven fluctuations be reduced. It was determined that the driver of surface elevation changes has a lot to do with the input of Mississippi River water. The data shows periods of extremely high pumping rates followed by up to a month of no pumping. If these extended periods of high or zero pumping can be changed less rapidly, significant changes to surface elevation might happen less frequently.

Lastly, the team recommends that SPRWS continues to monitor the system, specifically data pertaining to pumping rates, water quality, surface elevation, and wind-wave energy. Some of the raw data sets given to the team had missing or erroneous values. It is recommended that methods and measurement practices be adjusted to prevent misreads and periods of unavailable data. It would also be helpful to this study to monitor the flow rate out of Pleasant Lake as opposed to using the plant uptake flow rate values. This could be helpful for the data analysis and the model and could demonstrate more realistic trends with regard to Pleasant Lake.

6. Summary

Most of the shoreline surrounding Pleasant Lake shows some evidence of erosion. While there are many natural contributing factors to the erosion, it is likely that the fluctuating lake levels also play a role. Implementation of remediation techniques outlined by the "Pleasant Lake Shoreline Evaluation" and a wind and wave frequency analysis to determine the impacts of wave energy on the shoreline are good methods of restoring the shoreline and reducing erosion.

The lake level analysis revealed a general decline in peak pumping rates over the last 17 years, most likely due to increased water conservation efforts. The lake fluctuations stay within a 3-foot range month to month which meets the agreement held between SPRWS and NOHOA. Surface elevation fluctuations appear to be driven by the artificial input from the Mississippi River. The data show that dry years have higher pumping rates, as expected due to increased water needs by residents and lower lake levels, however the opposite trend is not observed in wet years.

The hydrologic model was built in HEC-HMS, but due to time constraints, the calibration process was not finished. It is recommended that the model is finished to gain more information about natural lake cycles to help determine optimal pumping rates. It was discovered that groundwater plays a significant role in lake recharge, contributing roughly 5% of the annual volume taken by the Lake McCarrons WTP for drinking water use.

By continuing to collect data and study Pleasant Lake and the surrounding watershed it is likely that SPRWS and NOHOA will be able to determine a more sustainable method of pumping.

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8. Appendices

Appendix 1. Abbreviations

Brief list of abbreviations used throughout the report.

DO – Dissolved Oxygen
NCDC – National Climate Date Center
NOHOA – North Oaks Homeowners Association
NRCS – Natural Resources Conservation Service
SAFL- Saint Anthony Falls Laboratory
SPRWS - Saint Paul Regional Water Services
SSURGO – Soil Survey Geographic Database
TP – Total Phosphorus
VLAWMO – Vadnais Lake Area Water Management Organization
WTP – Water Treatment Plant

Appendix 2. Key Maps

Maps used to illustrate site location and watershed information used for creating the HEC-HMS watershed model.

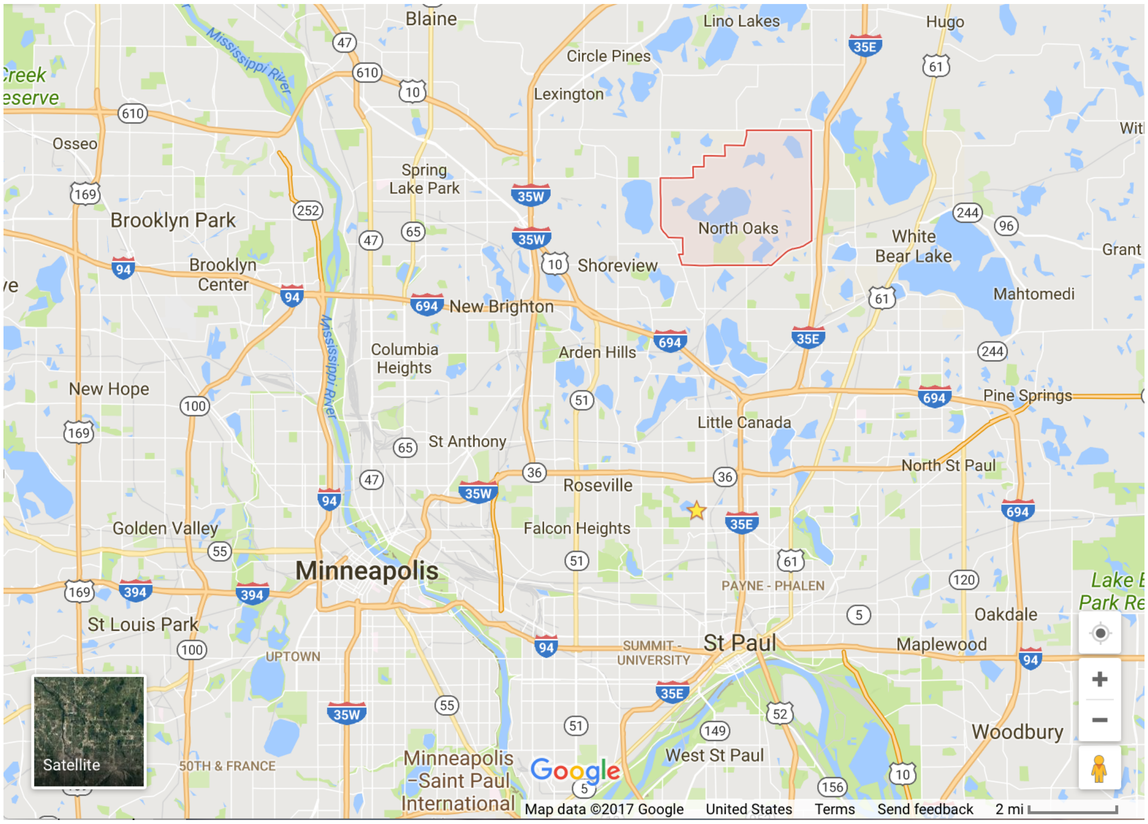

Figure A-1 Minneapolis-St. Paul Metro Area. Pleasant Lake is found in North Oaks, marked by the shaded region directly north of St. Pau (Google).

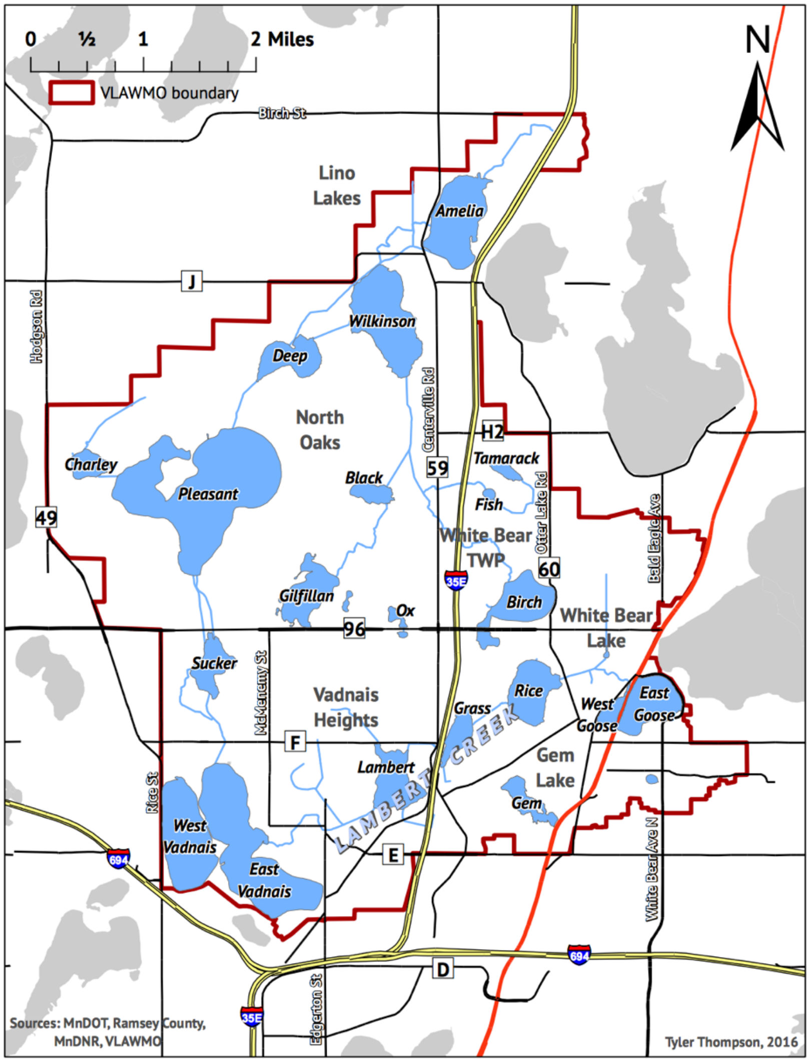

Figure A-2 Map of Vadnais Lake Area Watershed.

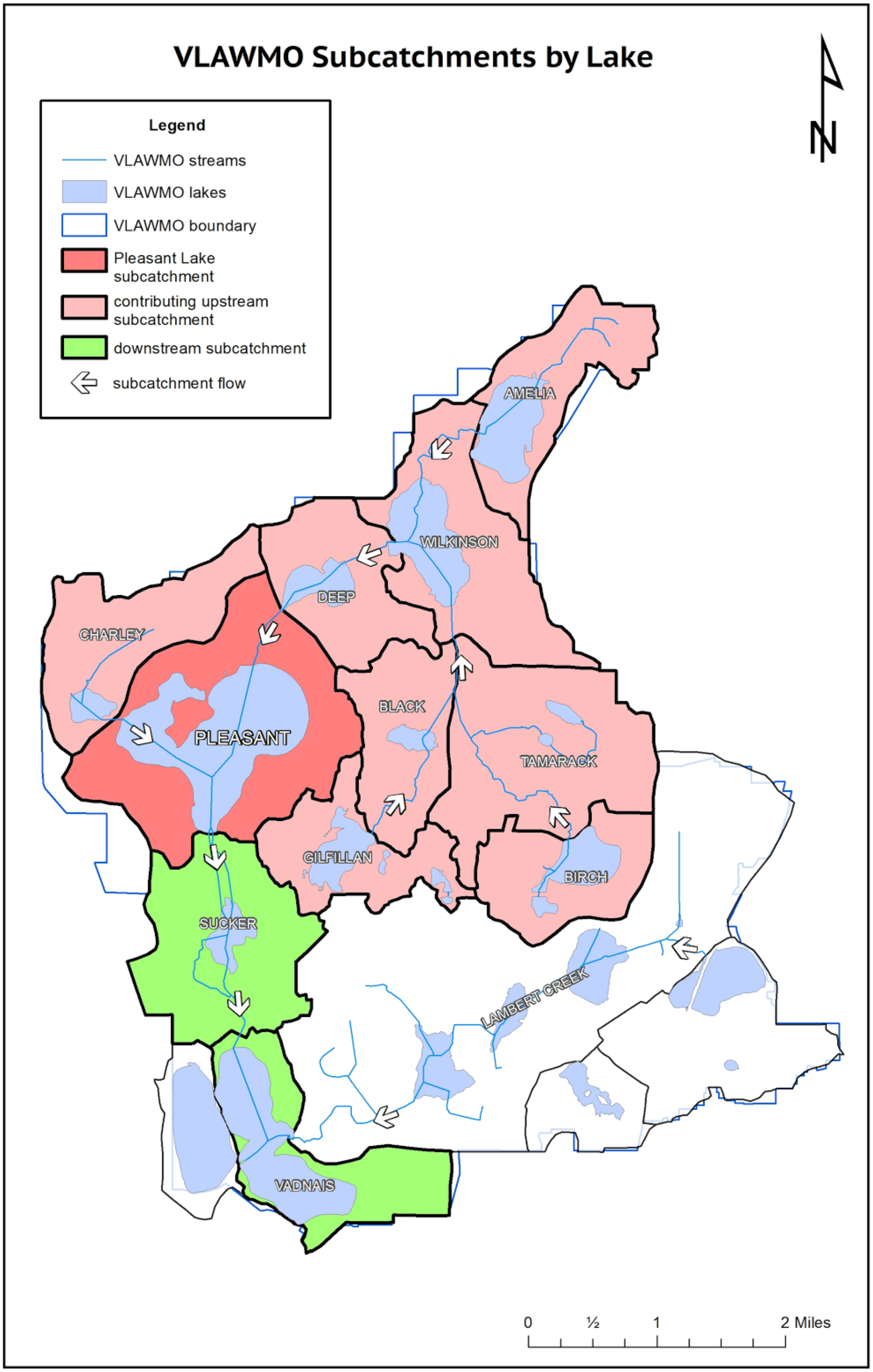

Figure A-3 Map of the Vadnais Lake Watershed and the orientation of subcatchment flows with respect to Pleasant Lake.

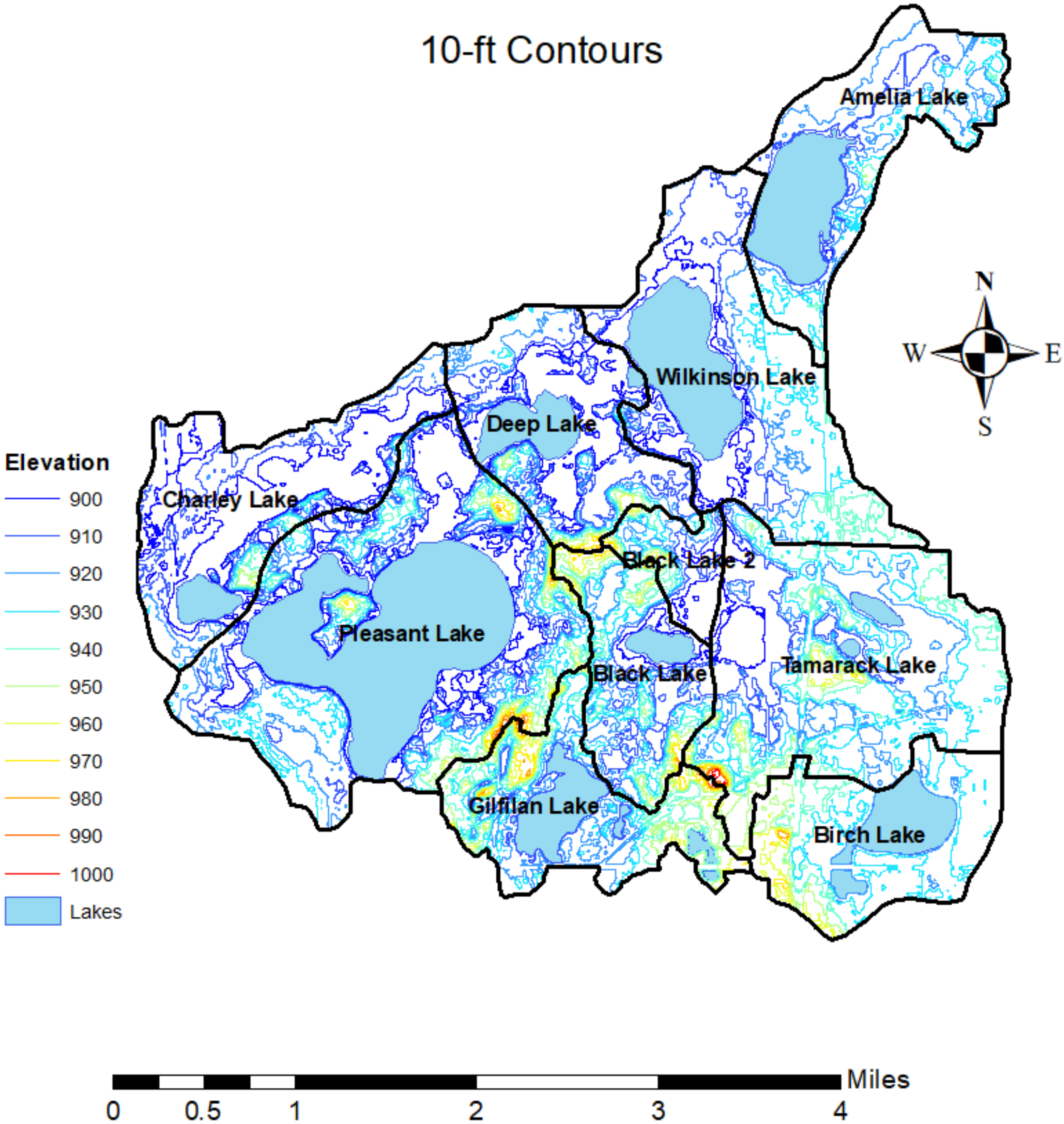

Figure A-4 Map of Contour Elevations of Subcatchments Upstream of Pleasant Lake

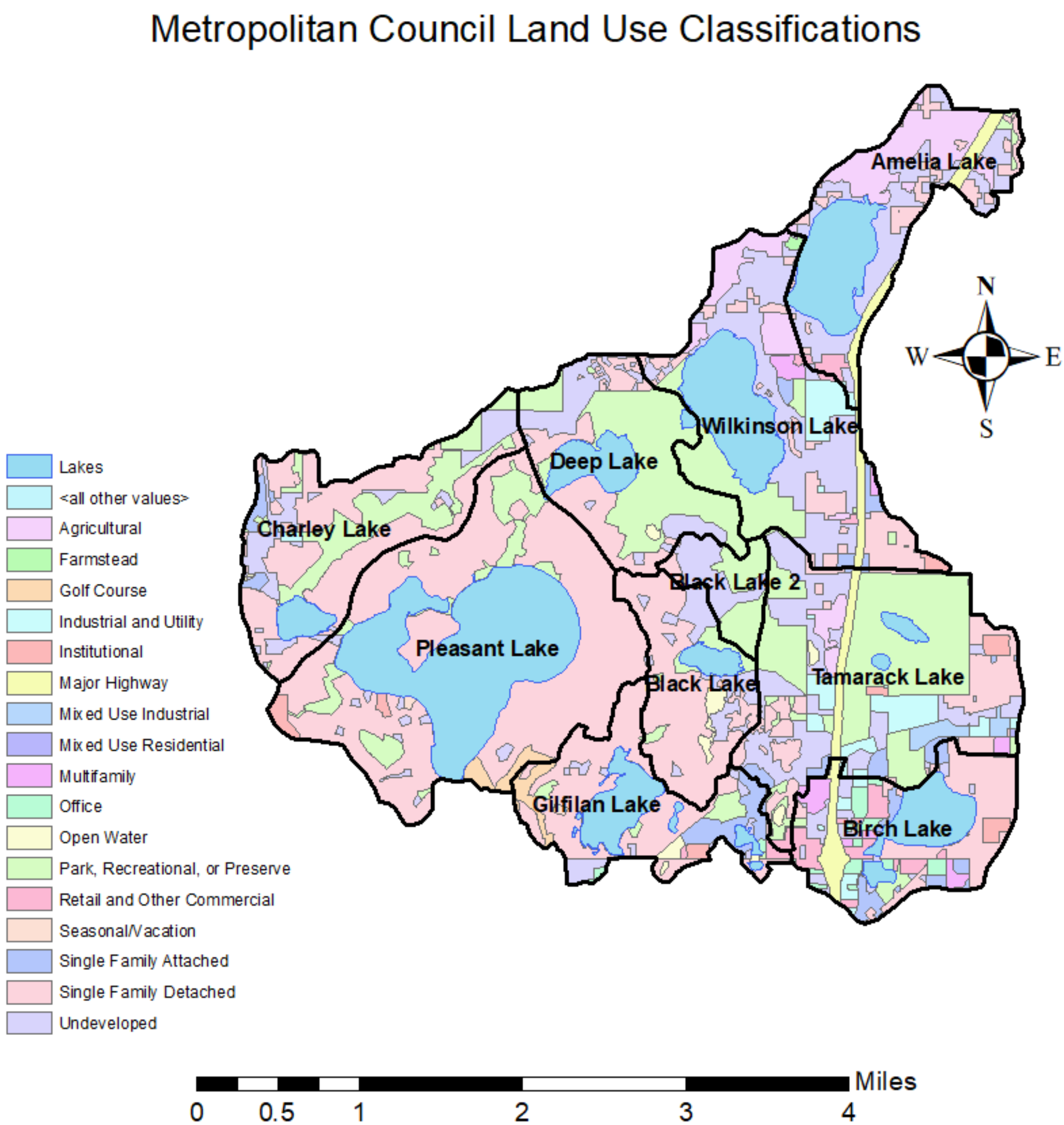

Figure A-5 Metropolitan Council Land Use Classifications of Subcatchments Upstream of Pleasant Lake

Appendix 3: Soil, Geology, and Wind

This section provides site background information used to understand soil, geology, and wind energy that contributes to erosion and also natural water inputs into Pleasant Lake.

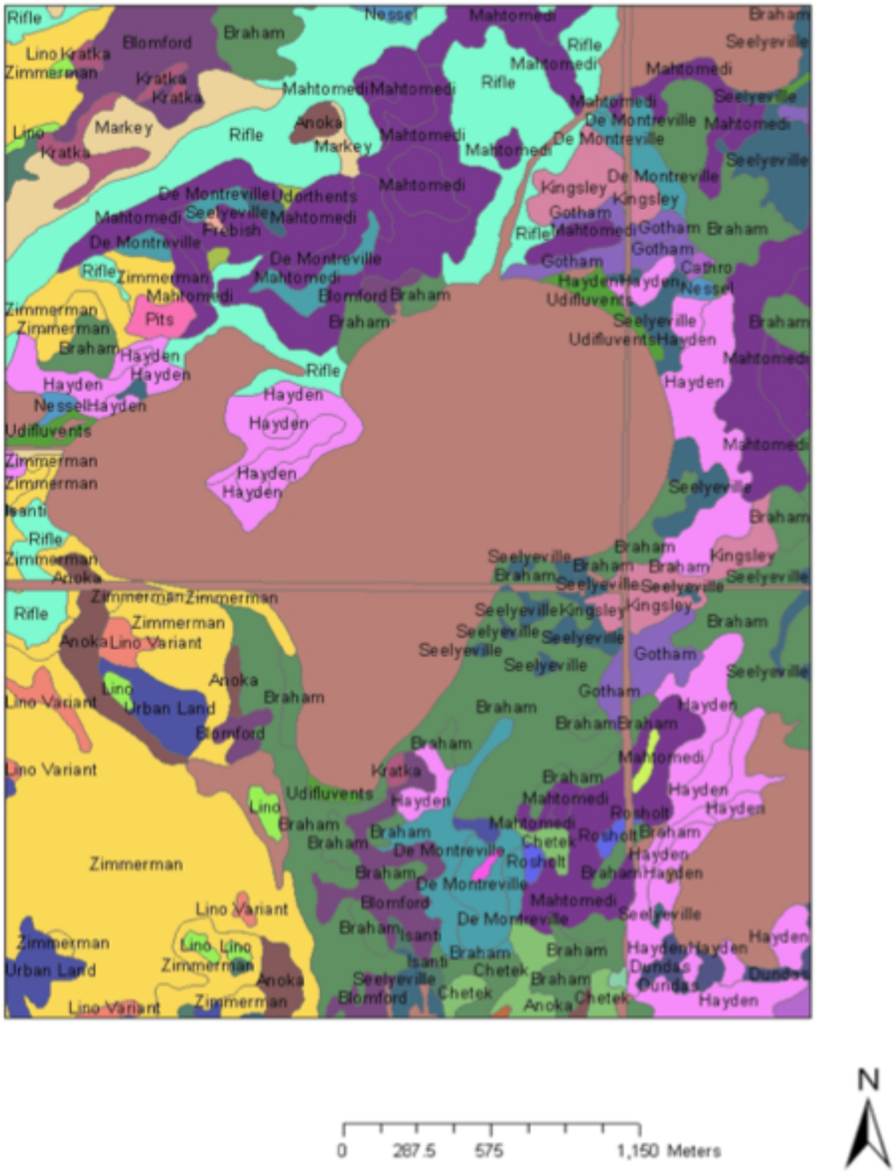

Figure A-6 Map of Soil Types Surrounding Pleasant Lake. Soil type is extremely important when evaluating shoreline erosion. In general, the soil surrounding the lake consists of fine sands and loamy sands which are fairly vulnerable to erosion (Walton 2009, 7-9).

Table A-1 Six main soil types along Pleasant lake Shoreline (Custom Soil Resource Report for Ramsey County, Minnesota 2017)

Soil Type	Percent of AOI* [%]	Description	Hydrologic Soil Group	Parent Material
Hayden	9.6	Fine sandy loam	B	Till
Braham	9.0	Loamy fine sand	B	Outwash over till
Zimmerman	3.7	Fine sand (loamy fine sand on slopes12-25%)	A	Sandy glaciofluvial deposits
Rifle	3.6	muck	A/D	Organic material
Seeleyville	2.6	muck	A/D	Organic material
Udifluvents	1.8	N/A	No	Sandy beach sediments

*Percent calculated using Web Soil Survey. See Appendix for Area of Interest (AOI) delineation used in calculation, water accounted for 64.5% of the total area.

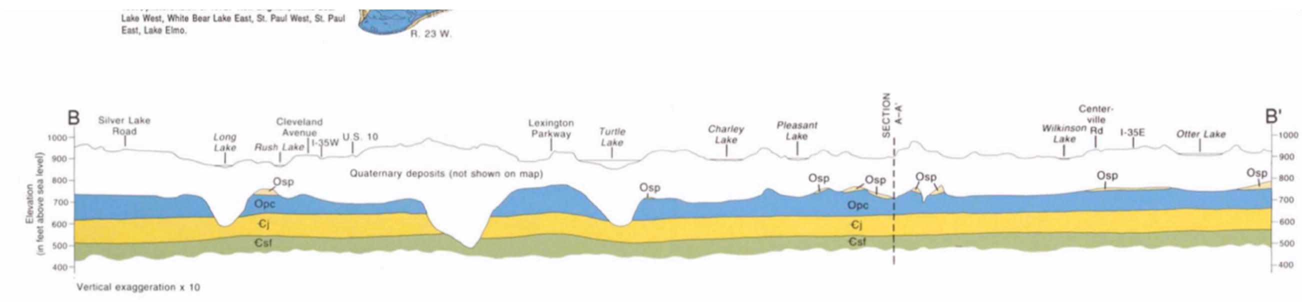

Figure A-8 Geologic cross-section of Pleasant Lake. Pleasant Lake is shown just to the left of the SECTION A-A dotted line. The white layer (Quaternary Deposits) is glacial till. The blue layer (Opc) is the Prairie Du Chein Group is a confined aquifer and the main contributing aquifer to Ramsey County. Notice that Pleasant Lake lies entirely in the glacial till layer and does not intersect with the Prairie Du Chein Aquifer (Meyer 1992).

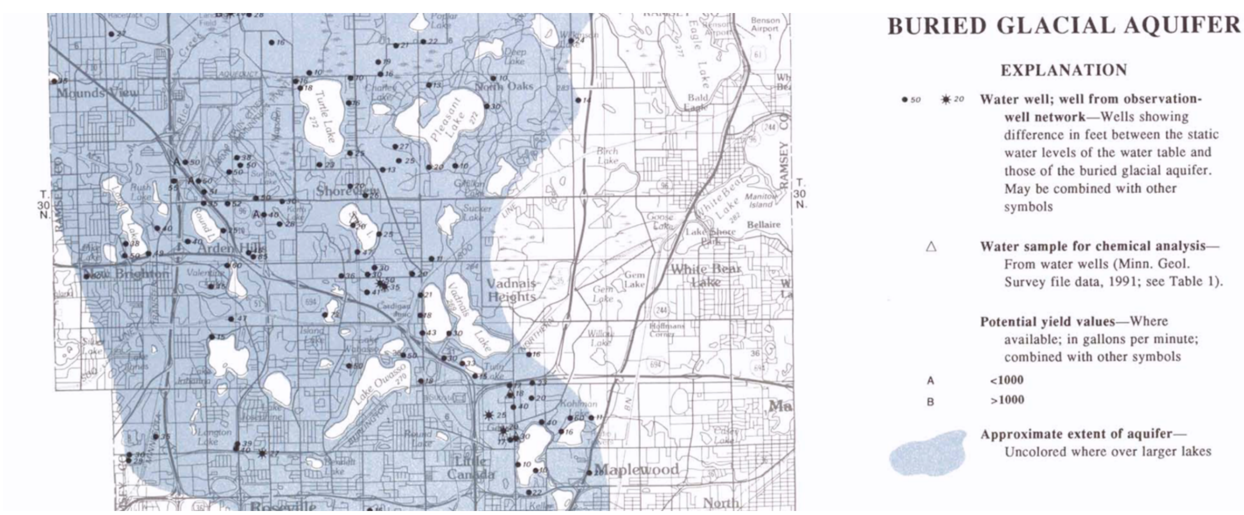

Figure A-9 Map of Buried Glacial Aquifer Beneath Pleasant Lake. Aquifer is located in a confined glacial till and is artesian in nature. It is likely that this aquifer (Meyer 1992).

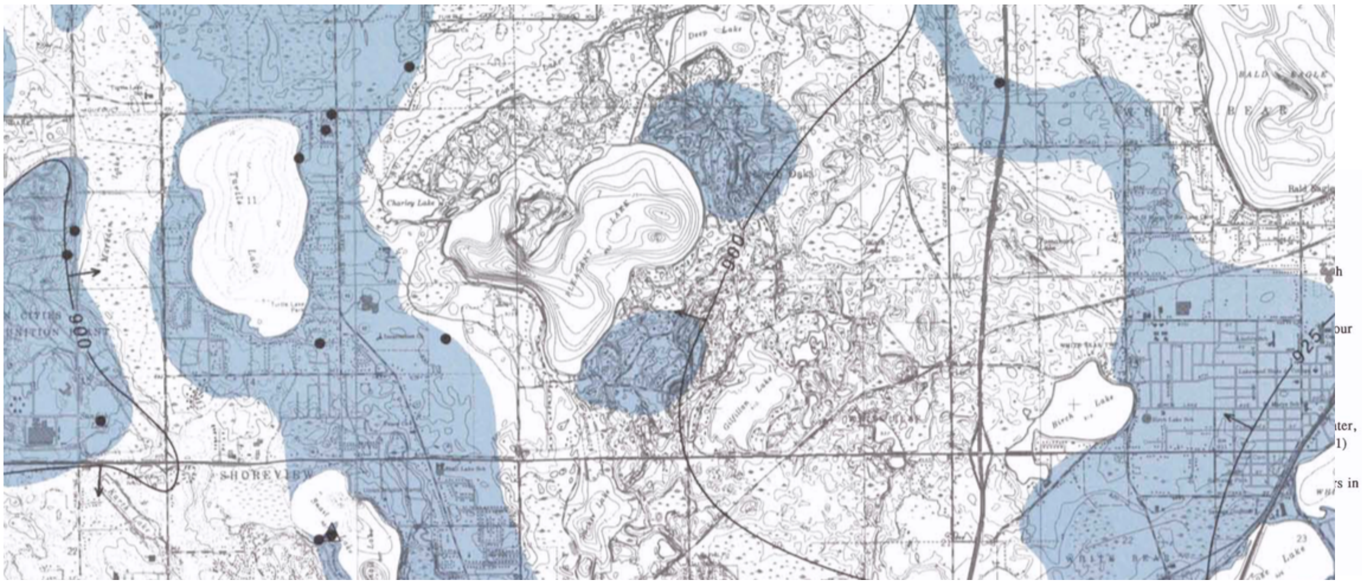

Figure A-10 Water Table Location Near Pleasant Lake. Notice that the water table intersects the lake in the NE and SE corners at an elevation between 875 and 900 feet above sea level (Meyer 1992).

Figure A-11 Reach Delineation. Used to identify areas of shoreline. Since 2009 many shoreline remediation projects have been done by NOHOA. most of these projects were focused on the Urgent priority areas which included the Island Peninsula, the Southwest Shore, the central portion of the East Shore, and Blue Water Lagoon. Reach delineation taken from (Walton 2009).

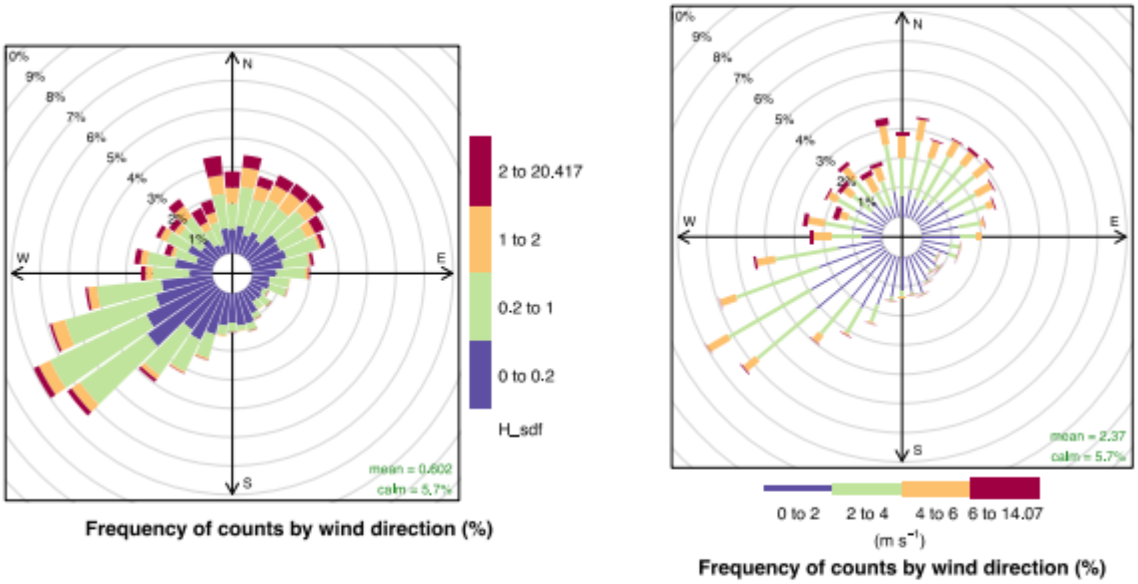

Figure A-12 Pleasant Lake wind and wave data summary. The left image shows wave height based on wind direction and the right image shows wind speed by direction.

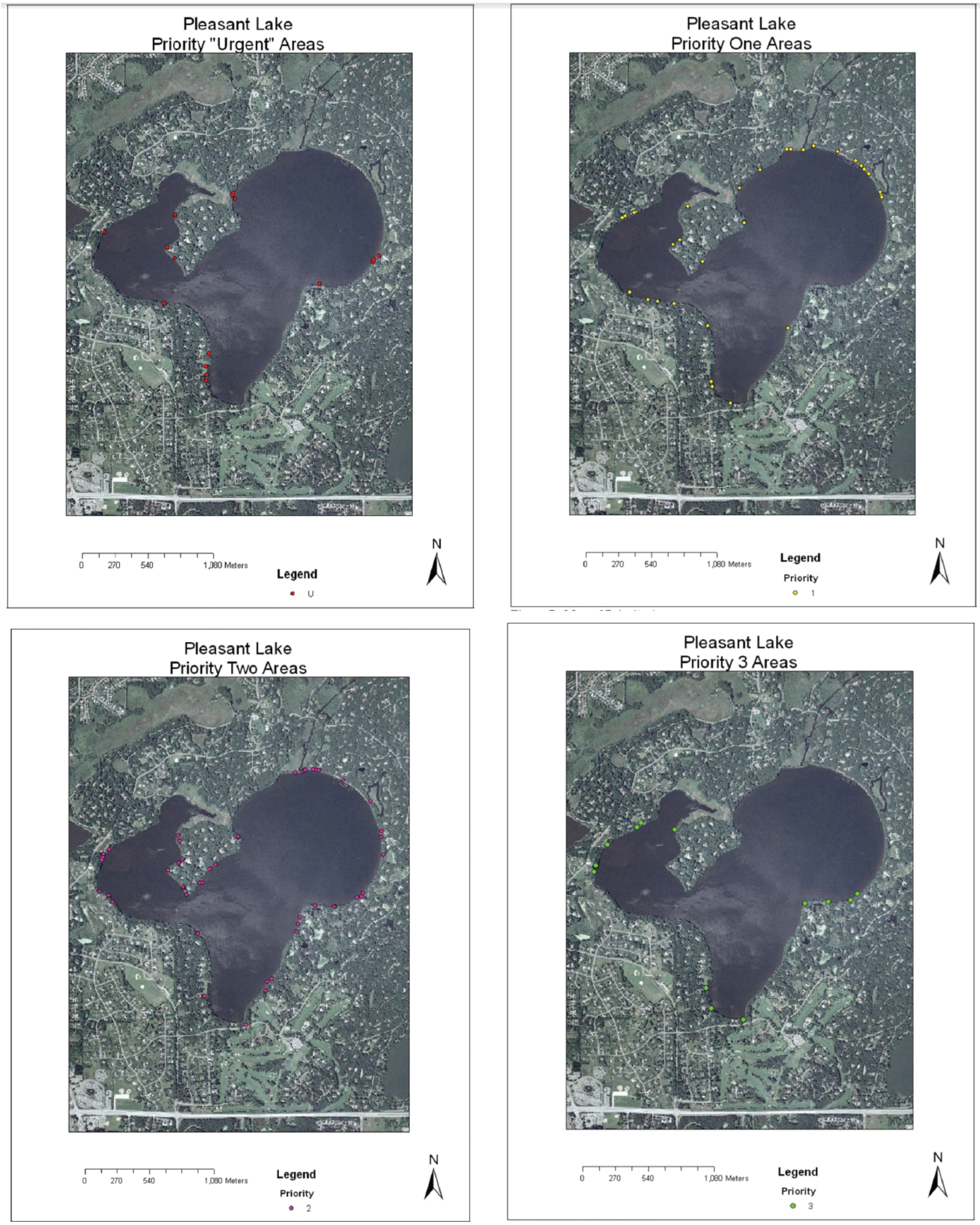

Figure A-13 Shoreline Erosion Priority Areas. The four maps are taken from the Pleasant Lake Shoreline Erosion Study. Each map depicts a different remediation priority level. Notice that the shoreline shows signs of erosion around almost the entire lake, however there is increased erosion priority areas on the SW tip of the lake, on the NE corner, and around the peninsula. It is possible the increased erosion in these areas is due to the fetch across the lake causing an increase in wind and wave energy on the shoreline.

Appendix 4. Water Quality Raw Data and Figures

Data and figures to illustrate water quality in Pleasant Lake.

Table A-2 Total Phosphorous in Pleasant Lake Raw Data

Sampling Date	Site ID	Total Phosphorus	Total Phosphorus
8/27/2007	62-10	1028.00	1.028
9/24/2007	62-10	205.42	0.205
4/29/2008	62-10	31.83	0.032
5/28/2008	62-10	63.26	0.063
6/26/2008	62-10	127.81	0.128
7/29/2008	62-10	333.97	0.334
8/19/2008	62-10	338.32	0.338
9/23/2008	62-10	217.66	0.218
10/30/2008	62-10	30.74	0.031
5/28/2009	62-10	102.92	0.103
6/25/2009	62-10	11.40	0.011
7/29/2009	62-10	254.95	0.255
8/31/2009	62-10	493.53	0.494
9/16/2009	62-10	836.61	0.837

Table A-3 Turbidity Raw Data in Vadnais Lake and Pleasant Lake at Varying Depths

Sampled Date	Location Name	Turbidity (NTU)
2016/4/18	Vadnais Lake South - 13m	0.866
2016/4/18	Vadnais Lake South - 3m	1.67
2016/6/8	Vadnais Lake North - 0m	1.59
2016/6/8	Vadnais Lake North - 3m	1.19
2016/6/8	Vadnais Lake North - 6m	0.85
2016/6/8	Vadnais Lake North - 9m	0.682
2016/6/8	Vadnais Lake South - 0m	1.26
2016/6/8	Vadnais Lake South - 3m	1.19
2016/6/8	Vadnais Lake South - 6m	0.852
2016/6/8	Vadnais Lake South - 9m	0.725
2016/6/8	Pleasant Lake East - 3m	1.8
2016/6/8	Pleasant Lake East - 6m	1.28
2016/6/8	Pleasant Lake East - 9m	1.15
2016/6/8	Pleasant Lake West - 0m	2.12
2016/6/8	Pleasant Lake West - 3m	2.13
2016/6/8	Pleasant Lake West - 6m	1.85
2016/6/8	Pleasant Lake West - 9m	1.33

Table A-4 Dissolved Oxygen and Temperature versus Depth Raw Data for Pleasant Lake

Date	Site	Depth (m	Temp	D.O. ppm
2000/4/18	61	1	6.10	13.90
2000/4/18	61	2	6.60	13.50
2000/4/18	61	3	6.60	13.00
2000/4/18	61	4	6.60	12.80
2000/4/18	61	5	6.60	12.70
2000/4/18	61	6	6.50	12.60
2000/4/18	61	7	6.50	12.60
2000/4/18	61	8	6.50	12.50
2000/4/18	61	9	6.50	12.50
2000/4/18	61	10	6.50	12.70
2000/4/18	61	11	6.50	12.50
2000/4/18	61	12	6.50	12.40
2000/4/18	61	13	6.50	12.70
2000/4/18	61	14	6.50	12.90
2000/4/18	61	15	6.50	11.00

Table A-5 Typical Ranges for Water Quality Parameters of Lakes in North Central Hardwood Forest Ecoregion

TP (ug/L)	Turb (NTU)	Secchi (m)	Chl-a (ug/L)
23-50	1-2	1.5-3.2	5-22

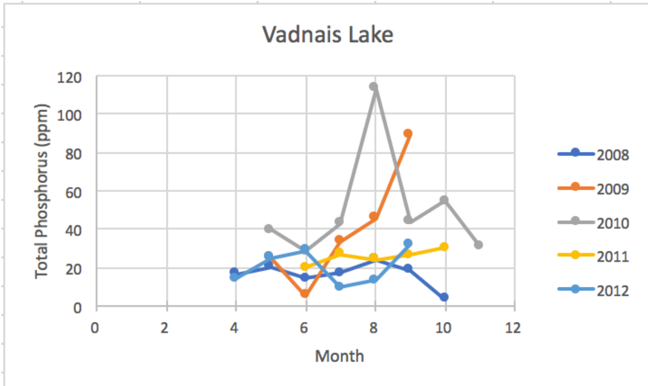

Figure A-14 Raw Data Plot of Total Phosphorous in Vadnais Lake

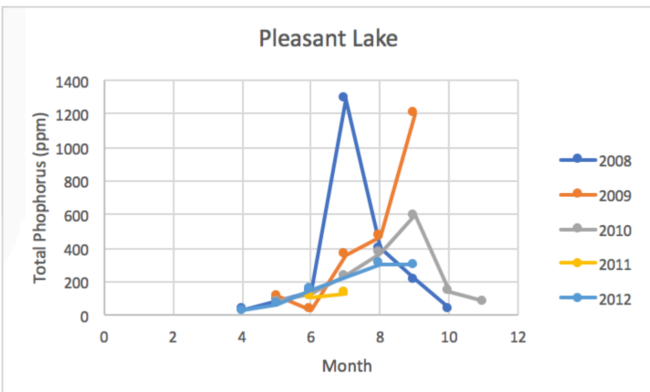

Figure A-15 Raw Data Plot for Total Phosphorous in Pleasant Lake

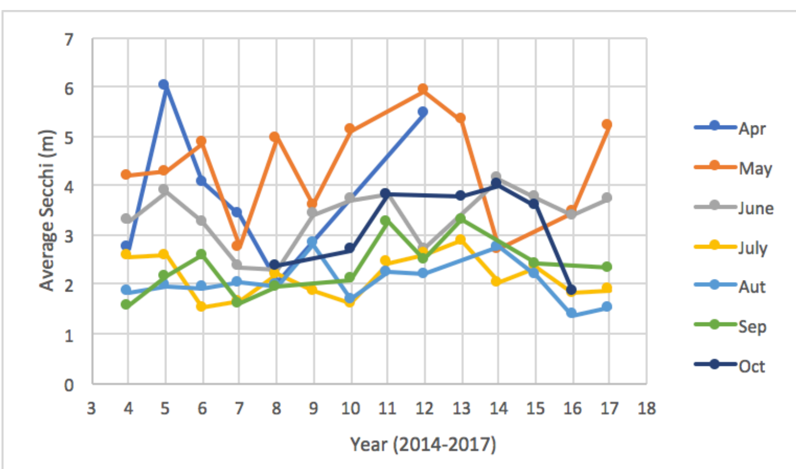

Figure A-16 Secchi Depth Raw Data Plot for Pleasant Lake

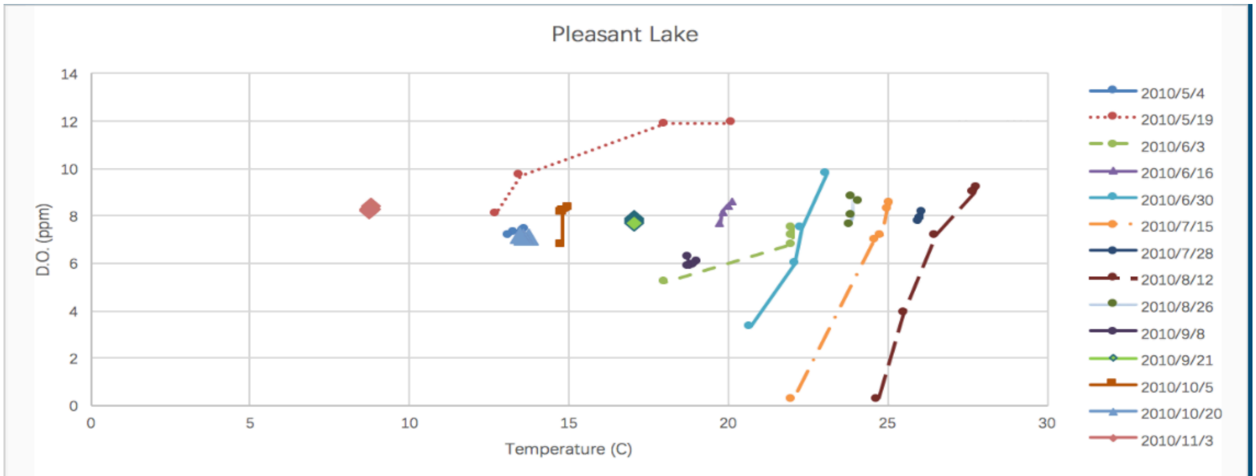

Figure A-17 Dissolved Oxygen Raw Data Plot for Pleasant Lake

Appendix 5. Water Surface Elevation Outliers and Data Analysis

Figures and data that illustrate the lake level fluctuations over time and their correlation with pumping data.

Table A-6 Outliers Manually Removed from Surface Elevation Fluctuation Dataset. Outliers were removed discreetly and were represented by a vertical line approximately bisected by the axis in Figures A-18, A-19, and A-20 pertaining to surface elevation fluctuation. These vertical lines indicated for example that a one-day drop in surface elevation was immediately followed by a one-day rise in surface elevation of approximately the same magnitude. All outliers removed have been recorded in Table A.5.1 below for the sake of organization.

Outliers:	
11/20/2003	5/15/2014
9/23/2004	8/14/2014
2/27/2006	10/8/2014
12/4/2009	10/16/2014
1/2/2010	11/18/2014
1/7/2010	7/5/2015
3/25/2010	

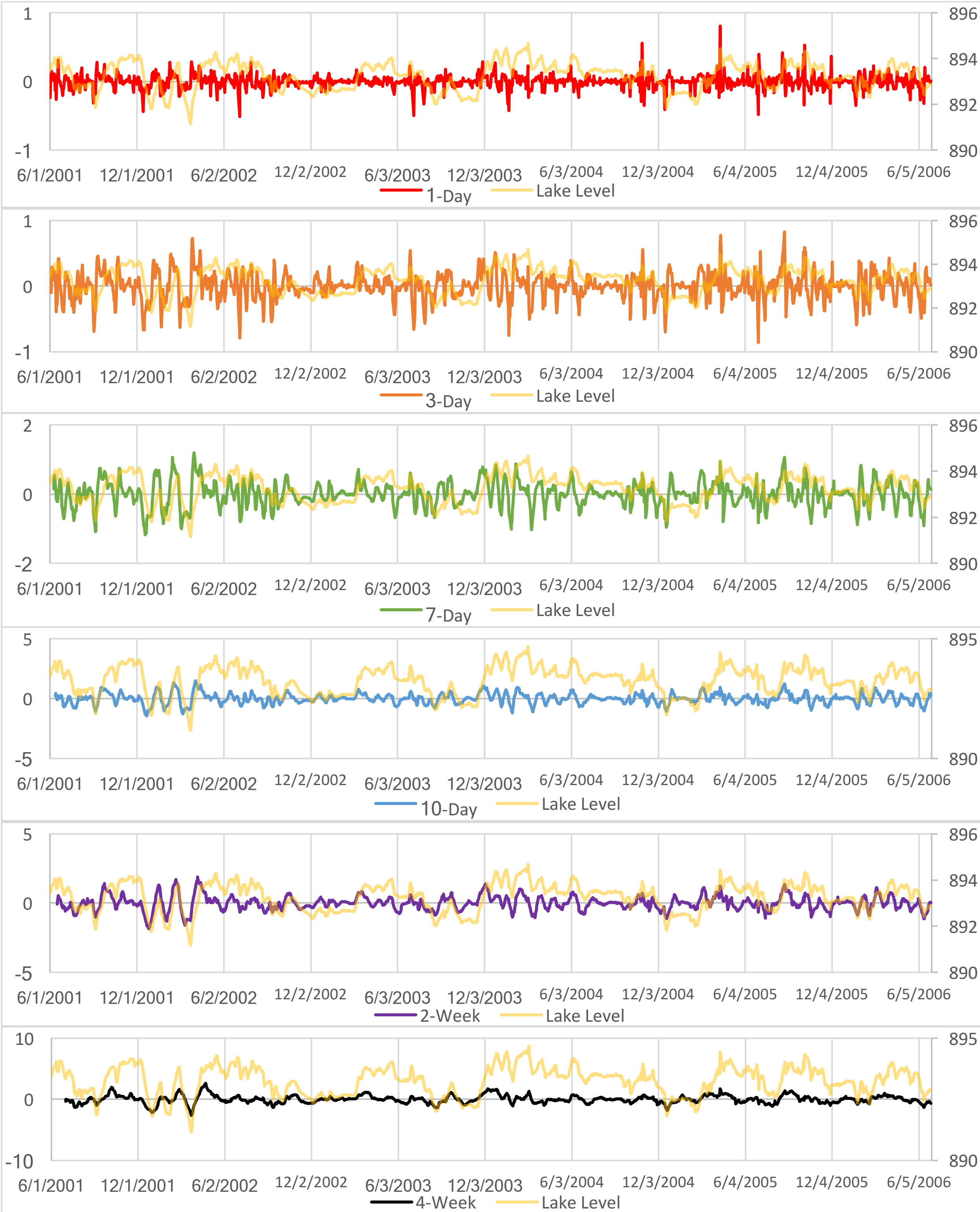

Figure A-18 Surface Elevation Fluctuation for June 2001 to June 2006 Over n-Days. The above figure shows the change in lake surface elevation or "Lake Level" over a period of n days for the years 2001-2006. This was done by subtracting the surface elevation level n days before the current level (n=1 day, 3 days, 7 days, 10 days, 2 weeks, and 4 weeks). Also shown in this set of figures is the surface elevation of the lake in feet above sea level. This figure is part one of a three-part fluctuation analysis. Part three was the one chosen for the results section of the report.

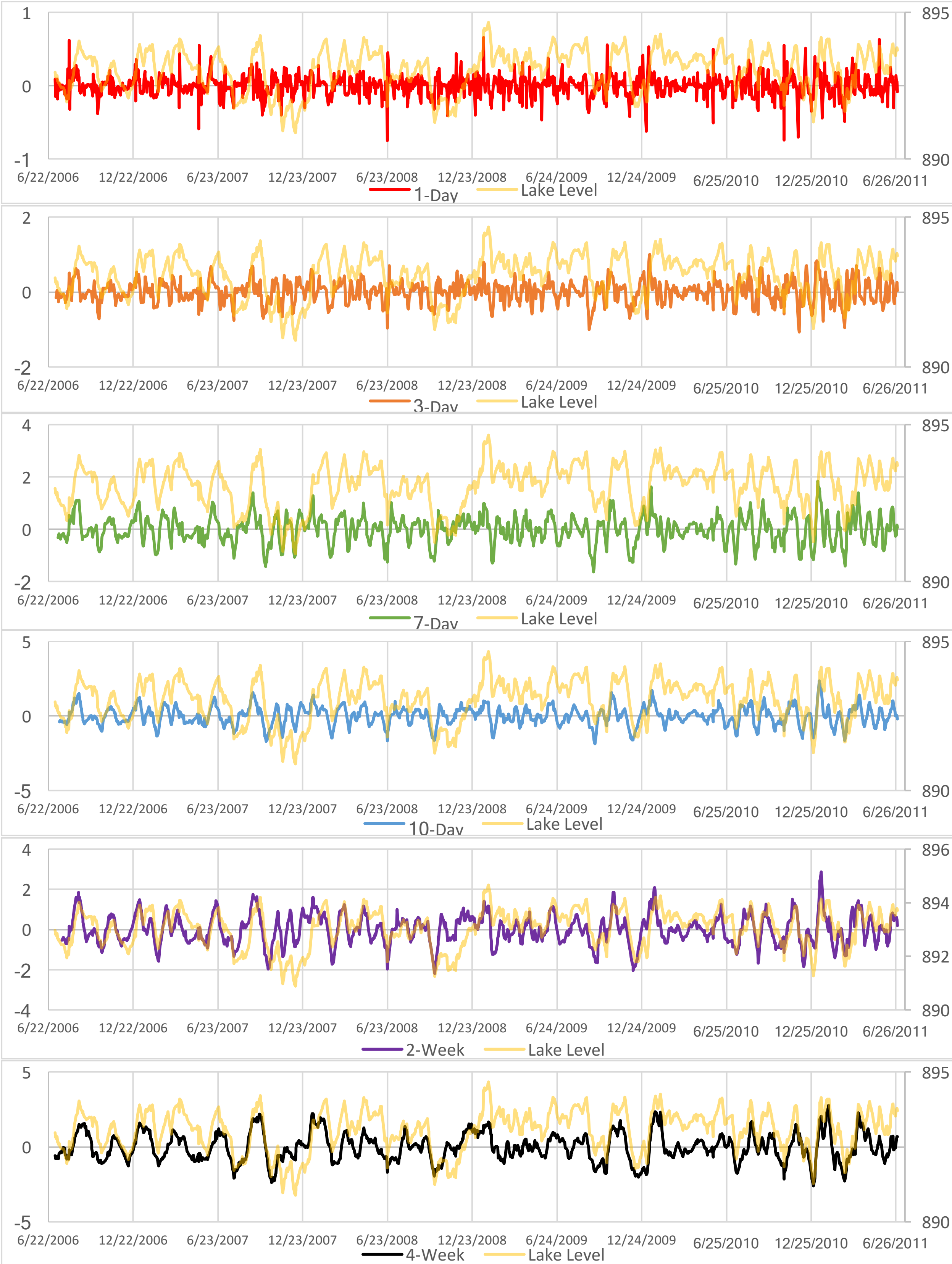

Figure A-19 Surface Elevation Fluctuation for June 2006 to June 2011 Over n-Days. This figure is part two of a three-part fluctuation analysis. The figure above shows the lake surface elevation changes from June 2006 through

June 2011. Both axes are in feet. One shows surface elevation and the other shows change in surface elevation over the designated time period.

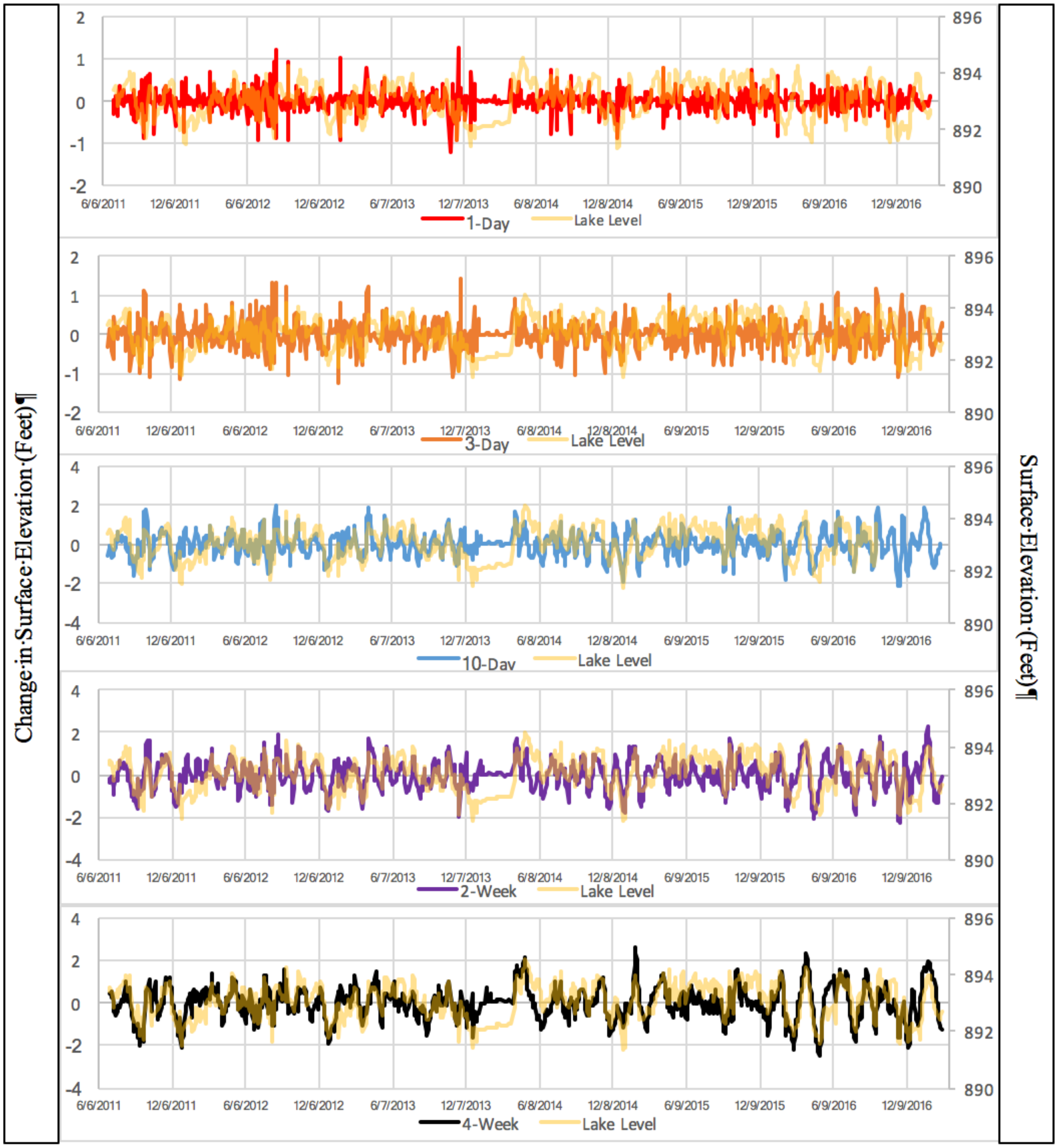

Figure A-20 Surface Elevation Fluctuation for June 2011 to June 2017 Over n-Days

Appendix 6: Model Parameter Calculations

Tables providing values calculated for use with the HEC-HMS watershed model.

Table A-7 Subcatchment Impervious Percentages

Subcatchment	Total Area (ac)	Impervious Area (ac)	Impervious Ratio ()	Impervious Percentage (%)
Charley	819	174	0.21	21
Pleasant	1852	933	0.50	50
Deep	717	125	0.17	17
Wilkinson	1108	243	0.22	22
Amelia	754	255	0.34	34
Gilfillan	631	263	0.42	42
Black	487	125	0.26	26
Tamarak	1290	289	0.22	22
Birch	647	388	0.60	60
Black 2	178	3	0.02	2

Table A-8 Subcatchment Saturated Hydraulic Conductivities

Watershed	Area (ac)	Total Area-Ksat (ac-in/hr)	Avg Ksat (in/hr)
Charley	819	1742	2.13
Pleasant	1852	8988	4.85
Deep	717	3714	5.18
Wilkinson	1108	7981	7.20
Amelia	754	1742	2.31
Gilfillan	631	1673	2.65
Black	487	2569	5.28
Tamarak	1290	7035	5.46
Birch	647	3339	5.16
Black 2	178	861	4.84

Table A-9 Hydraulic Remoteness Analysis

Subcatchment	Path Length (ft)	Start EL (ft)	End EL (ft)	Slope Y ()	Lag Time (min)
Charley	10311	924	894	0.29	516
Pleasant	4276	932	894	0.89	171
Deep	4966	940	894	0.93	76
Wilkinson	6914	940	896	0.64	126
Amelia	6229	936	908	0.45	125
Gilfillan	4944	966	910	1.13	66
Black	4377	914	900	0.32	63
Tamarak	12249	932	904	0.23	175
Birch	3158	956	920	1.14	14
Black 2	5113	970	904	1.29	43

Table A-10 Stage-Area-Outflow Curves for Each Lake in the Model

Deep				Amelia			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)	depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)

-8	900	0.40	11169
-4	896	0.27	999
0	892	0.15	0
5	887	0.023	0
6	886	0.014	0
7	885	0.00	0
9	883	0.00	0
10	882	0.00	0
11	881	0.00	0

Charley			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)
-12.8	905	0.3	7446.1064
-8.8	901	0.09	666
0	892.2	0.065	0
3	889.2	0.046	0
6	886.2	0.022	0
9	883.2	0.015	0
12	880.2	0.010	0
15	877.2	0.0024	0

Wilkinson			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)
-10.9	905	0.93	18615.266
-6.9	901	0.56	1665
0	894.1	0.16	0
2	892.1	0.15	0
3	891.1	0.15	0
4	890.1	0.070	0
5	889.1	0.0015	0

-13.5	920	0.88	11169.16
-9.5	916	0.56	999
-3.5	910	0.24	0
0	906.5	0.21	0
2	904.5	0.053	0

Black			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)
-12.1	910	0.13	3723.0532
-8.1	906	0.11	333
-2.1	900	0.08	0
0	897.9	0.016	0
1.9	896	0	0

Gilfilan			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)
-14.5	920	0.39	7446.1064
-10.5	916	0.24	666
0	905.5	0.15	0
5	900.5	0.12	0
10	895.5	0	0

Birch			
depth (ft)	El. (ft)	Area (mi^2)	Q (cfs)
-12.2	930	0.46	11169.16
-8.2	926	0.25	999
-2.2	920	0.18	0
0	917.8	0.16	0
10	907.8	0	0

Pleasant						
depth (ft)	El. (ft)	Area (mi^2)	H (ft)	H/D	Cd	Q (cfs)
-17.9	910	1.63	910	455	0.6	456.32
-7.9	900	1.40	900	450	0.6	453.80
0	892.1	0.98	892.1	446.05	0.55	414.15
2.5	889.6	0.95	889.6	444.8	0.48	360.94
5	887.1	0.77	0	0	-	0
10	882.1	0.61	0	0	-	0
15	877.1	0.50	0	0	-	0
20	872.1	0.41	0	0	-	0
30	862.1	0.15	0	0	-	0
40	852.1	0.026	0	0	-	0
50	842.1	0.0033	0	0	-	0