Final Report to the Muskegon River Watershed Assembly

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Ecohydrologic Evaluation of Removing the Higgins Lake-Level Control Structure

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Introduction

Higgins Lake, in Roscommon County, has experienced significant shoreline erosion, some of which has been attributed to high water caused by a lake-level control structure (dam) at lake's outlet into the Cut River. The erosion has been severe enough to concern the Higgins Lake Property Owners Association, and the structure's operations are non-compliant with the provisions of the Muskegon River Watershed Plan (O'Neal 2003). The effects of the erosion and accompanying disturbance to the lake bottom, surrounding vegetation, animal species, and neighboring aquatic habitats have had little study since the construction of a permanent dam in 1936. This is despite the fact that the lake and its environs provide significant fishing, recreational and economic benefits to the citizens of Michigan. For these reasons, we conducted a study of the area that included hydrology, wildlife, vegetation, and weather to provide a scientific basis to help local decision makers alleviate the erosion, minimize ecosystem impacts, and maximize recreational benefits from the lake.

As one of the largest inland water bodies in Michigan, Higgins Lake has a surface area of 10,186 acres. It includes a number of tributaries, and discharges into the Cut River, which then runs through Marl Lake and joins with Backus Creek, before entering Houghton Lake. The basis for the initial assessment that enhanced shoreline erosion exists is that the dam maintains artificially high water levels, causing a significant increase in the energy of waves striking shore. When heavy rain events occur, artificially high water elevations are raised further, thus exposing even larger areas of shoreline to enhanced erosion. In some areas, it appears that the shoreline has receded by 35 feet or more and portions of shoreline have been hardened with seawalls and/or rip-rap to limit erosion.

The Higgins Lake Property Owners Association (HLPOA) contacted DNRE Fisheries Division with their concerns regarding the significant shoreline erosion in 2010. Records and data from the 1939 Fisheries Division survey of the lake indicate reductions have occurred in the amounts of gravel bottom, floating vegetation, and emergent vegetation. In the interim, studies of the lake level control dam were done in 1956, 1969, and 1995.

Manipulation of the dam's height to control water levels in Higgins Lake historically resulted in significant variations to the streamflow in the Cut River, including periods with little to no outflow, which affects its fish communities and vegetation, along with those of Marl and Houghton Lakes. This is a concern for the fish species that use the Cut River for spawning, including walleye, a recreational sport fish that helps support an important fishery in Houghton Lake.

This study seeks to apply state-of-the-art data collection tools and computer models to measure the state of the Higgins Lake and Cut River systems, to model hydrologic and ecological function of these systems, and to simulate changes that would likely result from altered dam management or dam removal.

Findings By Task

In this report, we describe the findings of this project based on extensive evaluation of data and models for Higgins Lake, along with its basin and outlet. Our findings are described within each subsection, and summarized at the end of each Task. Tasks 1 through 5 are summarized in this report, as these were hydrology-related tasks completed by Michigan State University. Task 6, fish habitat modeling, was described in an earlier addendum to this report by the University of Michigan. Task 7, surveying members of the Higgins Lake Property Owners Association, is described in brief here as well, along with a presentation of overall survey results. Tasks 8 and 9 pertain to reporting, public presentations, and scientific manuscripts and publications which have been discussed in earlier interim reports. Task 10 is associated with administrative work conducted by the Muskegon River Watershed Alliance.

Task 1: Review Hydrogeologic, Environmental, and Engineering Data

This section describes the synthesis of existing data for the region. Data were compiled that describe the lake, its outlet (the Cut River), and the surrounding hydrogeologic system.

1.1: Outlet Control Structure Studies

Multiple engineering reports have been completed on the operation and maintenance of the the Higgins Lake control structure, which sits at the head of the Cut River (1940, 1941,1956, 1995, 2007). The 1956 report from the Michigan Department of Conservation Engineering and Architecture (MDCEA) titled "*Higgins Lake Level Control, Roscommon and Crawford Counties, Preliminary Engineering Investigation*" mentioned the the two previous studies; "*Memorandum on Proposed Outlet Dam for Higgins Lake, Roscommon County, Michigan"* (Ayers,Lewis,Norris, and May; 1940) and "*Control of Level of Higgins Lake"* (Fargo Engineering Co.;1941). These reports presented designs for new control structures to allow for more manageable openings. However, the operating improvements were not implemented.

Study from Spicer

The main purpose of the Spicer group report #118475SG2010 was to evaluate the structural integrity, functionality, and effectiveness of the Higgins Lake control structure. It described various measures of water loss from the lake, and provided recommendations about dam alterations that would retain more water.

Evaporation: Spicer used MSU's enviro-weather website for a station in Arlene Michigan (26 miles W-SW of Higgins Lake) to estimate the potential evapotranspiration (PET) for July and August of 2010. The PET rates for these months were 0.1 to 0.3 in/day. Spicer then removed transpiration from the calculations and relied on pan evaporation measurements at a NOAA station located 24 miles to the W-SW, outside of Lake City, Station ID GHCND:USC00204502. Their calculated monthly average evaporation during the summer for the recording period from 1967 through 2008 was 0.11 in/day with the highest rates of 0.15 in/day in July.

Wave Loss: Within Table 1 of the Spicer report, wave height with water loss over the dam was estimated for a sustained 24 hour period to be ~ 0.05 in/day

Spicer Report Table 1: Wave loss over the dam as a function of wave height.

Height (inches)	24-hr Loss (in/day)
4	0.03
6	0.05
9	0.08
12	0.10
18	0.16
24	0.21

Low Flow Channel Outlet: The low flow channel is approximately 4.75 feet wide and 3 feet high to the top of the dam catwalk. But the depth of flow through from concrete sill when the lake is at summer legal lake level is ~2 feet. Spicer calculated that the flow during summer levels would be 33 cfs, or 28 cfs with 1 foot of tailwater. Assuming no inflow, the lake level would drop 0.08 in/day at 33 cfs flow, and 0.07 in/day at 28 cfs flow. However, this drawdown calculation does not consider substantial inflows from groundwater and the the 2 tributaries, Big Creek and Little Creek.

Spicer Report Table 2: Summary of normal water loss from Higgins Lake

Water Loss	**Depth Loss (in/day)**
Evaporation	0.10-0.15
Wave Action	0.05
Low-Flow Channel	0.07

The main conclusion of this Spicer report was that the lake levels are affected by evaporation during the summer months and flow through the low flow structure of the dam, followed by wave loss. The report does not include any new measurements of Cut River flow to compare with outflow estimates from the dam at various lake elevations or dam orientations.

The 1995 report also found that flow out of Higgins Lake is limited by the capacity of the Cut River when flows exceed 110-120 cfs. This is due to the culverts at East Higgins Lake Drive.

1.2: Outlet Control Structure Description

The current Higgins Lake Control Structure consists of a series of 6 manipulable openings plus a 4.75 foot wide low flow channel (Figure 1.2.1). The naming scheme of the openings were adopted based on the daily records of the dam kept by the board of commissioners. The numbered scheme begins from the West to East. 1 through 3 are the stop log gates, 4 through 6 are the flop gates. These gates can be operated independently of each other, with typical configurations of gates 4, 5, or 6 open and with any combination of gates. Gate 4 is 15.5 ft wide, whereas gates 5 and 6 are 17.5 ft wide. Gates 1 - 3 measure 5 ft wide and are rarely opened, and in general impact flows much less than the flop gates opened. The dam structure has had various configurations through time (e.g., Figures 1.2.2 - 1.2.3).

Figure 1.2.1. Image of the 2015 outlet control structure looking toward Higgins Lake from the Cut River. The low flow structure is in the center of the picture.

Figure 1.2.2. Image of upstream and downstream side of the stop-log gates (2010 Spicer report). The flow through this section is governed by the use of 5 foot wide wood planks, which are rarely removed due to their unwieldy size and weight.

Figure 1.2.3. The outlet at Cut River, during a period when the full dam structure was not in place.

To quantify potential lake level drop scenarios, the outlet control structure was measured and surveyed, in particular the role of rocks adjacent to and within the structure were examined. Lakeward of the control structure, boulders form a loose pavement and are used as riprap along the sides of the shore and entry of the outlet. The presence of these are thought to be from the previous low head and rock dams as an attempt to keep lake levels high during dam out durations, see Figure 1.2.2. The boulders and cobbles are at approximately the same elevations of the flop gate sills along the upstream side of the outlet. Approaching the dam within hundreds of meters is a shallow, gravelly lake bed that appears to be natural in origin. Without any specific evidence to the contrary, it was assumed that this approach is unmodified from the historical condition.

The flow through the opening of the control structure is also lined with boulders and cobbles. It is unknown if the apron of this flow gate is concrete or just rocks. The downstream side of the control structure is primarily medium to coarse sand, which has a high probability of scouring under high flow events, such as during the initial opening of the flop gates each year. Signs of sediment erosion and deposition are apparent just upstream of East Higgins Lake drive culverts.

During a survey on May 2013 of the water levels along the Cut River (from the outlet to the inlet of Marl Lake) channel bottom elevation measurements were taken using a Trimble mapping grade GPS unit (Figure 1.2.4). A channel bottom elevation measured approximately 30 feet downstream of the control structure was 1152.07 ft, which is assumed to be close to the natural channel bottom, where "natural" is defined as unregulated. Channel elevation was recorded in 1956 for the *Higgins Lake Level Control, Roscommon and Crawford Counties* report of 1151.0 ft, indicating a 1.07 ft discrepancy, which could easily be associated with the location of the measurements. MSU's field crew measured elevations just downstream of the control structure, whereas the location of the Michigan Conservation Departments' measurement is unknown. The deeper channel historically could be a legacy of scour from the high flows experienced during logging years, with subsequent aggradation of the channel bed during more recent lower and stable flow periods. It could also be a legacy of reported dredging of the channel, which has since filled in with sediment.

Figure 1.2.4. Photo of GPS and total station survey set up along the Cut River at the culverts under East Higgins Lake Road.

1.3: Historical Lake Levels

The artificial control of the lake began during the lumber boom in the area from mid 1800's to the 1880's. During this period, a dam would be constructed each year, causing water levels to rise 3 to 4 feet to aid in the log runs down the Cut River. After the seasonal transport of the logs down the Cut River, the lake would remain at natural levels for the remainder of the year. After the logging industry left the surrounding area, the lake remained unobstructed until around 1911 when a recreational dam was erected. The new control structure was ambitious and caused enough erosion to have a consensus to remove it within a year after completion.

By 1926 a legal lake level of 1154.11 ft above mean sea level (amsl) was established to a datum provided by Fargo Engineering Co. and confirmed by the Michigan Conservation Department (MCD) in 1956. By 1936 a dam was constructed, but was difficult to operate at the desired level due to the width and height of the stop log gates. The 1941 Fargo report investigated the effects of the legal lake level on the shoreline. The conclusion was that the established lake level of 1926 was acceptable. The 1956 Michigan Conservation Department's report seconded that conclusion of the legal limit of 1154.11 ft amsl. But the same 1956 report also voiced strong concerns that higher water levels would begin to erode the shoreline, since it was already evident as a problem. The state made recommendations to lower the lake during winter and spring to counteract the erosive actions of ice push and spring melts. The 1956 recommendation of the lower winter elevation of 1153.5 ft amsl was to allow for the capture of snow melt and ensure if spring had abnormally high precipitation it would not exceed an elevation of 1154.11 ft. This recommended drawdown was to start by October 1st and the spring recovery was to start when the spring flows/melt had passed. The date on which dam management began its recovering toward the legal level was not mandated, but was an educated decision with practices that varied through time. MCD was very concerned of the inevitable damage to the lakeshore if lake levels were not at or below the legal level. The MCD viewed the legal level similar to a speed limit, not to exceed, but the ability to be lower.

The first USGS gage was installed on Flag Point on September 1, 1942. The zero value of the gage was set to 1148.74 ft AMSL, 1926 datum. The current USGS gage, located in the South Higgins State Park, has been present since October 1, 1976 (Data shown in Figure 1.3.1).

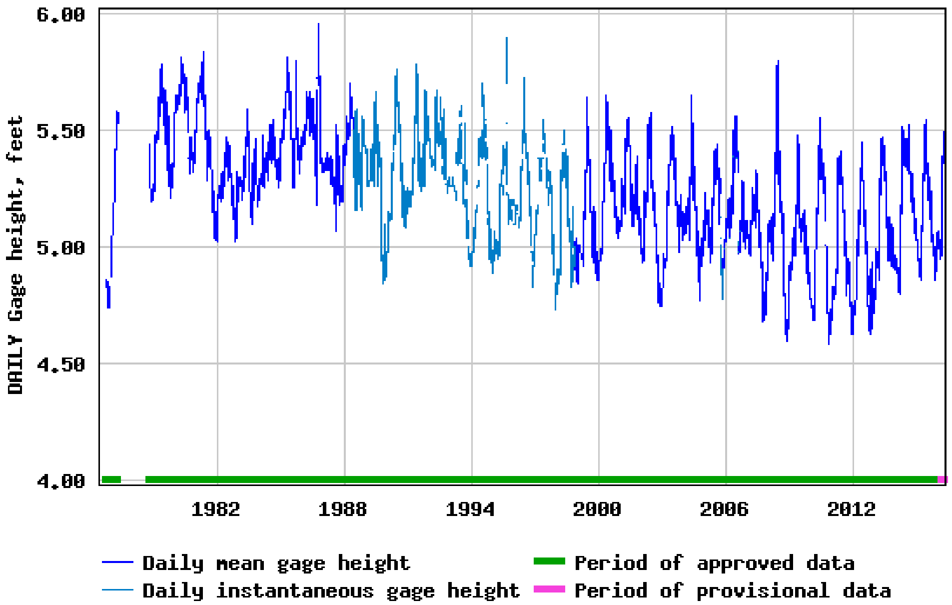


Figure 1.3.1: Graph of lake levels of Higgins Lake from 1976 to 2016 from the USGS gage station, 42805084411001. For reference, the gauge datum is 1148.74 ft, thus on this plot legal summer level is 5.37 feet, and winter levels are 4.62 feet for the 2009-2014 period, and 4.85 feet for all other years.

The original court ruling of 1926, relied on the state law of Inland Lake Levels Act 377 of 1921, and set the lake level at 1154.11 ft. During that period, little thought was made with regards to the flow of the Cut River ecosystem and the possible effects of future development around the lake. During the initial judgment there was no mention of seasonal adjustment. The Inland Lake Level Law, Act 194, Public Acts 1939, provided for establishment of additional levels above or below the legal normal. In 1982, the Circuit Court established a legal winter lake level, not to exceed a decrease of more than 6 inches below the legal summer level, 1153.61 ft amsl.

The most recent adjustment to the legal lake levels were from a 2009 Circuit Court judgement that lowered established winter lake level from 1153.61 ft to 1153.36 amsl for a 5 year period. This trial period expired during spring 2014, without a renewal or extension, thus the current winter legal lake level is maintained at 1153.61 ft amsl until April 1st or ice out, whichever comes first, then raised to the summer level.

1.4: Historical Lake Bathymetry

The bathymetry of Higgins Lake was first fully mapped during the winters of 1936 and 1937. For this effort, the survey crew (part of the Civilian Conservation Corps, or CCC) would wait until the ice was thick enough to support the weight of participants and allow for drilling holes to access the water. Lead lines were employed to reach the lake bottom and from the top of the ice the depth was recorded. The ice surface was surveyed in and used as the reference for elevation. The sample spacing within the shoal area was every 20 ft until the deep basin which then was every 50 ft. A maximum depth of 135 feet was recorded in the northwestern section of the north basin, while a typical shoal depth of less than 10 feet was recorded. Indeed, no data were available on depth variations within this zone, which necessitated Task 2 of this study.

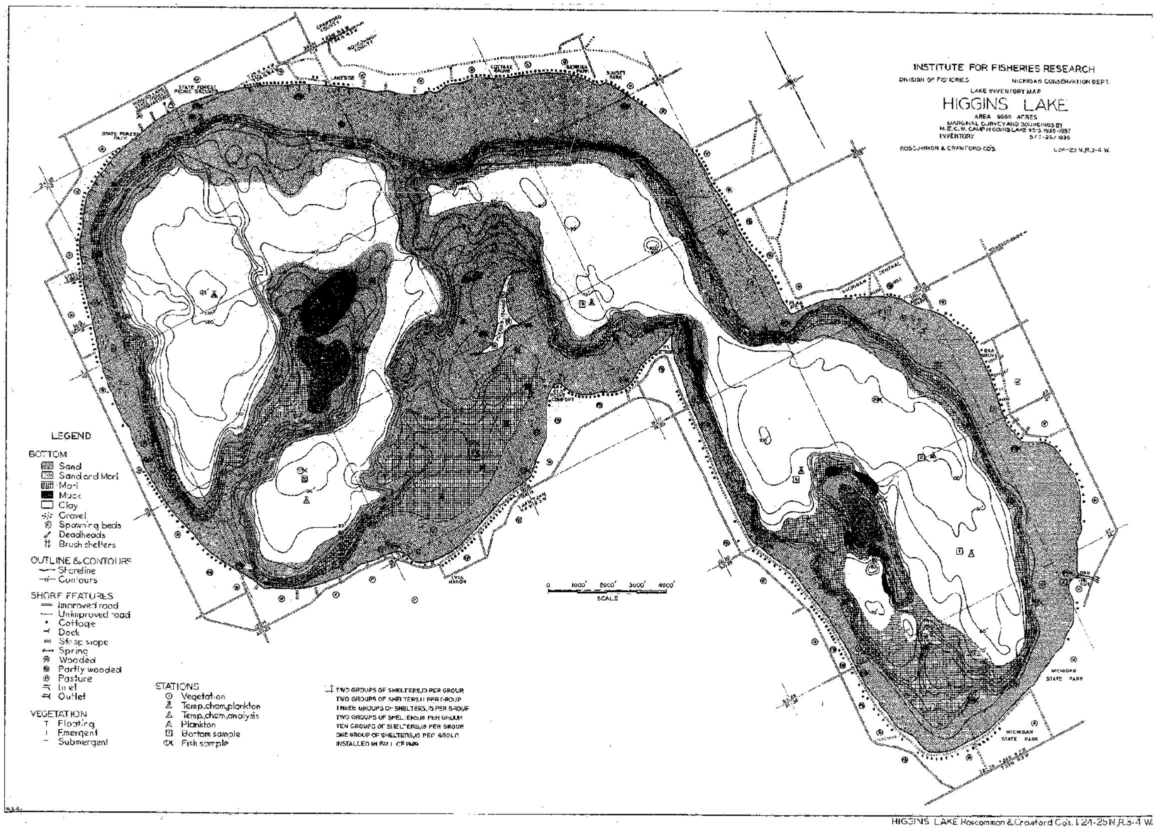
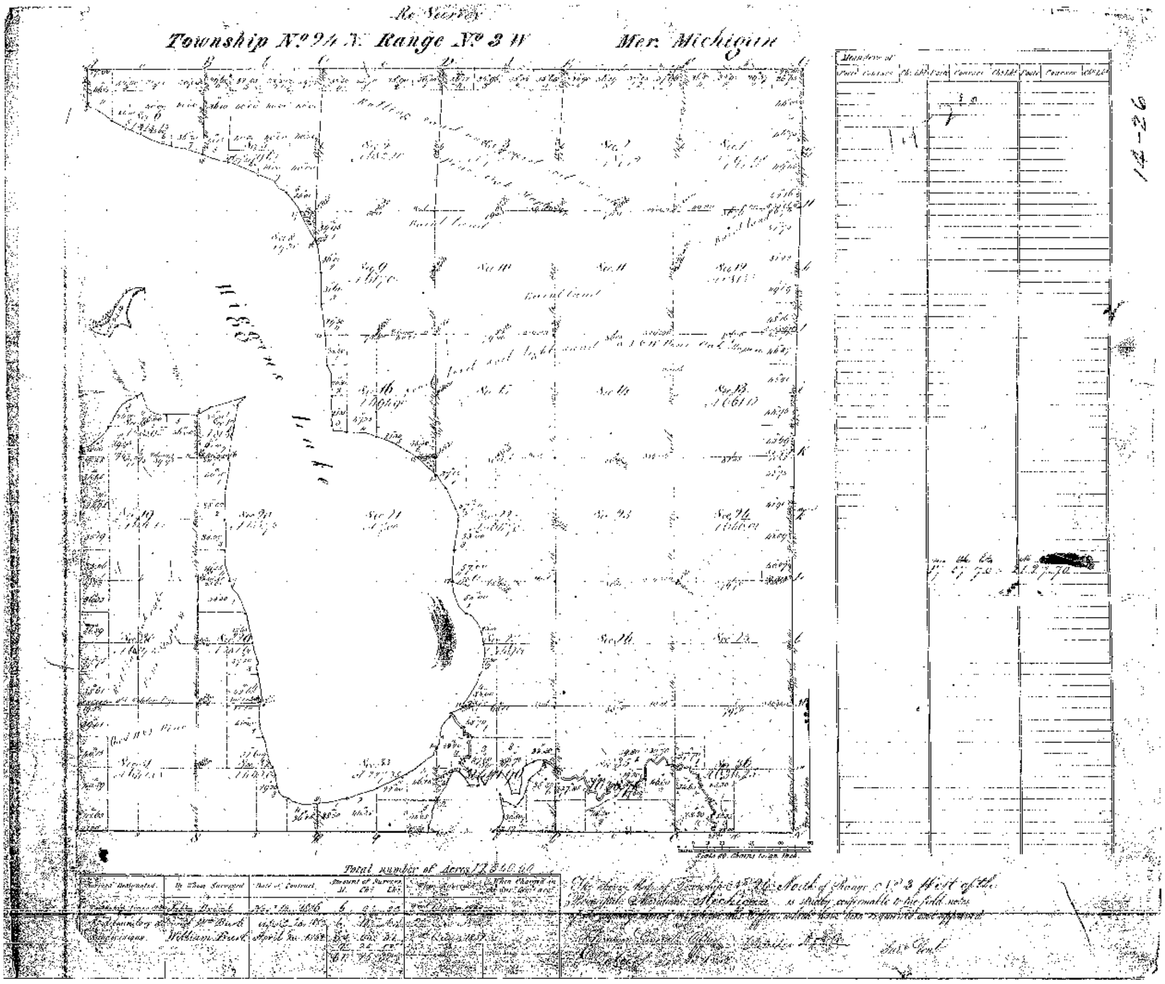


Figure 1.4.1. Original Division of Fisheries, Michigan Conservation Department bathymetric map of Higgins Lake, published in 1939. A higher resolution copy is available online from the Michigan Department of Natural Resources.

1.5: Historical Outlet Position/Depth

The Cut River was mainly used during the timber boom for the transport of logs; as stated in the *1956 Higgins Lake Level Control, Roscommon and Crawford Counties* report, the river was dredged to allow timbers to freely float to Houghton Lake. Any remnants of dredging during the late 1800's were not observed by MSU and UM field teams while performing the Cut River survey. According to the Public Land Survey Plat map of 1852 (Figure 1.5.1) the outlet has remained relatively in the same position to the present, even with many dam restructuring projects, including the latest in 1995. According to the 1956 report, the stream channel elevation was 1151.0 ft, which is difficult to confirm as the original unaltered channel bottom due to multiple modifications through time. According to correspondence with the Michigan DNR and DEQ in 2015, the agencies provided a letter from The Higgins Lake Property Owners Association, dated 1/3/1952. According to the written testimony of the acting president, Paul H. Bruske, during the 1950 reconstruction of the dam, Roscommon County removed "perhaps 100 tons of rock out of the inlet". The permit for the most recent modification of the lake level control structure in 1995, did not specify a channel bottom elevation at that time. Specification by the Michigan DEQ of the flow through section of the level control structure was to be open to the elevation of the river channel bottom. However, the contractor never supplied an elevation of the channel bottom to the state to allow



for comparison of historical elevations.

Figure 1.5.1. Public Land Survey map from 1852, accessed through the Michigan DNR General Land Office Plats Website.

1.6: Surface and Ground Watersheds

Understanding the hydrologic behavior of a system requires information on the influence of the landscape “upstream” of a point. This concept is well established, however the only important watershed of a lake is generally considered to be the area of the land surface that drains overland to a lake.

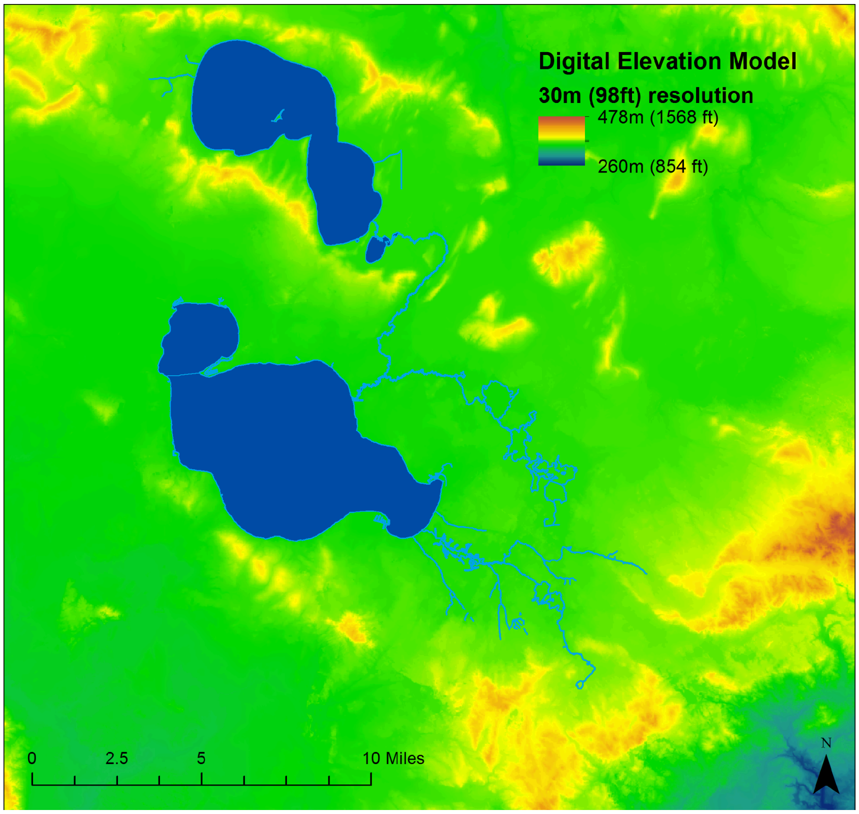
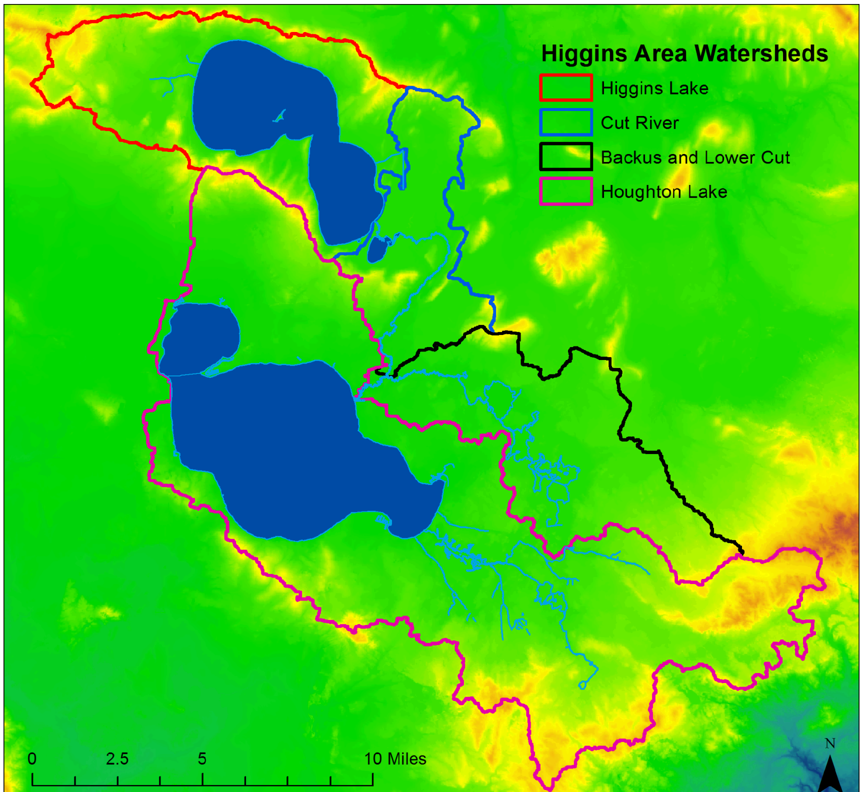


Figure 1.6.1. Connected hydrologic features from the Higgins, Cut, Backus, Houghton system overlain atop the National Elevation Dataset (NED) 1 arc-second Digital Elevation Model (DEM). This DEM has approximately 100 foot spatial resolution.

Figure 1.6.2. Map of the surface watersheds generated from the 1 arc-second NED DEM of Higgins Lake, the Cut River above the confluence with Backus Creek, Backus Creek and the Cut River below their confluence, and Houghton Lake



For this investigation, we extend this concept to encompass the region of groundwater drainage to the lake, hence the term groundwatershed.

Tools are widely available to calculate the surface watershed of lake, using detailed maps of surface elevations known as Digital Elevation Models (DEMs). Using a DEM, the flow direction of each map point is established, which are then summed to calculate the watershed. Figure 1.6.1 shows the Higgins/Houghton Lake system within a DEM. One can gain an intuitive understanding of watershed dimensions using the DEM alone, but a more detailed calculation can produce some surprises.

Figure 1.6.2 maps the surface watersheds calculated using the D8 flow direction algorithm in ArcGIS. Note that Higgins Lake has essentially no surface watershed on its southeast edge, proximal to its outlet. Also, the surface watershed areas in this map are somewhat exaggerated due to a simplifying assumption in the D8 flow algorithm. All internally-drained regions are removed prior to watershed calculation. The portion of the Cut River watershed north of the Higgins Lake outlet is actually drained by a wetland that connects only at much higher levels than typically occur in most years. Thus, in general, the Cut River has a functionally small watershed until its merger with Backus Creek near Houghton Lake.

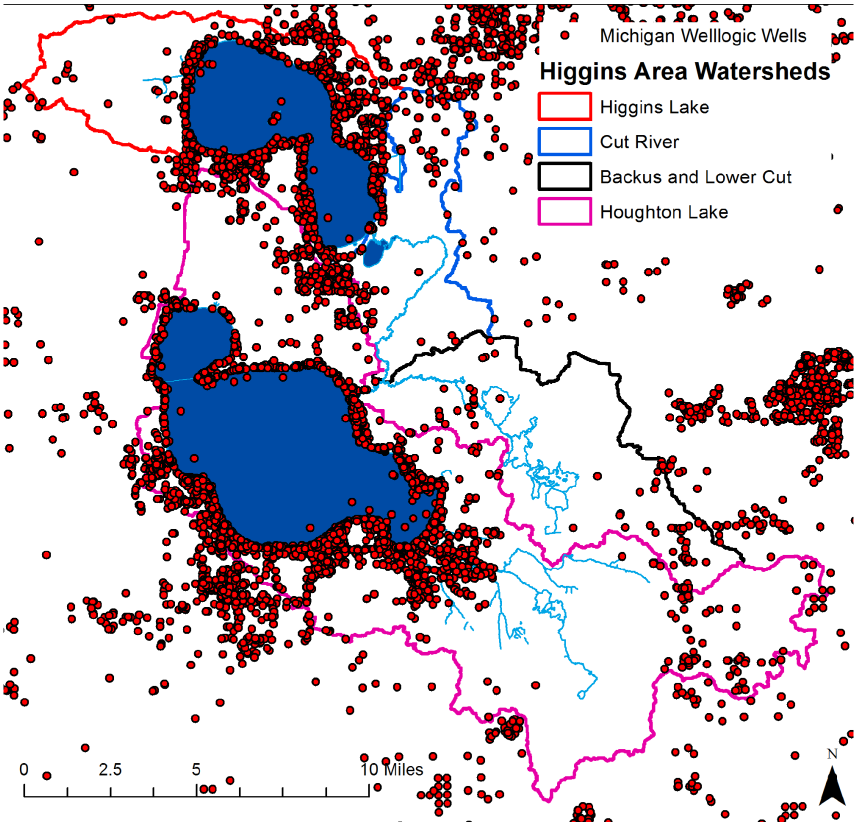


Figure 1.6.3. Map of drinking water wells retrieved from Michigan's Well Logic database for the Higgins Lake Area. Locations of wells are taken directly from database attributes and may contain some errors that are later addressed via filtering.

To map the groundwatershed, which is the source area of groundwater that flows into a water body, an equivalent of the surface DEM is needed: a water table elevation map. This can be obtained either through a groundwater model, or by interpolating a map of water levels using available measurements. The latter approach was selected here, and a database of drinking water wells was downloaded from the State of Michigan. Each of these wells has a measurement of static water level at the time of installation, which varies from the late 1960s to present day. The wells in this region are shown in Figure 1.6.3. There are a approximately 6,400 wells surrounding the lakes in this view of the lakes, and in some of the surrounding developed areas, while fewer are available in the less populated areas surrounding the lakes.

A variety of methods are available to create a map of water levels using these measurements. We chose a method known as Simple Kriging, which is an unbiased linear estimation method that uses the correlation between each measured value and its neighbors as a function of separation distance to produce a weighting map for how strongly each measurement impacts the the value at all other locations. As a first step before kriging, all wells in Michigan were downloaded, over 500,000 in 2015. These were filtered to remove water table estimates that were outside of 3 standard deviations from all others within a 1000 meter radius. This iterative outlier removal was repeated 3 times. These filtered data were then fit to a Stable semi-variogram model in ArcGIS, which produced a map of water tables for the entire Michigan Lower Peninsula. The Higgins/Houghton region of this map is shown in Figure 1.6.4.

Given this interpolated water table map, the D8 flow direction method could then be applied to calculate groundwatersheds for each of the hydrologic systems in the region. Separate groundwatersheds were calculated for Higgins Lake, Cut River, Backus Creek and the Lower Cut, and Houghton Lake. These are overlain on a map with the surface watersheds to show how the two systems differ. Note that Higgins Lake has a groundwatershed that is roughly 89% larger than its surface watershed. Given the significant northwestern extent of the groundwatershed, we would expect this portion of the lake to be a strongly groundwater gaining section. In contrast, the southeast portion of the lake has essentially no groundwatershed, thus we would expect this area to be a location of groundwater loss from the lake. This may be a region where groundwater loss feeds wetlands to the east of the lake.

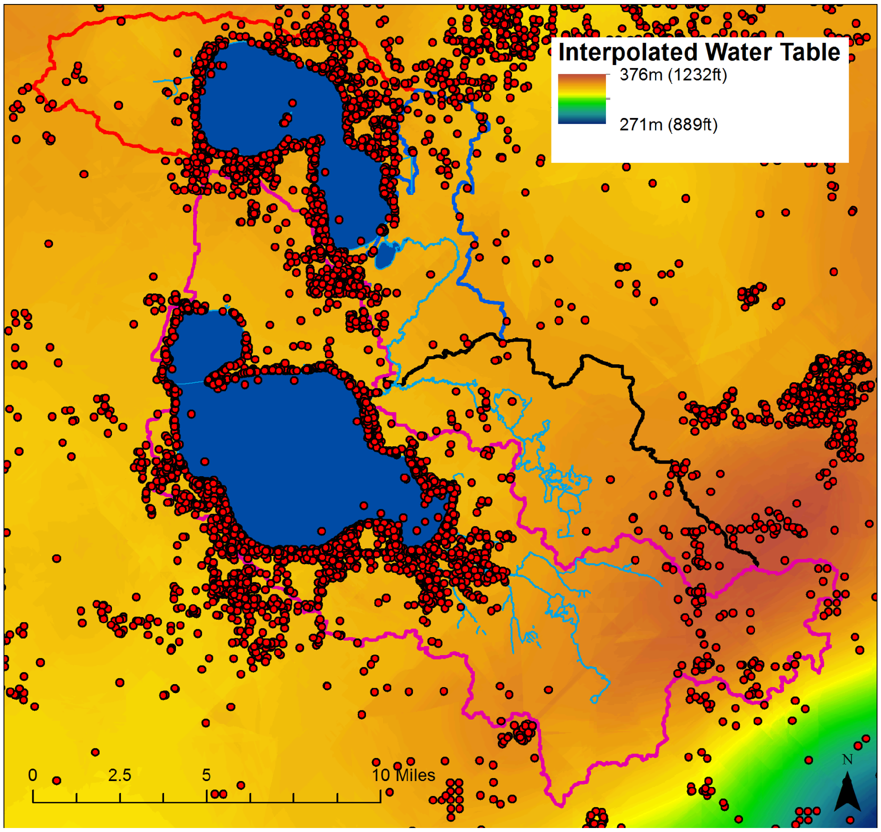


Figure 1.6.4. Map of interpolated water table elevations created using kriging.

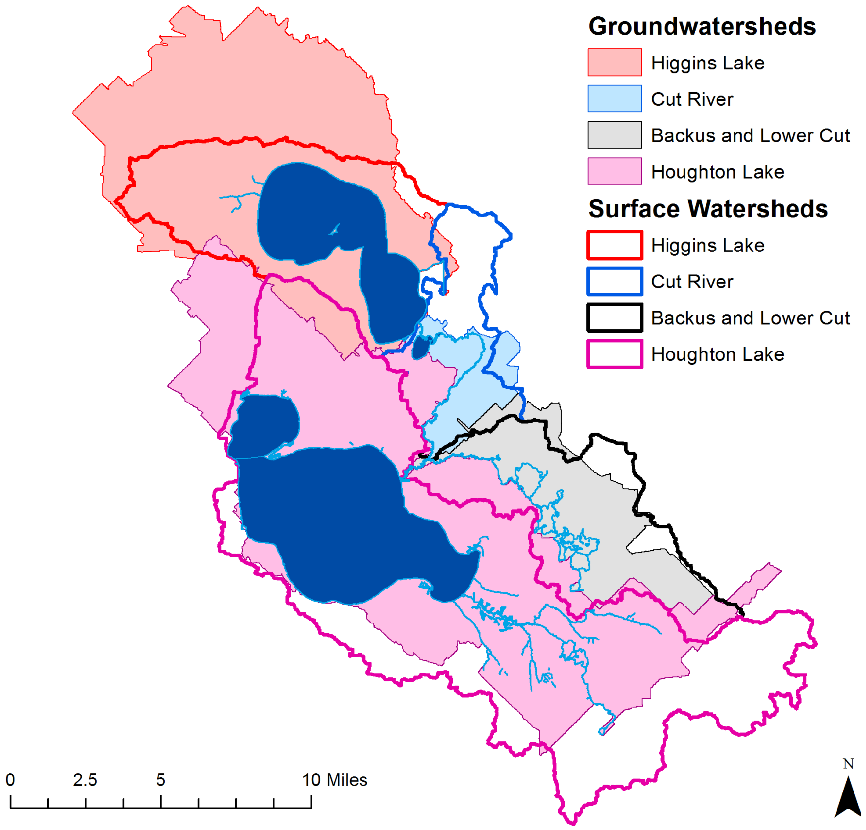


Figure 1.6.5. Map of groundwatersheds and surface watersheds for Higgins Lake, Cut River above the confluence with Backus Creek, Backus Creek and the Lower Cut River, and Houghton Lake. Note that there are large discrepancies between surface watershed and groundwatershed divides.

Another important observation from the groundwatershed and surface watersheds are that the upper Cut River has essentially no groundwatershed, and no functionally significant surface watershed. Thus we would expect that surface water inputs from Higgins Lake would dominate Cut River flows in the upper portion. Note too that Marl Lake is split down the middle in terms of its groundwatershed, where the eastern section of the lake is fed by groundwater while the western section likely loses groundwater toward Houghton Lake to the southwest.

1.7: Historical Weather and Climate Data

Hydrologic systems exist in dynamic balance with their landscape and the weather that ultimately drives the movement of water within them. To better understand the trajectories of the Higgins Lake region, we downloaded historical air temperature and precipitation data from NOAA's Global Historical Climatological Network (GHCN), which is a network of co-operative gauges maintained for at least 100 years. Precipitation shows little trend through time (Figure 1.7.1). On average, there is approximately 30 inches of precipitation per year, with a minimum near 20 inches and a maximum near 40 inches.

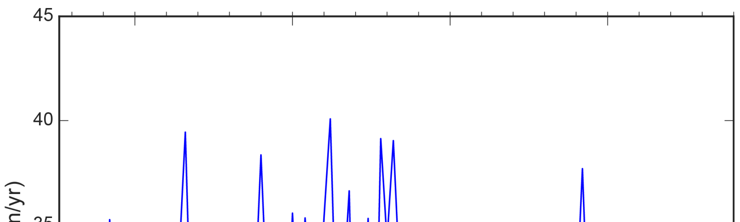
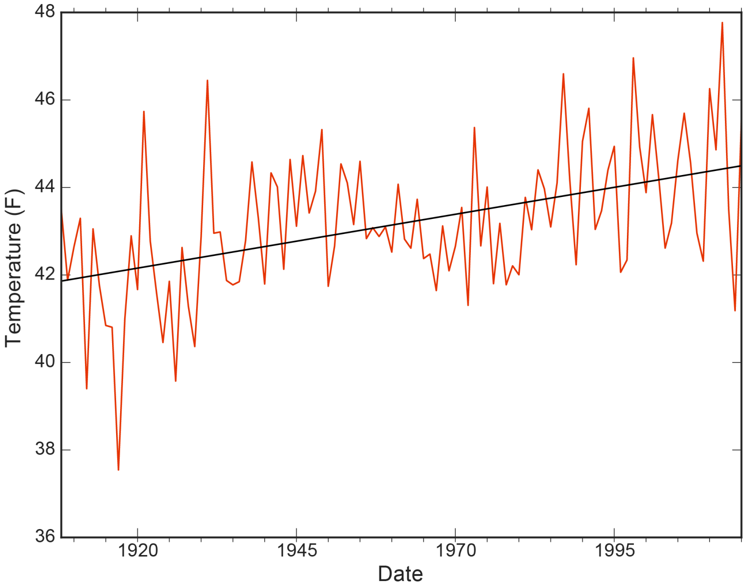


Figure 1.7.1. Plot of historical annual precipitation data from NOAA weather stations in Roscommon county, from 1908 to 2015. There is no significant trend in this dataset.

In contrast, average annual temperatures (Figure 1.7.2) show a strong warming trend over the last 108 years of record. Temperatures at the turn of the 20th century averaged approximately 42 degrees F, while the last decade has seen temperatures closer to 44 degrees. A linear trendline fit to these data has a slope = 0.25 degrees F/decade (significant at *p*<1%). These temperature trends are consistent with regional trends across the Great Lakes Basin during the same period.

Figure 1.7.2. Plot of historical daily average temperatures from NOAA weather stations in Roscommon county, from 1908 to 2015. A linear trendline is plotted in black.



Our period of investigation will focus on the latest 15 years of this period, but these longer term trends are shown to provide context for how systems behave within a longer time period.

1.8: Aerial Photo Synthesis, Shoreline and Cut River Channel Analysis

A significant effort was made to use historical aerial imagery to quantify changes in shoreline and Cut River position through time. Michigan has collected aerial imagery roughly each decade across the entire state since 1938; these photos are archived at Michigan State University.

The oldest view of the Higgins Lake region is provided by General Land Office surveys from the the 1850s. These maps were scanned and georeferenced (points on the map related to known points on the land surface, typically section lines that match current roads and intersections) and overlain on modern maps of the lake. Clearly, the lake is roughly the same dimension now as it was over 150 years ago (Figure 1.8.1). In particular, the shallow shelf that characterizes much of Higgins Lake recreation and shoreline concerns is not a product of human intervention, but is clearly a natural occurrence.

Figure 1.8.1. The original Higgins Lake survey from the Michigan public land survey plat maps from the mid 1800's. The plat map was georectified using aerial imagery underlay, provided by the USDA, taken on August 31 and September 1, 2012.

Each aerial imagery series consisted of multiple photos, which were scanned, contrast adjusted, georeferenced, and then mosaiced to produce a single image. Figure 1.8.2 shows the outcome of this process for the 1938 aerial imagery series.

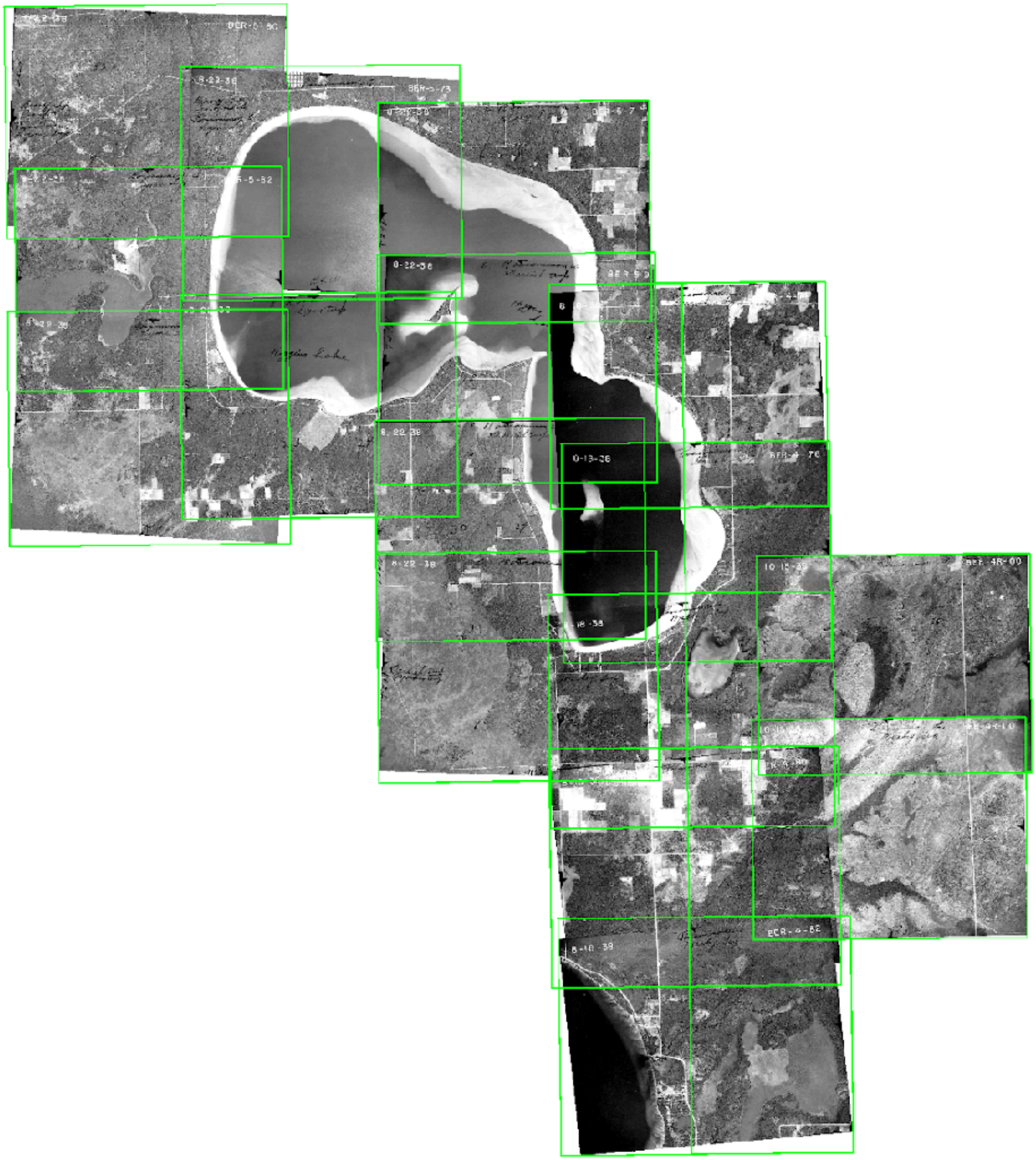


Figure 1.8.2. Mosaiced historical aerial imagery (1938) showing the separate images, with green outlines for each image.

Other series included 1952/1953 (incomplete), 1963, 1981, and 1992. High resolution satellite imagery is then readily available starting in the mid 2000s.

Using those aerial images, the shoreline of Higgins Lake was manually traced for each series (Figure 1.8.3). Note that at the large scale, very few changes are visible in the shoreline position. However, some areas across the lake have been consistently receding (eroding) shorelines through time, as visible in zoomed in portions of the region. For instance, Figure 1.8.4 shows a section of the northern part of the north basin of the lake. With the exception of the 1981 series (which has position errors across the lake) there is a consistent trend of erosion visible.

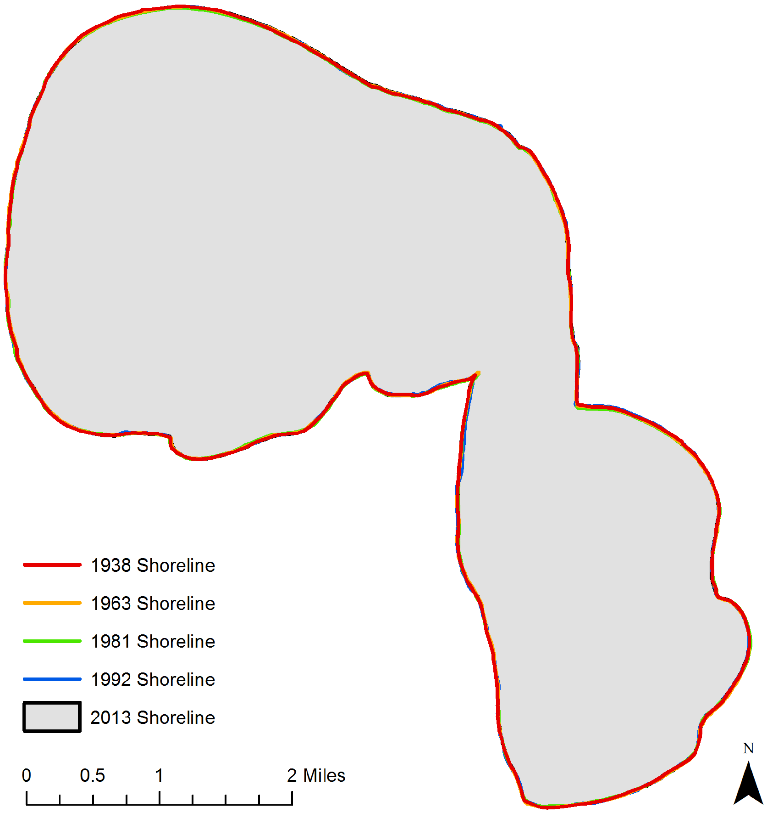


Figure 1.8.3. Map of shorelines manually digitized from historical aerial imagery. Note very few differences in shoreline position are notable at this scale.

To more systematically examine whether the imagery series provide evidence of shoreline change, a series of lines perpendicular to the shoreline were overlain along the perimeter of the lake. Intersecting these lines with the historical shorelines provided a direct measurement of shoreline change at each line (which were located 250 meters, 820 feet, apart). For each line, a linear regression of change relatively to the 2013 position was calculated, and used to quantify shoreline erosion rates. However, uncertainties in the imagery locations are significant enough that this information should be used as qualitative evidence for shoreline change rather than accurate estimates of erosion rates.

The uncertainty in location of the georeferencing position was assumed to be ~30 feet (10 meters). Then, total change in shoreline position since 1938 greater than 30 feet was assumed to provide evidence of significant erosion occurring, while rates between 0 and 10 were viewed as being evidence of low to moderate erosion, while shoreline erosion values of less than 0 (which would be migration of shoreline into the lake, which is likely not occurring on a broad scale) were assumed to have low likelihood of erosion. These were then mapped as Figure 1.8.5.

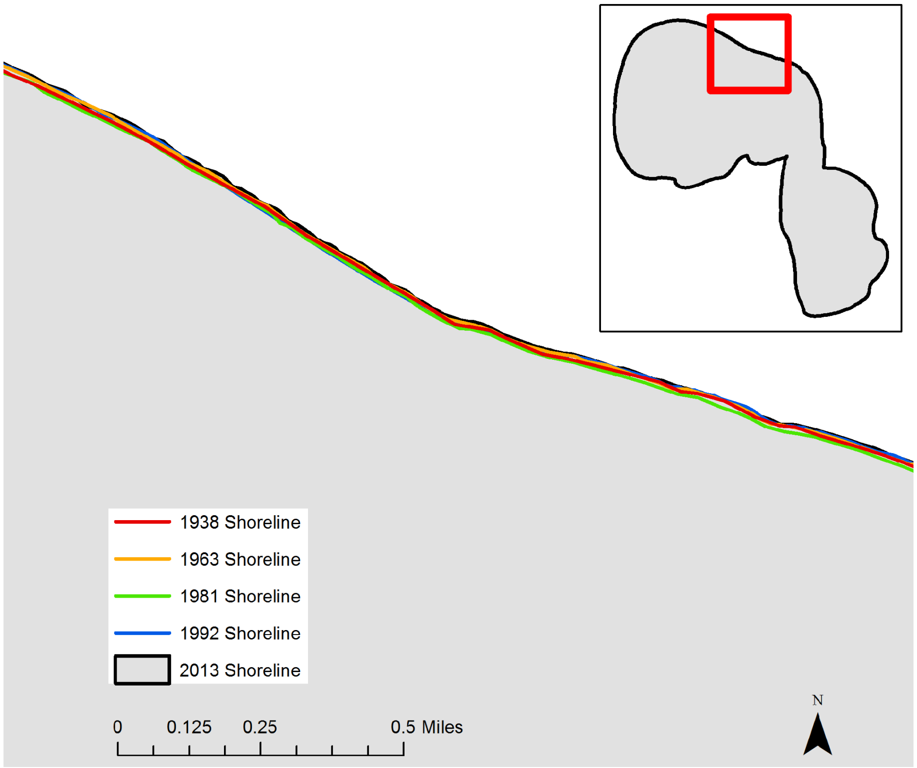


Figure 1.8.4. Zoomed map of a portion of the northeastern Higgins Lake Basin showing trends in shoreline position. An exception is the 1981 shoreline, which appears to be relatively offset across much of the lake area.

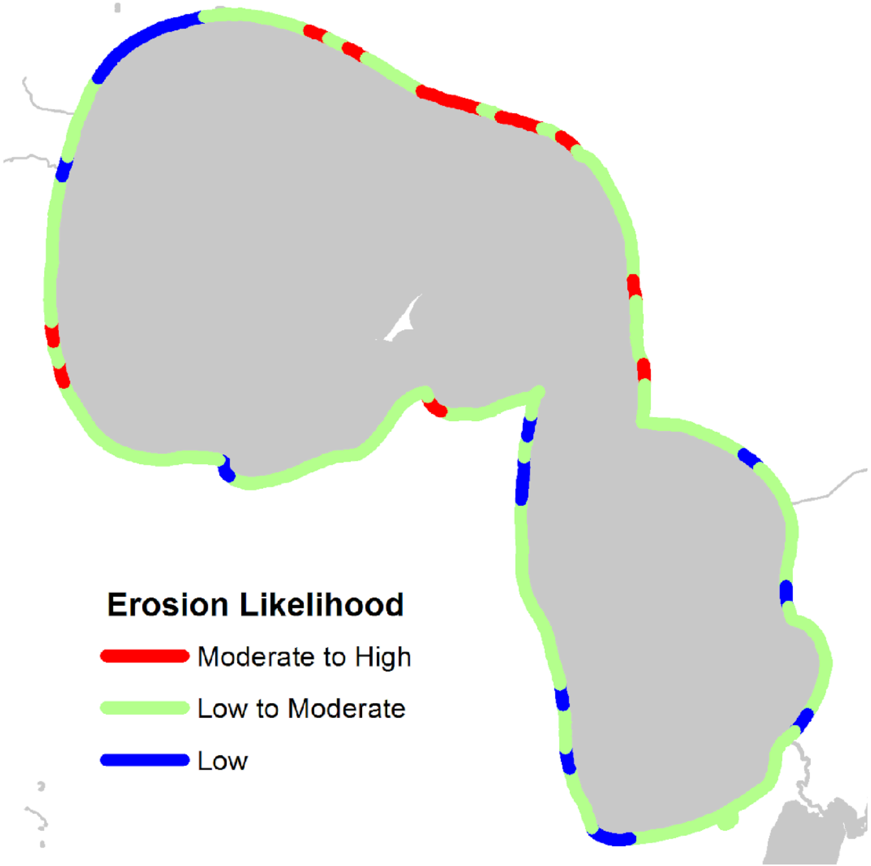


Figure 1.8.5. Figure of the erosion likelihood, mapped using thresholds of uncertainty established by georeferencing the historical aerial imagery.

Evidence of moderate to high erosion rates are present in four sections of Higgins Lake, on the eastern and northern sections of the North basin, the lower western section of the North basin, and a small strip of the southern portion of the North basin. Evidence of low to moderate erosion is present across much of the rest of the North basin, except for the northwestern portion where shorelines appear stable. The South basin also appears to have more stable shorelines.

Changes in the position of the Cut River channel were also mapped through time. These images were more problematic to georeference due to the relative lack of roads adjacent to the river. Thus, position uncertainties are relatively high, but shape of channel within a series is robust. Figure 1.8.6 shows the five time series overlain with few changes visible at this scale (with a few exceptions).

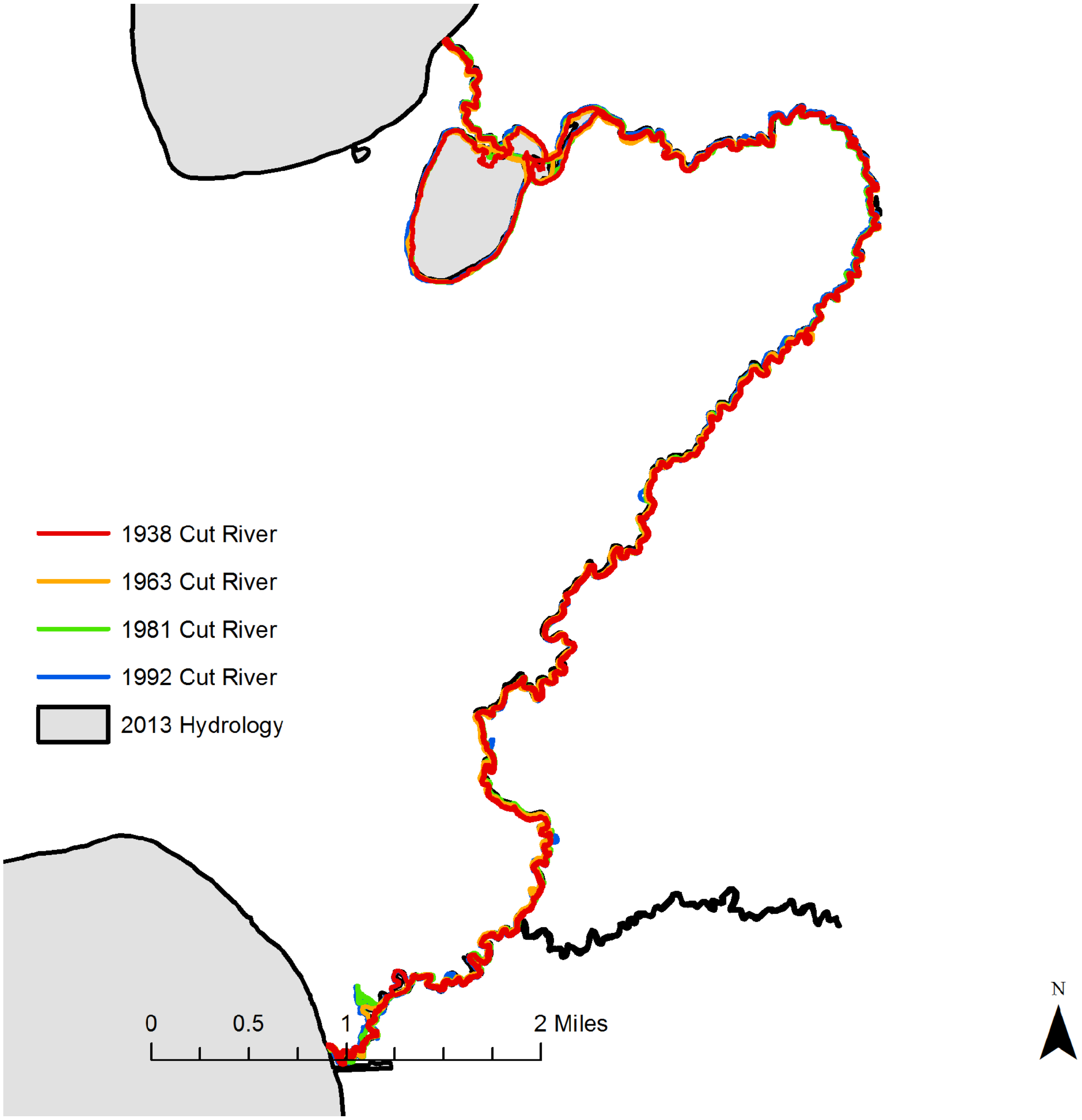


Figure 1.8.6. Map of Cut River stream banks manually delineated from digitized aerial imagery. Note few changes are visible at this scale.

Figure 1.8.7 provides a zoomed in view of a section of the lower Cut River above Backus Creek that shows some interesting changes in the meandering course of the channel, with changes visible on the roughly decadal scale intervals between these aerial imagery series. It is clearly an actively meandering channel, but has changed little in its bulk course since 1938.

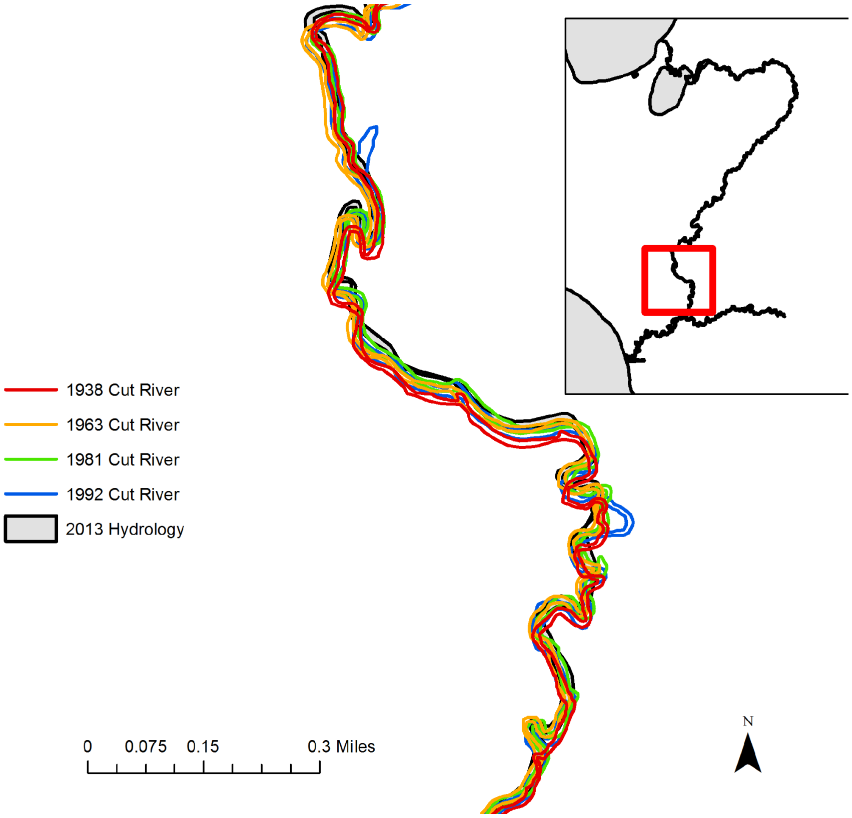


Figure 1.8.7. Zoomed map of one section of the Cut River showing observable changes among the aerial imagery series. Note, general parallel shifts in channel position are related to inaccuracies in georeferencing, not channel shifts. Changes including production of new meanders and cut-offs, visible in the lower half of the zoomed channel, are genuine changes in Cut River morphology.

1.9: Lake Level Scenarios to Be Considered

The hydrological and ecological teams came together to establish a series of lake level change scenarios that would allow for a wide range of issues to be investigated such as fishery habitat loss or increase; vegetation loss or increase; shoreline position change; as well as the effects of groundwater elevation. The lake elevations that were used to investigate the ecological and hydrological effects on the lake and its surrounding environment include: 1154.11 ft amsl (legal summer level), 1153.61 ft amsl (legal winter level), 1153.78 ft amsl (4 inch lowering), 1153.36 ft amsl (9 inch lowering), 1153.027 ft amsl (13 inch lowering), 1152.61 ft amsl (18 inch lowering), 1152.443 ft amsl (20 inch lowering). The decrease of 18 inch and 20 inch in lake level is an assumed maximum reduction if the lake level control structure were to be permanently opened or removed respectively. Initially, the 6 inch drop scenario was assumed to be the smallest change that would be considered, however following analysis of Task 5.4 we added a scenario with a 4 inch lowering of lake level due to the lower than expected simulated lake level declines.

Task 1 Findings Summarized

- No evidence of different outlet position in recorded history
- No evidence of significantly deeper outlet or within-lake approach historically
- Little change in bulk position of shorelines over time: lake area largely unchanged
- Evidence of significant shoreline erosion in some regions, particularly the NE and W quadrants of the North basin.
- Lake level scenarios between 4 and 20 inch drop defined for further analysis in Tasks 2, 5, and 6 (separately reported).

Task 2: Bathymetric and Shoreline Surveys

This Task encompasses data collection efforts on Higgins Lake during the summers of 2012 and 2013. These included collection of both depth data and photos for characterizing shoreline character (i.e. armored, not-armored) as well as a comprehensive count of numbers of docks on the lake.

2.1: Shoreline Character and Docks Survey

During the shoreline bathymetric surveys, described in Task 2.2, an extensive photographic survey was conducted. These photos were taken with a GPS-integrated digital camera following standard procedures: 1) take the photo while facing directly toward the shoreline, so that the GPS location can be readily mapped to the shoreline location, 2) take a photo of each transition of shoreline character, 3) take a single photo for each dock, even if multiple docks are in the same field of view. In total, over 2,000 photographs were taken providing a thorough inventory of both docks and shoreline character. The docks dataset is described below in Task 2.2.

Even though the camera included a internal GPS, the accuracy was only to within 10 meters. However, by matching the timestamp of the photographs allowed a more accurate differential GPS unit on the Acoustic Doppler Current Profiler (ADCP, described below) being used for bathymetric data collection, the GPS coordinates to be updated to an accuracy of +/- 1 meter. Using the georeferenced images the research team was able to manually classify shoreline characteristics as armored, natural vegetation/beach, or cobble riprap. From these classified images, a total percentage of armored shoreline was calculated for each 250 meter (820 foot) section of shoreline (FIgure 2.1.1).

The presence of shoreline armoring is likely indicative of past erosive activity, which is supported by the fact that the areas of the lake with the highest percentages of armoring have less likelihood of active erosion (Figure 1.8.5). In particular, the western edge of the South basin shows this inverse relationship. Another potential explanation for this relationship is that the addition of seawalls to areas that are not otherwise needed may actually result in unintentional erosion of adjacent property owners as wave energy is concentrated at the edges of the armoring. This may therefore cause the perceived necessity of armoring to propagate along the shore.

A literature review published by the U.S. Army Corps of Engineers titled *The Effects of Seawalls on the Beach*, (Kraus, N., 1988) underscores the complexity of shore armouring. Below is a summary of four different questions Kraus asked and answered in their review:

- *What is the maximum scour depth at a seawall?* The depth of scour is dependent on the occurrence of waves, wave duration, the reflectivity of the wall, and the initial beach morphology. In general wave height within deep water appears to be a good estimate. However, scour depth is decreased if the reflection coefficient of the seawall is reduced.
- *Is the amount of sand scoured equal to the amount eroded across the adjacent beaches without structures?* The volume of material scoured at a seawalls have similar magnitudes and variations as the volume of the adjacent non-armored shores, but the data is highly variable due to nearshore beach morphology and offshore bathymetry which affects the attenuation of wave energy.

- *Do seawalls accelerate or enhance erosion?* Ways that a seawall can enhance erosion to adjacent non-armored shore are by acting as a groin on the updrift side and impounding sand and causing the waves to flank the sides. Other erosive properties of seawalls include an increase in turbulence from wave reflection and enhancement of transport by short crested wave systems from reflected waves.
- *Is it beneficial to design seawalls to be "softer"?* Studies have concluded that slanting permeable seawalls have smaller reflecting coefficients and suffer less local scour than vertical or near vertical walls. These softer structures appear to mitigate local scour and allowed the beach to respond in a similar way as natural beaches.

The photo database collected for this project provides a baseline assessment to examine future changes in shoreline condition. This provides a valuable resource to organizations working to improve the reflection coefficients of existing armoring, and provides for best practices in the event of newly installed seawalls.

Another potential future use of this data would be to assess the impacts of shoreline armoring on property values. Indeed, studies have shown that armoring can have a negative effect of property values for the entire lake community including the non-waterfront property owners (Kriesel and Friedman, 2003). Kriesel and Friedman find that at first, the few individual waterfront owners that install shore stabilization have a substantial initial increase in property value. However, as more waterfront property owners install seawall stabilization the values drop to original levels. The study also concludes that if erosion of the shore is left unabated, the non-waterfront property has the potential to lose 23% of the value. But this same study also concluded that if the shore is primarily armored this also leads to an overall decrease of property values and a decrease in public use of the lake.

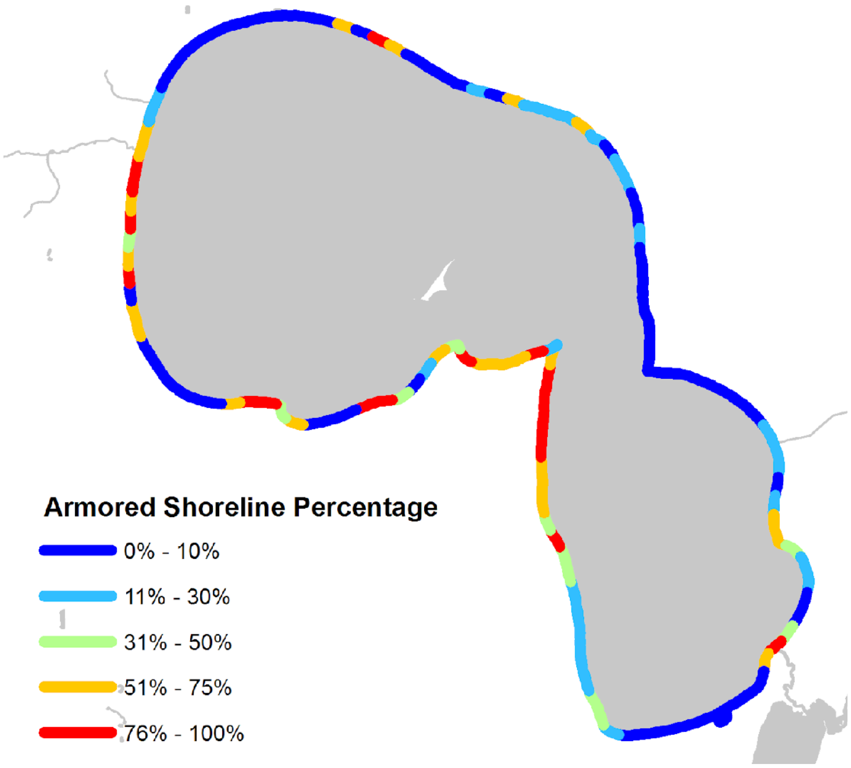


Figure 2.1.1. Map of shoreline armoring percentage averaged within 250 m (820 ft) sections of shoreline.

2.2: Bathymetric Survey

One of the primary products of this project is a new near-shore bathymetric survey conducted primarily within the first 10 feet of lake depth. As noted in Task 1.4 above, this section of the lake has no further bathymetric detail provided by the 1930s map, yet is the portion of the lake most sensitive to changes in lake level, due to either natural fluctuations or changes in dam management.

Additionally, for the purposes of the ecological assessment conducted for Task 6, a new deep basin and drop-off (the region between the shallow shelf and the deep basin) bathymetric survey was needed. As part of this survey, new instruments would provide not just depth but sediment characteristics (sand, gravel, or soft sediment).

To conduct a near-shore bathymetric survey with accuracy within the first two feet of lake depth, several novel methods were applied: 1) multiple lake level transducers would be installed around the perimeter of the lake to capture bulk fluctuations in lake elevation due to wind-driven seche, 2) a new very high frequency depth sounder would be used that can accurately obtain depth measurements down to approximately 20 centimeters, and 3) a filtering method would be used to remove the effect of waves from the dataset.

As a final product, the near-shore survey and the deeper survey would then be stitched together. This required applying a novel interpolation scheme that captures the unique structures of each of the three lake bathymetric regions: the shallow shelf, the drop-off, and the deep basins.

Spatial Lake Level Analysis

Figure 2.2.1. Photo of water level logger installation.

The MSU field crew, assisted by the UofM field crew installed 6 pressure transducers (FIgure 2.2.1) around the perimeter of the lake shore, at locations shown in Figure 2.2.2. The crews chose to place the transducers onto dock posts to allow easy access and minimal disturbance. At each location the crews used a Trimble GPS to measure the water level for a starting reference of the pressure data. The transducers recorded pressure in millimeters, which relates to the height of water above the unit. The water elevation from the locations were to be used to investigate the lake's surface relief from the north basin to the outlet. The data was also collected to link the 6 regions to the bathymetric survey based on their spatial relationship.

These transducers recorded lake level data every 3 minutes for the duration of the bathymetric survey, approximately 4 days. We assessed the data from this deployment and determined that: 1) our data collection took place primarily during periods of relatively calm water, where no significant differences in levels between the gauges were observed, and 2) the accuracy of vertical positioning was not sufficient to determine if wind-driven seche was present during times of rougher water. Although two of the transducers failed to record data, these failures did not affect our overall task of linking lake elevation to the new bathymetric data. The USGS lake elevation gage located at the South Higgins State park records elevation every 15 minutes, which proved to be sufficient to link the depths recorded during the bathymetric surveys to actual water level elevations.

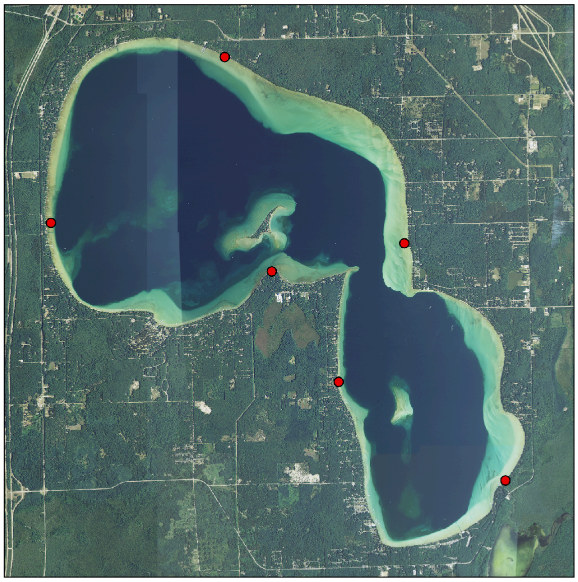


Figure 2.2.2. Map of water level loggers deployed around the lake.

Shallow Bathymetric Survey Methods

The shallow bathymetric survey was conducted using a Sontek S5 RiverSurveyor Acoustic Doppler Current Profiler (ADCP), a device that records depth, current velocities beneath the instrument, velocity relative to the lake bed, and with an integrated GPS provides either 1-meter accurate GPS, or optionally a 1-cm accurate GPS with the deployment of a secondary base station. All data were logged on the instrument at a rate of 1/second (1 Hz). The ADCP was mounted on a custom designed boat mount fabricated by the MSU Physics Machine Shop (Figure 2.2.3). The mount was capable of lowering and raising to best position the ADCP within the water column but with minimal drag. This allows for greater boat speeds, increasing the overall rate of data collection.

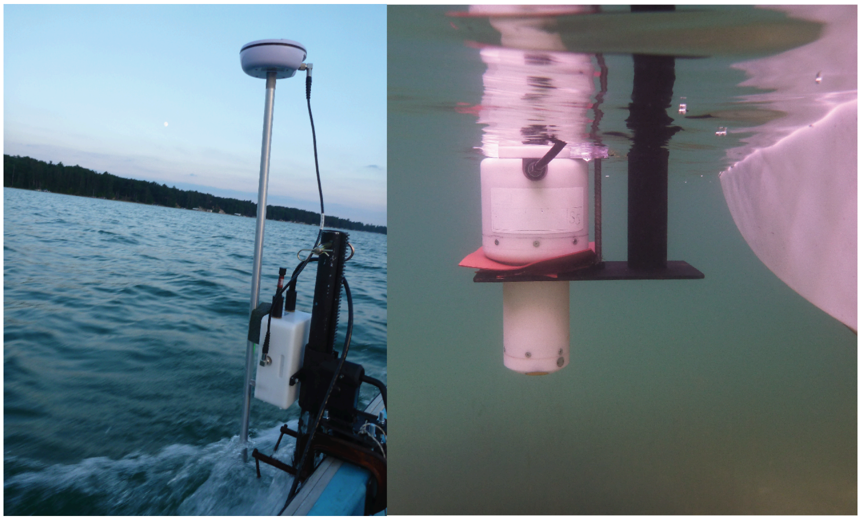


Figure 2.2.3. Image of MSU's boat deployment of Sontek RiverSurveyor S5 ADCP with an integrated differential GPS . The image on the left shows the instrument during data collection. The photo on the right shows an underwater view of the instrument while at rest. When the boat was in motion the instrument rose further up in the water.

The ADCP was attached to the starboard (left) side of a 14 foot tri-hull Boston Whaler. During the 2012 survey, MSU's average boat speed during data collection was approximately 4.5 mph (3.9 knots). The following year, MSU's field crew used kayaks towing the ADCP on a small foam boat to measure near shore depths as shallow as 7 inches. This single kayak survey involved involved close to 7 days of field effort.

We designed a custom survey pattern to efficiently cover the shallow shelf area. This "warp and weft" pattern included four survey lines, 3 roughly parallel warp transects followed the 0.5, 1.5, and 3 meter depths contours, and a 4th zig-zag weft line to provide greater detail about the depth variation across contours (Figure 2.2.4). The presence of docks and the draft of the boat limited the shallowest line in some cases. In addition to the main shoreline, the central island, known as "Treasure Island" in the North basin and the submerged island within the southern basin were surveyed. Real time depths were referenced by the use a transom mounted Garmin Fish Finder. The fishfinder was also used to navigate our route during data collection. A fifth survey line was added in 2013 for the kayak traverse, with the goal of recording the shallowest depths the instrument could record around the entire perimeter of the lake. This was conducted during summer, thus additional depth data were collected as the kayak was forced to trace an outline of essentially each dock around the lake.

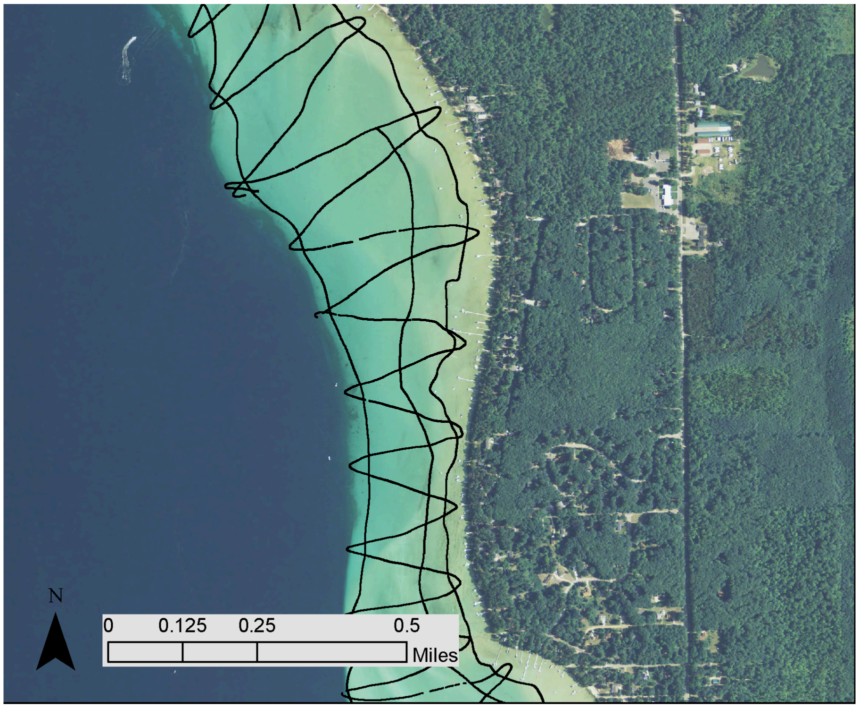


Figure 2.2.4. The warp and weft pattern employed for shoal allowed for optimal data collection.

Following data collection, the data were filtered using two methods: 1) all depth data values of 0 were rejected, and 2) a spectral low-pass filter (Butterworth filter) was designed to remove the effects of waves and boat pitch from the depth data. This spectral filter successfully removed the high-frequency "noise" and produced a clean series of depth along the boat track. The filter parameters were carefully tuned such that peak depths were not excessively smoothed (Figure 2.2.5).

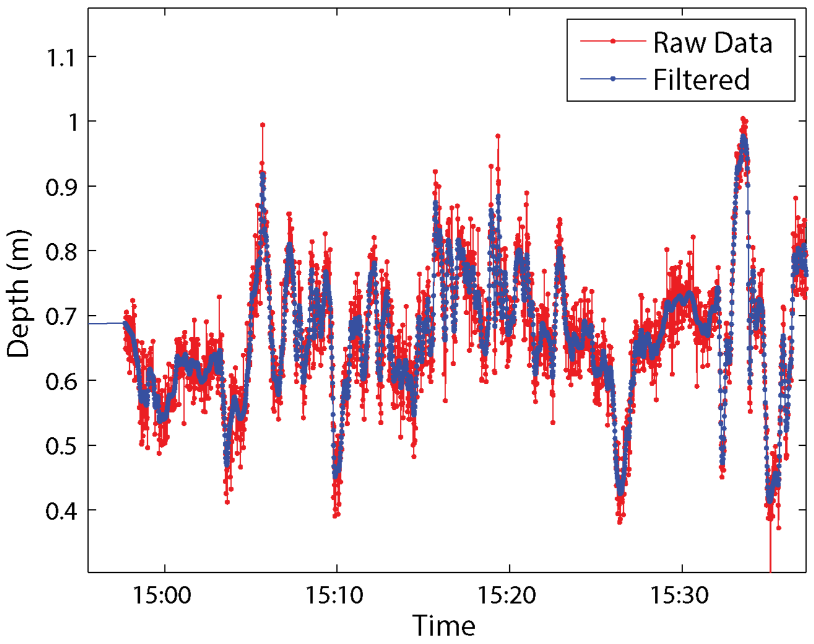


Figure 2.2.5. Raw and spectral-filtered bathymetric data.

Deep Basin Bathymetric Survey Methods

The UM personnel performed the off shore deep basin (>3 meter) data collection using multiple instruments including a Navitronic's Lowrance HDS-8 sonar unit with an integrated WAAS enabled GPS, a Imagenex Yellowfin tow behind side scan sonar. The survey patterned was conducted within a typical survey grid spacing of 400 meters. The average speed for the deep basin data collection was approximately 4 mph. Further details are provided about this survey in the Addendum report for Task 6.

Interpolation of Whole-Lake Bathymetry

When both groups completed their portion of the data collection there was a total of more than 779,000 depth points. But before the two data sets could be merged, the groups needed to first process the data in a similar way. MSU's data were spectrally-filtered as described above, while the UofM team did not need to use these methods as the depths recorded were significantly greater than the high frequency noise due to waves or other noise sources during data collection. The merged depth dataset, which contained roughly 642,000 points after rejecting 0 depth data and merging duplicated depth data, were transformed to bottom elevations adjusted to the varying lake levels by using the 15 minute sampling interval USGS gauge.

During the initial data collection MSU and UofM each survey overlapped in a zigzag pattern along the 3 meter depth shoal-slope zone. This was an integral step to perform a quality assurance and quality control of the separate data sets. The merged dataset was imported into ArcGIS ArcMap (Figure 2.2.6) to begin the interpolation.

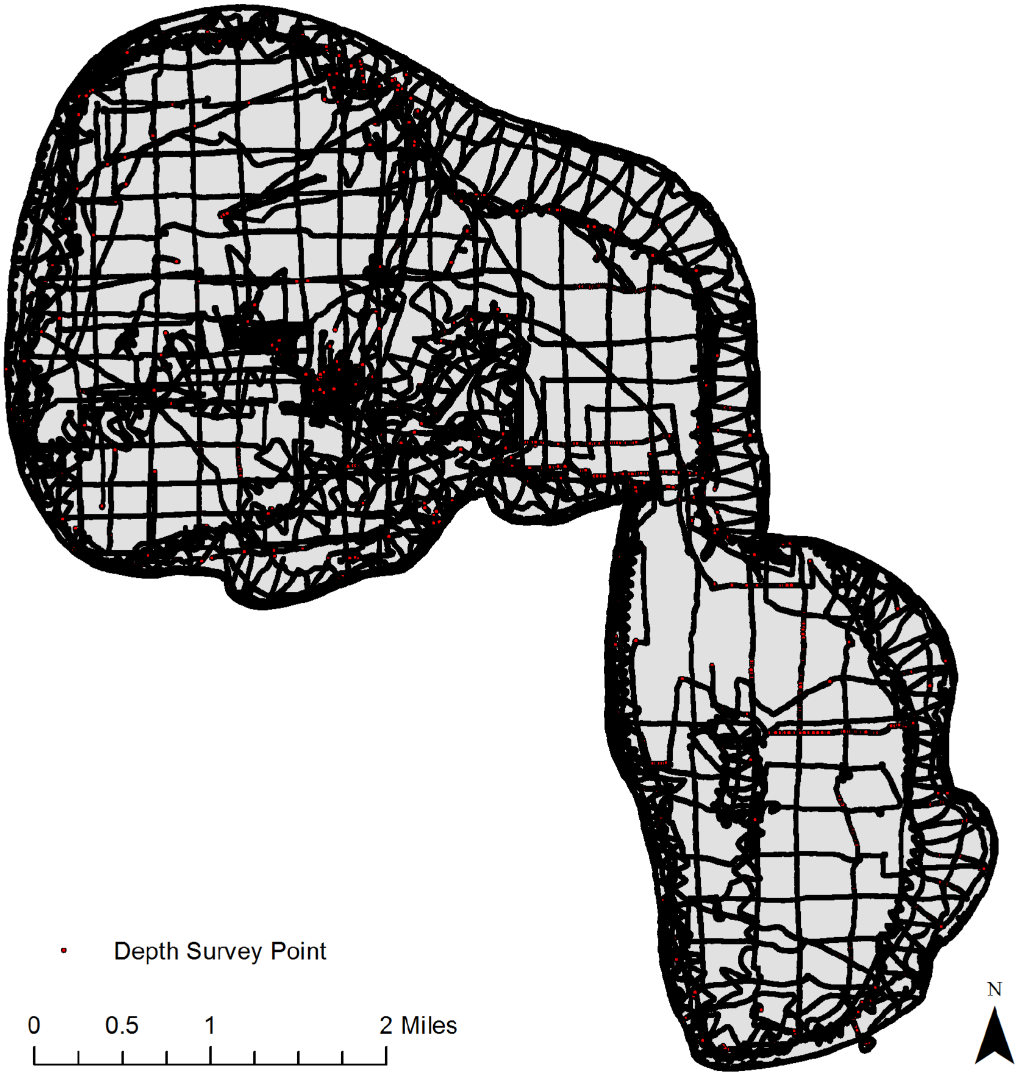


Figure 2.2.6. Map of all points included in the interpolation, a total of 642,902 points remained after quality control was completed.

Interpolation Techniques

Due to the complex nature of the Higgins Lake bathymetry, interpolating three data across all three lake zones proved exceptionally difficult. Methods that smoothly interpolated the deep basin with the drop off tended to underpredict shallow shelf depths, for instance, this is known as the Gibbs phenomenon. MSU researchers tested methods including: Spline, IDW, Kriging and finally Zonal Kriging.

- Spline interpolation works by estimating grid cells values by fitting a minimum curvature line through each of the data points. Spline interpolation works best when the data does not include extreme geomorphological features and the data set is relatively small.

- Inverse distance weighting, known as IDW, interpolates by averaging the data values of nearby points. The closer the neighboring data point is to the estimated cell, the more weight it is given. IDW is usually more appropriate when large sets of data that does not include steep drop offs and the data set is known to represent maximum and minimum values. This method will average the data to create an overall smooth surface.
- Kriging is similar to IDW, as it forms weights from the surrounding data values to predict the unmeasured locations. Unlike IDW, kriging weights are derived from a semivariogram as described above in Task 1.6 that takes into consideration the spatial structure of the data. Predictions are made based upon the semivariogram and the arrangement of the nearby measured values.
- Zonal Kriging is an adaptation of Kriging that allows for separate interpolation within distinct zones, in this case depth bands that defined the shallow shelf, drop-off, and deep basin. Then, the three zones need to be merged in a way that preserves continuity across the boundaries.

A literature review of zonal kriging methods resulted in a range of guidance in terms of how to construct the zones, and in particular how to handle the region where the zones come in contact. To define the zones, we analyzed the depth data to determine the locations where slopes became significantly different. In particular, the drop-off zone is characterized by very steep slopes, whereas the shallow shelf is quite flat, and the deep basin in between. Cutoff depths were determined from this analysis, and are shown in Figure 2.2.7. A preliminary whole-lake kriged map was constructed to define the depths of the zones, while depth values were used to subselect data that would be included in each zonal krig.

To handle the overlap region, we created a weighting map that is then multiplied by each zonal kriging estimate. This weighting map smoothly interpolates between each zone krig map. The width of the overlap zone was adjusted to minimize the difference between the observed values and the interpolated values, as well as visually to minimize interpolation artifacts that can arise.

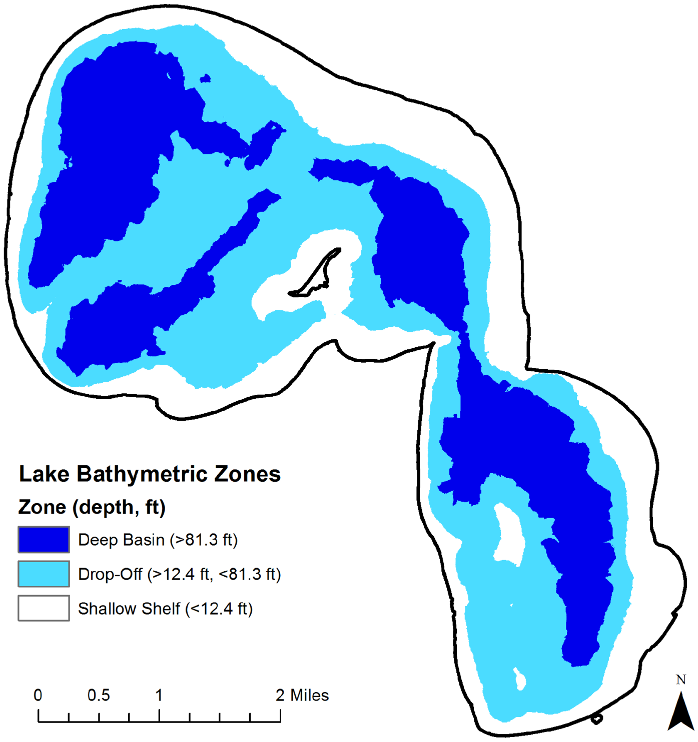


Figure 2.2.7. Map of the lake bathymetric zones used for the zonal kriging method.

The final output from the zonal kriging method is shown as a relief map in Figure 2.2.8. This new map provides an unprecedented level of detail, both in the shallow region of particular interest to this study, as well as in the steep drop-off of critical ecological importance, and in the deeper basins as well. This data could also be used to provide better navigational data for the lake, particularly for highlighting hazards that arise due to lake level fluctuations. Furthermore, it can be used as a baseline dataset to assess future changes in lake bathymetry that might result from continued shoreline erosion, or lake level changes.

For the sake of comparison, contours were generated from the new map (FIgure 2.2.9) that match those in the original 1939 dataset (Figure 2.2.10). While making direct inferences between these two maps should be done carefully because of the errors in the original map dimensions, there are some notable differences in positions of the 10 foot contour (Figure 2.2.11). In particular, the new 10 foot contour is almost always located toward the deep basin relative to that in the 1939 map. If differences between the two maps were random this would not be the case. Furthermore, there are several areas of distinct differences, which in comparison to the erosion likelihood map (Figure 1.8.5) show commonalities. Together, these are suggestive, though not definitive evidence for, shoreline-erosion induced changes in the location of the 10 foot contour resultant from the movement of sediment eroded from the shoreline.

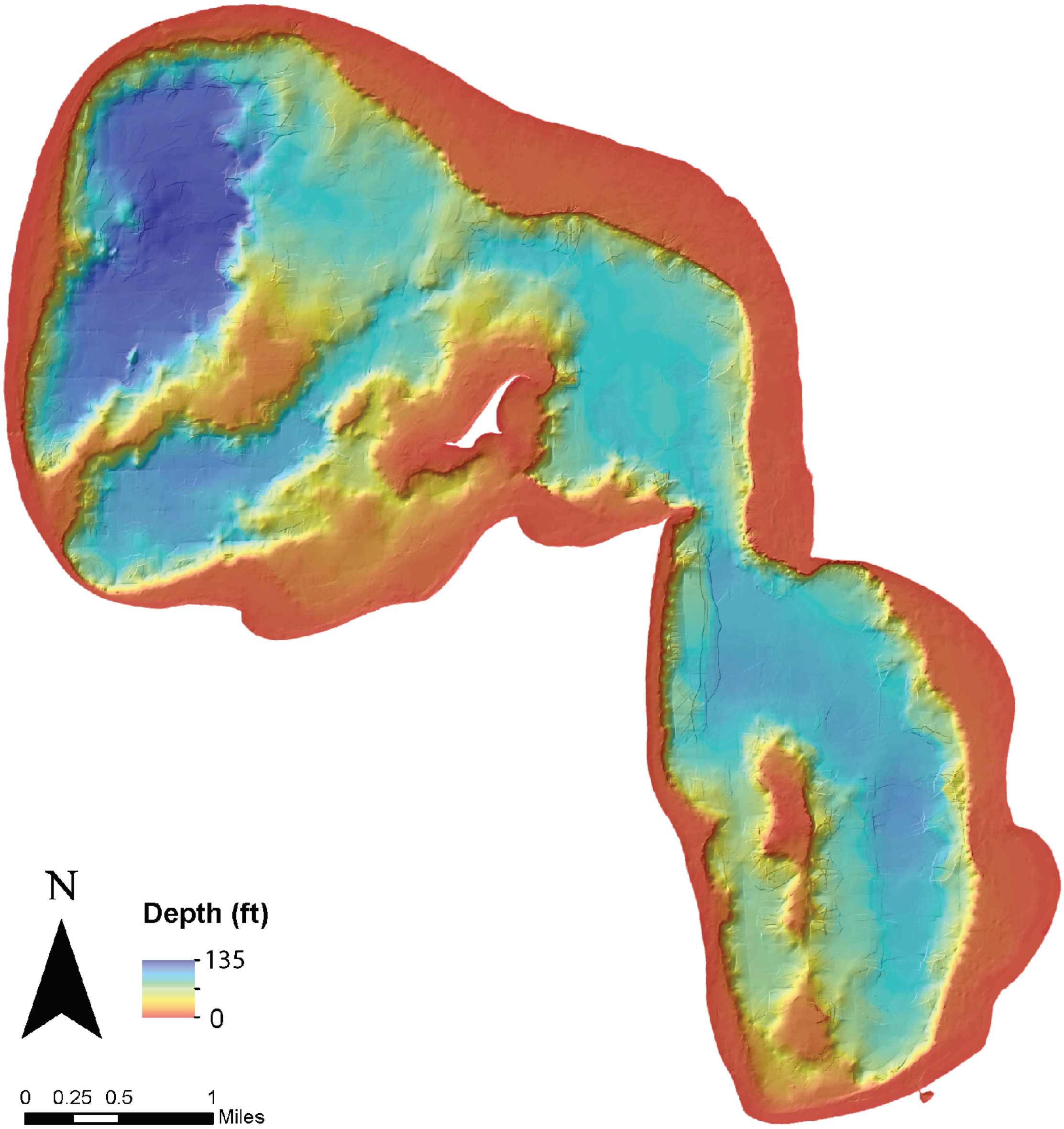


Figure 2.2.8. Relief Map created using the bathymetric data collected by UM and MSU during 2013 and 2014. The image is constructed using a 3x3 meter cell size.

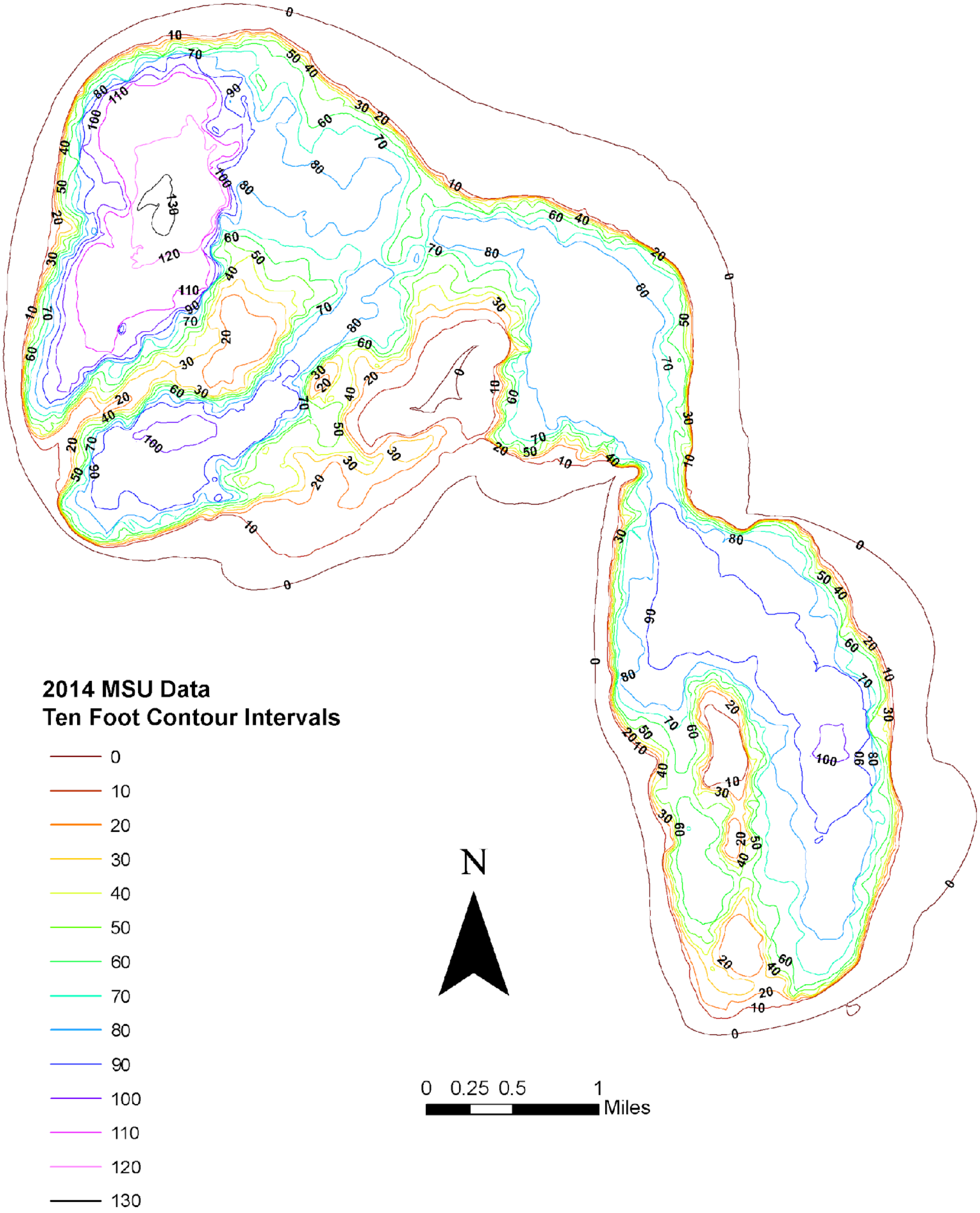


Figure 2.2.9. New bathymetric map contoured at 10 foot intervals.

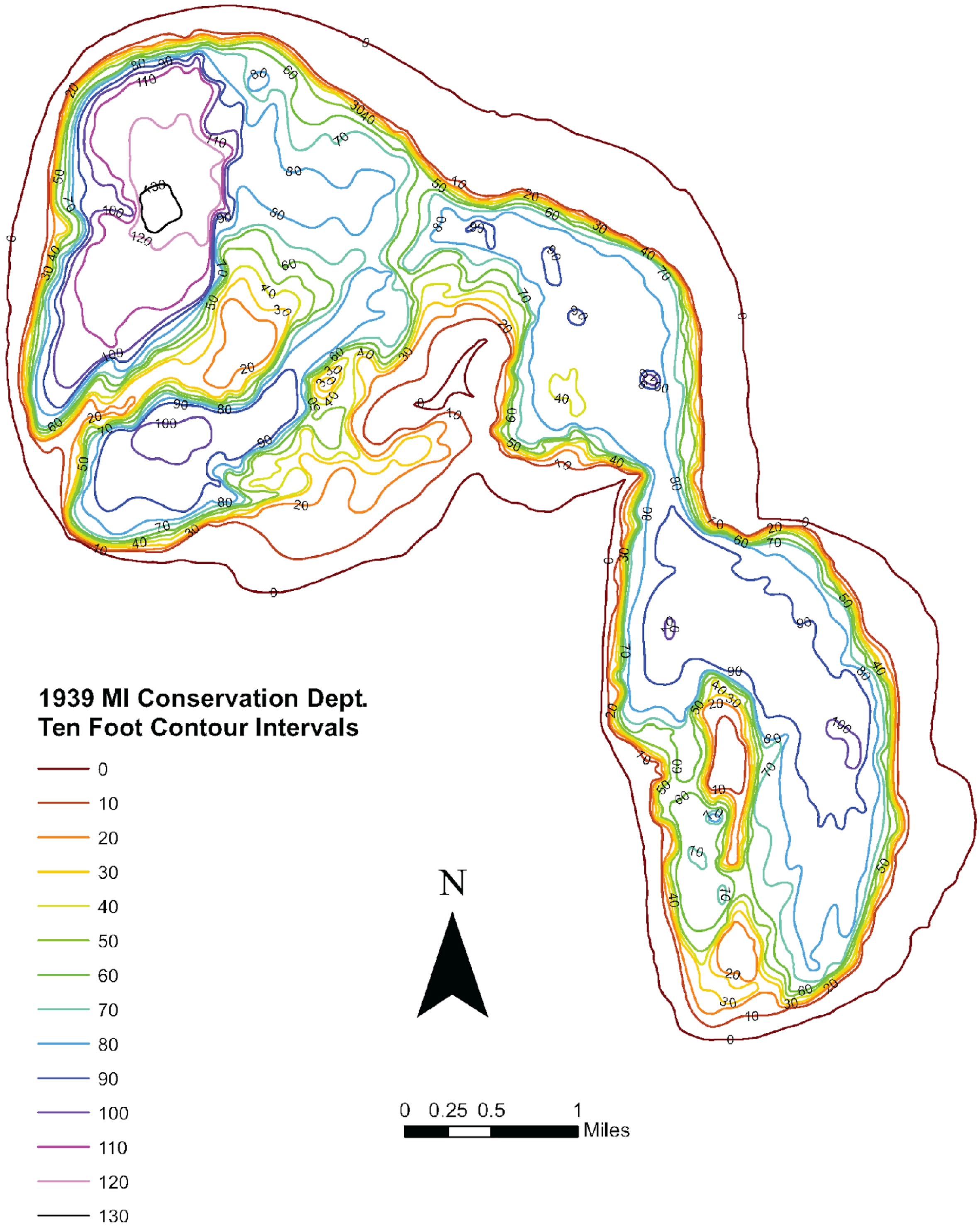


Figure 2.2.10. The original 1939 Michigan Conservation Department bathymetric map digitized and displayed in the same color scheme as the new contour map.

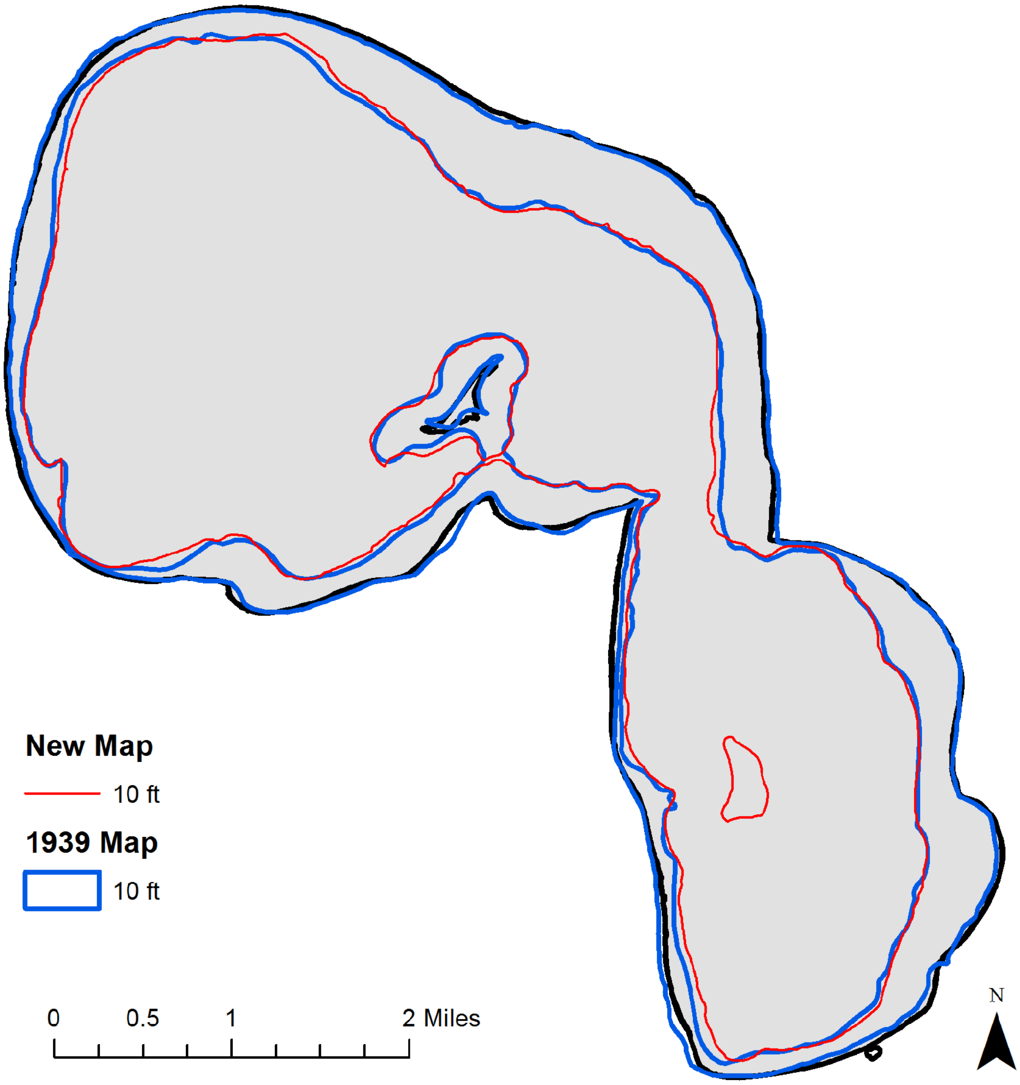


Figure 2.2.11. Map comparing the new 10 foot contour (red) to that of the original 1939 map (blue). Note that the outer blue ring should overlap the black lake outline, where it does not there are errors in the original map dimensions and care should be taken in interpreting differences between the new and old 10 foot contours.

2.3: Evaluation of Lake Level Scenarios

Now that a comprehensive digital map of Higgins Lake bathymetry is available, the impacts of changed lake levels can be assessed on a variety of important areas: 1) changes in shoreline position (and lake area), 2) dredging that would be necessitated at lake access locations and marinas, and 3) changes in dock length by residents of the lake.

Changes to Shoreline Position and Lake Area

Perhaps no impact of changed lake level is as significant as changes in shoreline position. This impact would be felt most directly in terms of increasing the length of beach between the lake and property owners, providing a buffer from erosion and in some cases substantially increasing property sizes. Lake area would decrease in direct proportion to the increase of riparian landowner property area, with all of the changes occurring in the shallow shelf region.

Contours were created at depths of 4, 6, 9, 13, 18, and 20 inches relative to the current summer legal lake level (Figure 2.3.1). These contours show some areas where shoreline changes would be significant across the more extreme scenarios, particularly in the North Basin and in the South Basin adjacent to South Higgins Lake State Park. We assumed that a new shoreline would form at approximately the location of the depth contour representing that lake level drop (i.e. a 6-inch drop shoreline forms at the 6-inch depth contour).

To more quantitatively assess how shoreline positions change, shoreline changes were averaged within polygons encompassing 250 meters (820 feet) of Higgins Lake shoreline--the same analysis sections used in the erosion likelihood map (Figure 1.8.7), and armoring percentage map (Figure 2.1.1). While each scenario was assessed, only the 4-inch and 9-inch drop are displayed. These were chosen because they represent the mean conditions of two altered dam-management strategies (keeping the dam open at all times, and removing it) discussed in greater detail in Task 5.4.

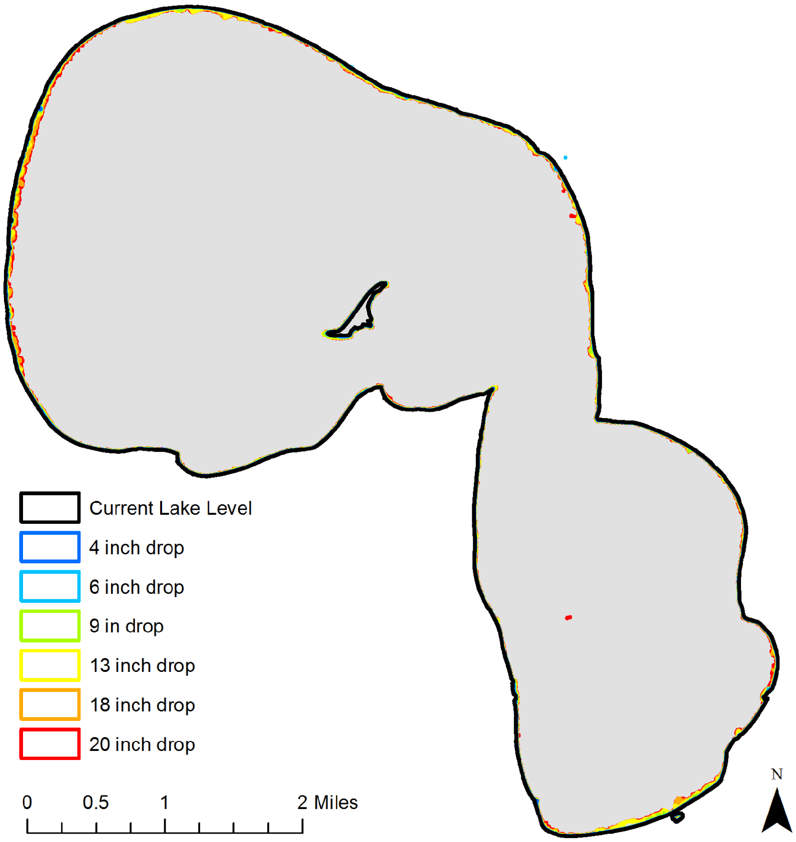


Figure 2.3.1. Map of shorelines overlain from each lake level drop scenarios.

In Figure 2.3.2 below, the 4-inch lake level drop scenario is shown. The area of most significant change is on the western edge of the North basin, while the area with least change is on the western edge of the South basin. Changes ranged from 9.3 feet to as much as 24.6 feet, on average across the 820 foot wide polygons. These numbers represent a recession of the shoreline away from the current lakeshore toward the center of the lake, thus increasing the buffer between properties and increasing total dry property dimensions.

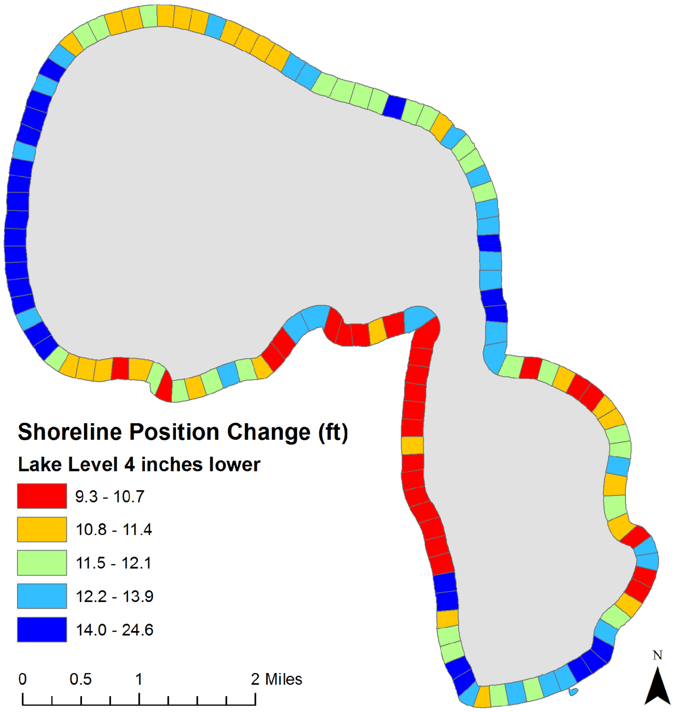


Figure 2.3.2. Map of shoreline position changes (toward the center of the lake) under a 4-inch lake level drop scenario. Colors indicate 20% quantiles of shoreline position changes across analysis polygons.

A similar map for the 9-inch lake level drop is shown in Figure 2.3.3, with similar patterns of change but larger overall magnitudes. Here changes range between 15.7 and 62.9 feet.

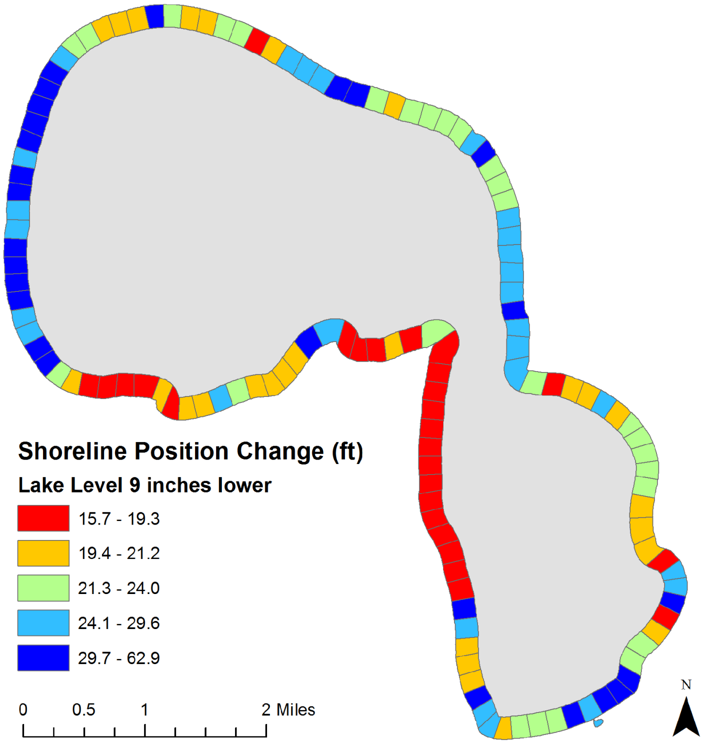


Figure 2.3.3. Map of shoreline position changes (toward the center of the lake) under a 9-inch lake level drop scenario. Colors indicate 20% quantiles of shoreline position changes across analysis polygons.

Averaging across all lake polygons for each scenario produces Table 2.3.1. From this table we see that on average shoreline position migrates lakeward by 12.3 feet in the 4-inch drop scenario, and as much as 83.6 feet in the 20 inch drop scenario. It should be noted here, however, that the lake level modeling in Task 5.4 shows that the more extreme scenarios are highly unlikely to occur, *even in the absence of any lake level control structure*.

Shown in Table 2.3.2 is the change in lake area as a result of each scenario. For the 4- and 9-inch drop scenarios, lake area decreases by 25 and 69 acres, respectively (0.3 to 0.7% decline). The extreme scenarios show declines of as much as 2% or more of lake area, again with the caveat of high unlikelihood that these scenarios would ever occur. Note that all of the land lost by the lake is gained by riparian property owners.

Table 2.3.1. Shoreline position changes (toward the center of the lake) averaged across the analysis polygons for each of the lake level drop scenarios investigated.

Lake Level Drop Scenario (in)	Average Change in Shoreline Position (ft)
4	12.3
6	17.0
9	25.3
13	45.1
18	64.1
20	83.6

Table 2.3.2. Lake area for all scenarios, along with percent change in lake area calculated relative to current area.

Lake Level Drop Scenario (in)	Lake Area (acres)	Change in Area (%)
Current	10,258	
4	10,223	-0.3
6	10,210	-0.5
9	10,189	-0.7
13	10,140	-1.1
18	10,088	-1.66
20	10,043	-2.1

Changes to Depth in Dredged Areas

Several locations around Higgins Lake are currently dredged for boat passage and mooring, five of which are shown in Figure 2.3.4. These locations would be directly affected by any lake level change, and the need for dredging would increase.

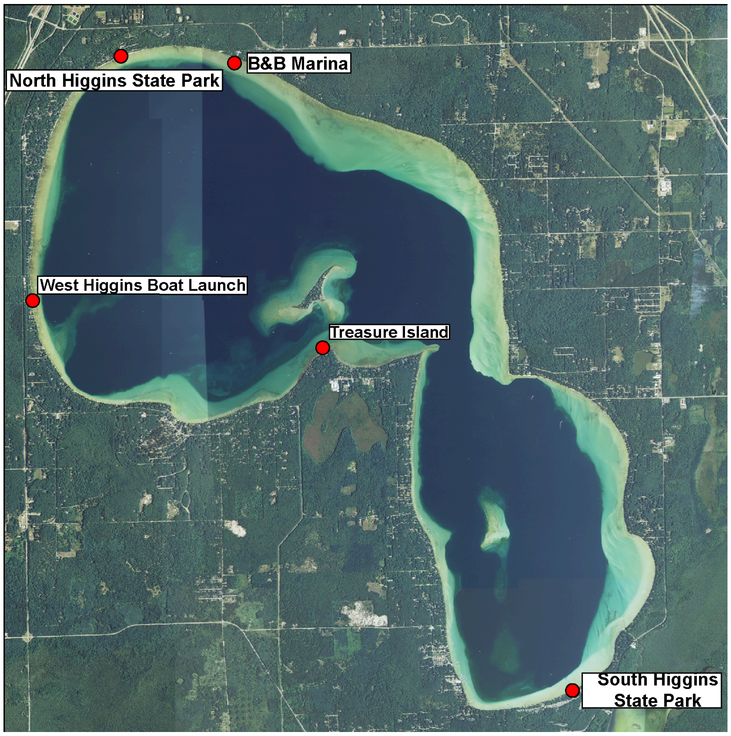


Figure 2.3.4. Locations of the dredging volumes calculated. Areas were selected based upon the feasibility and reliability to delineate either boat launches or marinas via aerial imagery.

Using the scenarios for change in lake levels, researchers calculated the volume needed to be dredged to maintain a 3.3 ft depth within the boat launches and marinas. This depth was used out of simplicity since the original measurements were in meters and due to regulations for boat launches requiring a depths between 3 and 4 ft.

Because of the higher resolution needed for this assessment, a different methodology was needed to assess dredging requirements. First, by using the collected depth data from the Sontek ADCP of the nearshore and overlaying a grid, the areas of sparse data was manually interpolated. From these data points of each area of interest Thiessen polygons were constructed within ArcGIS. These polygons divide the area of interest into regions within which each known point is the nearest neighbor for interpolation. The Thiessen polygons were then used to calculate the surface area of each data point grid cell. Each grid cell was evaluated to determine the depth required to remain in compliance with navigational water regulations of 3.3 ft water depth.

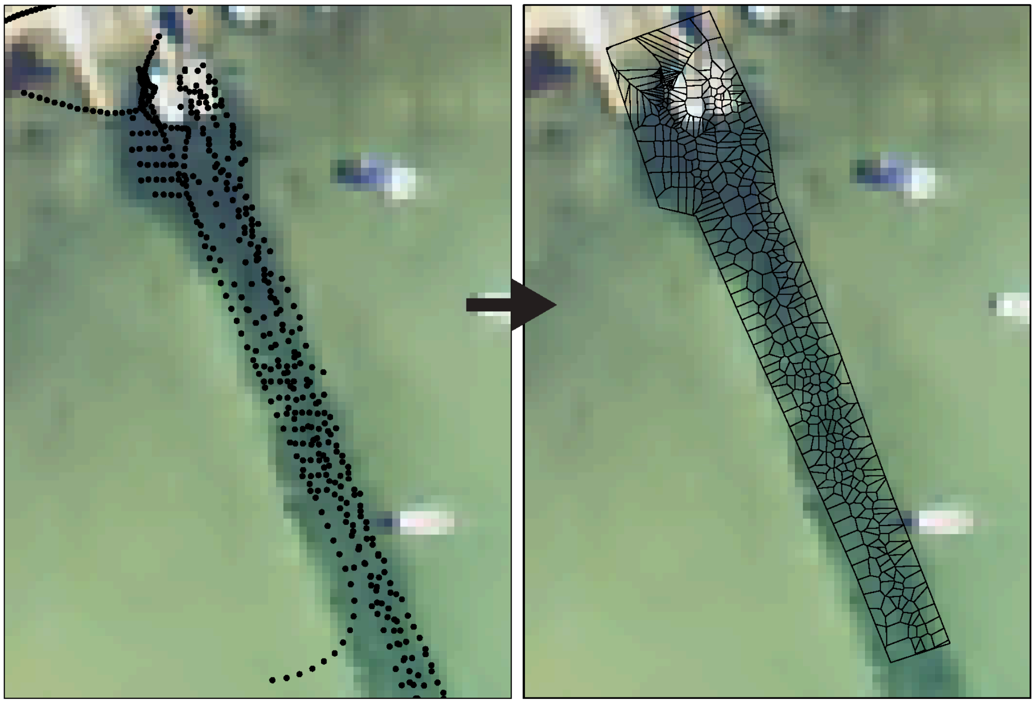


Figure 2.3.5. Graphic illustrating the workflow of calculating the dredging volumes of North Higgins State Park's boat launch. Black dots indicate the data points used to construct Thiessen polygons to calculate area

Note, not all marinas and launches met this current requirement, thus we quantified the dredging need under lake level change scenarios and subtracted out the current need (a dredging backlog, effectively). This isolates the changes caused by the lake level scenarios alone.

Table 2.3.3 lists the volumes for each area of interest and for each scenario. Clearly, South Higgins Lake State Park and B&B Marina would incur the greatest impacts in terms of dredging due to lake level changes. The other three areas of interest have approximately an order of magnitude less requirements. Note again here that the more extreme scenarios should be considered highly unlikely to occur, as mentioned above as well and below in Task 5.4.

Table 2.3.3. Dredging volumes for all lake level scenarios

Lake Level Drop Scenario (in)	Dredged Volume (cubic yards)	Marina/Boat Launch
4	914	B&B Marina
6	989	
9	1480	
13	2133	
18	3282	
20	3283	
4	45	North Higgins State Park
6	54	
9	72	
13	113	
18	195	
20	243	
4	89	Treasure Island
6	109	
9	141	
13	182	
18	234	
20	255	
4	53	West Higgins Boat Launch
6	75	
9	138	
13	251	
18	446	
20	533	
4	854	South Higgins State Park
6	1312	
9	2058	
13	3133	
18	4563	
20	5147	

Changes in Dock Length

Another direct impact of lake level changes would be in altering the lengths of docks required for adequate depths at the dock ends. This subtask quantifies those potential changes.

Dock presence was calculated in two ways: 1) Every dock was visually identified and photographed with a GPS-enabled camera during the 2012 bathymetric survey, and 2) All docks visible in satellite imagery from 2011 were drawn on a map. The two surveys produced different numbers of docks: 1207 (including approximately 30 potential duplicates) were photographed during the July in-lake survey, while 934 docks were identified from the June 21, 2011 satellite imagery. Potential sources for this discrepancy (about a 20% undercount from the satellite imagery) include variable times of dock installation by lake residents, as well as possible missed dock features (however the satellite imagery were very high resolution and docks were clearly identifiable).

Nevertheless, the satellite data were needed for quantitative analysis of dock length changes under different lake level scenarios. Figure 2.3.6 shows a zoom of the central portion of Higgins Lake with the manually digitized docks in that region. To quantify dock length changes independently of the exact dock count, as well as to increase the accuracy of the overall analysis, dock length changes under varying lake levels were analyzed within 250 meter (820 foot) shoreline polygons, rather than on individual docks.

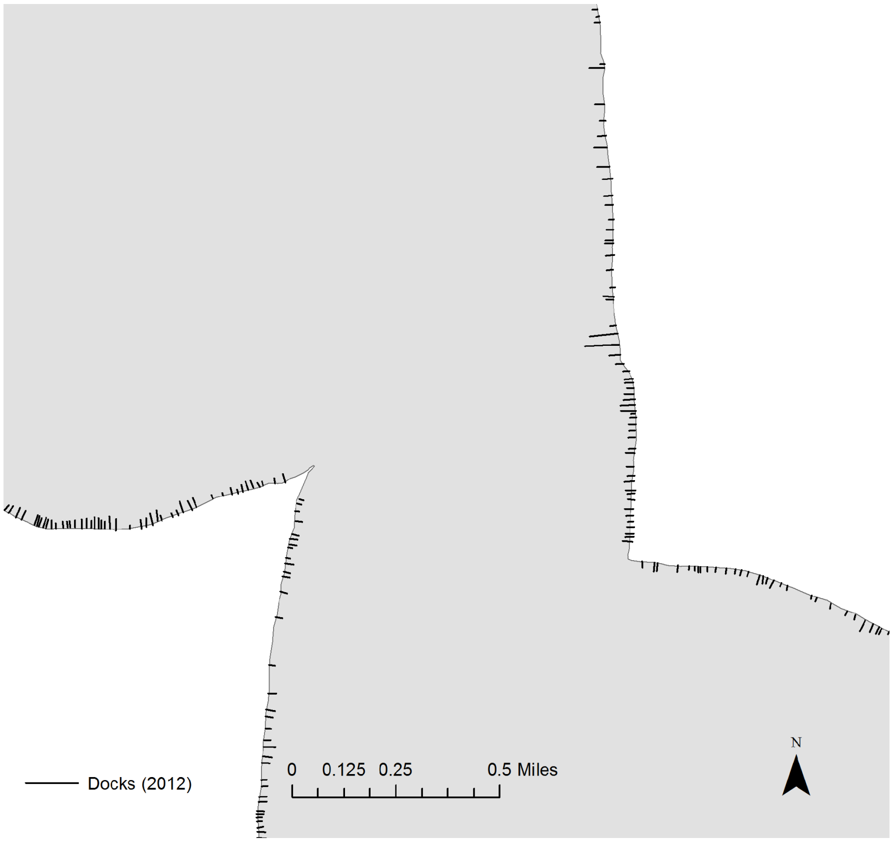
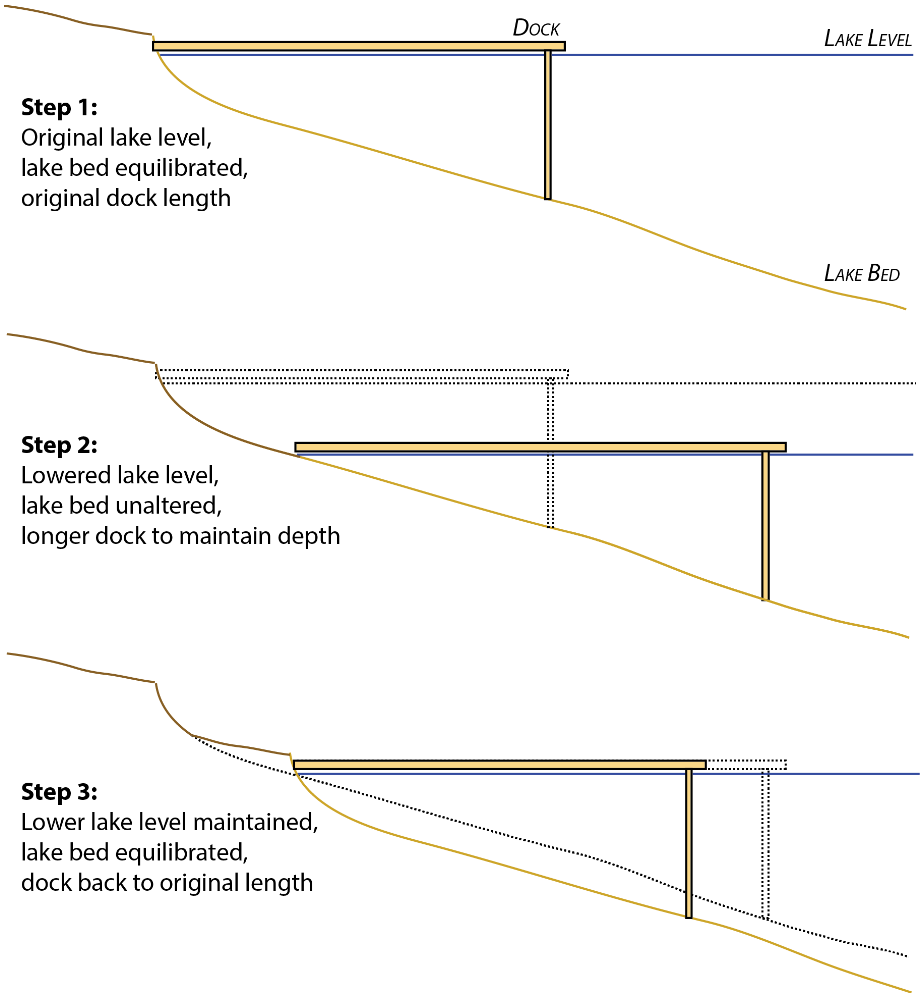


Figure 2.3.6. Map showing docks manually digitized from satellite imagery from 2011. Each black line is a single dock in this map. This map is zoomed to the central portion of the lake to enhance detail of individual docks.

Before deciding on a method to quantify dock length changes, the researchers consulted the literature on how nearshore depth profiles change as a result of water level changes. The outcome of this literature review was that the issue is extremely complex, and beyond the scope of this study. Nevertheless, we developed a conceptual model for how dock lengths would change as the nearshore profile evolves in response to lake level changes. This model is drawn in Figure 2.3.7.

Step 1 of this graphic shows the current situation, where the lake depth quickly increases very near the shore and then slows to a more gradual increase with greater distances. A dock located at this point has a depth presumably set to allow navigation for a particular watercraft or recreational use.

Figure 2.3.7. Conceptual diagram of how the lake bed profile might evolve in response to lowered lake level.



Step 2 shows the immediate aftermath of a significant lake level decline. The lake bed has not had time to adjust, the dock is moved outward to the new shoreline location, and lengthened in order to maintain adequate depth at the end of the dock.

Over time, however, as the lake redistributes sediment in response to the lowered depth, the profile will likely evolve to something approximating the original profile. This profile is controlled by two factors: sediment supply, and wave energy. Assuming no change in armoring status, neither factor will be greatly affected.

Step 3 then displays the outcome of the evolution back to the original profile, where the dock can return to its original length, only now it is located lakeward of its original position.

With this conceptual model then, eventual dock lengths would likely be similar to their current lengths. These lengths are summarized in the now-familiar 250 meter (820 foot) analysis polygons. Dock lengths average between 42 and 206 feet across these polygons.

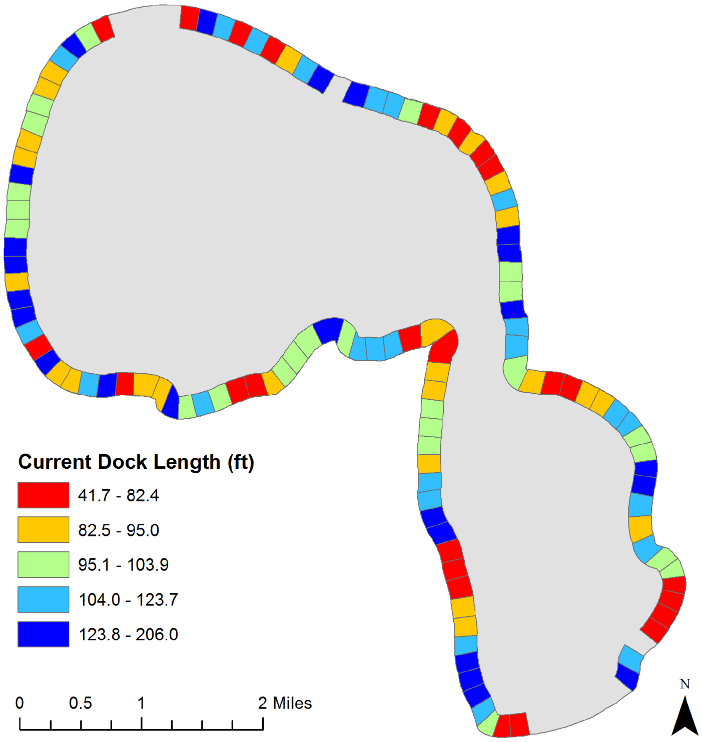


Figure 2.3.8. Map of current dock lengths averaged within polygons each covering 250 meters (820 feet) of shoreline. Only polygons with docks at the time of the analysis are shown. Colors indicate 20% quantiles of dock length.

The actual procedure to calculate the changes in dock length within each polygon proved to be somewhat complex. Each polygon was allowed to have its own average dock-end depth, which necessitated creating a whole series of contours of depth across the lake, intersecting them with polygons, and then looping over the scenarios.

The outcome of this analysis should be considered a *temporary* change in dock length that would be produced only if the lake level were dropped over a very short time period. A more careful management strategy would assess changes in depths that occur in response to both lake level lowering and subsequent sediment redistribution, particularly following ice-free storm events.

Figure 2.3.9 shows the changes in dock length calculated with this method for the 4-inch drop scenario. Changes in length ranged from essentially 0, to as much as 257 feet in at least one polygon. These changes are not randomly occurring around the lake, and fall particularly heavily in the western section of the North basin.

Shown in Figure 2.3.10 are the changes for the 9-inch drop scenario. These are similar in pattern to Figure 2.3.9, only more extreme.

The across-polygon averages are detailed in Table 2.3.4. On average, dock lengths would increase under this method by 73 feet for the 4-inch drop scenario, and 155 feet for the 9-inch drop. More extreme scenarios have greater average changes, with the same caveats as above. A second caveat with this analysis is added that this method is fairly simplistic, and does not account for the dynamic lake processes that shape the bathymetry of the shallow shelf zone.

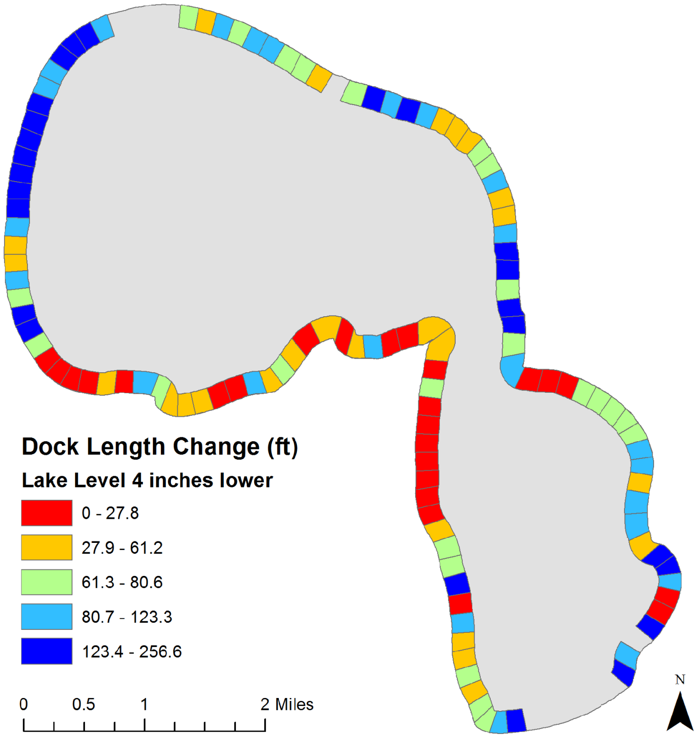


Figure 2.3.9. Map of dock length change (scenario - current) under a 4-inch lake level drop scenario. Colors indicate 20% quantiles of dock length.

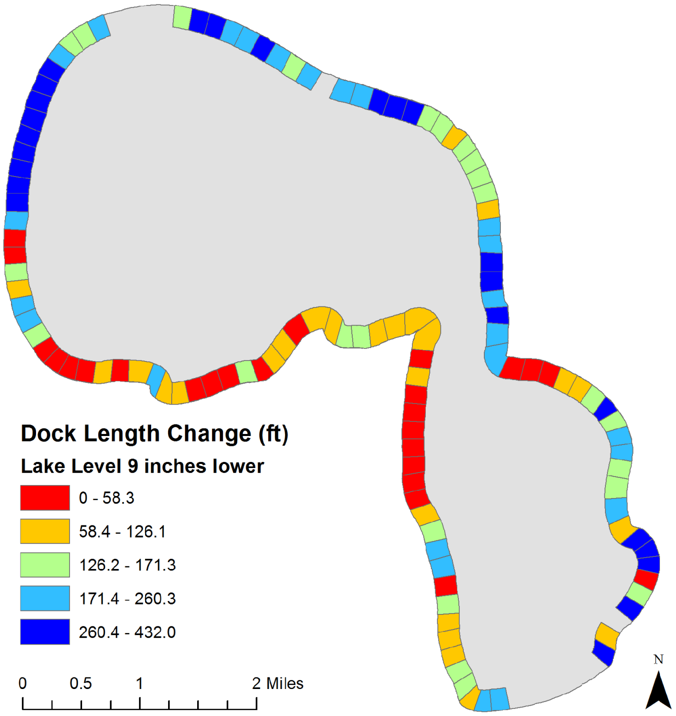


Figure 2.3.10. Map of dock length change (scenario - current) under a 9-inch lake level drop scenario. Colors indicate 20% quantiles of dock length.

Table 2.3.4. Dock length changes averaged across the analysis polygons for each of the lake level drop scenarios investigated.

Lake Level Drop Scenario (in)	Average Change in Dock Length (ft)
4	73.0
6	108.1
9	154.7
13	186.7
18	244.5

Task 2 Findings Summarized

- A single lake level gauge proved sufficient for translating lake depths to bottom elevations in a multi-day, multi-team survey.
- New methods were pioneered to produce a highly accurate bathymetric map in the deep basins, steep drop-offs, and shallow shelves of Higgins Lake.
- The new map provides unprecedented detail of Higgins Lake bathymetry.
- Evidence of change in position in the 10-foot contour between 1939 and 2013 is suggestive of sediment transport due to shoreline erosion.
- Shorelines change significantly under the most likely 4- and 9-inch drop scenarios, receding lakeward by 12.3 and 25.3 feet on average under these two scenarios respectively.
- Erosion impacts would be significantly lower under the lowered scenarios due to the increased land buffer and greater distance from structure and trees.
- South Higgins Lake State Park and B&B Marina would require dredging approximately 900 cubic yards of sediment under the 4-inch drop scenario, and 2000 and 1500 cubic yards in the 9-inch drop scenario. Other areas of interest saw lower declines.
- With ample caveats, dock lengths would need to increase significantly in the short term if lake levels were abruptly lowered, but over the long term would likely remain similar to those in use now.

Task 3: Cut River Morphological and Flow Surveys

This Task entails a detailed characterization of the morphology (channel shape and position) of the Cut River and how streamflow changes along its length in response to groundwater inputs.

3.1: Stream Profile Data Collection

In May of 2013, the MSU and UofM teams floated the entire length of the Cut River in order to characterize the depth of the channel, its habitat diversity, and flow changes along its length. The plan was to traverse the Cut River during a period of baseflow and before leaf out to ensure GPS coverage. During this process, the MSU crew towed the same Acoustic Current Doppler Profiler (ADCP) used for the lake shelf bathymetry survey behind a canoe while following a zig-zag path down the channel. The ADCP simultaneously records location (X,Y) with an onboard GPS, total depth (down to approximately 15 feet), flow velocity beneath the unit at multiple depths, movement relative to the stream bed, and a number of other parameters. Thus, it can be used to build a complete profile of stream channel depth. The instrument records each parameter once per second. The ADCP setup is shown in Figure 3.1.1.

Figure 3.1.1. Field setup for collection of stream profile data, with an ADCP towed behind a canoe.

The Cut River was floated during a two-day float, stopping at West Lansing Road at the end of Day 1 (May 23rd, 2013), returning for the remainder of the channel on Day 2. A map of all non-zero depth measurements from the ADCP is shown along the boat track in Figure 3.1.2. At the end of Day 1, due to battery issues, the onboard GPS cut out, and the position was inferred using the bottom track position alone--which can accumulate errors. This accounts for the mismatch between the boat track and the channel position beginning midway between the stream gauges HL-CR-4 and HL-CR-2 (described in Task 4). After the batteries were recharged overnight, GPS signal was maintained for the remainder of the float. In general, median track depths were approximately 2.1 - 2.2 feet, shallowest track depths of approximately 0.7 feet and deepest of 8.1 feet.

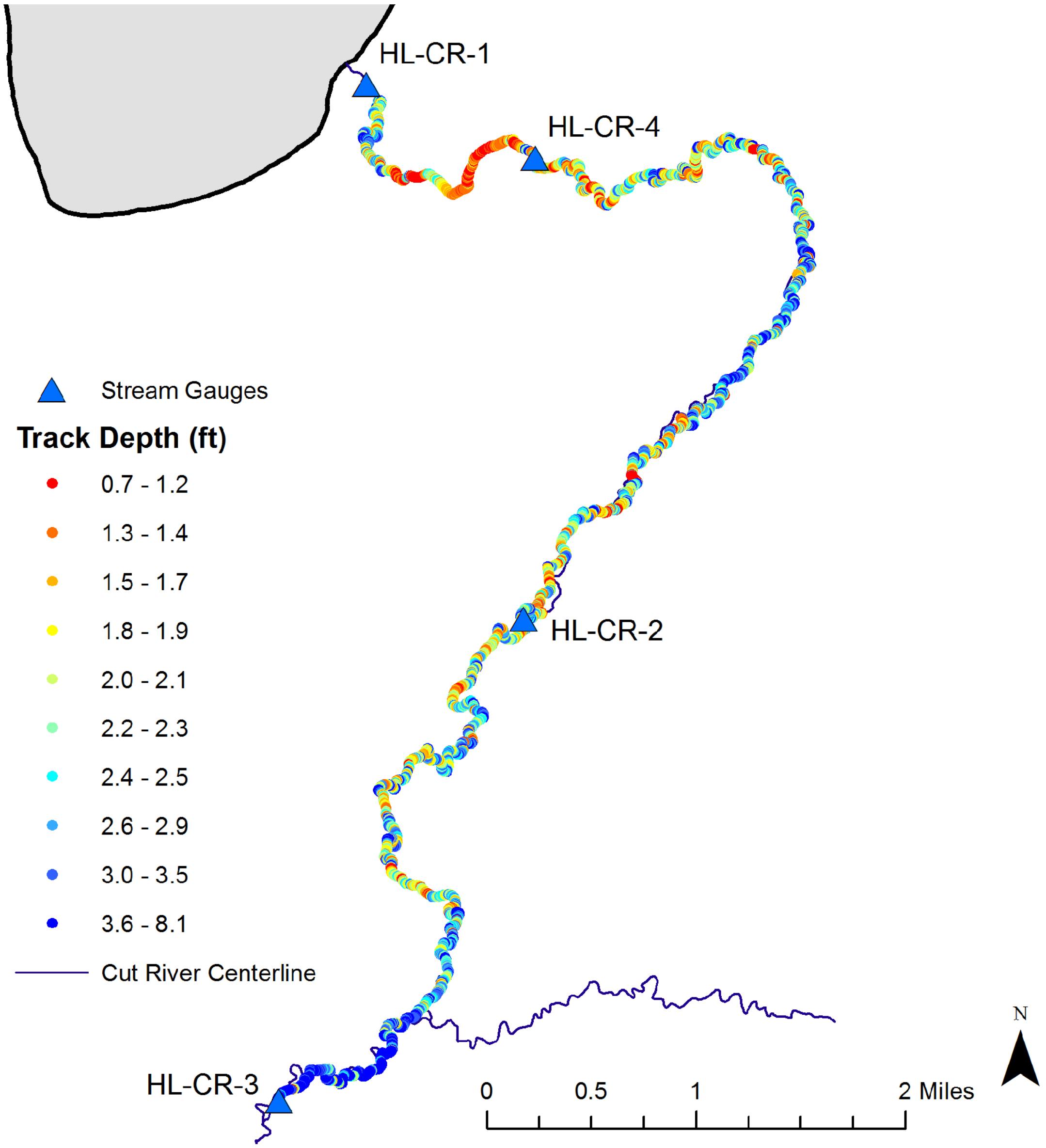


Figure 3.1.2. Map of continuous depth measurements made along the Cut River and through Marl Lake. Note some deviations from the main channel due to discontinuous GPS data above HL-CR-2. Colors represent 10% quantiles of channel depth.

To better understand how the data collected along the zig-zag boat track correspond to average channel depth (an important ecological habitat parameter), the measurements were matched to the channel position, and then averaged along each 50 meter (164 foot) length of channel. Average depths in the channel are shown in Figure 3.1.3. There are clearly bulk sections of the channel that are shallower (including Marl Lake), and in proximity to HL-CR-2, as well as deeper sections, mid-way between HL-CR-4 and HL-CR-2, and then again downstream of the confluence with Backus Creek. In general, median channel depths were approximately 2.3 - 2.4 feet, with shallowest average depths of approximately 0.9 feet and deepest of 7.2 feet.

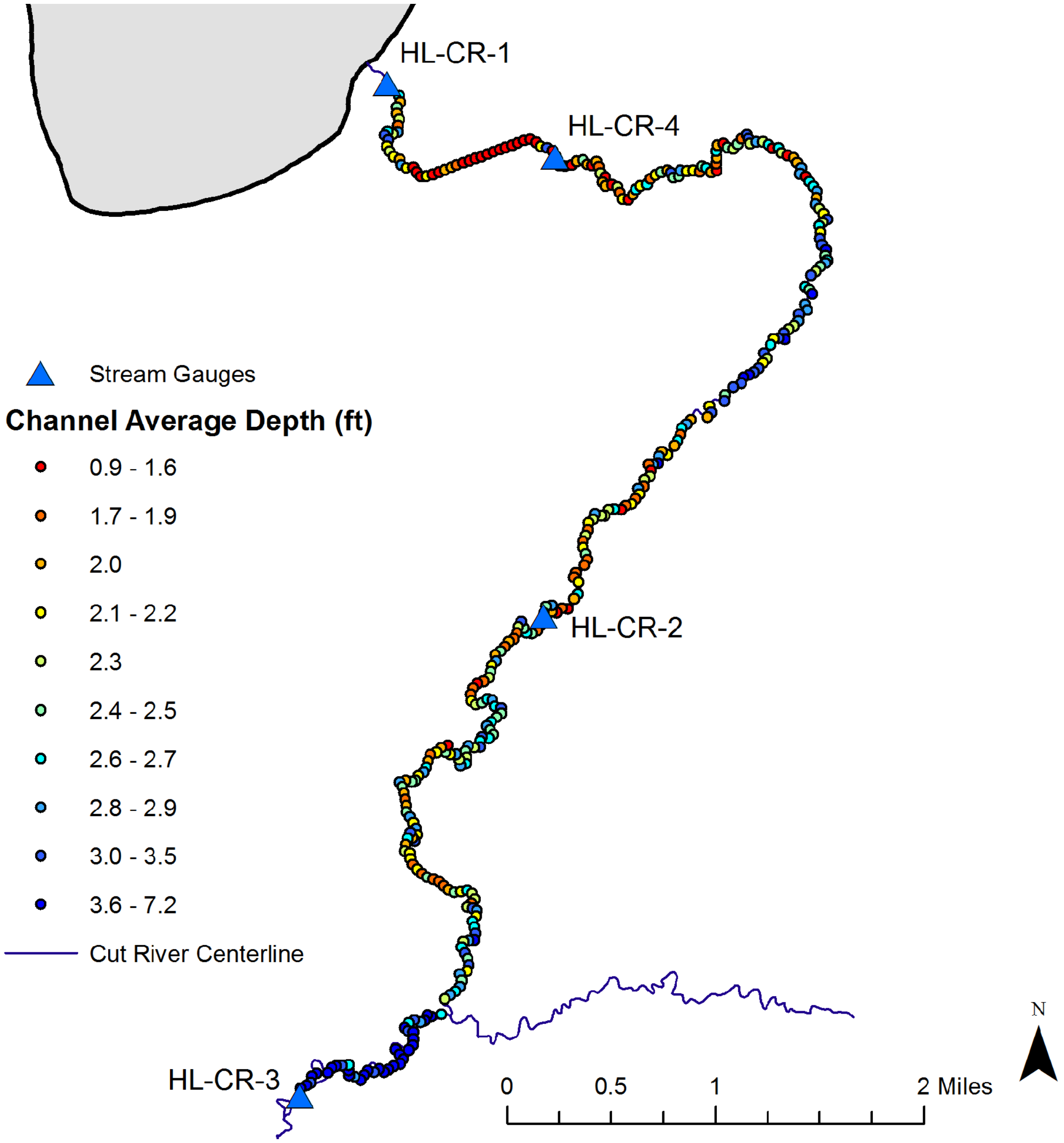


Figure 3.1.3. Map of depth measurements averaged along the stream channel. The actual boat track followed a zig-zag pattern down the channel, thus this represents rough averages along each 50 meter (164 feet) channel section. Colors represent 10% quantiles of channel depth.

Viewed another way, Figure 3.1.4 plots the deepest portion of each 50 meter segment, also known as the channel thalweg, as elevation down the channel. Due to discrepancies in channel elevation data among the multiple sources collected for this project, approximate linear water surface elevation is shown instead, roughly matching the elevations of Higgins and Houghton lake at the upstream and downstream ends, respectively. Clearly, after the confluence with Backus Creek, flow is hydraulically restricted by the channel depth and proximity to Houghton Lake. This is a historical consequence of the elevation of Houghton Lake and the subsequent flooding of the surrounding area. This region of the river is unique, with multiple winding distributary channels and deep, slow, river flows. Above that, however, the stream has a moderate gradient, with minimally impeded flows.

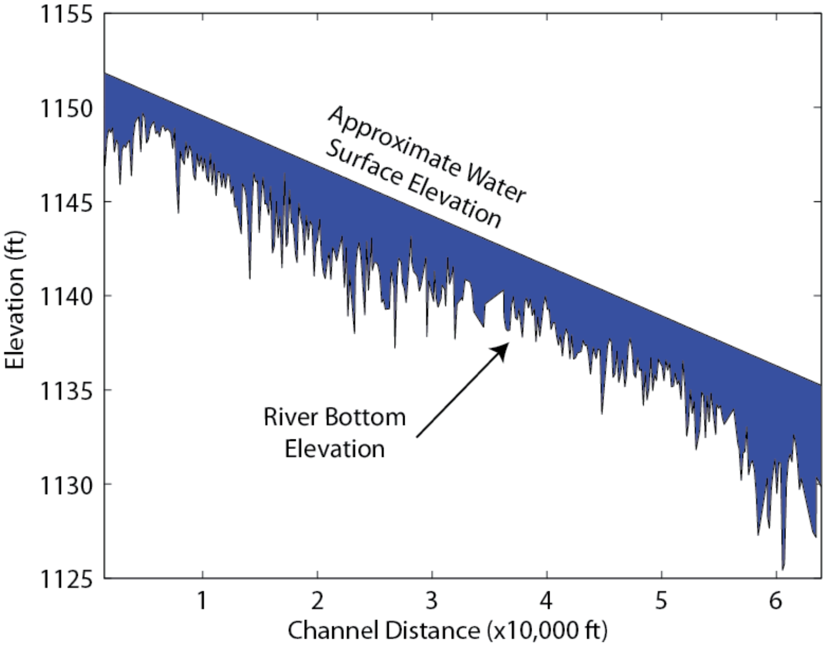


Figure 3.1.4. Plot of approximate river thalweg (deepest point in the channel cross-section) versus channel distance, starting at the gauge HL-CR-1 and ending at HL-CR-3.

3.2: Cut River Longitudinal Flow Profile

During the float, the crew paused intermittently to collect cross-sectional flow and velocity measurements of the channel. One such measurement is shown, taken just upstream of the HL-CR-2 (West Lansing Road) gauge site (Figure 3.2.1). In this procedure, the ADCP is attached to ropes and pulled laterally across the stream by people at either bank. This is repeated multiple times and the resultant flow measurements averaged to better quantify the true flow, as well as estimate flow uncertainties. Channel flows are complex, and non-uniform. The ADCP provides an unprecedented view into how these flows vary across the channel and with depth.

In total, the crew stopped to measure 17 flows during the two day float. The float began immediately after three gates on the dam were opened, sending a flood wave downstream. The first four stops all had flows in excess of 100 cubic feet per second. Across Marl Lake however, flow was back down to roughly 49 cubic feet per second, showing the role of Marl Lake in buffering flood wave progression downstream. Because of this, the team decided to install a fourth gauge, HL-CR-4 (on May 28, 2013), at a point just downstream of the Marl Lake outlet to better understand its role hydrologically.

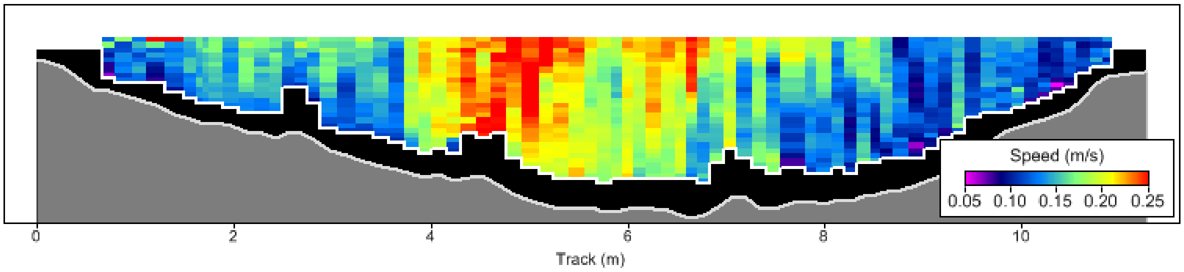


Figure 3.2.1. Example ADCP cross section showing channel depth and width with flow velocity as colors (from site HL-CR-2).

As Marl Lake acts a retention pool for the water it also has the potential to acts as a sediment trap. Local fisherman repeatedly complained about how Marl lake has become a “mud hole” and the depth has been becoming shallower. This fisherman also stated that the fish diversity has changed over the years. This could possibly be due to annual variability but, since UM or MSU did not perform a bathymetric survey of Marl Lake, it is unknown if or how changes have occurred.

From the Marl Lake outlet to West Lansing Road, the Cut River gained approximately 15 cubic feet per second in flow. A repeat measurement at the same point showed that flow had increased little due to the flood wave upstream by the start of the second day. Continuing downstream to a point shortly before the Backus Creek confluence, flow increased by only 8 cubic feet per second (cfs), but then added another 30 cfs after joining with Backus Creek. The system continued strongly gaining flow for the remainder of its short traverse to Houghton Lake, suggesting a strong groundwater input at this section.

Overall, by the time the Cut River reaches West Lansing Road, flow from the outlet of Higgins Lake accounted for approximately 77% of the flow in the channel. By the confluence with Backus Creek it was down to under 50%, and by the time the Cut River reached Houghton Lake the flow from the outlet of Higgins Lake accounted for under 33% of the total channel flow.

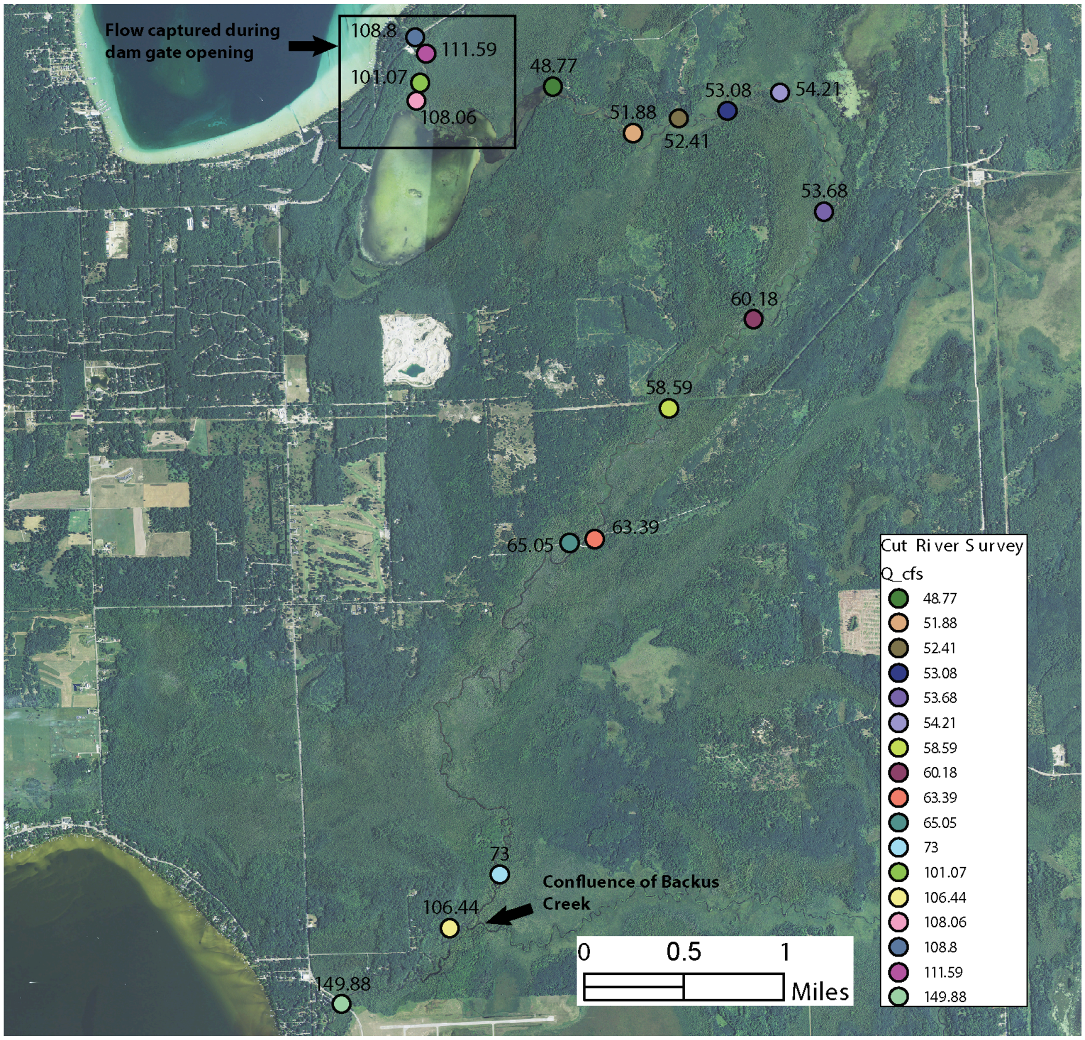


Figure 3.2.2. Map of all ADCP flow cross sections (late May 2013 flow cross sections)

Task 3 Findings Summarized

- The Cut River is in most places approximately 2.3 feet deep on average, and flows relatively swiftly during moderate flow periods.
- Downstream, near Houghton Lake, the Cut River is backed up due to the flooding of the land that formed the present day Houghton Lake. These are where depths in the channel are greatest.
- The Cut River is a beautiful and ecologically significant stream, flowing unimpeded through miles of wetland and stream habitat. Its diversity provides an excellent recreational resource as well.
- More than 75% of the flow for the Cut River upstream of West Lansing Road comes from Higgins Lake during baseflow periods.
- Additional flows from surface water and groundwater downstream of Backus Creek significantly reduce the impact of Higgins Lake outlet flows on Houghton Lake inputs.

Task 4: Install Flow Monitoring Equipment on Cut River

Continuously monitoring streamflow provides an excellent data source to more fully understand the hydrologic function of a system. This Task describes the installation and maintenance of four water depth recording gauges, and how those gauges can be used to quantify streamflow and learn about system behavior in response to dam management.

4.1: Gauge Installation and Maintenance

On July 28th, 2012, the MSU crew installed three automated data logging pressure transducers and temperature probes. These probes recorded data every 30 minutes. Figure 4.1.1 shows two photos of these gauges and their installation. The procedure consists of installing a gauge inside of a PVC housing attached to a fence post driven into the streambed. At that time, streamflow is measured across the channel, and the height of the water is recorded both by the instrument as well as on a manual water level gauge attached the the outside of the housing.

Figure 4.1.1. Installation of a stream gauge and discharge measurement on the Cut River at West Lansing Road (Site HL-CR-2).

Figure 4.1.2 shows the locations of the first three sites installed on July 28th: HL-CR-1 at East Higgins Lake Road, HL-CR-2 on West Lansing Road, and HL-CR-3 on East Houghton Lake Drive (M-100). These gauges were maintained until July 2015, when they were retrieved with their housings left intact for later redeployment if desired.

A fourth site, HL-CR-4 was added immediately downstream of Marl Lake after the role of Marl Lake in buffering flows was made evident in Task 3.

At the times of installation, a survey-grade GPS was used to measure gauge height and establish a local datum for each gauge-allowing for elevation corrected streamflows to be calculated.

Figure 4.1.2. Map of gauge locations, with dates of installation.

4.2: Rating Curves and Stream Flow

The gauges record water height above the gauge, which must be transformed to stream discharge via a rating curve. The rating curve defines a functional relationship between recorded stream height, and measured stream flows during specific site visits. In general, establishing a rating curve takes more than 4 measurements at various points along the curve, and further confidence is gained via repeat visits at a variety of stages.

During each visit, streamflow was measured using either the ADCP, or a cross-sectional wading method conducted with an OTT Acoustic Digital Current Meter (ADCM). Each are state-of-the-art measurement tools with interfaces that quantify the quality of stream discharge measurement and uncertainties in them.

Following the fourth site visit, rating curves were first established, that were then updated for each subsequent visit, provided that the flow measurement met the criteria for inclusion (an issue primarily impacting the HL-CR-3 site, which is hydraulically affected by Houghton Lake). The final curves after the latest visit are shown in Figures 4.2.1 and 4.2.2. R^2 values for these curves are all quite high, between 97.5% and 98.6%.

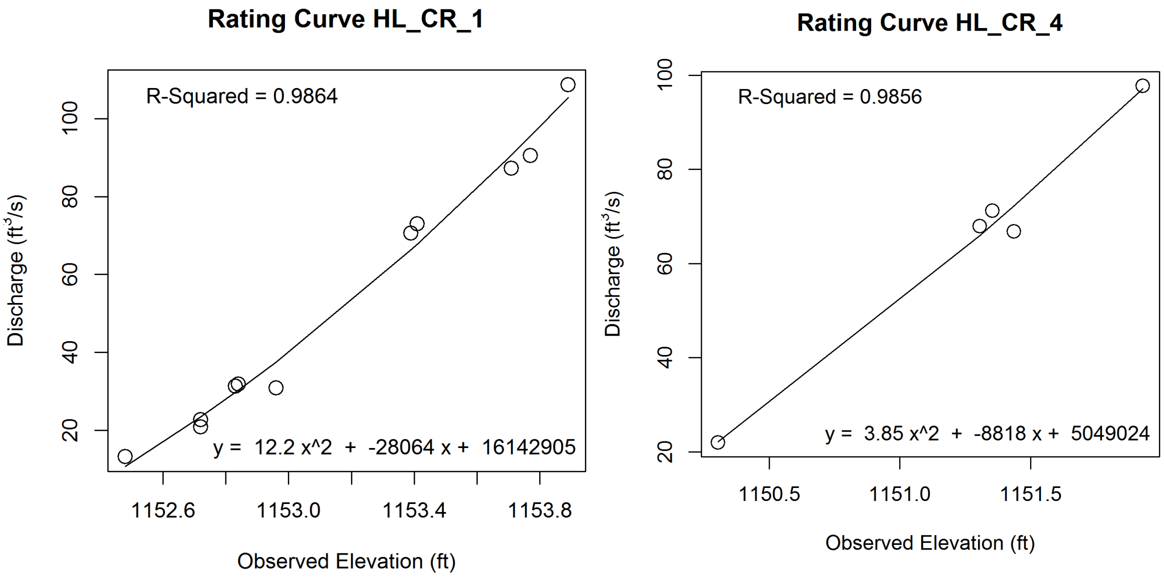


Figure 4.2.1. Rating curves for HL-CR-1 and HL-CR-4

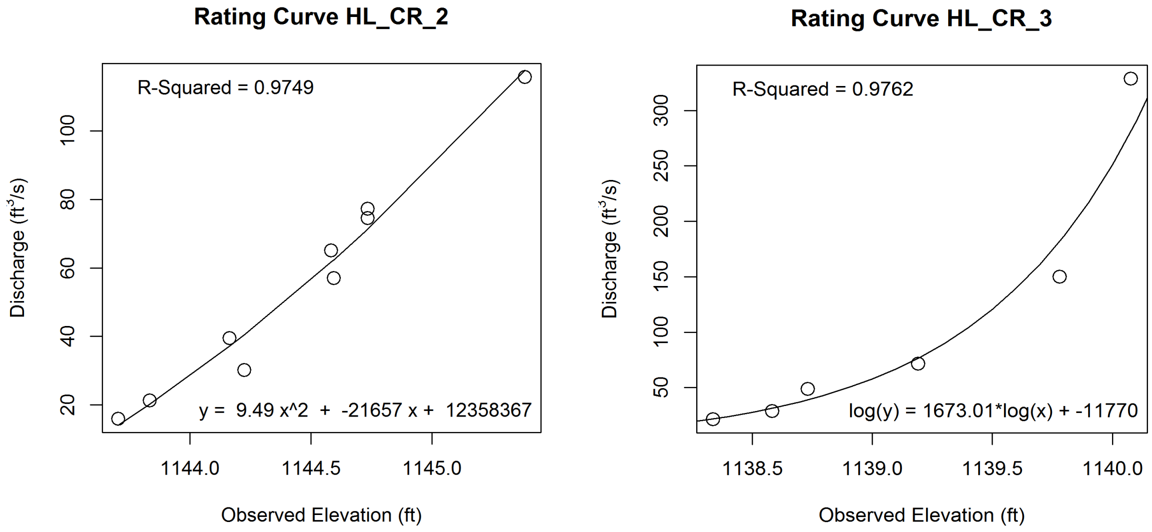


Figure 4.2.2. Ratings curves for HL-CR-2 and HL-CR-3.

Using these rating curves, and after transforming recorded stream stage to elevations using the surveyed site datum, continuous hydrographs for each site were developed (Figure 4.2.3). Significant gaps in the record occurred at sites HL-CR-2 and HL-CR-3 due to instrument and battery failures. All instruments were retrieved in July of 2015.

Site HL-CR-1 is clearly impacted by the management of the Higgins Lake outlet dam, where flows are abruptly discontinuous whenever gate configurations are significantly altered. For gate openings, the stream requires approximately 1 hour to fully equilibrate by the time it reaches HL-CR-1. Flows range between approximately 5 cubic feet per second to over 120 cubic feet per second at this gauge.

Flows at HL-CR-4 vary across roughly the same range as HL-CR-1, suggesting little to no gain in flows between them. Rather the highest flows are damped by Marl Lake. Responses to the dam configuration changes are muted in time due to Marl Lake, and examined further below.

The discontinuous record at HL-CR-2 (West Lansing Road) limits some of the conclusions that might be reached about relative flows, nevertheless peaks are significantly higher, approximately twice as high, than the upstream gauges. Though in lower flow periods the flows are roughly equal. HL-CR-3 shows significant gains in flow during wetter periods, commensurate with its larger surface and ground watersheds.

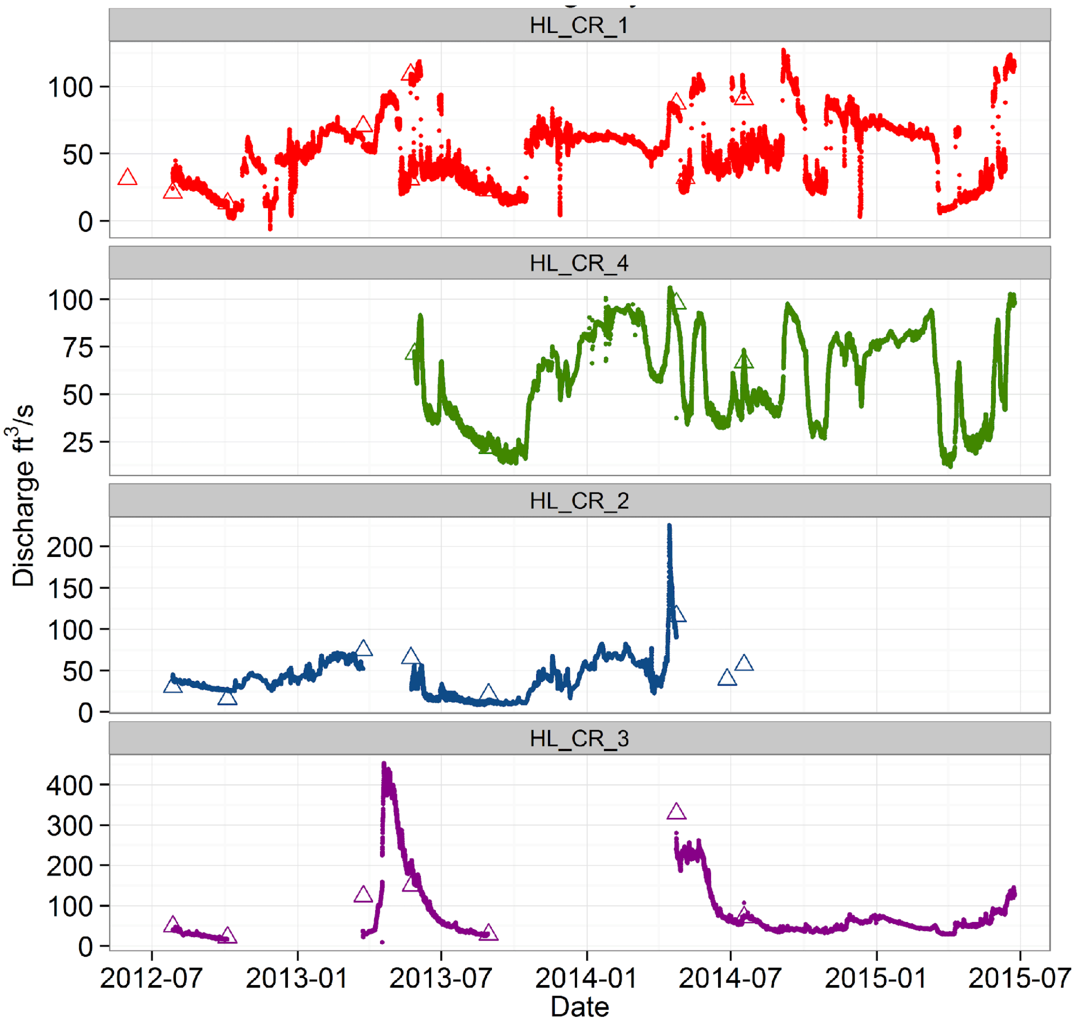


Figure 4.2.3. Rated discharge at all sites for the complete period of record. Observed flows are shown in similarly-colored open triangles.

To better compare relative streamflows, the four gauges are plotted for the most continuous segment in Figure 4.2.4. Here, the role of the downstream surface and groundwatersheds is obvious in determining total flow into Houghton Lake, particularly during high flow periods. During low-flow periods, Higgins Lake outflows account for a much larger proportion of streamflow entering Houghton Lake. Groundwater provides a significant boost in flows for gauges HL-CR-4 and HL-CR-2 downstream of Higgins Lake. Note that this occurs during the months and a year where net groundwater contributions from Higgins Lake are particularly negative (Figure 5.3.4), suggesting that the stream and Marl Lake may capture some of the groundwater lost from the lake during that period. 2013, a year with less groundwater loss from Higgins Lake, shows less of a flow increase.

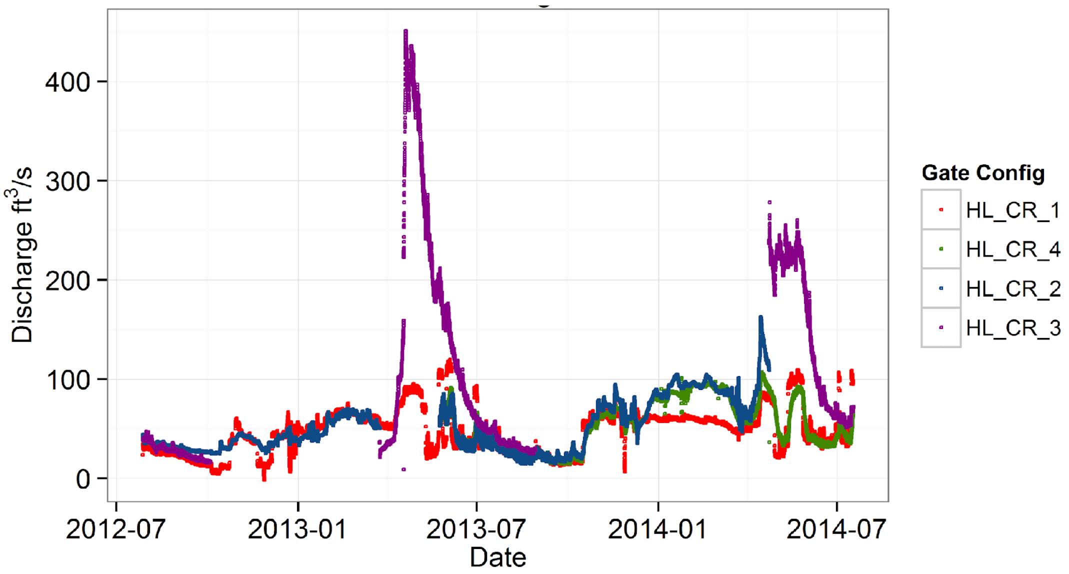


Figure 4.2.4 Rated discharge overlain for a two year period to show site flows relative to each other.

4.3: Dam Configuration Rating Curve

A significant unintended benefit of monitoring flow on the Cut River so close to the Higgins Lake outlet was the development of stage-discharge rating curves for various configurations of lake outlet dam gates. Using meticulous records kept by the Roscommon County Commission, and made available through the HLPOA website, data for the years 2012-2014 were digitized. The average daily flow was then classified based on the dam gate configuration, and outliers (which occurred on days where the gate configuration changed mid-day) were then removed. The result is Figure 4.3.1, which shows highly linear behavior of Cut River flows as a function of both Higgins Lake Elevation and outlet gate configuration.

In Figure 4.3.2, each gate configuration on Figure 4.3.1 was then regressed, producing four separate stage-discharge rating curves. These allow for much greater specificity in the role of the dam in managing lake levels, and should provide a benefit to the Roscommon county commissioners. With the exception of the dam fully closed rating curve, the R^2 for each of these regressions were quite good.

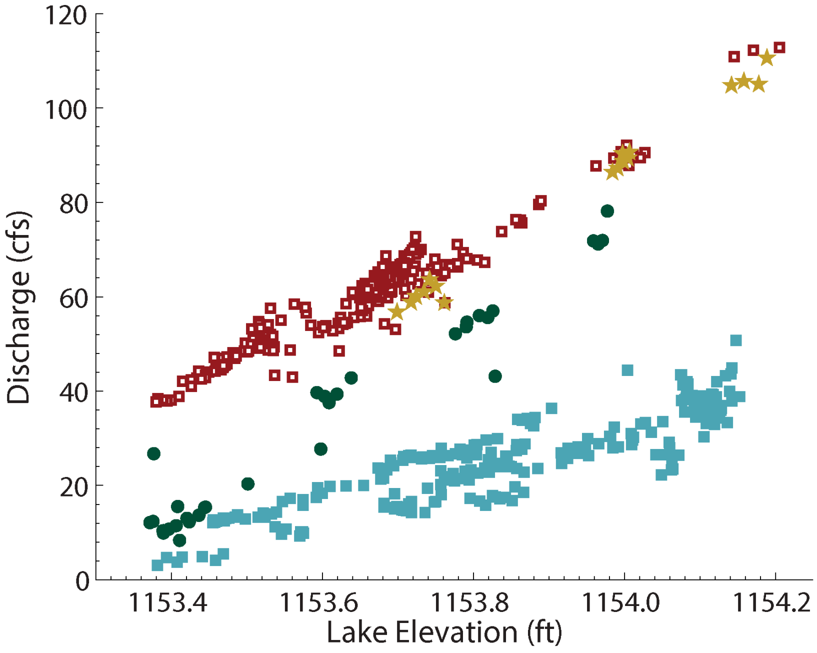


Figure 4.3.1. Discharge at the Higgins Lake Outlet (measured at HL-CR-1) as a function of lake elevation and dam Configuration. Data from 2012-2014. **Red Open Box**: All Flop Gates open; **Blue Box**: All Flop Gates Closed; **Slate**: One Flop Gate Open **Gold Star**: Two flop Gates Open; Flop gate 6 and the combination of Gates 4 and 5 were rarely used.

One interesting observation from Figure 4.3.1 is that for this three year period, the dam has largely been managed as “all closed” or “all open” with little use of either a single gate or two gates. Within this report, designation of “All Open” or “All Flop Gates Open” pertains to the tilt/flop gates 4, 5, and 6 of the lake level control structure. The scenario of “All Closed” or “All Flop Gates Closed” also only pertain to tilt/flop gates 4, 5, and 6. This is likely in response to the limited information available to the dam manager about how the dam should be operated to achieve specific level targets and over what time that target can be expected to be met and maintained.

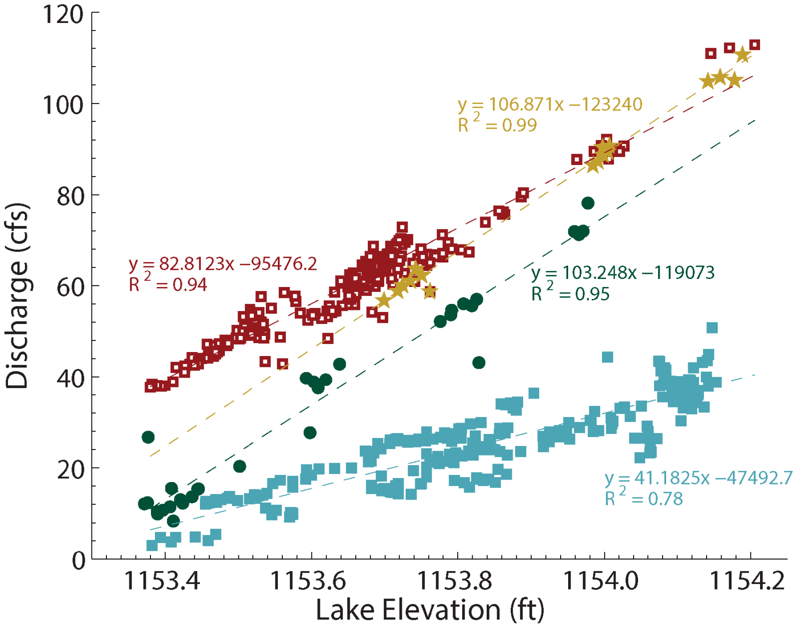


Figure 4.3.2. Rating curves of for each dam configuration. **Red Open Box**: All Flop Gates open; **Blue Box**: All Flop Gates Closed; **Slate**: One Flop Gate Open **Gold Star**: Two flop Gates Open; Flop gate 6 and the combination of Gates 4 and 5 were so rarely used we were unable to generate a realistic stage discharge relation.

4.4: Impacts of Outlet Control Structure Management on Cut River Flow

Operating a dam such as this results in discontinuous flows, and the passage of both flood and stage drop waves downstream. Figures 4.4.1 and 4.4.2 illustrate a portion of the spring of 2013 and 2014, with changes in dam configuration overlain atop measured changes in discharge. Clearly evident is how quickly flow responds at HL-CR-1, typically within an hour flow can more than triple. This flow takes significantly longer to reach downstream, however, due to Marl Lake.

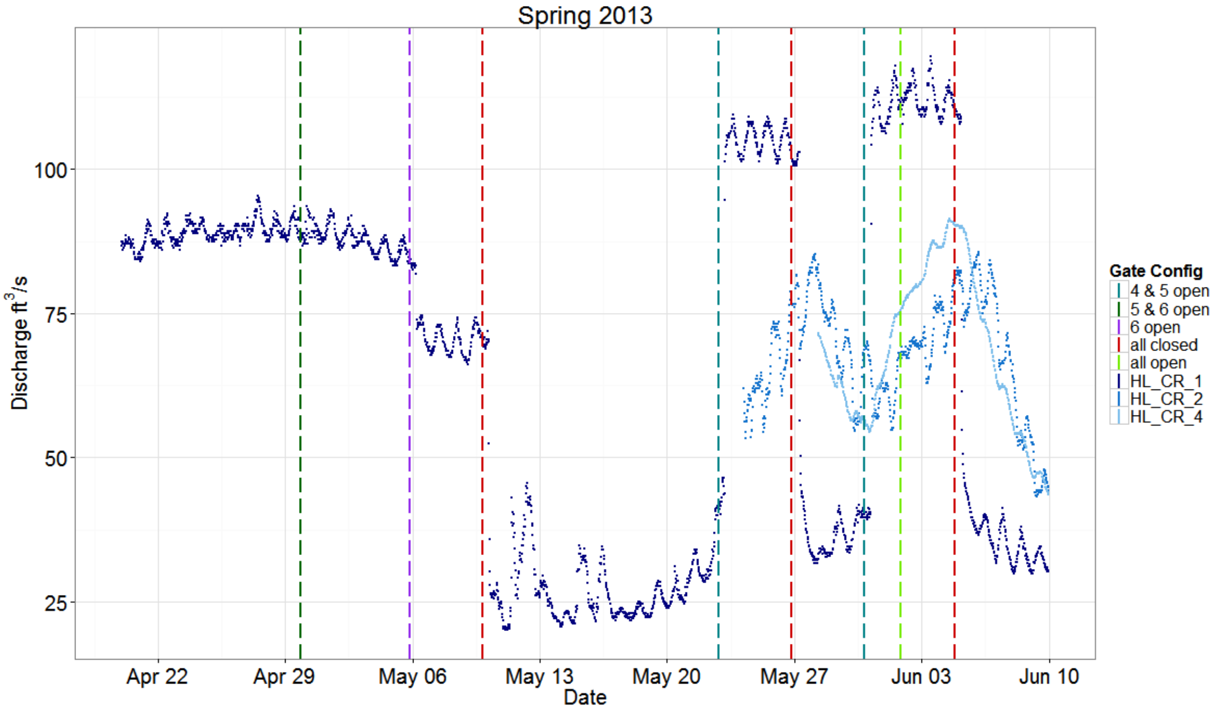


Figure 4.4.1. Plot of rated stream flows at HL-CR-1, 2, and 4 along with dam gate configurations for the Spring of 2013.

The damping effect of Marl Lake can be best seen in May of 2014, in Figure 4.4.2. Two events, first a drop in flows at HL-CR-1 due to dam closure in late April, and then a rise due to dam gate opening in mid-May have a significantly time-lagged impact at HL-CR-4, just downstream of Marl Lake. In general, Marl Lake buffers the response time by nearly two weeks, having both a positive and negative impact on stream flows, but helping to reduce the variability in the flows downstream. In June, following gate closure for the summer, the drop is more rapid, with a buffer of only about one week. This is likely due to reduced groundwater inputs to Marl Lake later in the season.

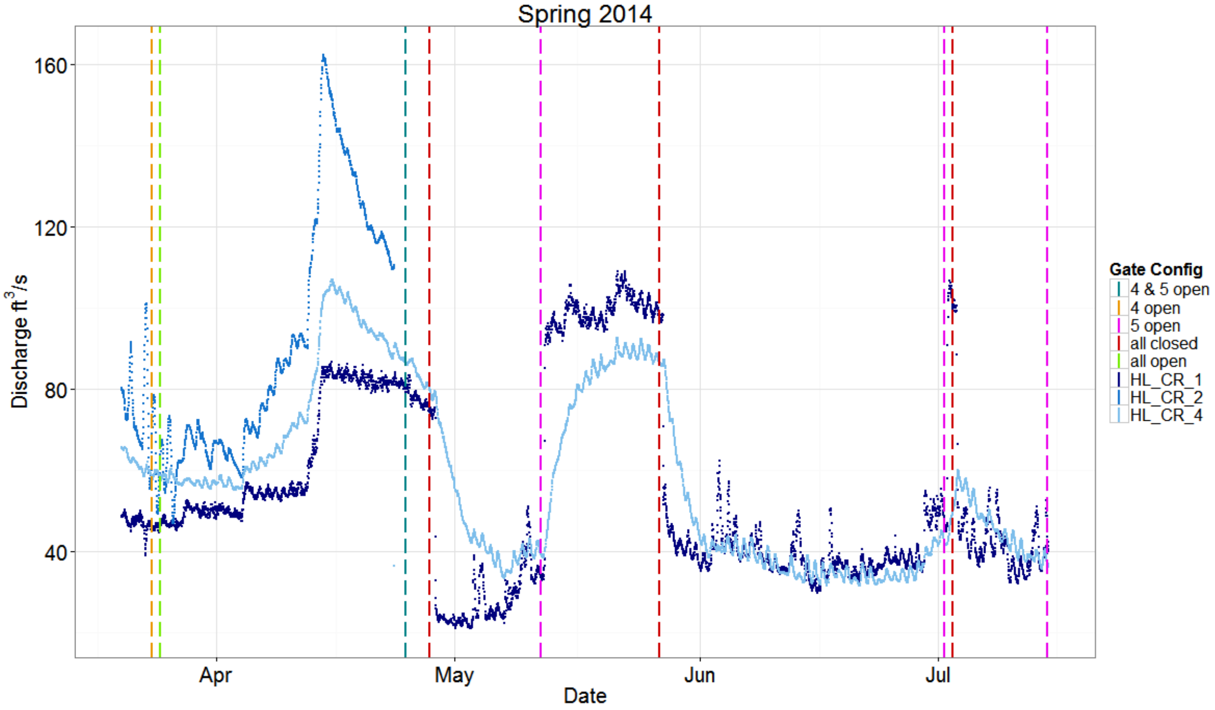


Figure 4.4.2. Plot of rated stream flows at HL-CR-1, 2, and 4 along with dam gate configurations for the Spring of 2014.

Task 4 Findings Summarized

- Water level and temperature was monitored continuously at three locations for nearly three years, with some missing sections, and fourth for approximately two years.
- Good rating curves for each site were developed.
- These data provide further evidence that the Cut River gains relatively little flow for much of the year from groundwater.
- The placement of a gauge just downstream of Marl Lake shows its influence in moderating flows further down the Cut River, particularly during times of rapidly fluctuating flows such as the spring.
- Good dam configuration rating curves will provide managers of the outlet control structure better tools to manage lake levels.

Task 5: Hydrologic Modeling

This task includes applying simulation models to predict the hydrologic (flow and storages of water in the environment) and hydraulic (movement of water in response to pressure gradients) behavior of Higgins Lake, the Cut River, and their watersheds. Specifically, three types of models are applied:

1) HEC-RAS, a hydraulic model that predicts streamflow and stage (height) in actual stream channels in the presence of flow obstructions such as dams, bridges, or culverts for a given input upstream stage.
2) The Landscape Hydrology Model (LHM), an integrated surface and subsurface hydrologic model that predicts water movements across the landscape and through the subsurface through time, in response to climate inputs.
3) A novel water-balance model for Higgins Lake that integrates weather data, historical dam management behavior, and LHM outputs to offer predictions of lake level response to changes in the environment or dam management.

The specific applications of each of these models are detailed in the sections below.

5.1: Hydraulic Modeling of the Cut River Outlet

In Task 5, we have applied HEC-RAS to simulate the flow conditions in the Cut River immediately at the Higgins Lake outlet. The model encompasses a section immediately downstream of the Higgins Lake control structure, through the culverts for East Higgins Lake Drive, and continuing downstream for approximately 1000 feet. The configuration of the model is shown in Figures 5.1.1 and 5.1.2 below. The model was built using GPS-surveyed cross sections, which were then interpolated to a series of more closely spaced virtual cross sections. Dimensions of both the dam outlet and culvert geometries were explicitly measured as well.

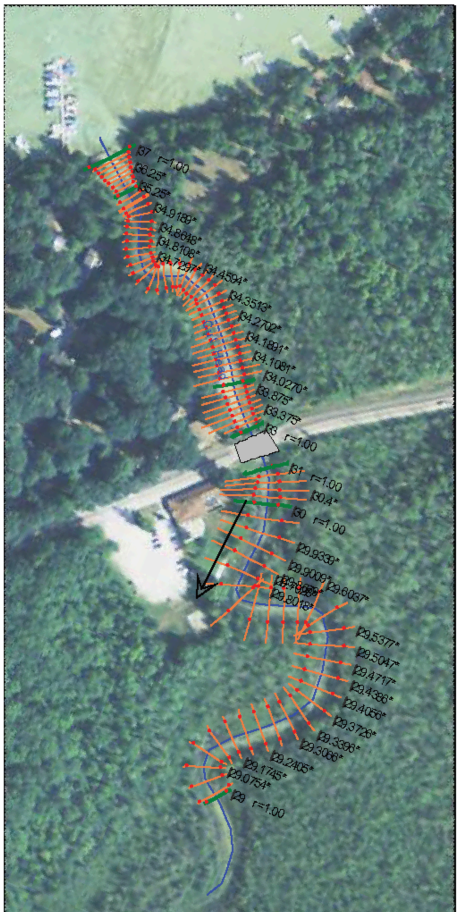


Figure 5.1.1. Overview of the HEC-RAS stream geometry cross sections overlain on a satellite image showing the dimensions and extent of the model. Measured cross-sections are shown in green, while interpolated virtual cross-sections are shown in orange. The culverts under East Higgins Lake Road are indicated as a grey box.

The model was calibrated by adjusting channel and floodplain roughness (a parameter with general value ranges for a specific channel/floodplain type), as well as the degree of sediment build up within the three culverts. The calibration adjusted parameters to better match simulated and observed water levels for flow data we collected at the HL-CR-1 location (immediately upstream of the culverts; See Figure 5.1.3). The calibration successfully captured both the low and higher flow behavior of the stream channel. Additionally, it provided a reasonably robust prediction of the flow behavior of the Higgins Lake outlet section of Cut River under higher flow conditions than those we observed for the creation of our stage/discharge rating curves (Figure 4.2.1).

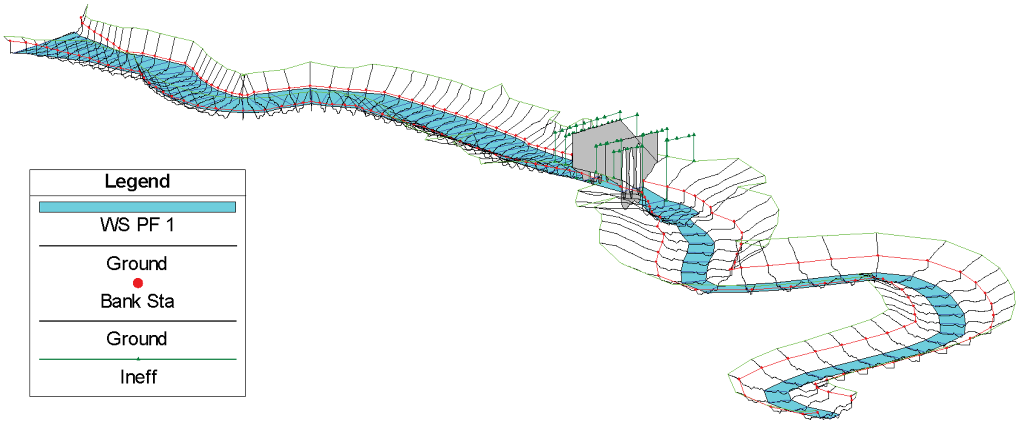


Figure 5.1.2. Three dimensional view of the Cut River outlet HEC-RAS model. The vertical relief in figure was exaggerated by a factor of 30 to more clearly illustrate bank height and channel morphology. The water level shown in blue illustrates a hypothetical minimum discharge of 0.35 cfs before becoming stagnant.

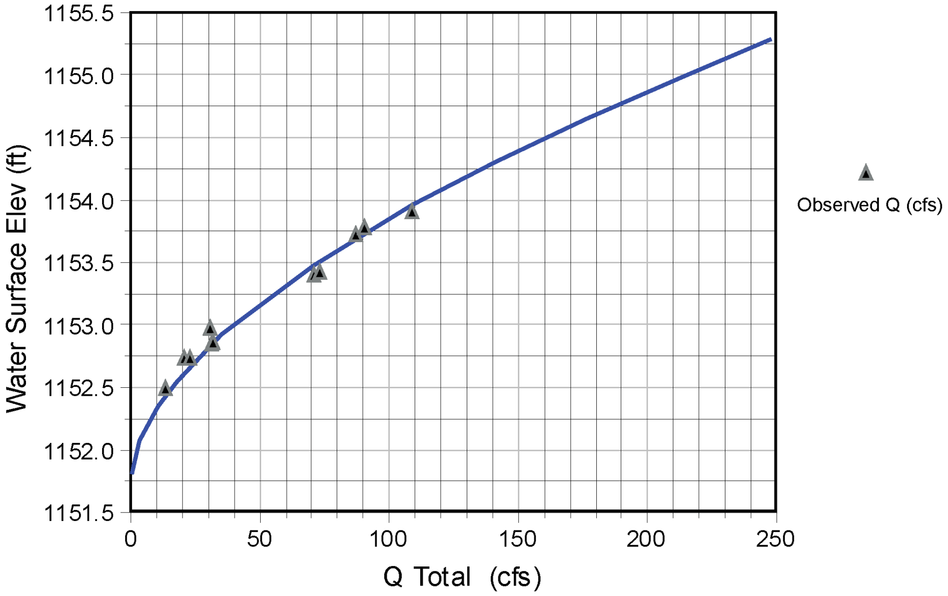


Figure 5.1.3. Rating Curve HEC-Ras Modeled of HL-CR-1. The Hec-Ras Model was calibrated using the observed discharge and water elevation data collected during site visits by MSU personnel.

The primary application of this model was to obtain a prediction of the stage/discharge relationship of this section of the Cut River in the absence of an outlet control structure (the No Dam scenario). The observed stage/discharge rating curves under various dam gate configurations developed within section 4.3 can inform all other lake level scenarios, but the HEC-RAS model is required to understand how the lake will respond were the outlet control dam to be removed.

For this, the farthest upstream cross section in the HEC-RAS model was queried to determine its stage/discharge behavior (Figure 5.1.4). Note the differences between the rating curve for this upstream section and that at the bridge just 750 feet downstream. For instance, at 100 cubic feet per second of flow through the channel, the upstream cross section is at an elevation of ~1153.86 feet (Figure 5.1.4) while for the same flow at the culverts, the stage would be ~1153.80 feet (Figure 5.1.3), a significant difference for lake level predictions where differences in scenarios are on the order of 4 inches, or 0.33 feet.

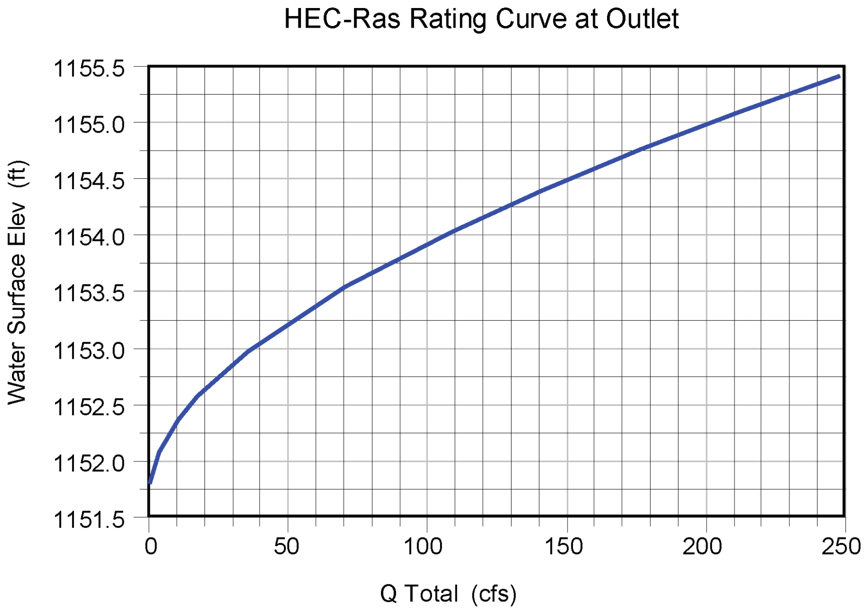


Figure 5.1.4. Rating Curve HEC-Ras Modeled Immediately downstream of Dam. The rating curve is representative of a non-obstructed outlet from Higgins Lake.

5.2: Lake Groundwater Discharge and Evaporation Predicted with the Landscape Hydrology Model

The Landscape Hydrology Model (LHM) was chosen to simulate the regional hydrology surrounding Higgins Lake. This project leveraged two existing LHM models: one built for an expanded region surrounding the Muskegon River Watershed (EMRW), and another for the Lower Peninsula of Michigan (LPMI). These two model boundaries are shown in Figure 5.2.1 below.

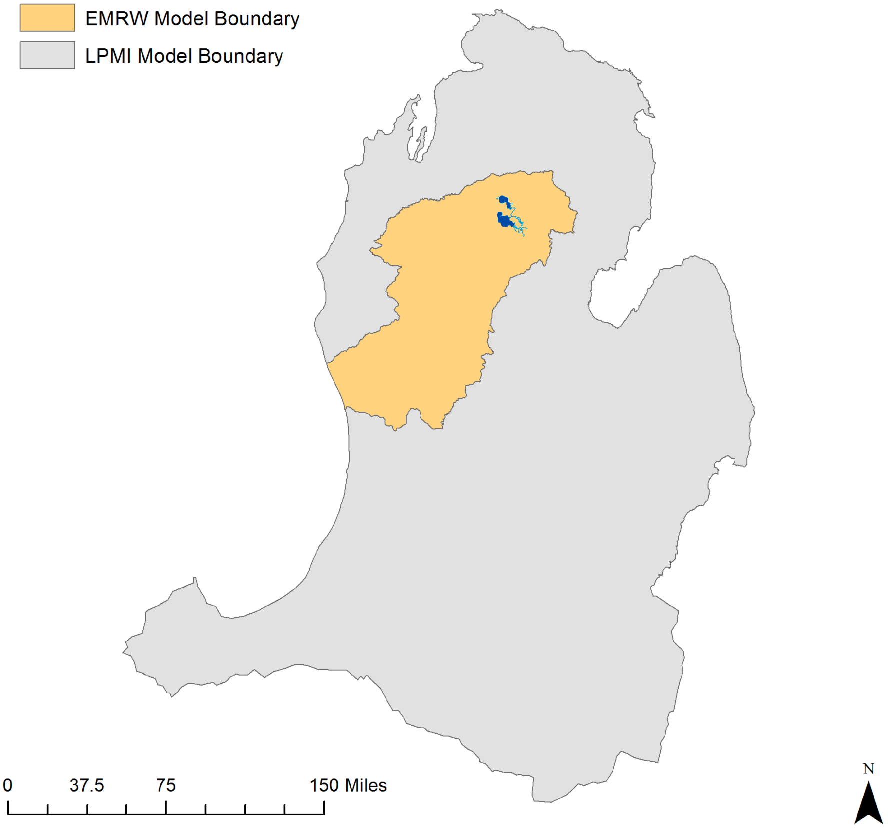


Figure 5.2.1. Map of the EMRW (orange) and LPMI (grey) model boundaries with the Higgins-Cut-Houghton watershed system overlain.

LHM simulates the entire terrestrial hydrologic cycle on an hourly basis, driven by weather data inputs, and parameterized using soil and sediment data from maps, over a region discretized into grid cells. Within each grid cell, equations dictate the movement (or fluxes) and storage of water. This type of model is called a spatially-explicit, process-based model. Figures 5.2.2 and 5.2.3 below illustrate the different components of the water cycle simulated, and how LHM discretizes the landscape.

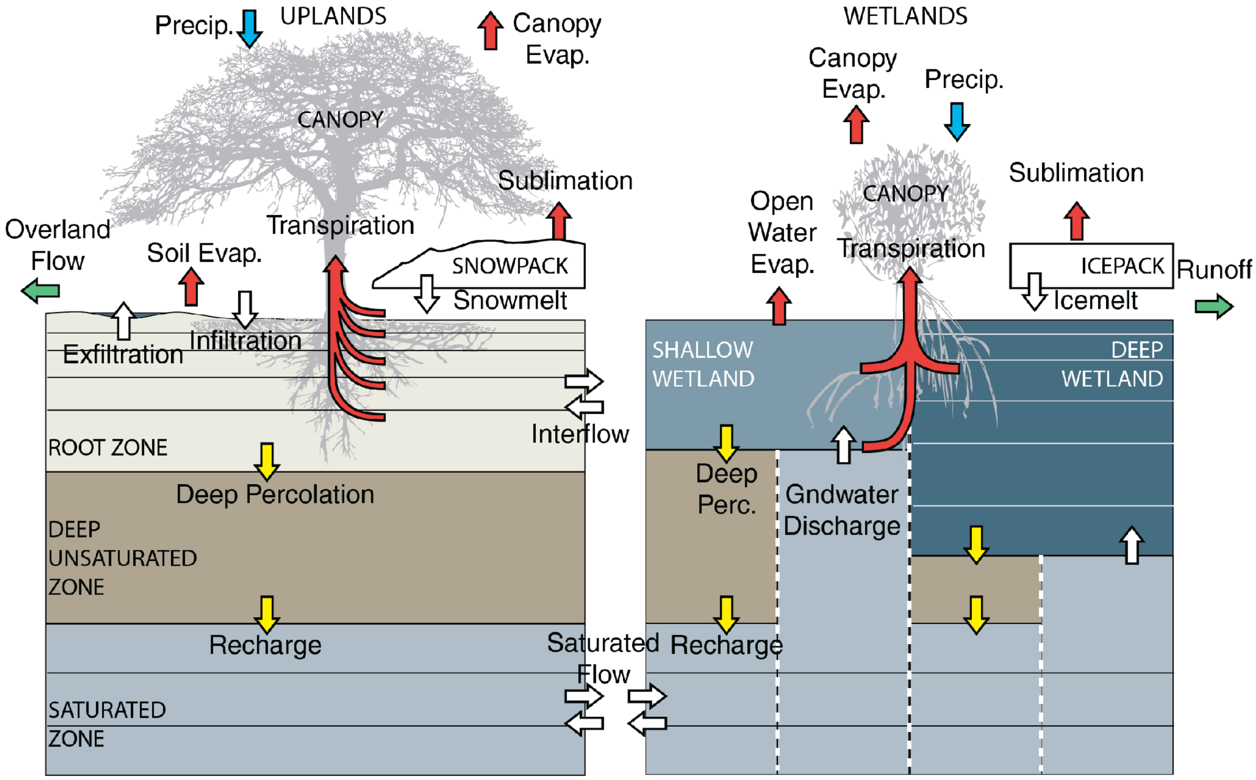


Figure 5.2.2. Conceptual model of hydrologic fluxes simulated by LHM.

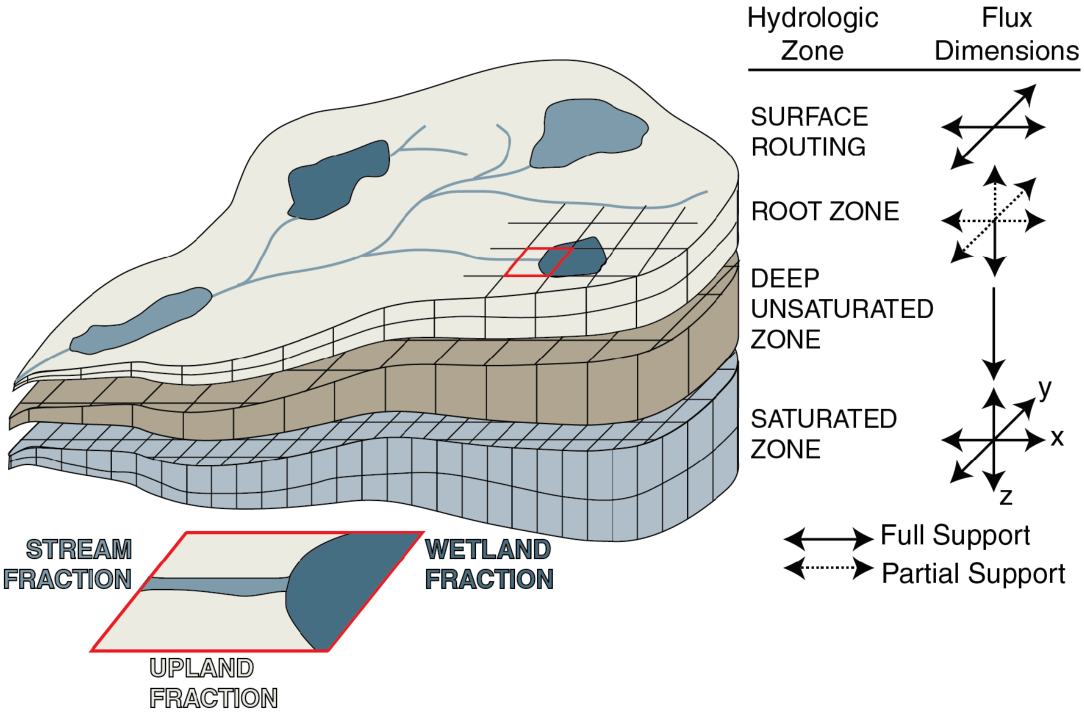


Figure 5.2.3. Conceptual model of the landscape discretization scheme in LHM.

The EMRW model grid cells have a surface resolution of approximately 425 meters on a side, while the groundwater model uses 106 meter cells; the model simulates the 1980 to 2007 period. The LPMI model cells have a surface resolution of 500 meters, and simulates the period of 2000 - 2014. However, the LPMI model does not have a groundwater simulation linked at the time of this report.

This project requires a simulation period similar to the LPMI model, but also a description of groundwater inputs to Higgins Lake for the whole period. The EMRW model has all of the necessary components, but does not extend to 2014. To bridge this gap, we decided on an approach referred to as process-inferred statistical modeling. That is, we used a statistical model to represent the more complex physical processes of the full LHM simulation. We then applied this statistical model to simulate a flux we didn't have (groundwater inputs to Higgins Lake for the full period) using something we do have (groundwater recharge simulated by the LPMI model for that period).

For this approach, simulated groundwater inputs to Higgins Lake (represented in cubic feet per second) for the full 1980 - 2007 period (Figure 5.2.4) were decomposed into two components, annual average inputs (Figure 5.2.5), and monthly average inputs to Higgins Lake (Figure 5.2.6).

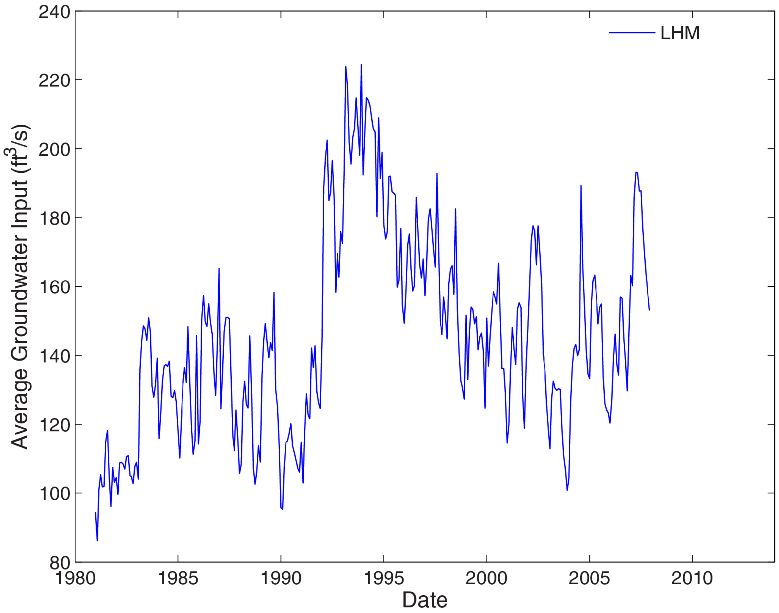


Figure 5.2.4. Monthly LHM-simulated groundwater input (inflow) to Higgins Lake for calendar years 1981 - 2007, expressed in cubic feet per second.

Annually, LHM-simulated average groundwater inputs to Higgins Lake varied between approximately 110 and 210 cubic feet per second, with significant multi-year year cycles. Much of the 1990s decade saw higher inputs than either the 1980s or early 2000s.

To better understand how fluxes into the lake vary by month, Figure 5.2.6 plots inputs as a percent of total annual input--this is essentially the seasonality of input. As expected, fluxes were highest in the spring months following snow melt and prior to the growing season for plants. Also shown as a shaded range is one standard deviation of monthly fluxes, essentially a measure of how much these monthly fluxes varied across years. During the spring, fluxes varied approximately 0.5% of the total input from the mean, while during the late summer and fall this variability increased to as much as 1% of the total annual input. Capturing this variability is important to simulating particularly "wet" or "dry" months in terms of groundwater inputs to the lake.

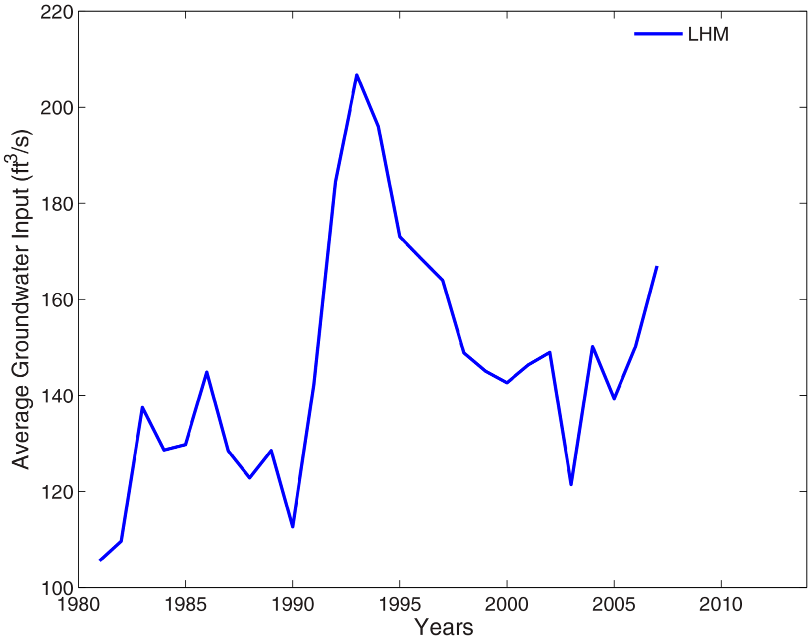


Figure 5.2.5. Plot of LHM-simulated groundwater inputs to Higgins Lake for the calendar years 1981 - 2007, expressed as an average flux rate in cubic feet per second.

Two statistical models were created to describe both the annual total input to the lake, as well as the seasonal cycle of inputs. The annual model is a distributed lag regression model, in which water year (October - September) groundwater recharge within the Higgins Lake *groundwatershed* is summed and used to predict the time lagged calendar year (January - December) groundwater inputs to the lake. This analysis showed that calendar year inputs are sensitive to groundwater recharge up to three water years prior. In other words, according to the LHM simulation of the EMRW, the Higgins Lake groundwater system has a roughly 3 year "memory" of groundwater recharge. Thus, four parameters were used in the regression: current water year groundwater recharge, along with 1-year, 2-year, and 3-year lagged recharge. This statistical model provided a very good fit to annual LHM-predicted values (Figure 5.2.7), with a coefficient of determination (R^2) of 94% (100% would indicate a perfect model fit), and an average error of only 3.4%.

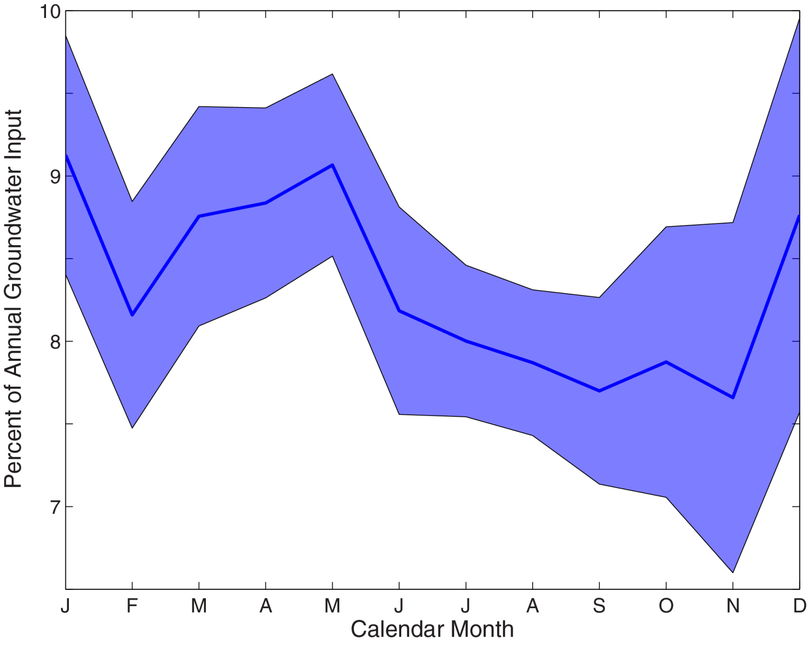


Figure 5.2.6. Plot of monthly averages of model-simulated groundwater input to Higgins Lake from 1980 - 2007 as a percent of annual simulated input. The blue line indicates the mean simulated flow for that month across years, while the shaded area includes +/- 1 standard deviation from the mean.

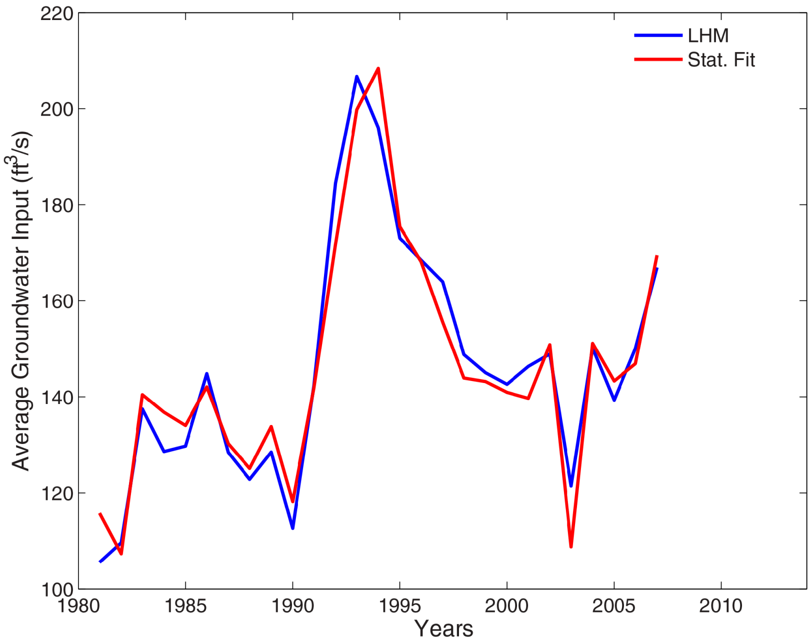


Figure 5.2.7. Plot of LHM-simulated and statistically-fit annual groundwater inputs to Higgins Lake. for the calendar years 1981 - 2007.

Statistically modeling the monthly variability was somewhat more complex. The chosen model structure was to sum the average monthly input to the lake (Figure 5.2.6) and a modeled “anomaly”, or a departure from normal, predicted using LHM-predicted *groundwatershed* recharge. First, annual normal groundwater recharge was calculated for all years. Monthly recharge values were then divided by annual totals to calculate the monthly recharge anomalies relative to normal. This anomaly was then regressed against a similarly-calculated anomaly for LHM-simulated groundwater input to the lake. This allowed for groundwater recharge alone to the predict the anomaly for groundwater input to the lake. This model-predicted anomaly was then added to the average monthly cycle of groundwater input, which was finally multiplied by annual average groundwater input (Figure 5.2.7). The final result is shown in Figure 5.2.8. This model of monthly groundwater input to Higgins Lake is derived solely using LHM-simulated recharge, and compared to LHM-simulated groundwater inputs had an R^2 of 81%, and mean monthly error of 6.7%, and a Nash-Sutcliffe efficiency (a measure of model goodness-of-fit commonly used by hydrologists, with values of 1 meaning a perfect fit, and anything above 0 meaning a model that does better than simply using a single average value) of 0.81.

With the combined annual and monthly statistical models calibrated, they were then applied to calculate annual (Figure 5.2.9) and monthly (Figure 5.2.10) groundwater discharge into Higgins Lake for 2000 - 2014 using only the LPMI simulation of groundwater recharge in the Higgins Lake groundwatershed. The annual model predicting 2000-2014 discharge provided similar predictions to the model fit to 1980 - 2007 discharge, although the monthly model was not quite as accurate. The LPMI and EMRW simulations differ in two key aspects: weather and soils data. These differences mean that the LPMI model predicts a somewhat different seasonal cycle of recharge than does the EMRW model. Nevertheless, the model provided reasonable predictions of the groundwater input on a monthly basis to Higgins Lake.

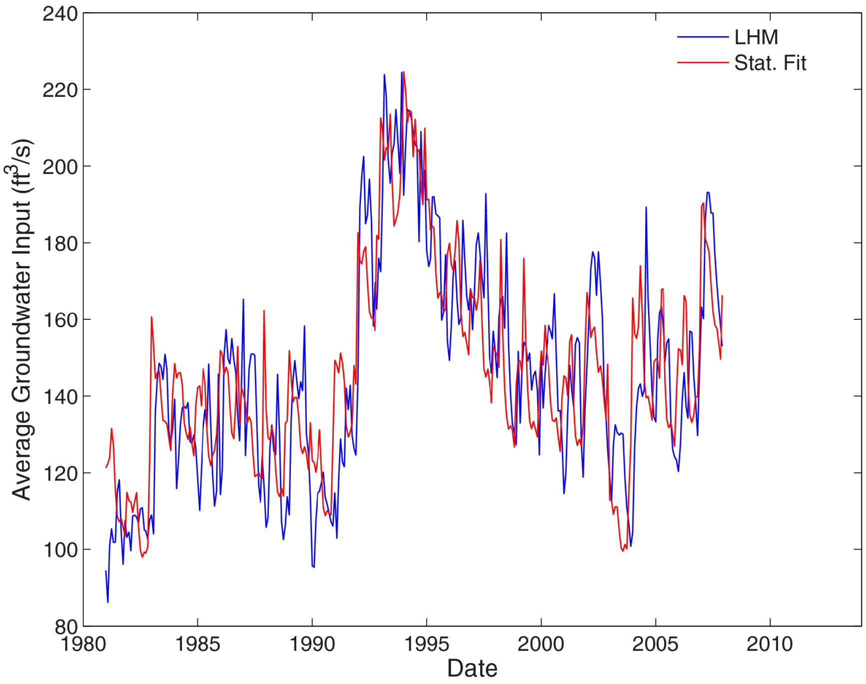


Figure 5.2.8. Plot of LHM-simulated and statistically-fit monthly groundwater inputs to Higgins Lake. for calendar years 1981 - 2007.

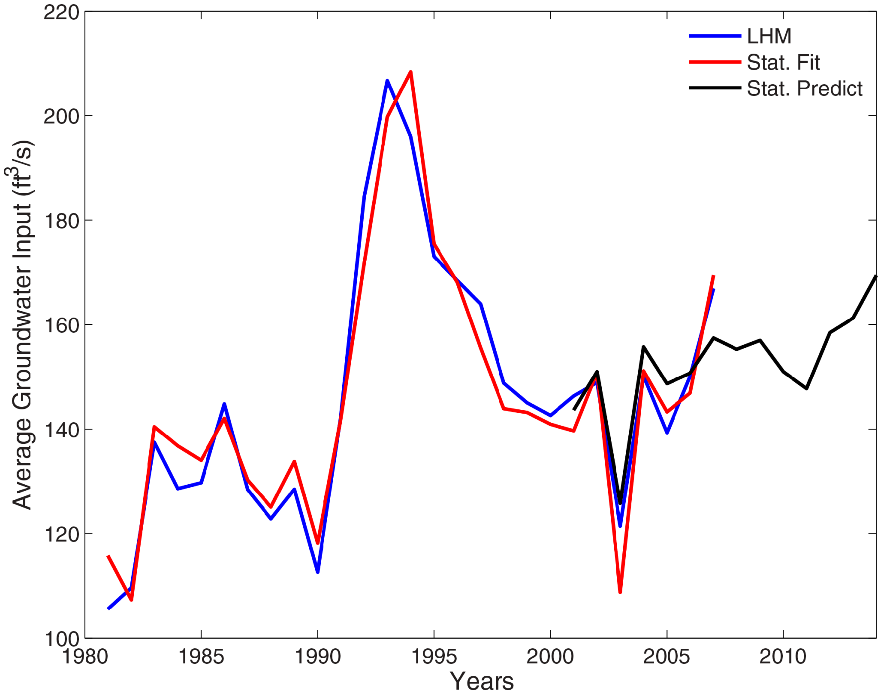


Figure 5.2.9. Plot of annual average groundwater input in cubic feet per second from the Landscape Hydrology Model (blue), a statistical model fit to the LHM prediction (red), and that same statistical model applied to the LPMI simulation results from 2000 - 2014.

Another key simulation component of the overall Higgins Lake water balance is evaporation from the lake. Estimates of lake evaporation are driven by simulated lake temperatures, along with weather inputs including air temperature, wind speed, relative humidity, and solar radiation. It is also affected by the simulated ice cover condition of the lake.

LHM simulates 1-dimensional heat transport within lakes, incorporating the influences of wind-driven convection (circulation of water vertically), density-driven mixing (that drives seasonal stratification and mixing), and lake ice buildup. Temperature is impacted by radiation exchange with the atmosphere (long and short wave, diffuse and direct), sensible heat exchange (direct warming/cooling via the presence and natural convection of warm/cold air above the lake), and latent heat exchange (warming/cooling caused by condensation onto the lake, or evaporation of water from the lake).

Figure 5.2.11 below illustrates air temperature from the NLDAS dataset, averaged over the June - September period of each year. Based on this evaluation, Higgins Lake air temperatures have been experiencing a steady and significant increase in average summer temperature from 1980 - 2015 at a rate of 0.84 degrees F/decade (with a *p* value of <1%).

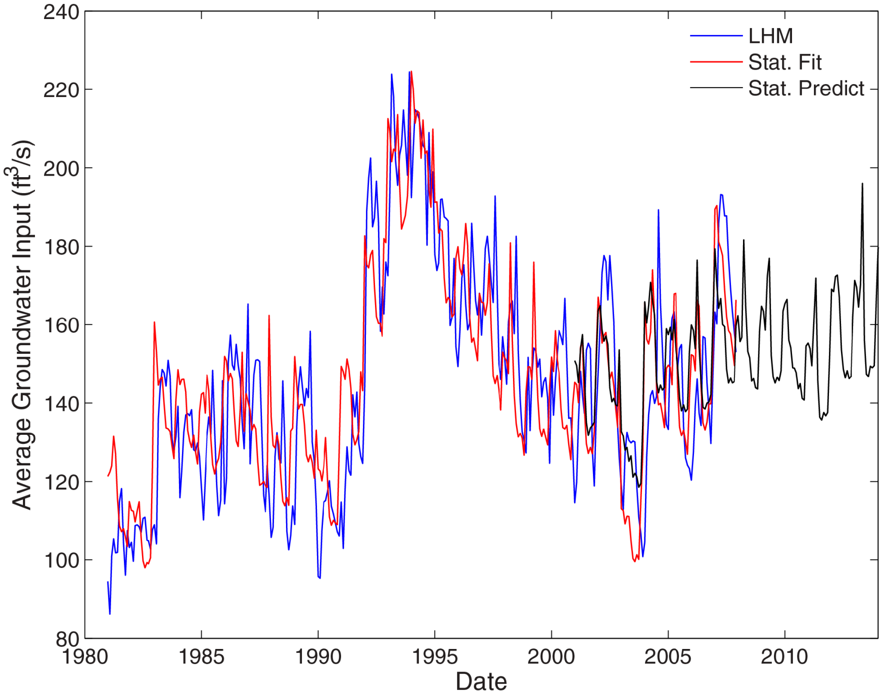


Figure 5.2.10. Plot of monthly average groundwater input in cubic feet per second from the Landscape Hydrology Model (blue), a statistical model fit to the LHM prediction (red), and that same statistical model applied to the LPMI simulation results from 2000 - 2014.

The increase in summer temperature has been a driving force for increased evaporation, as simulated by LHM. Figure 5.2.12 shows annual lake evaporation simulated by the LPMI model for 2000 - 2014. Although the time series is somewhat short for robust trend estimation, there appears to be an increasing trend of evaporation at a rate of 3.79 cubic feet per second/decade ($p = 0.15$). In general, lake evaporation averages between 17 and 34 cubic feet per second over the course of each year, and can fluctuate greatly between years. This evaporation rate would correspond to an equivalent loss of water from the lake between 14.5 and 28.9 inches each year.

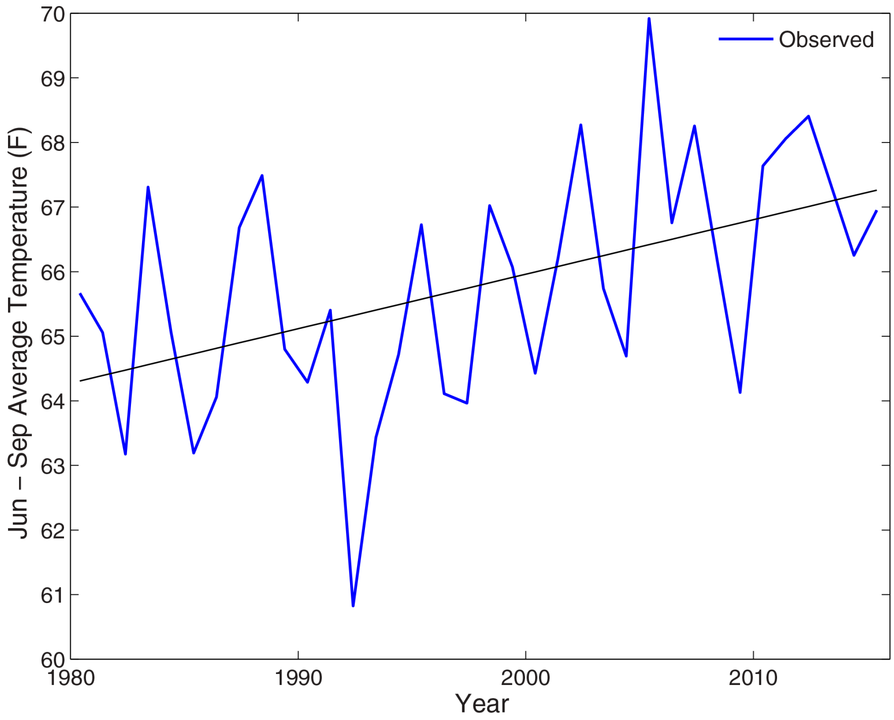


Figure 5.2.11. Plot of June - September average air temperatures over Higgins Lake from 1980 - 2015.

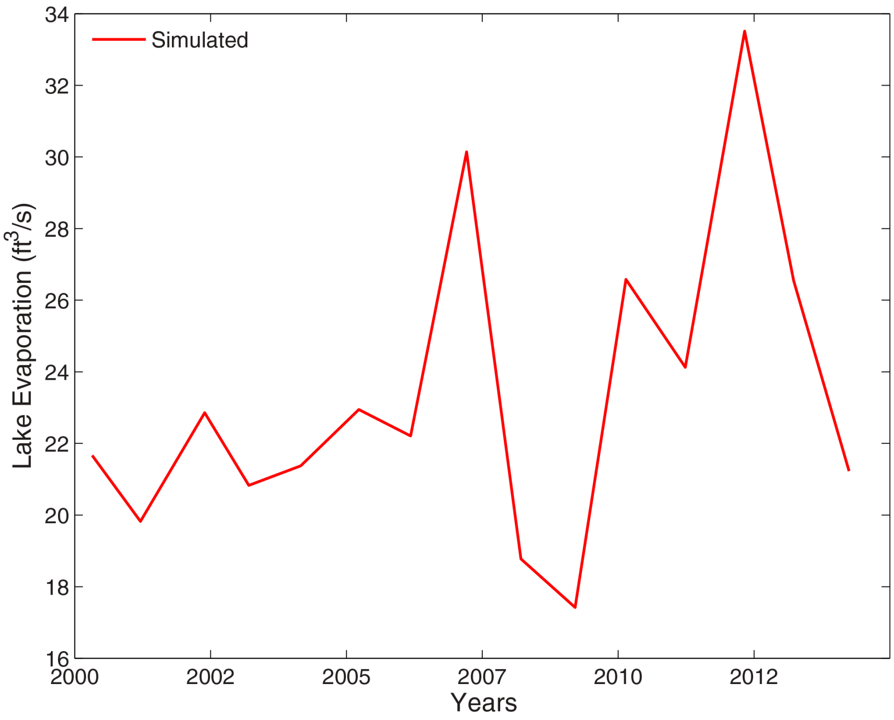


Figure 5.2.12. Plot of simulated annual lake evaporation from 2000 - 2014, in cubic feet per second.

Evaporation is clearly not constant throughout the year, and varies considerably from month-to-month (Figure 5.2.13). During some years (2012, for instance), evaporation rates exceeded 100 cubic feet per second, while simulated evaporation drops to 0 during most winters. In other years, peak evaporation was much lower, such as approximately 50 cubic feet per second in 2009.

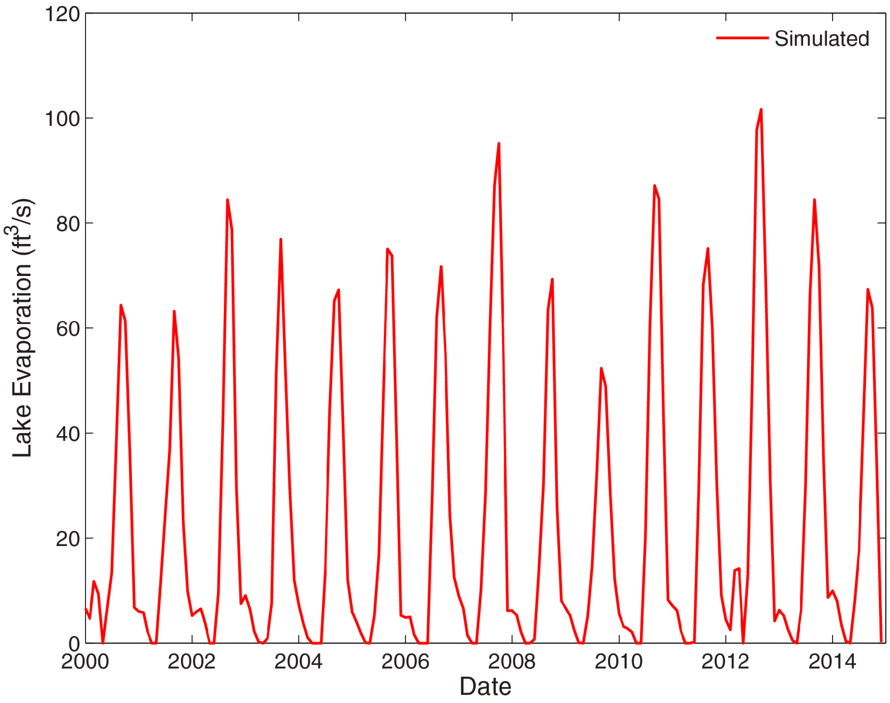


Figure 5.2.13. Plot of simulated monthly lake evaporation from 2000 - 2014, in cubic feet per second.

Averaging across the 15-year LPMI simulation reveals greater detail about the seasonal cycle of evaporation on Higgins Lake. Contrary to our perception of evaporation rates, large lakes such as Higgins do not peak in the hottest summer months, but rather in September or October, as shown in Figure 5.2.14. Evaporation during peak summer months (June, July, and August) averages between 5 and 50 cubic feet per second. These rates are equivalent to 0.01 - 0.1 inches per day, averaging roughly ½ of the estimate provided by the Spicer group (Task 1.1).

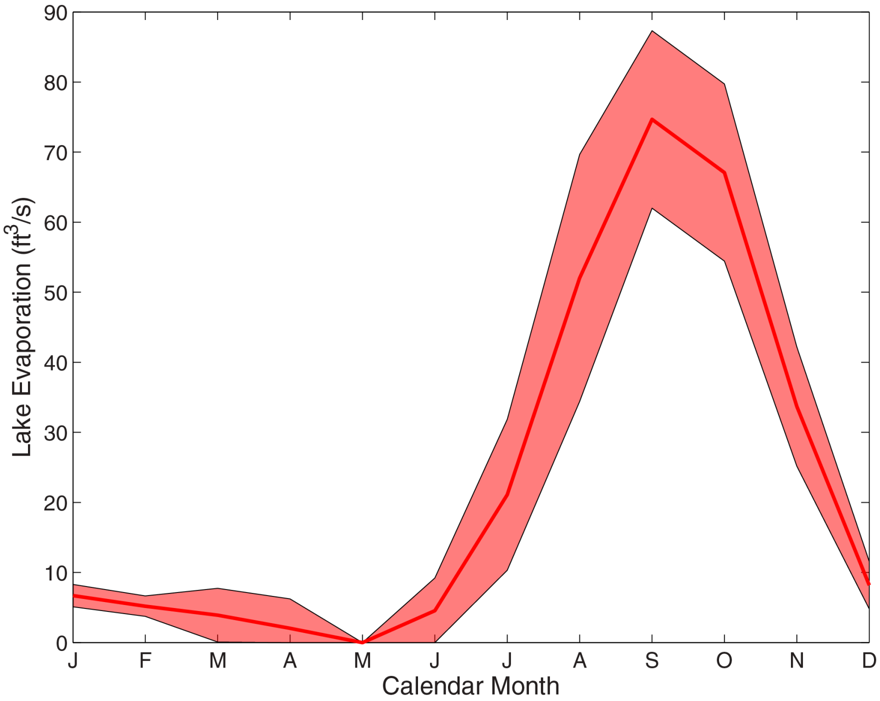


Figure 5.2.14. Plot of simulated monthly lake evaporation cycle, averaged from 2000 - 2014, in cubic feet per second. The shaded region indicates +/-1 standard deviation in monthly input.

5.3: Simulating Lake Levels with a Lake Mass-Balance Model

LHM provides detailed monthly (in fact, hourly, though the data were resampled to monthly periods for this analysis) estimates of critical input and output fluxes for Higgins Lake. To more fully understand what drives lake level dynamics, we first need to construct a conceptual mass balance, which is shown in Figure 5.3.1. For this analysis:

- Precipitation comes from hourly climate data from the National Land Data Assimilation System (NLDAS-2), aggregated daily.
- LHM provides: Surface water inputs, condensation, and evaporation
- The process-inferred statistical modeling described in Task 5.2 provides groundwater inputs
- Outlet flow will be described in this section, using the stage/discharge rating curves developed in 4.3 for the outlet control dam
- Lake storage is known using the gage height data from the USGS
- Groundwater loss will be estimated using what is known as a “residual mass balance approach” described below.

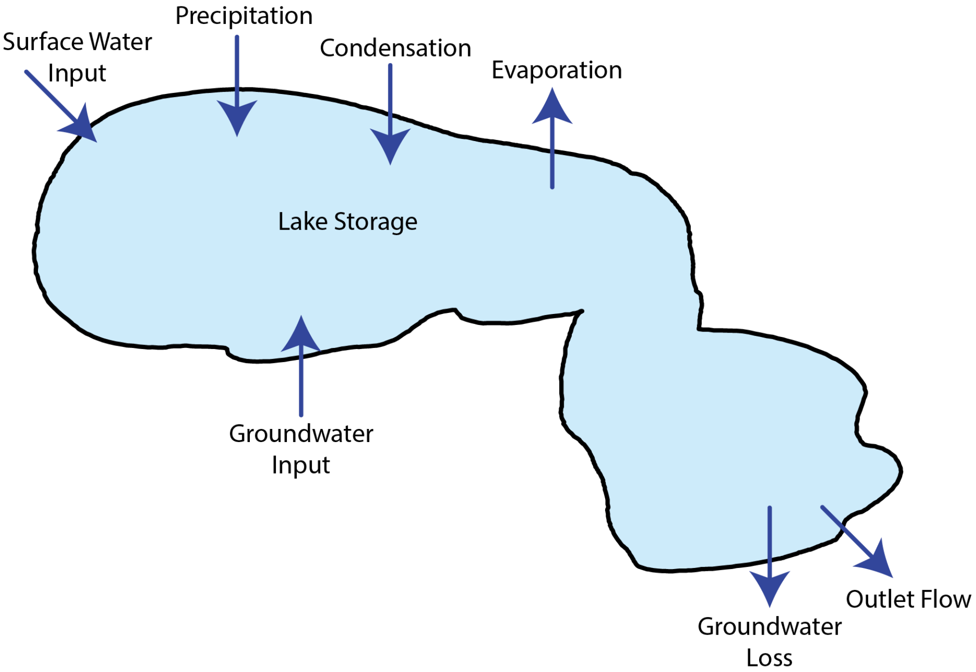


Figure 5.3.1. Conceptual diagram of the mass balance of Higgins Lake.

Represented in equation form, the Higgins Lake Mass Balance is:

$$\Delta S = P + E_{in} - E_{out} + G_{in} - G_{out} + Q_{in} - Q_{out} \qquad \textbf{Equation 1}$$

where: ΔS is Higgins Lake storage, $P$is precipitation, E_{in} is condensation, E_{out} is evaporation, G_{in} is groundwater discharge input to the lake, G_{out} is groundwater loss from the lake, Q_{in} is input streamflow, and Q_{out} is outlet streamflow.

This subtask will first describe the derivation of the outlet stream flow term, then the groundwater loss term. Finally, it will apply these models to simulate change in lake level (storage), and compare this to observed data.

Detailed daily records of Higgins Lake outlet control structure gate configurations have been published in monthly hand-written reports since 2008 and are maintained up to present day. These records describe the open/closed status of the dam's six adjustable gates (flop gates). For this model, three years of those records from 2012 to 2014 were digitized. Those digital records were then used with observed lake elevations during that same period to develop a multinomial logistic regression model that predicts the probability of a particular outcome (all gates closed, 1 open, 2 open, or 3 or more open) versus lake level. Furthermore, separate models were created for the summer (April 15 through October 31st) and winter (November 1st through April 14th) periods. This is because there are separate legally-defined lake level targets for each of these periods, and the dam is managed accordingly.

Figure 5.3.2 plots the winter and summer models. These are somewhat complicated, but are best understood by picking a particular level, and then observing the probabilities of any particular gate configuration being used at that time. For instance, at the two different winter lake levels in use during the 2000-2014 modeling period, the most likely gate configuration is 3 or more open, with probabilities between 72 and 81 percent. As levels drop further, it becomes more likely that only 1 gate would be open. Conversely, during the summer it is far more likely that all gates remain closed, until lake levels are above the legal level, at which point the most likely configuration becomes a single gate open. Very rarely are all three gates open during this period.

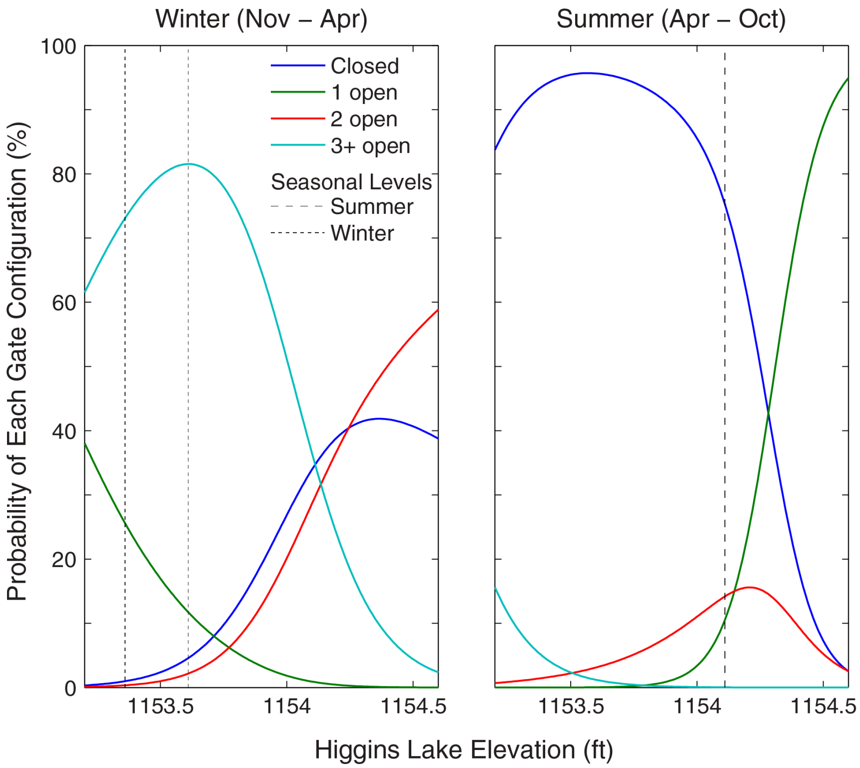


Figure 5.3.2. Plots of the probability of the dam outlet flop gates being in each condition (Closed, 1 gate open, 2 gates open, or 3 or more gates open) versus the lake level on Higgins Lake. Legal lake levels for each season are shown in the corresponding plot, note there are two winter lake levels depending on the year. The Winter and Summer management differs significantly, thus separate models were developed for each season.

Because this model predicts gate configuration with a certain probability, if the model is run 100 times, then 100 different outcomes would occur, though on average the bulk probabilities would match those in Figure 5.3.2. Thus for estimating lake levels and stream outflows, the model was run 100 times in order to better capture the variability in flows/levels that would result from dam management.

The first step in validating this gate configuration model is to compare Cut River outlet streamflow to observed values. This is a two step process: First, observed lake levels for the 2012 - 2014 period and observed gate configurations were used to predict Cut River outflow using the dam configuration rating curves in Figure 4.3.2. These are shown as the red time series in Figure 5.3.3, observed flows at the HL-CR-1 gauge are shown in blue. Second, the observed lake levels from 2000 - 2014 were used with the multinomial logistic regression model to predict gate configurations, which along with the dam rating curves predict outlet discharge. This procedure was repeated 100 times, resulting in the black line (mean) and shaded region (+/- 1 standard deviation) of simulated flow for the entire simulation period.

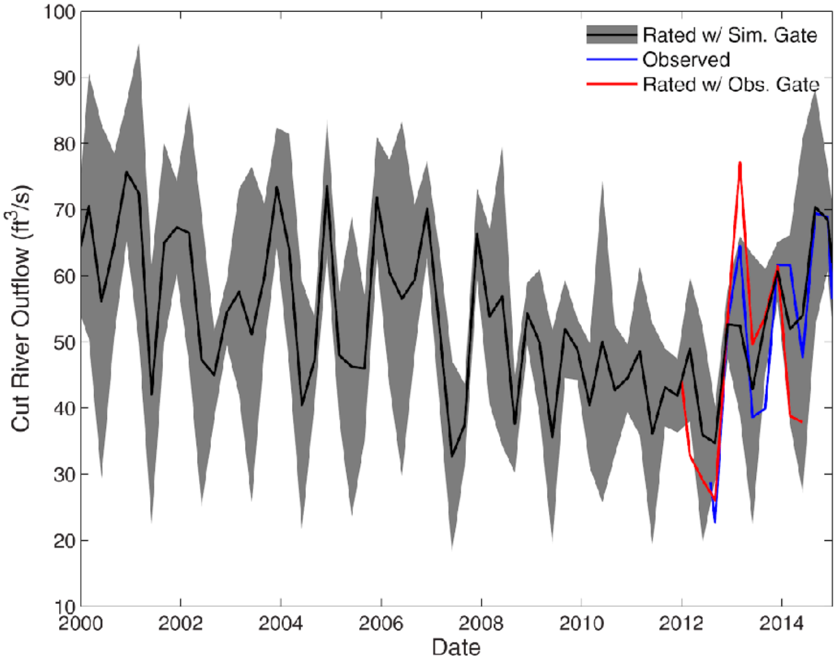


Figure 5.3.3. Plot of seasonal average outflows from Higgins Lake into the Cut River, including observed flows at HL-CR-1 (blue), flows calculated from the dam configuration rating curves above (Figure 4.3.2) and approximately 3 years of digitized dam management records (red), flows calculated using the dam configuration rating curves and a probabilistic simulation of dam gate management (black, with shaded +/-1 standard deviation).

The only remaining unknown quantity in the Higgins Lake Water Balance is then groundwater loss term. This was estimated using a residual mass balance approach. For this, Equation 1 is rearranged:

$$G_{out} = P + E_{in} - E_{out} + G_{in} + Q_{in} - Q_{out} - \Delta S$$ **Equation 2**

Which allows for groundwater loss to be solved for directly. This approach inherently assumes that the errors across the observed and modeled water balance terms are small. This is, in general, a reasonable assumption. However, groundwater input to Higgins Lake is not directly measurable, and therefore difficult to directly validate. Rather than assuming that this approach yields a direct estimation of groundwater loss, we assume that it also incorporates some error in modeled groundwater input, thus a more accurate representation is:

$$G_{in} - G_{out} = G_{net} = \Delta S - P - E_{in} + E_{out} - Q_{in} + Q_{out}$$ **Equation 3**

Where G_{net} is net groundwater input to the lake.

Solving for net groundwater input using daily values of the other mass balance terms, and then averaging monthly results in output shown in Figure 5.3.4. This shows that, in general Higgins Lake is a strongly gaining lake from groundwater, but some months it is a net contributor to the groundwater system. Thus the lake is best seen as a groundwater flow through lake.

Physically, this is a reasonable conclusion, given the surface and ground watersheds shown in Figure 1.6.5. The groundwater and surface water sheds of the southeast portion of Higgins Lake extend essentially no further than the lake itself, thus this is very likely a groundwater outflow location.

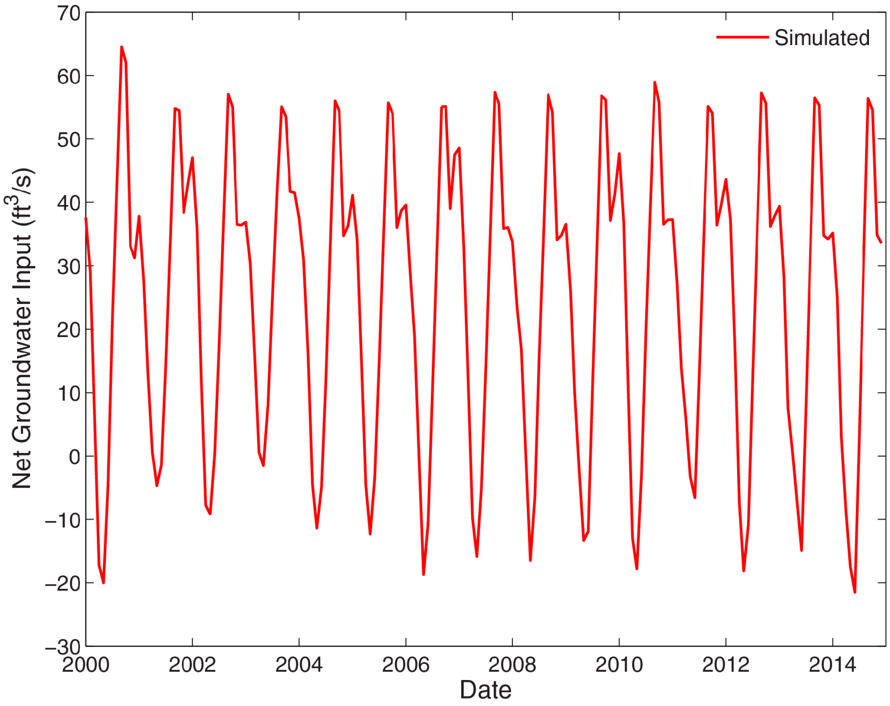


Figure 5.3.4. Simulated net (input - output) groundwater input for the model period 2000 - 2014.

Looking at the simulated net groundwater input on a monthly average basis shows an interesting seasonal cycle (Figure 5.3.5), where from March through May the lake likely contributes water to the regional groundwater system. For the rest of the year, particularly during high evaporation periods in September - October, the lake is strongly gaining on the whole. The lake also gains significantly during the winter.

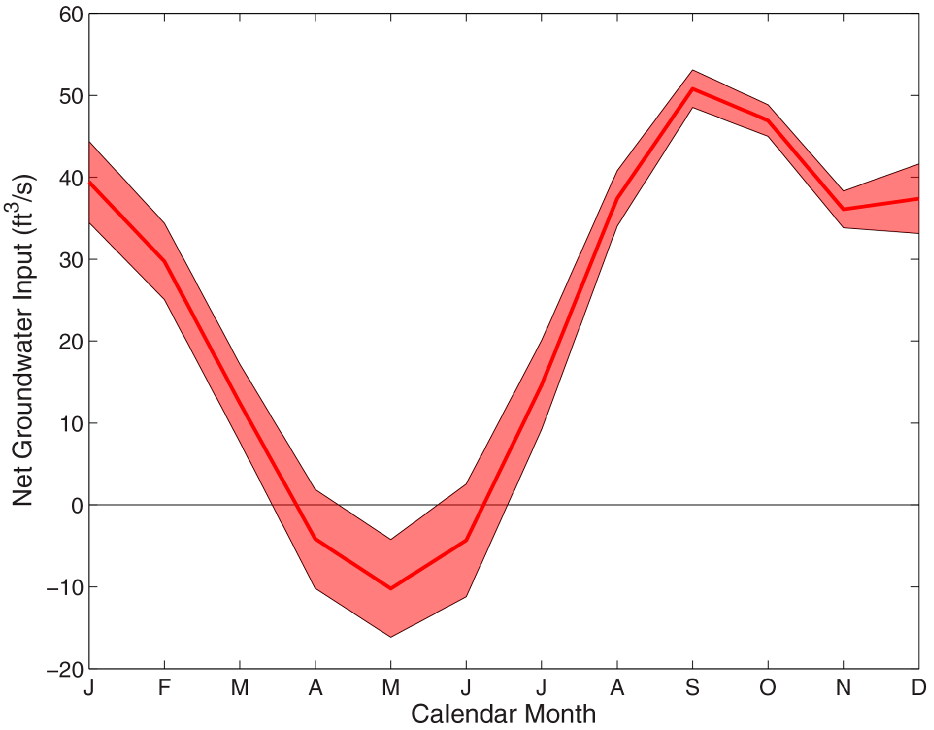


Figure 5.3.5. Simulated monthly net (input - output) groundwater input averaged over the model period 2000 - 2014. The shaded region indicates +/-1 standard deviation in monthly input.

With all terms of the lake mass balance known, we can return to Equation 1, and use the model to predict change in storage (lake level) in Higgins Lake, and compare the model's behavior to observed lake levels. The model simulates daily changes in lake level, based on the inputs from LHM and climate, then simulates statistical dam configuration using the models developed in this section, which provides a dynamic outlet flow response. The model was run 100 times to better capture the probabilistic behavior of dam management. The output of this is shown in Figure 5.3.6.

In general, the model does a good job of capturing lake level dynamics, some years matching behavior very well, while in others the peak and trough levels are not accurately matched. For the 2000 - 2014 period, the model had a mean absolute error of 1.61 inches in level, and an R^2 of 50%, with a Nash Sutcliffe Efficiency of 0.36. Overall, this is a good model with significant predictive power.

Since the model was calibrated to dam management during a period of lower winter lake level targets (as this was the only digital management data available), it is likely to underpredict winter levels. However, the model still provided good results in general.

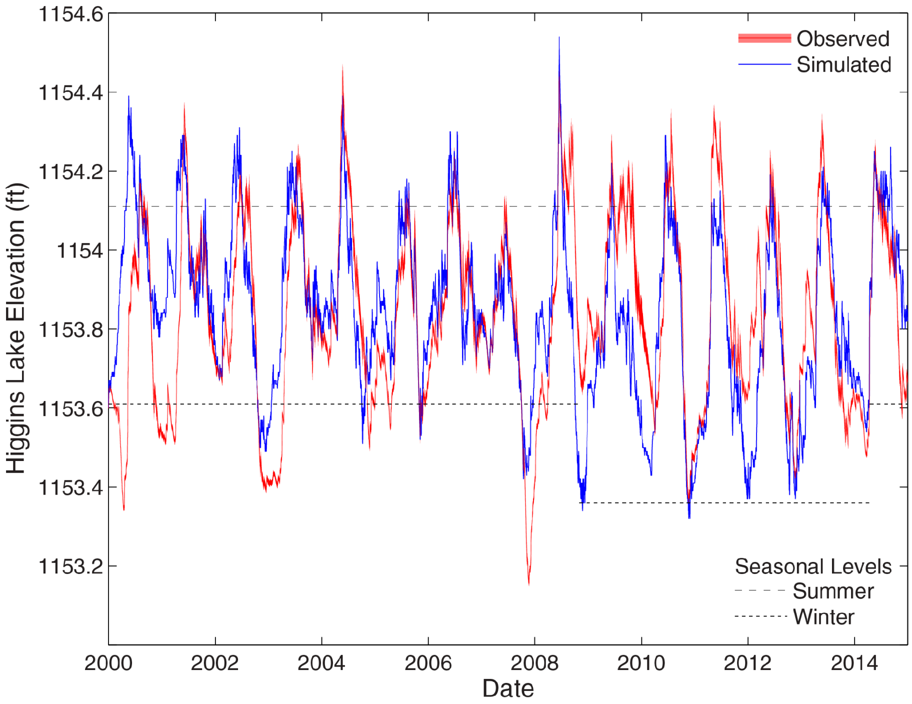


Figure 5.3.6. Plot of simulated and observed Higgins Lake elevations in feet for the period 2000 - 2014. Barely visible are the +/- 1 standard deviation of simulated levels for the 100 simulation runs.

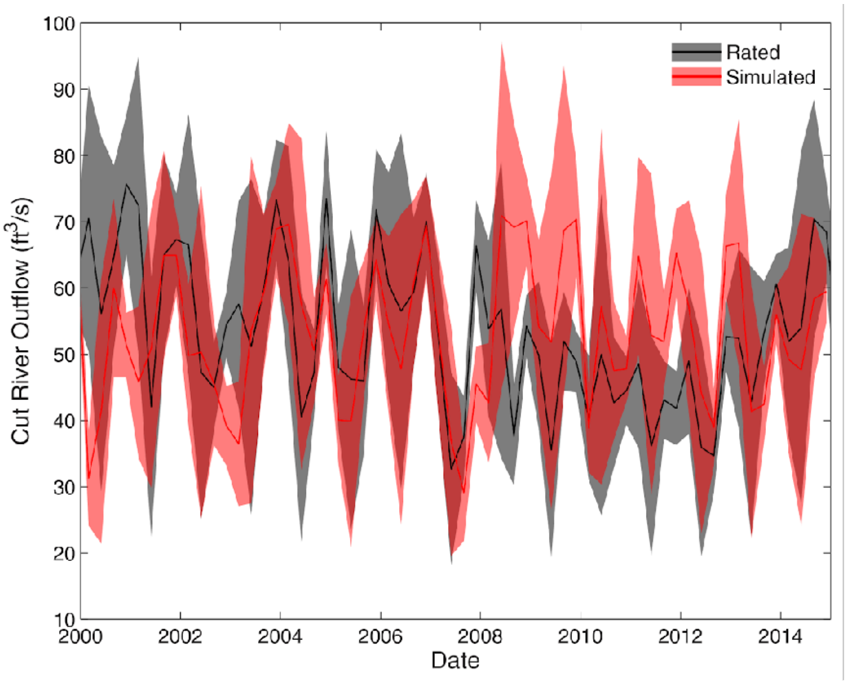


Figure 5.3.7. Plot of seasonal Cut River outflows from Higgins Lake using the dam configuration rating curves and the dam management model (Rated) along with outflow predicted using simulated lake levels and the dam management model (Simulated).

Finally, given the simulated lake levels, dynamically predicted outflows were plotted against outflows predicted using observed lake levels (Figure 5.3.7). In general, the models agree within a single standard deviation in monthly outflows. However, some years, 2008-2009 in particular, the dynamic lake level model overpredicts Cut River outflows.

5.4: Evaluation of Lake Level Scenarios with Mass Balance Model

The full suite of models can then be applied to simulate Higgins Lake levels in response to altered dam management, or hypothetically speaking dam removal. This section investigates two such change scenarios, in which: 1) the dam is left fully open at all times, but remains in place, and 2) where the dam is removed. The first scenario is evaluated by foregoing the dam management model and setting the gate configuration as all open. The second scenario removes both the dam management model and the dam configuration rating curves, and represents Higgins Lake outflows using the HEC-RAS outputs shown in Figure 5.1.4.

These scenarios are overlain with the current management simulation in Figure 5.4.1. As expected, simulated levels are lower for both scenarios, with peaks not reaching the same elevations, and troughs lower than under current management. However, it is also clear that the change in levels is not as large as was expected during the initial development of the lake level scenarios. Because the sill of the the outlet control structure is approximately 18 inches below legal lake level, we originally assumed that this would be the level to which summer lake levels could reach, however this never occurred. Nor did the 20 inch lowering which we considered possible with dam removal occur in our simulated scenarios.

Figure 5.4.2 plots the monthly differences between the two alternate scenarios and current lake level management. In general, the always open scenario oscillates between 6.5 and 0.5 inches below current levels on an annual basis, while the no dam scenario exhibits roughly the same pattern, but between 10 and 4 inches below current levels. The no dam scenario shows a greater degree of variability in differences from current.

Figure 5.4.3 plots the daily lake levels as a probability of occurrence, with winter and summer levels split out separately. Somewhat surprisingly, winter levels are not strongly impacted by the dam open scenario, but are more affected in the no dam scenario. Summer levels show that the dam always open scenario results in about the same lowering relative to current management as does the dam removal relative to the dam open scenario. The lowest lake level in all scenarios was approximately 18 inches below the current legal summer level, and had a very low probability of occurrence < 1%. Thus, the 18 inch drop scenarios considered in Task 2.3 should be considered highly improbable for the summer, and the 20 inch drop essentially not possible.

In fact, this model likely overstates the lower levels because it does not dynamically adjust for the increases in groundwater inputs that would occur with lower groundwater levels. As lake levels decline so would groundwater loss, and groundwater gain would increase, thus the estimates shown here should be considered pessimistic in terms of lake level declines for these scenarios.

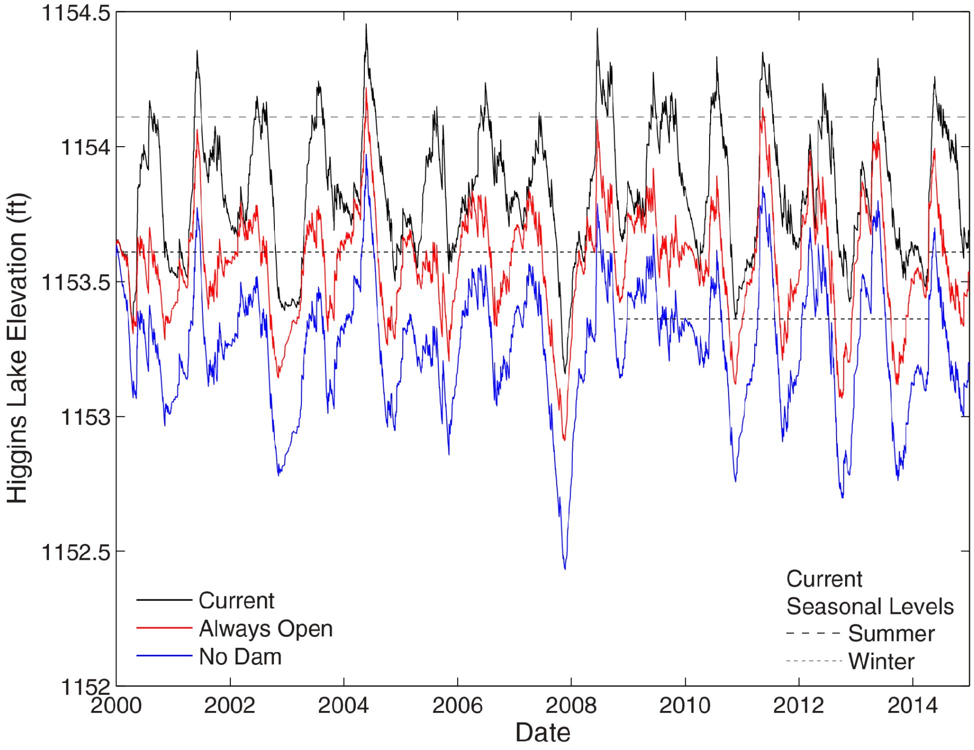


Figure 5.4.1. Plot of daily lake levels simulated by the Higgins Lake Water Balance model for the simulation period 2000-2014. Three scenarios are shown: 1) Current management of the dam, 2) Leaving the dam fully open at all times, and 3) Removing the dam.

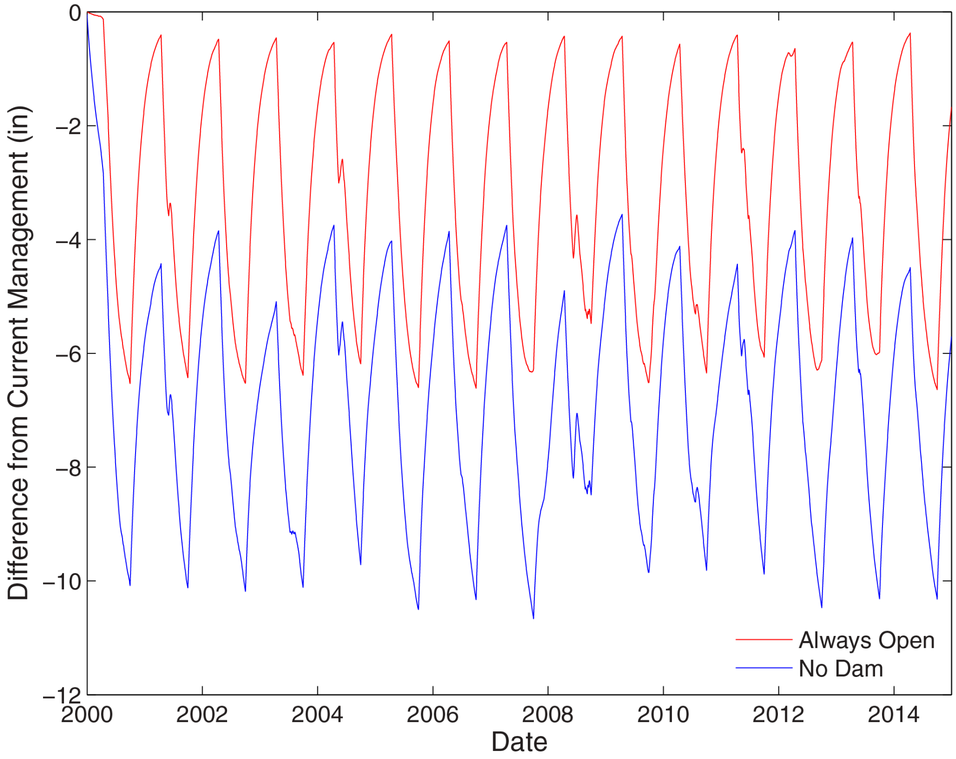


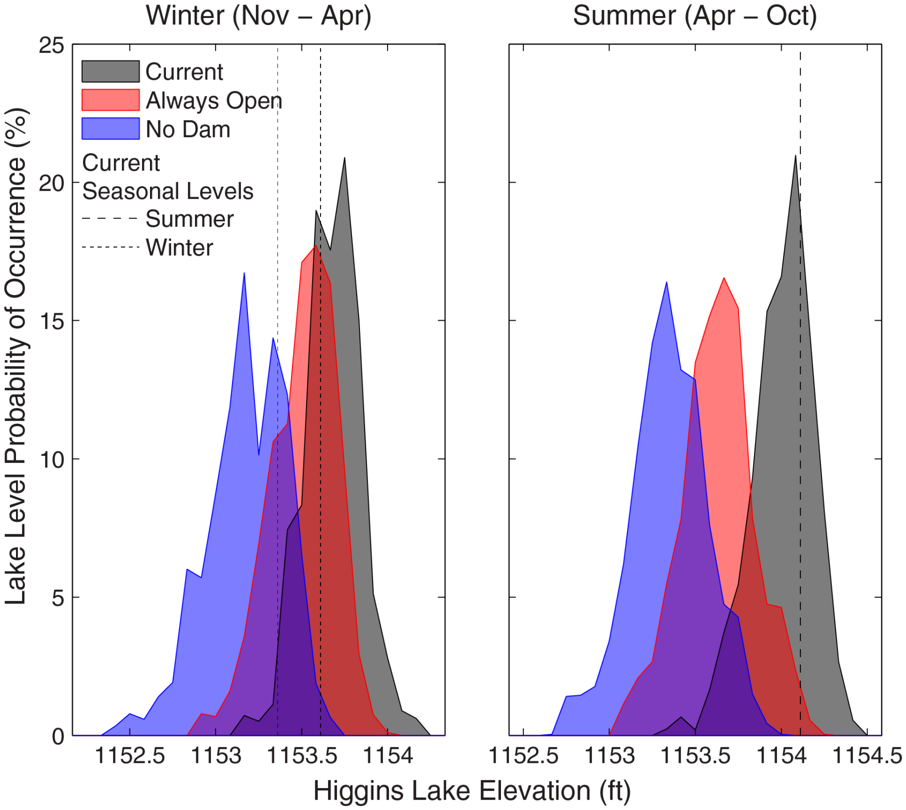
Figure 5.4.2. Plot of the monthly differences between current dam management and the two alternate dam scenarios, in inches.

Perhaps most importantly for recreational and ecological lake uses, the mean summer and winter lake level changes for the two scenarios are shown relative to current management in Table 5.4.1. During winter, levels were an average of 2.4 inches lower in the always open scenario, and 6 inches lower in the no dam scenario. During summer, levels were on average 4.8 inches lower in the always open scenario, and 8.4 inches lower in the no dam scenario. As was mentioned above in Task 2.3, this is why these two scenarios were chosen to present the spatial impacts of lake level changes on intermediate dock length, and final shoreline position.

Table 5.4.1. Average (mean) lake levels during the summer and winter periods for each of the three simulated lake level scenarios. Units are in feet of elevation.

Dam Scenario	Winter (elev. ft)	Summer (elev. ft)
Current	1153.7	1154.0
Always Open	1153.5 (2.4 inches lower)	1153.6 (4.8 inches lower)
No Dam	1153.2 (6 inches lower)	1153.3 (8.4 inches lower)

Figure 5.4.3. Histograms of summer and winter lake levels averaged across the 2000 - 2014 daily water balance model for each of the three dam management scenarios. Both winter legal levels are plotted in dotted vertical lines, and the summer in dashed vertical. Histogram bins are 1 inch, thus the vertical axis can be used to infer the probability of each 1-inch bin occurring under each scenario.



Altering dam management will also impact flows on the Cut River, which are plotted as histograms of daily values in the summer and winter separately in Figure 5.4.4. Note that the two dam management change scenarios have essentially the same probabilities, which is expected because the level of the outlet within such a small margin has little impact on flows--only active management will create seasonal storage. Indeed, the summer flows under the unmanaged scenarios are significantly higher, approximately 25 cubic feet per second, whereas winter flows are lower by a somewhat smaller margin.

Critically from an ecological perspective, the unmanaged dam scenarios keep flows within a 50 cfs target range for most of the year, which is highlighted in the ecological impacts report on Task 6.

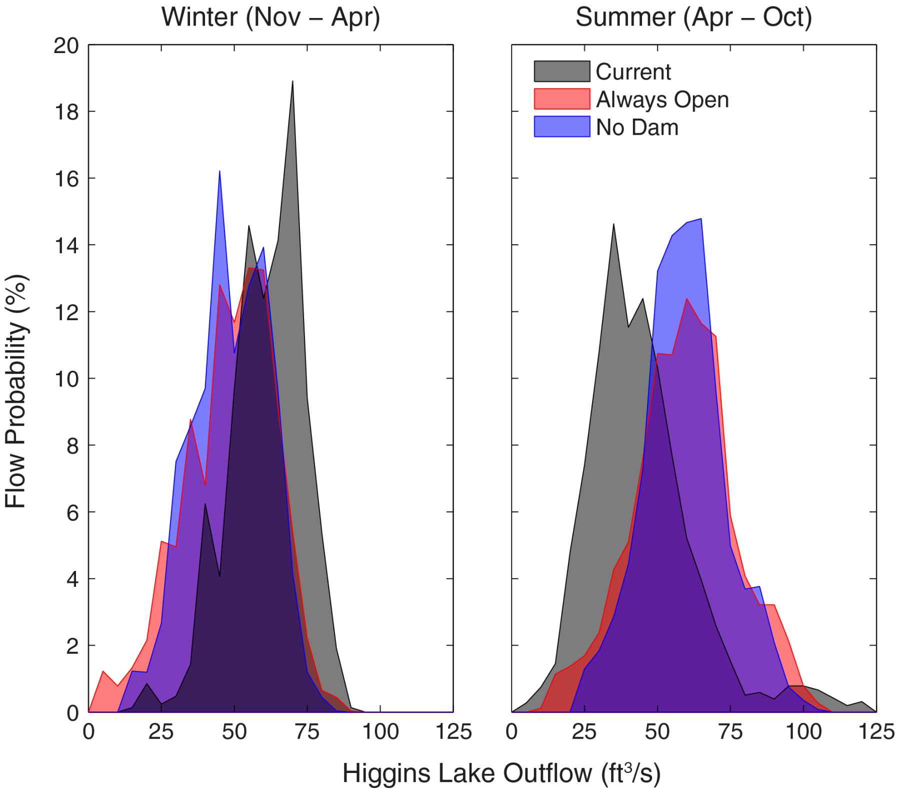


Figure 5.4.4. Histograms of summer and winter Higgins Lake Outflow through the Cut River for the three scenarios. Histogram bins are 5 cubic feet per second, thus the vertical axis can be used to infer the probability of each 5-cfs bin occurring under each scenario.

Task 5 Findings Summarized

- A suite of hydraulic (HEC-RAS), hydrologic (LHM), and statistical models (groundwater input and dam management) were used to calculate the terms of a dynamic lake level model.
- This lake level model produced reasonable daily estimates of Higgins Lake levels, within 1.6 inches of the actual observed level on average.
- Two scenarios, in which the dam is left open at all times, and where the dam is theoretically removed, were investigated with the dynamic lake level model.
- Mean changes in summer lake levels were 4.8 inches lower for the always open scenario, and 8.4 inches lower for the no dam scenario.

- These level changes are much smaller than would be expected assuming that the lake would drop to the lowest elevation of the current dam (18 inches below current summer level), or the lake outlet bottom (20 inches below current summer level).
- This dynamic lake level model likely over predicts level declines, due to the lack of a feedback with the groundwater system that would occur in reality.
- The level drop scenarios with changes greater than 9 inches thus represent increasingly unlikely scenarios, with essentially no chance of the 18 or 20 inch drop scenarios occurring.
- Cut River outflows from Higgins Lake are enhanced during the summer in the unmanaged scenarios, reaching 50 cfs for most of the summer (and winter as well).

Task 7: Survey of Higgins Lake Landowner Concerns

In this task we briefly summarize the results from a local residents survey conducted by Huron Pines, a project partner. The survey lists the top 5 concerns of respondents coded into 12 categories. Notably, boating, beach use, and water quality were the top three concerns of respondents.

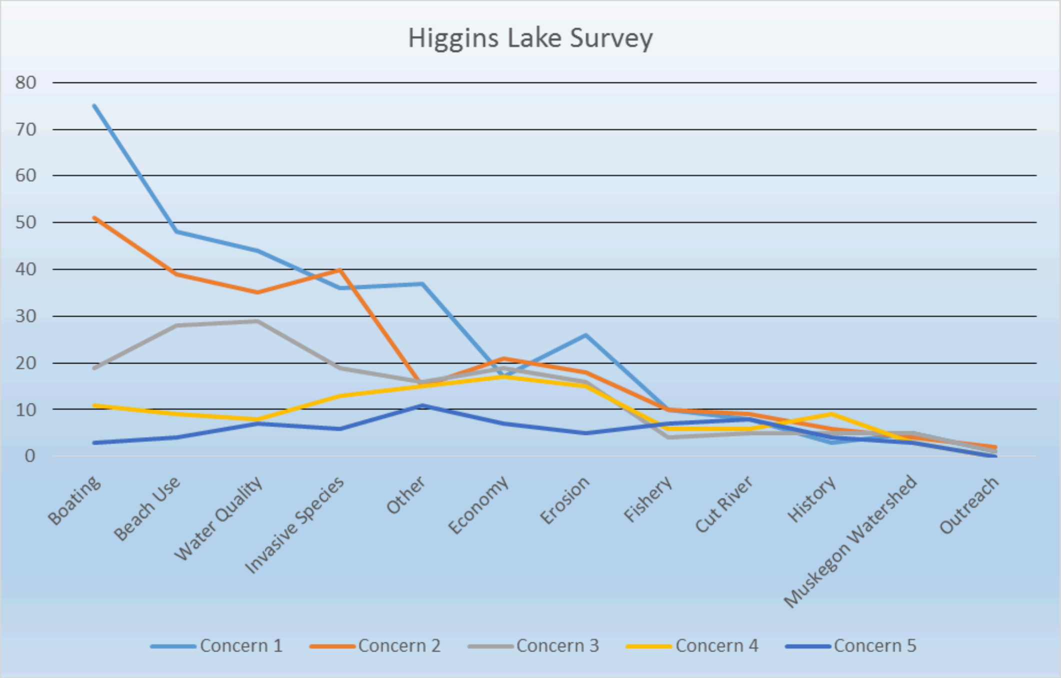


Figure 7.1. Plot of survey responses grouped into broadly-defined categories. Numbers of responders indicating each category is plotted, line colors denote the order of concern listed, from most important (Concern 1) to least important (Concern 5).

Conclusions

The key findings from each of the Tasks 1-5 are detailed in subsections above. Most significant among them are that:

- A state-of-the-art hydrologic study has been completed that provides Higgins Lake area residents, dam managers, and state regulators with an unprecedented view of the lake.
- No credible evidence of significantly lower lake levels or outlet position/configurations in recent (post-settlement) history was found
- Strong evidence for active shoreline erosion was observed at many locations around the lake.
- This study produced a series of outputs that will benefit managers, conservation groups, residents, and researchers.
- The new bathymetric map produced by this study provides the detail needed to assess potential changes in shoreline, dredging, and dock lengths due to lake level changes
- The first continuous multi-year and longitudinal flow datasets have been collected for the Cut River, which highlight:
    - The role of Higgins Lake in maintaining flows on the Cut River, and
    - The relatively minor role that management of the control structure at the outlet of Higgins Lake plays in determining Houghton Lake inputs downstream, except in short periods when gates are opened.
- Dynamic lake level modeling has shown that even with drastically altered dam management, or even fully removing the dam, lake levels are unlikely to drop more than 9 inches on average during summer months.
- Scenarios in which the dam is either left open or removed lead to higher summer outflows and somewhat lower winter outflows, which may be of ecological importance (see Task 6 report).

References

Kraus, N. C. 1988 "The effects of seawalls on the beach: an extended literature review." *Journal of Coastal Research* Special Issue No. 4, p 1-28.

Kriesel, W., and Friedman, R., 2003, “Coping with coastal erosion—Evidence for community-wide impacts”, *Shore and Beach*, v. 71, no. 3, p. 19–23.

Phillips, B., and Rasid, H., 1996, “Impact of Lake Level Regulation on Shoreline Erosion and Shore Property Hazards: The Binational Case Experience of Lake of The Woods”, *The Great Lakes Geographer*, v. 3, no.2, p. 11-28.

Appendix A

Cumulative Probability of Outflow During Summer, Table

Flow(cfs)	Prob_Curr(%)	Prob_Open(%)	Prob_NoDam(%)
5	0.235294	0	0
10	1.01961	0.117647	0
15	2.54902	1.2549	0
20	7.17647	2.62745	0
25	14.2745	4.31373	1.29412
30	25.9608	6.70588	3.13725
35	40.1176	10.9804	6
40	51.7255	16.0784	10.4314
45	62.902	23.6863	17.7255
50	74.3137	34.4314	30.9412
55	82.2353	45.1373	45.2157
60	87.2157	57.5294	59.8824
65	91.2941	69.1765	74.6667
70	93.8431	80.4314	84.3137
75	95.098	86.3137	89.2941
80	95.9608	90.3922	92.9804
85	96.5098	93.6078	96.7451
90	96.9412	96.8235	98.8235
95	97.6863	98.9412	99.5686
100	98.1569	99.7255	99.9216
105	99.0196	100	100
110	99.5294	100	100
115	99.7255	100	100

120	100	100	100

Appendix B

Cumulative Probability of Outflow During Winter, Table

Flow(cfs)	Prob_Curr(%)	Prob_Open(%)	Prob_NoDam(%)
5	0	1.22909	0
10	0	2.01434	0
15	0.273131	3.34585	1.22909
20	0.990099	5.49676	2.42404
25	1.26323	10.618	5.08706
30	1.67293	15.5685	12.5982
35	3.10686	24.3428	21.1676
40	9.49129	31.1369	30.8638
45	13.3834	43.9399	47.0809
50	23.0113	55.6163	57.8354
55	37.2482	68.9314	70.6043
60	50.2561	82.1782	84.534
65	64.6637	91.2598	94.1618
70	82.7586	96.6541	98.3271
75	92.1475	98.8733	99.522
80	97.6784	99.522	99.9659
85	99.8976	99.9659	100
90	100	100	100
95	100	100	100
100	100	100	100

105	100	100	100
110	100	100	100
115	100	100	100
120	100	100	100

Appendix C

Cumulative Probability of Lake Levels During Summer, Table

Level(ft)	Prob_Curr(%)	Prob_Open(%)	Prob_NoDam(%)
1152.5	0	0	0
1152.58	0	0	0
1152.67	0	0	0.588235
1152.75	0	0	2.11765
1152.83	0	0	3.52941
1152.92	0	0	6.19608
1153	0	0.392157	10.4706
1153.08	0	2.27451	18.0392
1153.17	0	4.23529	31.6078
1153.25	0	7.92157	46.0784
1153.33	0.27451	14	60.6275
1153.42	1.01961	24.6667	75.4118
1153.5	1.41176	39.4118	85.6078
1153.58	4.86275	55.5686	91.4902
1153.67	9.21569	71.4118	96.1176
1153.75	15.4118	84.4706	99.0196
1153.83	27.1373	90.2353	99.7255

1153.92	45.5686	94.9804	100
1154	62.5882	98.1961	100
1154.08	82.3137	99.8039	100
1154.17	93.451	100	100
1154.25	98.549	100	100
1154.33	99.6863	100	100
1154.42	100	100	100
1154.5	100	100	100

Appendix D

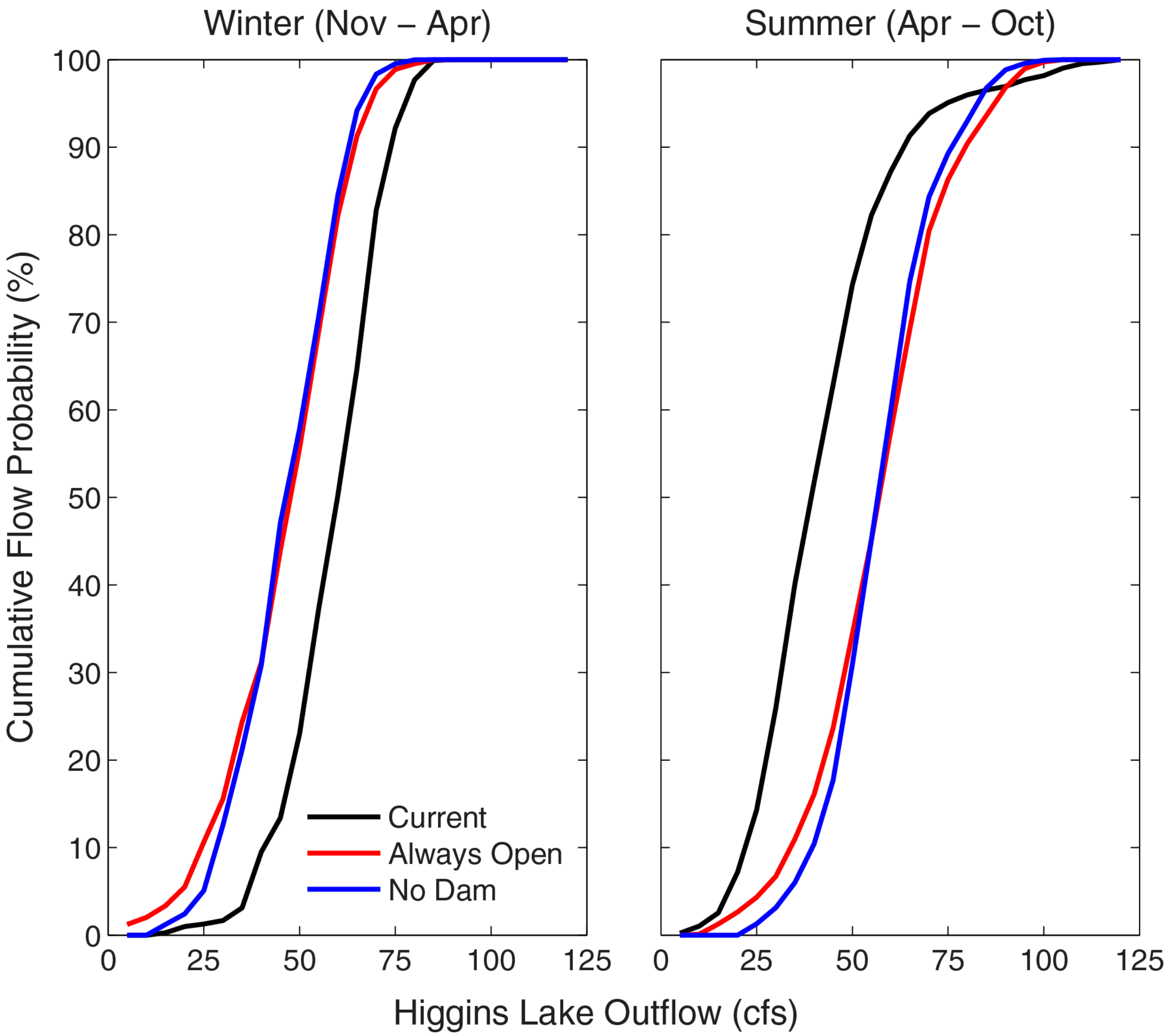
Cumulative Probability of Lake Levels During Winter, Table

Level(ft)	Prob_Curr(%)	Prob_Open(%)	Prob_NoDam(%)
1152.25	0	0	0
1152.33	0	0	0
1152.42	0	0	0.955958
1152.5	0	0	1.33151
1152.58	0	0	2.18505
1152.67	0	0	3.51656
1152.75	0	0	8.02322
1152.83	0	0.238989	12.9737
1152.92	0	1.12666	20.5531
1153	0	2.25333	30.4882
1153.08	0.170707	4.30181	46.8078
1153.17	1.02424	10.2424	57.5964
1153.25	1.70707	16.7293	71.1506

1153.33	5.90645	28.4397	85.0461
1153.42	12.564	44.3837	94.6398
1153.5	26.3913	62.0348	98.4978
1153.58	46.5005	79.72	99.8293
1153.67	63.4005	92.8645	100
1153.75	84.9778	98.0881	100
1153.83	93.24	99.522	100
1153.92	97.3028	100	100
1154	98.8392	100	100
1154.08	99.5903	100	100
1154.17	100	100	100
1154.25	100	100	100

Appendix E

Cumulative Probability of Outflow Figure



Appendix F

Cumulative Probability of Lake Level Figure