CENTRAL SANDS LAKES STUDY REPORT: FINDINGS & RECOMMENDATIONS

For Submittal To The Wisconsin Legislature

May 27, 2021

Plainfield Lake, October 2017
Photo Credit: The DNR Water Use Section

This document was developed by the Wisconsin Department of Natural Resources (DNR) with technical support from the Wisconsin Geological and Natural History Survey (WGNHS), the United States Geological Survey (USGS), and partners from the University of Wisconsin System. Questions regarding this document or the Central Sands Lakes Study should be directed to DNRDGCentralSands@wisconsin.gov.

EXECUTIVE SUMMARY

Over the past 60 years, we have observed low water levels in lakes and streams in Wisconsin's Central Sands Region. Various researchers have studied the relationship between land use and impacts to water resources in the Central Sands Region. Their work has shown that the two main causes of water level changes are weather and the pumping of high capacity wells. Weather varies considerably from place to place and from year to year. The number of high capacity wells in the Central Sands Region have increased over the past few decades, which has raised concerns about pumping of groundwater and the impacts on water levels.

In response to these concerns, the Wisconsin Department of Natural Resources (DNR) evaluated and modeled Pleasant, Long, and Plainfield Lakes in Waushara County to determine whether groundwater withdrawals cause a significant reduction in lake levels below their average seasonal levels, as directed by the Wisconsin State Legislature, specifically Wis. Stat. § 281.34(7m) (2017 Wisconsin Act 10). This report describes the findings of the Central Sands Lakes Study (the study) and recommends a broad plan to address impacts to the three lakes and other water resources in the Central Sands Region.

To determine whether groundwater withdrawals cause a significant reduction in lake levels below their average seasonal levels, the DNR developed two main study questions. The DNR's first study question was: *Do groundwater withdrawals affect lake levels at Pleasant, Long, and Plainfield Lakes?* To answer this question, the DNR collaborated with state and federal agencies, and the University of Wisconsin System to characterize the geology of the study area and construct a state-of-the-art groundwater flow model.

The DNR's second study question was: *Is this reduction significant to the lakes' ecosystems?* The DNR defined "average seasonal level" to be the range of high, median and low lake levels and "significant reduction" as a deviation from this natural range strong enough to cause a significant impact or change to the ecosystem and/or human use of the study lakes.

Our findings confirmed that the study lakes and other surface water resources in the Central Sands Region are well connected to groundwater. We focused our study on high capacity wells that pump water for irrigated agriculture, since 95-99% of the groundwater withdrawals in the near-lake modeling area were used for irrigated agriculture. Our model results indicate that current groundwater withdrawals from irrigated agricultural reduce lake levels in Pleasant, Long, and Plainfield Lakes. Current-irrigated agriculture has caused a significant reduction in lake levels resulting in impacts to human uses (e.g., boating), fish, plants, and chemistry on Long Lake and human uses and plants on Plainfield Lake. We labeled Pleasant Lake as "caution" because estimated lake level reductions may impact lake stratification, yet the reductions are within model uncertainty (Figure 1). Furthermore, we found lake level reductions from potential-agricultural-irrigation scenarios could cause impacts on dock usage on Pleasant Lake.

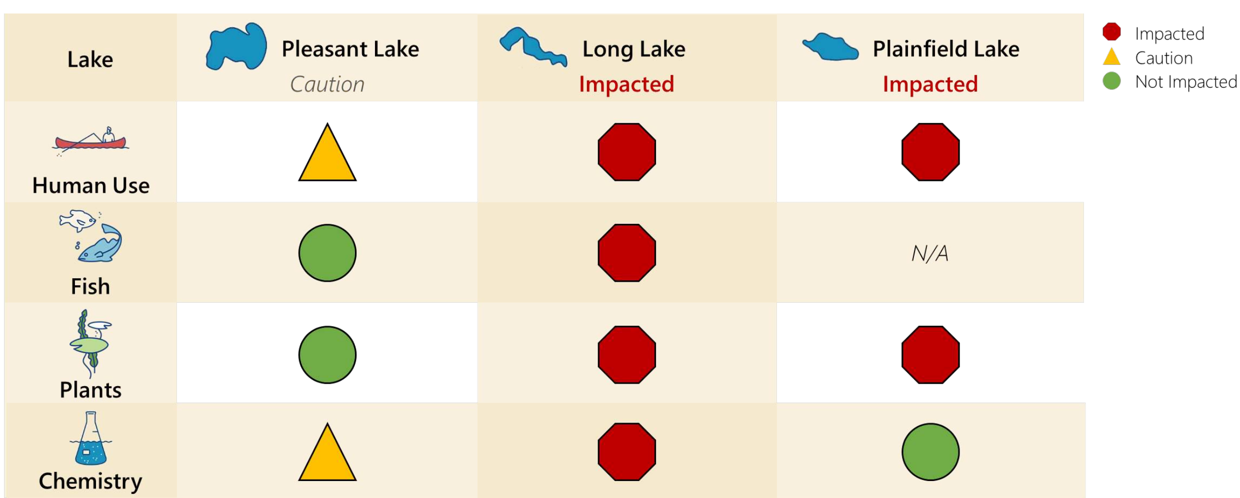


Figure 1 Signs indicate significant reductions in lake levels and ecosystem impacts to Pleasant, Long and Plainfield Lakes.

This study helped us to understand the factors that control the impact of high capacity wells on the study lakes including: distance of high capacity wells from the lakes, pumping rates, landscape position, lake depth, and lake shape. Our results quantify the relative roles of weather and groundwater withdrawals on recharge relative to the groundwater system and lake levels in the Central Sands Region. We found that precipitation is the primary factor affecting lake level fluctuations. We also found that smaller, but persistent reductions of lake levels are attributable to the collective, far-reaching effects of high capacity well pumping.

The DNR determined that the number of high capacity wells responsible for significant reductions of water levels are so numerous that site-specific management measures often considered for water resource protection are likely to be prohibitive. Therefore, the DNR does not recommend site-specific special measures. Instead, the DNR recommends a comprehensive Central Sands regional approach through the creation of a water use district. This recommendation for a collaborative, stakeholder-driven model does not involve immediate water use management changes that warrant an economic analysis. However, the DNR believes additional groundwork is needed to further water use management on a regional scale.

Other states have successfully applied regional water use management through a water use district approach. While leadership from state and regional agencies is necessary, identification and implementation of best practices need to originate from local stakeholders. Stakeholders could select best practices such as water trading, water allocations, conservation, and efficiency measures.

STUDY PURPOSE

Wisconsin's Central Sands Region lies east of the Wisconsin River and encompasses 1.75 million acres in parts of Adams, Marathon, Marquette, Portage, Shawano, Waupaca, Waushara and Wood counties. The Central Sands Region is characterized by thick sand and gravel deposited by glaciers near the end of the last ice age. These sand and gravel deposits form a highly productive aquifer that provides groundwater for: irrigated agriculture, livestock, public and private water supply, industry, and commercial uses.

STATUTORY REQUIREMENTS

Wisconsin State Statutes [s. 281.34 (7m) (b-f)] outlined the requirements of the Central Sands Lakes Study. The specific guidelines are as follows:

- Determine whether groundwater withdrawals are causing or are likely to cause significant reduction in any of the three lakes below its average seasonal water levels.
- Establish if there is a connection and causal relationship between groundwater withdrawals and lake levels and verify that connection and causal relationship through field work or field study and modeling.
- Determine whether to recommend special measures related to groundwater withdrawals, if the study findings show significant reduction of lake levels.
- Prepare legislatively required reports

One way to extract groundwater is by high capacity wells - wells that have the capacity to withdraw groundwater at rates of at least 70 gallons per minute (approximately 100,000 gallons per day). The average capacity of high capacity wells used for irrigated agriculture is 1,000 gallons per minute, or 1,440,000 gallons of water per day. In the Central Sands Region, prior to the 1960's there were about 110 high capacity wells, and today there are approximately 3,100 active high capacity wells (Figure 2). The impact of high capacity wells on water resources has been a concern, especially during drier, low water periods. Recreational water users enjoy the 800 miles of trout streams and over 300 lakes in this region for fishing, waterfowl hunting and boating. Since the 1960's, studies in the Central Sands Region have noted the connectivity of these water resources - groundwater sustains the ecological health and diversity of the lakes, streams, rivers, wetlands and springs (Weeks and Stangland (1971), Kraft et al. (2010) and Bradbury et al. (2017)).

Due to continued questions about the role of high capacity wells and low water levels, the Wisconsin State Legislature passed 2017 Wisconsin Act 10, directing the DNR to conduct a study. The statute, § 281.34(7m), Wis. Stats. defines the area to be studied, the study framework, and the study timeline (see sidebar for a summary of statutory requirements). The statute named the three lakes for the Central Sands Lakes Study: Pleasant Lake, Long Lake, and Plainfield Lake in Waushara County.

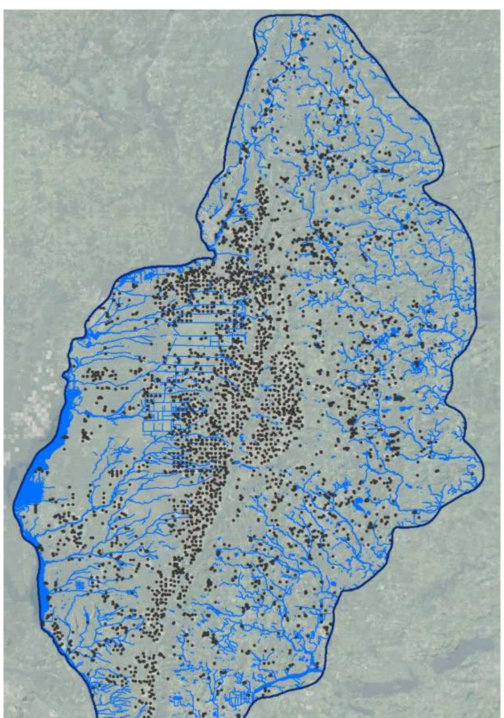


Figure 2 Map of Wisconsin's Central Sands and general locations of high capacity wells

To complete the Central Sands Lakes Study, the DNR Water Use Section collaborated with the Wisconsin Geological and Natural History Survey (WGNHS), the United States Geological Survey (USGS), and the University of Wisconsin System (UWS).

In this *Findings and Recommendations Report*, the DNR summarizes to what extent groundwater withdrawals are causing significant water level reductions on Pleasant, Long, and Plainfield Lakes. This report provides a high-level overview of the study, presents key findings, and contains the DNR's recommendations on how to address groundwater withdrawal management in the Central Sands Region. The study appendices describe the background science, evaluation, and modeling analyses that provided the findings for this report (available on [the Central Sands Lakes Study website] as separate documents). We also provide a series of overview, methodology, and findings presentations on the study website.

The DNR held a comment period (April 6 through May 7, 2021) and a virtual public hearing on April 21, 2021 on the Central Sands Lakes Study findings and recommendations. The DNR has posted all comments and a summary of response to comments on the study website. This final report was prepared and submitted to the Wisconsin State Legislature prior to the June 3, 2021 statutory deadline.

STUDY AREA

As directed by Wis. Stat. § 281.34(7m)(b), the DNR developed a state-of-the-art groundwater flow model to answer the question: *Do groundwater withdrawals affect lake levels in Pleasant, Long, and Plainfield Lakes*? To effectively model and evaluate the three study lakes, the DNR looked at the study area from both regional and local scales. At the regional scale in the Central Sands model area, the DNR used major rivers, the Plover and Wisconsin Rivers to the west, and the Tomorrow, Waupaca, Wolf, and Fox Rivers to the east to define the geographic boundaries. The Central Sands model area includes approximately 75% of the Central Sands Region. This report uses the “Central Sands model area” interchangeably with “the study area”. The three study lakes: Pleasant, Long, and Plainfield are near the middle of the Central Sands model area (Figure 3).

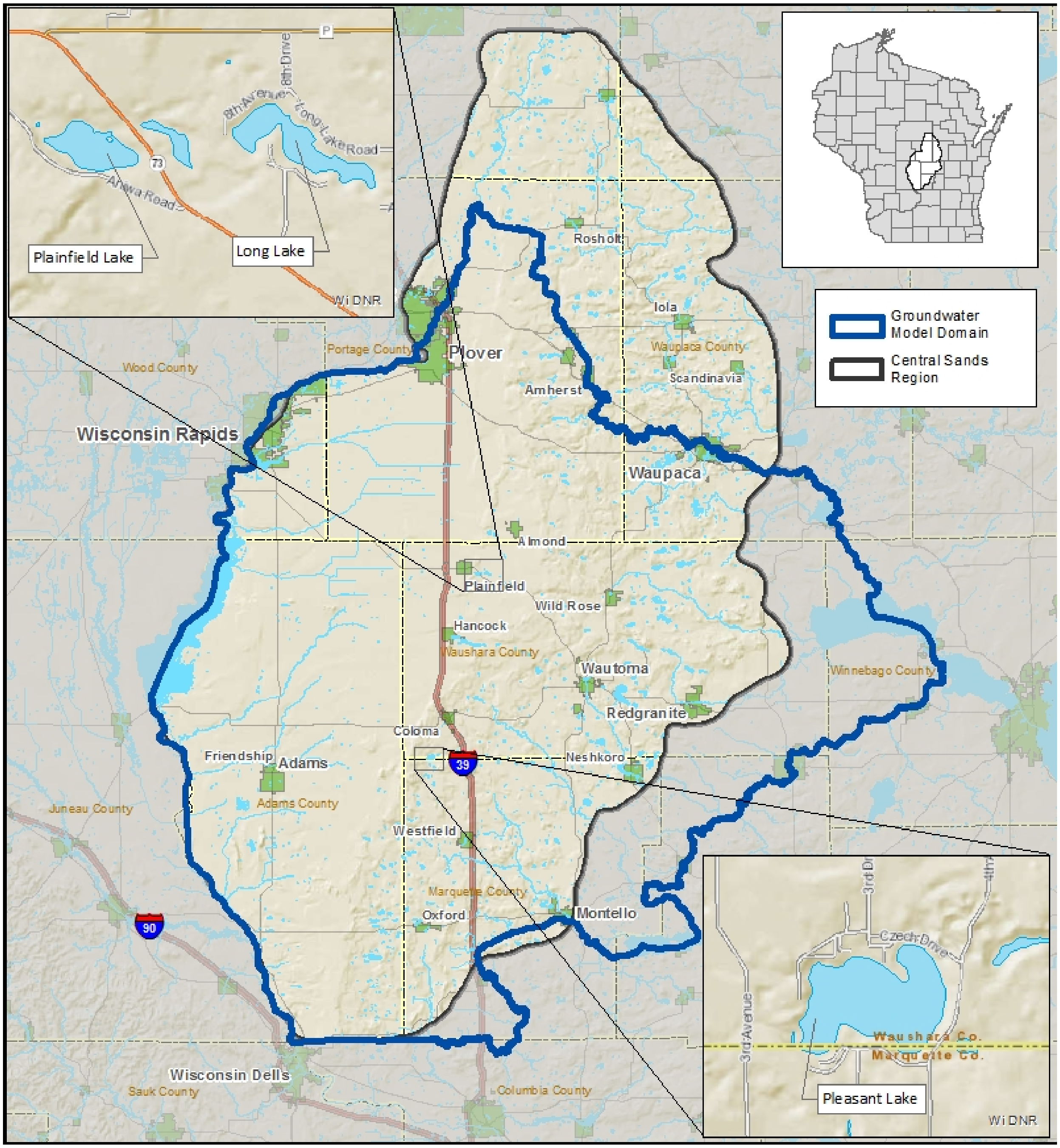


Figure 3 Central Sands Model Area (groundwater model domain), Central Sands Region, and location of the three study lakes: Pleasant, Long, and Plainfield

In the Central Sands model area, the primary land use types are forests (~700,000 acres) and agriculture (~570,000 acres). The forest land cover consists of approximately 85% deciduous trees, 14% evergreen trees, and 1% mixed. The agricultural land use category includes irrigated, unirrigated crops, and pasture and occurs in the central portion of the Central Sands model area. Corn is the most common crop. Irrigated agriculture land use accounts for approximately 15% (~240,000 acres). The remaining land use in the Central Sands model area is made up of wetlands, urban areas, and open water (Figure 4).

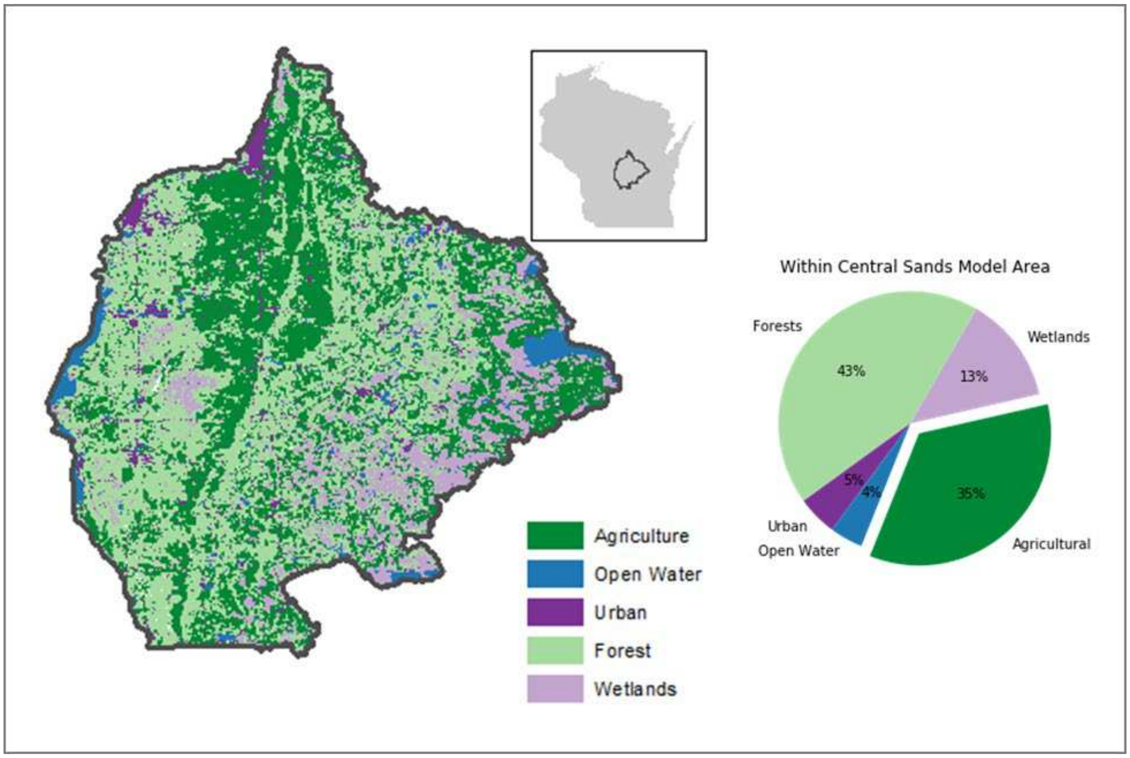


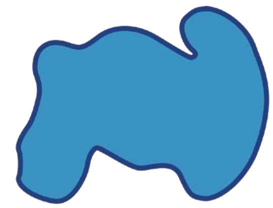
Figure 4 Central Sands Model Area Land Use Pie Chart with Corresponding Map of Land Use Coverage. 2018 land use data from the Cropland Data Layer (United States Department of Agriculture) and the Wiscland 2.0 data layer.

Figure 5 One goal of the study was to determine if groundwater withdrawals are significantly reducing lake levels on Plainfield Lake. DNR staff took the left picture in August 2011 and right picture in October 2019.

THE STUDY LAKES

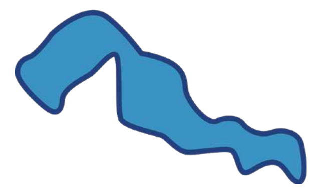
The study focused on three lakes located in Waushara County within the Central Sands Region: Pleasant Lake, Long Lake, and Plainfield Lake (Figure 3). For more information on the study lakes see Appendix B.

Pleasant Lake



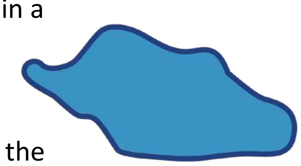
Pleasant Lake is the largest of the three study lakes, with a maximum depth of 24 feet and a surface area of 120 acres (source: Register of Waterbodies (ROW)). Pleasant Lake has many homes along the shoreline and is used for fishing, swimming, water skiing, and boating. Pleasant Lake is mesotrophic. Mesotrophic lakes are characterized by moderate plant and algae growth, medium nutrient levels, and are fairly clear with submergent plants. Pleasant Lake is the only one of the study lakes that stratifies - meaning the lake forms a warm upper and cold lower layer. Stratification is important for water quality and aquatic organisms. Pleasant Lake also has hard water, good water clarity and a high-quality aquatic plant community. It supports a fishery consisting of bluegill, pumpkinseed, perch, largemouth bass and northern pike, in addition to other non-game and small fishes.

Long Lake



Long Lake is a 40-acre lake with a maximum depth of 14 feet (source: ROW). During DNR plant surveys in 2019, the maximum depth was 12 feet. Long Lake has many homes along the shoreline. Long Lake supports a stunted bluegill and bass fishery and is used for wildlife viewing, fishing, swimming and slow/no-wake boating. Long Lake is shallow, well-mixed, and mesotrophic. Long Lake occasionally experiences low dissolved oxygen levels, even though there are mechanical aerators in the lake to improve oxygen levels.

Plainfield Lake



Plainfield Lake is a 29-acre lake with maximum depth of 12 feet (source: ROW). Plainfield Lake is within a State Natural Area and has a few homes on the shoreline (Figure 5). The lake is home to a rare, federally-protected plant and has high quality emergent wetlands. The lake only supports fish intermittently and is primarily used for wildlife viewing, birdwatching, and waterfowl hunting. Plainfield Lake is a shallow, well-mixed, oligotrophic lake. Oligotrophic lakes are typically clear, due to the low algae, productivity and nutrient levels in the lakes. Plainfield Lake has hard water (high alkalinity, calcium and magnesium concentrations).

DATA COLLECTION AND METHODS

The DNR began with an extensive literature review, by studying the geology, including a collapsed tunnel channel that hosts Long and Plainfield Lakes, the lakes, and by monitoring the groundwater system to understand what factors could cause lake levels to rise and fall. This effort was one of the most comprehensive studies of geology, groundwater and lakes within the Central Sands Region. The DNR and our partners compiled existing information and collected over two years of field data to aid in characterizing the lakes, the geology, and how groundwater moves in the study area. Although our two years of lake data collection occurred during wet periods, the extensive use of historical data and interviews with experts in other states aided in understanding the lakes in both wet and dry periods.

To support the groundwater flow model, and to characterize the lakes and their ecosystems, WGNHS led geological data collection and assisted in monitoring groundwater levels to understand the interaction between the groundwater system and the study lakes. The USGS developed, and the DNR and the WGNHS assisted with, a regional groundwater flow model and smaller inset groundwater flow models focused specifically on areas immediately surrounding the three lakes. The DNR led the field effort to characterize resources in the three lakes and nearby land uses to support the determination of impacts. The DNR also surveyed lake property owners to characterize human uses, such as recreation, for the lakes.

The statute required the DNR to show a hydrologic connection, or the flow and exchange of water, between groundwater and the study lakes. The DNR conducted various field methods and analyses to establish this connection.

For example, we verified the hydrologic connection by installing seepage meters, miniature piezometers, and monitoring wells around all the lakes (Appendix A). Our evaluation of stable isotopes and water chemistry of both groundwater and lake water showed groundwater inflow and outflow at Pleasant Lake (Appendix B).

The groundwater flow modeling process and lake characterizations worked hand in hand toward our study goals. Lake characterization determined the amount of reduction that are significant for each of the study lake and the modeling provided us baseline lake levels and told us what types of changes result from current and potential groundwater withdrawals (Figure 6). We cover more details on field data collection and methodology in Appendices A, B and C of this report and in our Central Sands Lakes Study methodology presentations.

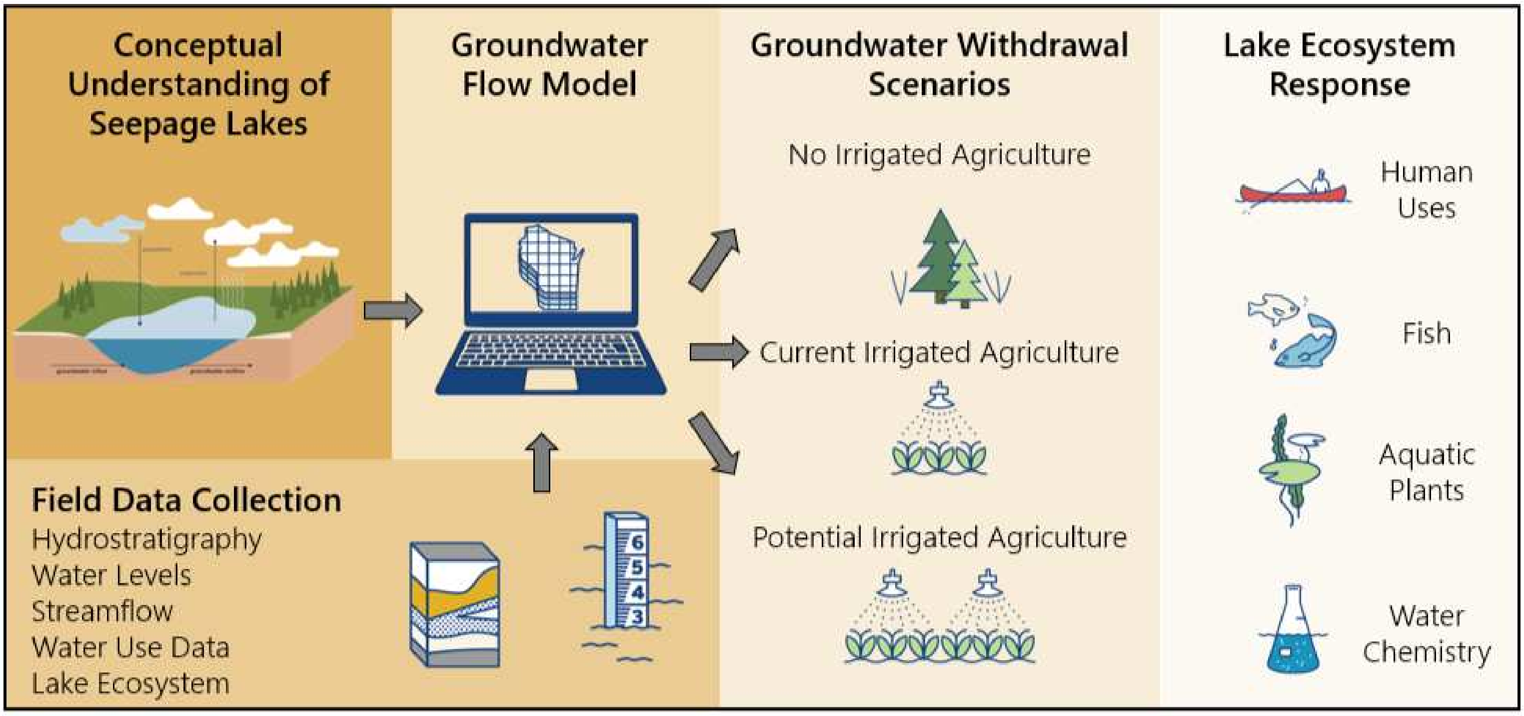


Figure 6 The Central Study Lakes Study Process Diagram

LAKE LEVELS: PLEASANT, LONG, AND PLAINFIELD

We compiled water level observations from four sources to develop a historical lake level dataset: 1) Waushara County lake monitoring records, 2) the USGS National Water Inventory System, 3) DNR monitoring records, and 4) estimates of shoreline elevations from the United States Department of Agriculture and DNR historical aerial photographs. Based on recorded lake level observations, the water levels of Pleasant, Long, and Plainfield Lakes fluctuate. The fluctuations are related to the lakes' geographical position near the regional groundwater divide, far from any large water bodies, that would control and/or stabilize water levels. During the study period precipitation rates were high and the lake levels were near or above their highest recorded observations (Figure 7).

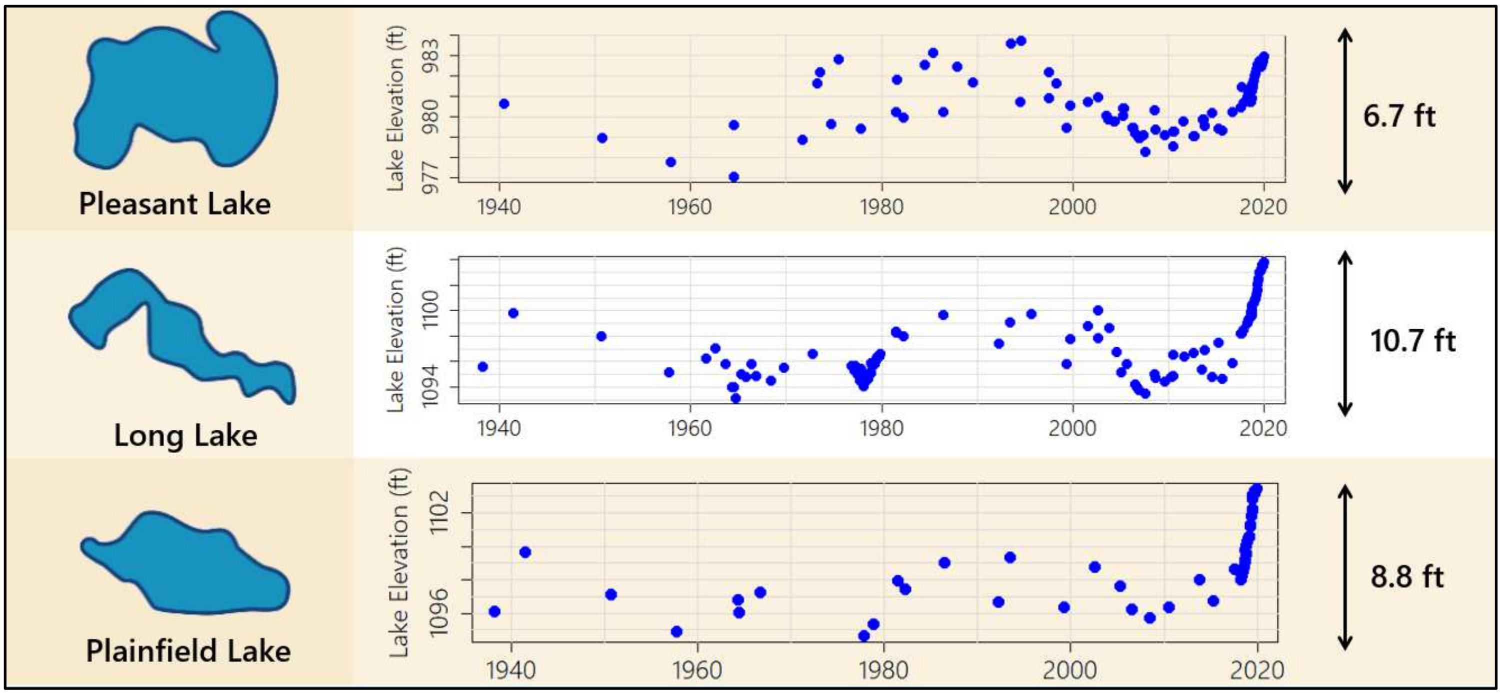


Figure 7 Graphs of lake level observations for Pleasant, Long, and Plainfield Lakes by year (1938 – 2020).

Lake levels on the three study lakes vary by up to 11 feet. These fluctuations are ecologically important to the study lakes and we incorporate the natural variation into our definition of "an average seasonal water level." As part of this study, we determined how much the lake levels were affected by groundwater withdrawals as opposed to weather.

Factors that Influence Lake Levels

Pleasant, Long, and Plainfield Lakes are seepage lakes, meaning they have no streams or rivers flowing into or out of them (Figure 6). Water levels in seepage lakes tend to fluctuate more dramatically than those in drainage lakes, where lake levels are controlled by streamflow out of the lake (Perales et al., 2020). The sources of water in the study lakes are precipitation and groundwater. Precipitation affects lake levels in two ways: 1) rain or snow falling on the lake surface or 2) precipitation contributing to recharge that then flows through the ground and into the lake. Recharge is the amount of water that moves through the soil and reaches the groundwater (water table). Below, we summarize how the geology of the region affects groundwater movement and the study lakes; how land use and recharge impact groundwater levels; and how we used modeling to characterize how groundwater withdrawals may be reducing lake levels (Figure 8).

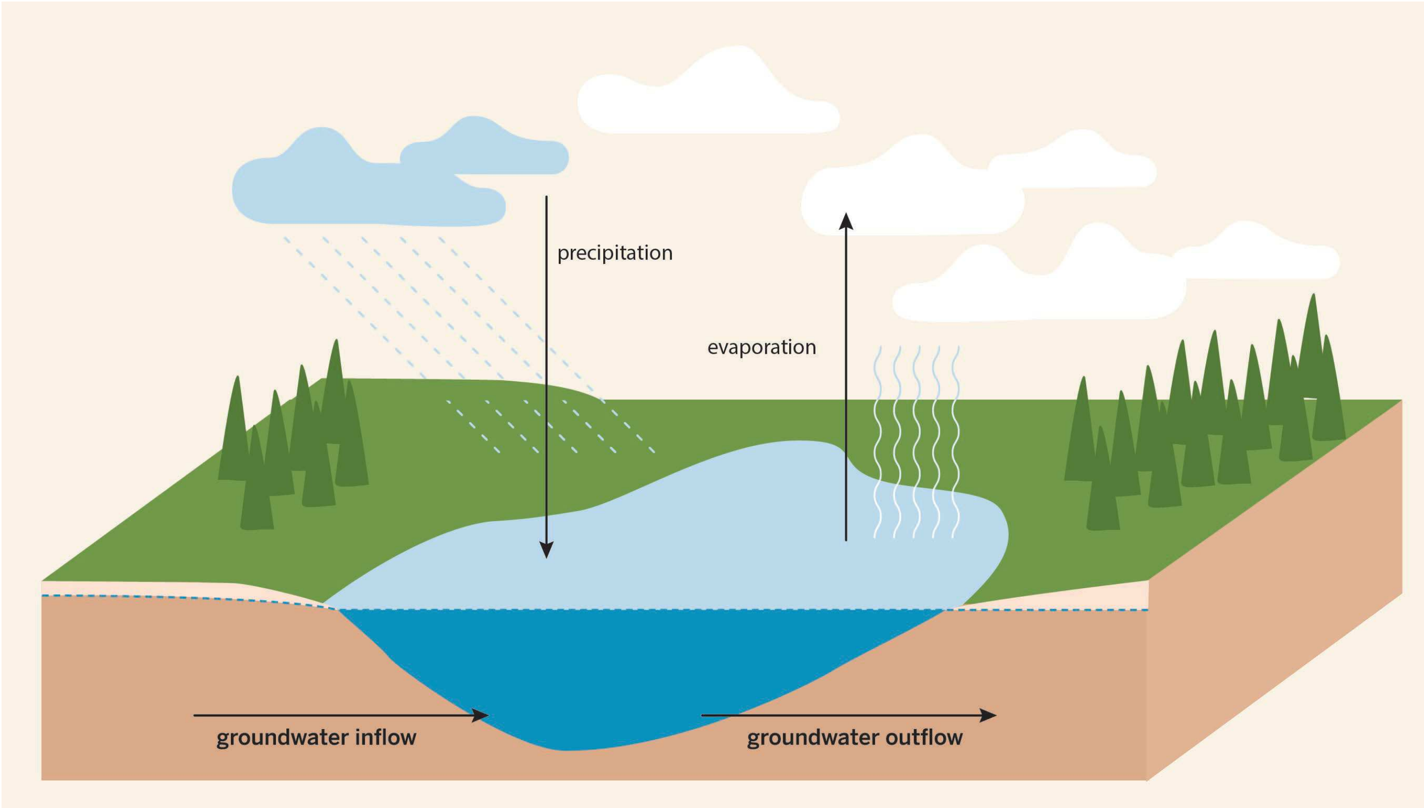


Figure 8 All three study lakes are seepage lakes, meaning they have no streams or rivers flowing in or out of them. The sources of water in the lakes are precipitation and groundwater.

STUDY AREA HYDROSTRATIGRAPHY

To understand how Long, Plainfield, and Pleasant Lakes interact with groundwater, and to build the groundwater flow model to reflect real-world conditions, we needed to understand the hydrostratigraphy of the Central Sands model area. Hydrostratigraphy categorizes and maps geologic materials based on how different layers of rocks and sediments affect the movement of water. Our work focused on hydrostratigraphy near the study lakes.

The WGNHS and the DNR examined the geology of the region by conducting field investigations and by referencing existing data sources. Existing data sources included geologic materials reported in thousands of existing well construction records, geologic logs described by WGNHS, and past geologic reports and mapping work in the study area.

We identified gaps in the existing data and conducted field investigations focused on areas around the three study lakes. The WGNHS field studies included drilling and collecting sediment from around the study lakes and in the Plainfield Tunnel Channel – a land feature due to glacial collapse that includes Long and Plainfield lakes. At most of these borehole locations, WGNHS also installed monitoring wells. We used these small-diameter wells to record water levels, sample water chemistry, and test how groundwater moves through the subsurface. We also used water levels from many other wells across the region to help develop the groundwater model.

The Central Sands has four main categories of geologic materials, or hydrostratigraphic units, and groundwater moves differently through each type: crystalline bedrock, sandstone bedrock, sand and gravel and silts and clays. Water moves easily through the sand and gravel and it is the primary hydrostratigraphic unit we see in our compiled data. In some places, this unit is several hundred feet thick. Most high capacity wells in the Central Sands Region draw water from this aquifer, and it easily transfers water in and out of lakes and streams.

Although extensive data was collected from the subsurface, the data points need to relate to one another to appropriately represent and model the entire groundwater system. Understanding the processes that were happening as glaciers deposited sediments in different parts of our study area helps us to do this. Figure 9 shows the different depositional environments from the glaciers in the Central Sands model area. To read more about the depositional environments and hydrostratigraphic units see Appendix A.

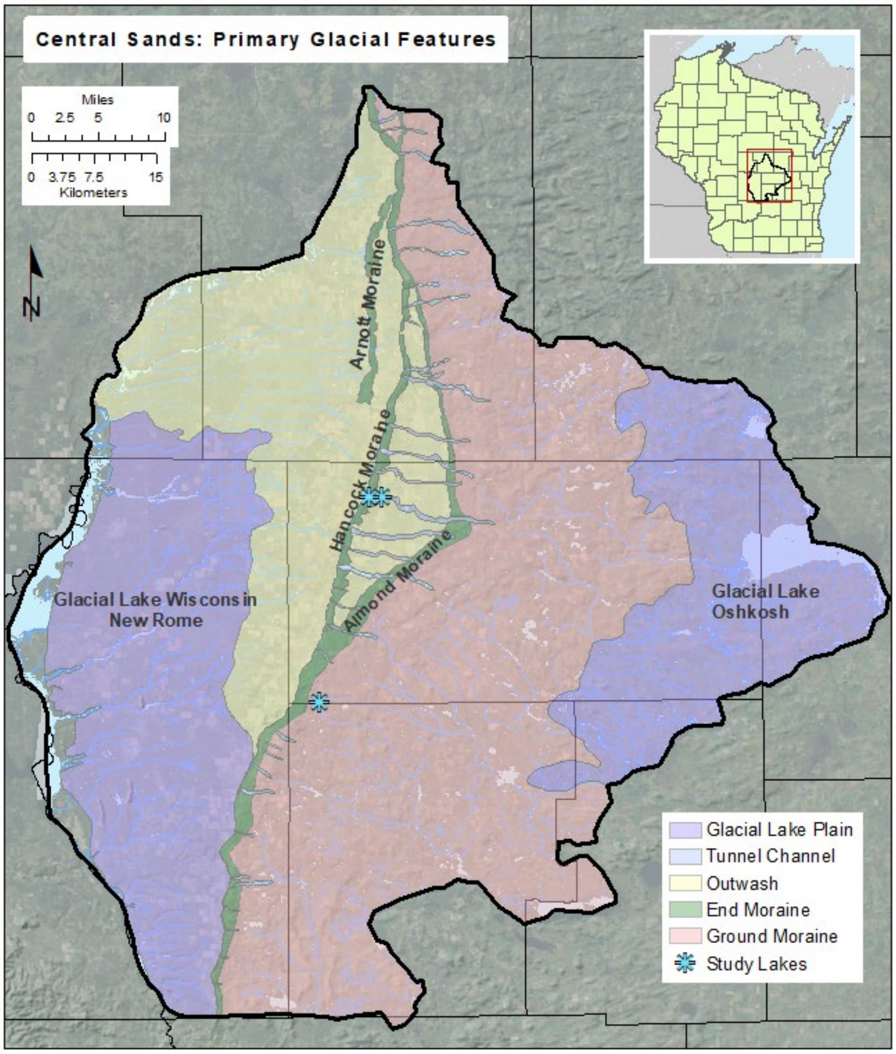


Figure 9 Areas of glacial deposition in the Central Sands model area (from WGNHS, Appendix A).

Figure 10 shows the distribution of coarse and fine sediments in a cross section of the study area. All three study lakes are located high on the landscape, near the groundwater and surface water divides, where water levels are more variable. West of the divide, groundwater flows toward the Wisconsin River in the Mississippi River basin and east of the divide groundwater flows toward the Fox-Wolf River system in the Lake Michigan basin (Figure 10). More information on data collection and how the sediments were deposited and mapped is in Appendix A.

The WGNHS and the DNR conducted field work to determine how well the lakes were connected to groundwater. We installed monitoring wells at thirty-two sites around the lakes: twelve around Pleasant Lake, ten sites around Long Lake, and ten around Plainfield Lake. We studied groundwater flow through the lakebeds, sampled water chemistry, and compared water levels in the lake to surrounding wells. The conclusion drawn from these studies was that, while water may move slightly slower through the lakebed than through the surrounding aquifer, water can and does move freely between them. We used this lakebed data to inform the groundwater flow model.

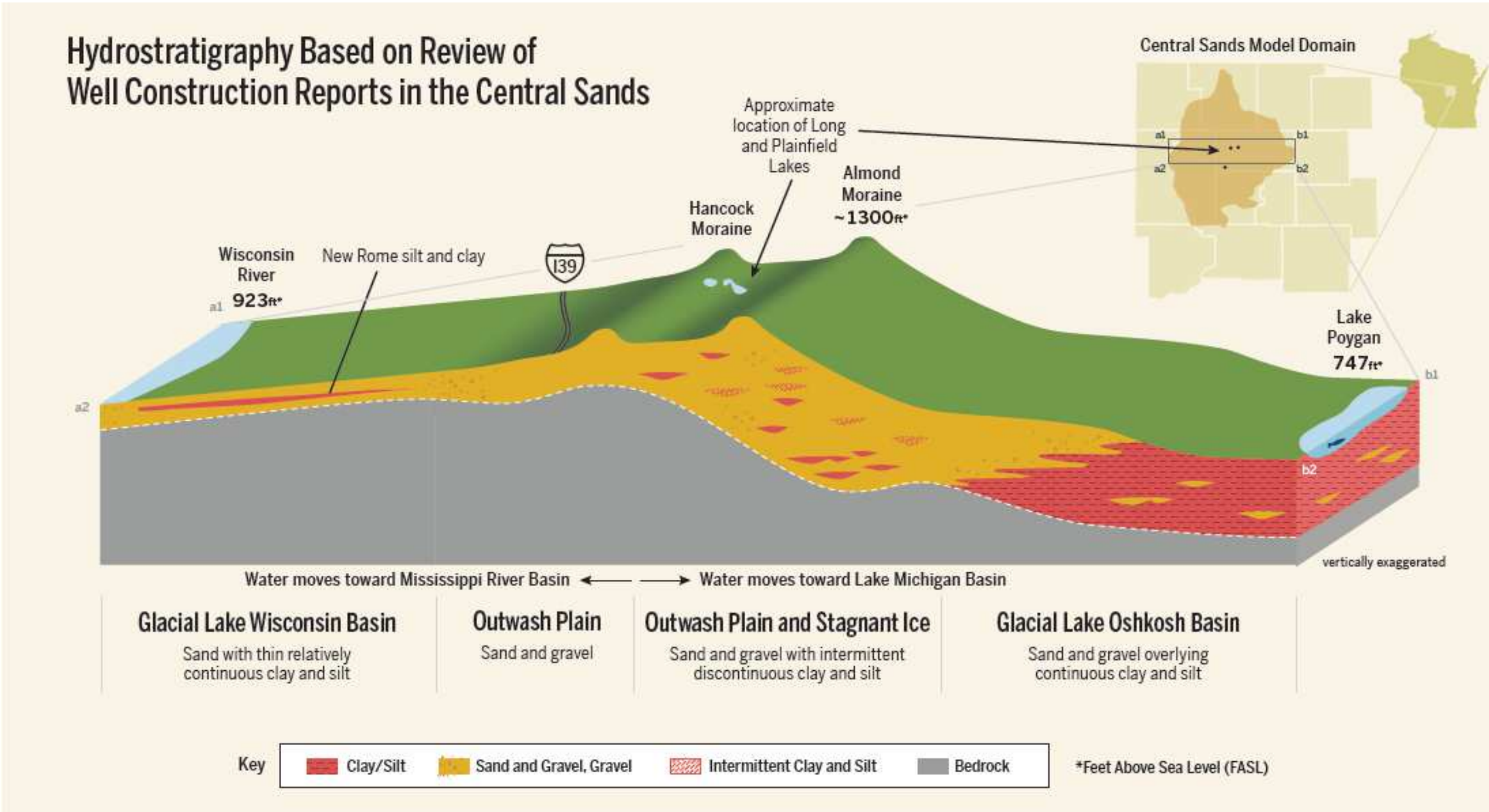


Figure 10 Drawing of landscape and sediments along a west to east profile through the center of the modeling area.

The Central Sands Region's primary sediment type and aquifer is sand and gravel. In some areas, layers of fine-grained materials like silts and clays can also affect the pathway or timing of groundwater flow. Some of these fine layers are found near Long Lake. However, multiple sources of evidence show that these layers do not separate the lakes from the groundwater flow system (Appendix A). Pleasant, Long, and Plainfield lakes are all well-connected to groundwater.

LAND USE AND RECHARGE

The hydrostratigraphy is one component that influences how much water enters and leaves the groundwater system. It is important to consider the primary hydrologic inputs and outputs, a process called the water budget. The water budget is critical to evaluating and modeling the hydrology of the three study lakes and answering the question: *Do groundwater withdrawals affect lake levels in Pleasant, Long, and Plainfield Lakes?* One of the most important components of the water budget is recharge, the amount of water that percolates through the subsurface and reaches the water table.

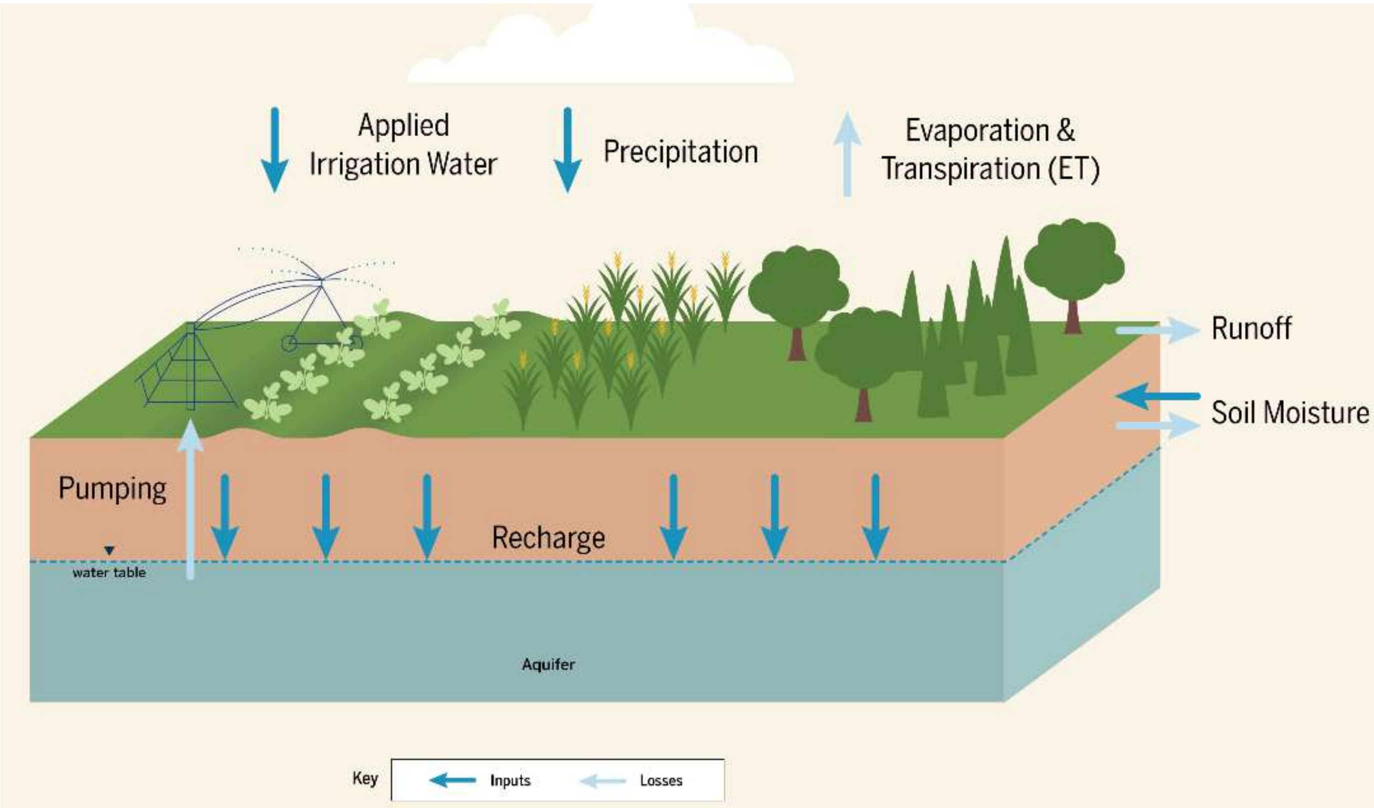


Figure 11 Groundwater Budget Diagram

For the study, we investigated many factors controlling variation of groundwater recharge under different land uses. The key components for our recharge model (Soil Water Balance) and our groundwater flow model were precipitation, evapotranspiration (ET), and high capacity well pumping (Figure 11). ET is the amount of water that is transpired (is given off as water vapor) by plants or evaporates directly into the atmosphere without infiltrating to the water table. All these components are connected, and ET, pumping, and recharge are all influenced by land use. Two of the questions we asked in the beginning of the study were: *Did "unimpacted" land conditions ever exist?* and *If a parcel of irrigated land was changed to a different land use type with no groundwater withdrawals, what change would that make to lake levels?*

The DNR researched land use history in the region to determine whether historic lake level observations collected before widespread irrigation began in the 1960s could represent 'unimpacted' conditions. Our review of literature regarding historical land use showed that human activities changed the movement of water in the Central Sands Region for at least a century before the beginning of irrigated agriculture. Widespread landcover changes included: lumbering, land clearing for dry-land farming, widespread planting of trees, widespread ditching for wetland conversion, and the growth of grasslands or scrub (Appendix F). Teasing out the effects of these changes is beyond the scope of our study, but we concluded that 20th century lake level records collected prior to widespread irrigation are also likely impacted by various human activities, and not just irrigation practices.

To understand the impact of land use on lake levels in the Central Sands, we looked at irrigated agricultural land and non-agricultural land to see how different evapotranspiration and recharge vary. Land use controls how much evapotranspiration there is (e.g. pine trees and potatoes use water differently), and land use controls how much pumping there is (potatoes are usually irrigated, pine trees are usually not). For irrigated land parcels, water is pumped and then applied back onto the land surface. Depending on the crop, irrigated water needs vary. Some of that applied water is taken up by the plant, and either stored in the plant or transpired. For unirrigated parcels, the water available for evapotranspiration is mostly from precipitation. Our focus is on irrigated agriculture because 95-99% of groundwater withdrawals near the study lakes are used for irrigation; in other parts of the Central Sands, pumping for other uses, or from other ponds or surface waters, could have their own impacts to lake and stream levels.

To quantify the impacts of irrigated agricultural pumping on lake levels, we came up with three scenarios: one where we kept current irrigated agricultural parcels, another where we replaced all the irrigated agricultural parcels with non-agricultural land uses, and a third where we added additional irrigated agricultural parcels by converting non-agricultural land uses (see "Modeling Scenarios" below). We based the substituted non-agricultural land uses on existing land use patterns for non-irrigated lands in the Central Sands so they would be realistic (Appendix F). Since recharge is difficult to measure directly, we used a Soil Water Balance model to estimate those recharge rates.

THE SOIL WATER BALANCE MODEL

We used a complex water budget tool, the Soil Water Balance Model, to estimate recharge as an input to the groundwater flow model. The Soil Water Balance Model accounts for changes in precipitation, temperature patterns, evapotranspiration rates, soil moisture rates, and how much groundwater is extracted and used for different crops, and does so at a daily scale, which allows us to look at trends in recharge throughout the year (see Appendices C, D and F).

The results from the Soil Water Balance model are validated against independent measurements and estimates, such as water use reporting and modeled evapotranspiration estimates from products such as NASA's MODIS data. While the predictions from the Soil Water Balance model compare reasonably well with the independent estimates and measurements, there is still some uncertainty in how the model performs at estimating recharge. To account for uncertainty in our recharge estimate, we used the Soil Water Balance model with 349 combinations of parameters to produce a range of recharge estimations. We used this range of estimates to produce a range of possible lake drawdown estimates. The results of our approach for recharge estimation tell us the following:

- Precipitation has the largest effect on how much water reaches the water table, with more recharge in wetter years and less recharge in drier years.
- While precipitation largely controls recharge, land use and irrigation have smaller but persistent impacts on recharge.
- Differences in precipitation and evapotranspiration patterns, land use, soil types and many other factors can lead to different recharge rates – even on nearby fields.
- When making comparisons, we need to look at effective recharge, not total recharge for irrigated agriculture. Effective recharge accounts for applied irrigation and pumping.

GROUNDWATER MODELING: ARE GROUNDWATER WITHDRAWALS REDUCING LAKE LEVELS?

We combined the Soil Water Balance model with the Central Sands groundwater flow model to reproduce real-world observations from years 2012-2018. We chose the 2012-2018 time period because it includes reported water use records to simulate groundwater withdrawals, as well as the most complete set of measurements of lake levels, groundwater levels, and streamflows for us to see how well the model is performing. We used the location and reported groundwater withdrawal rates of approximately 3,000 currently operational high capacity wells within the study area. Once we developed a model that was able to reasonably reproduce real-world observations for the 2012-2018 period, we were able to use it to simulate lake levels of our study lakes under different modeled scenarios.

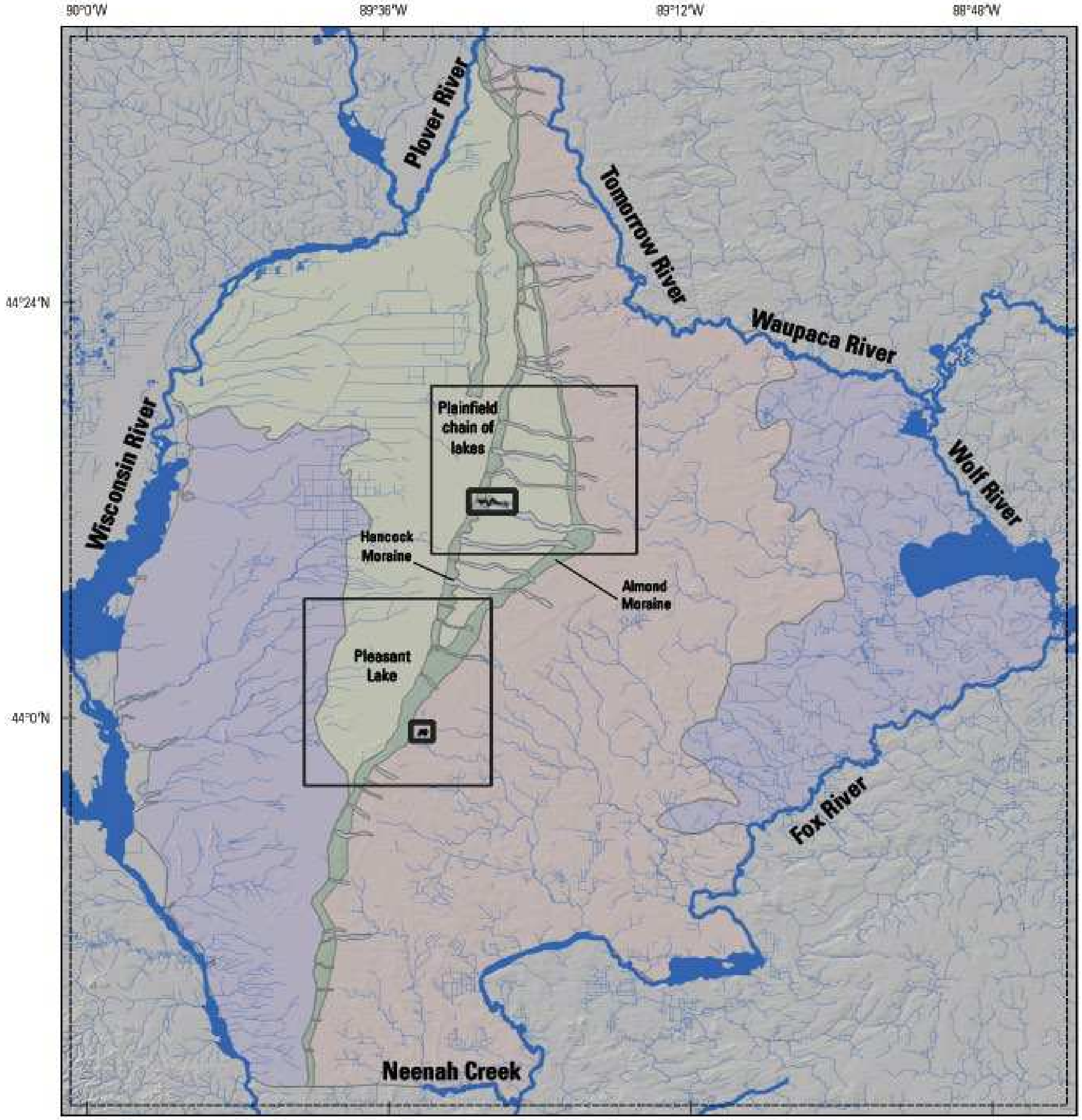


Figure 12 The Central Sands model area extends to major surface water bodies (in blue). The black rectangles are the boundaries for inset groundwater models around areas of interest. The smaller rectangles are modeled areas with even more refinement around the study lakes.

Modeling Scenarios

We used the model to determine if groundwater withdrawals reduce lake levels from the "average seasonal water level." We created three scenarios to help us answer this question – a "no-irrigated-agriculture" scenario, a "current-irrigated-agriculture" scenario, and a "potential-irrigated-agriculture" scenario. We focused on just irrigated agriculture because 95-99% of all groundwater pumping within the inset models (areas zoomed in around the lakes) is currently being used for irrigating crops (Figure 12). For these scenarios, we used a longer, 38-year time period in order to represent a range of weather conditions (corresponding to the climate between 1981 and 2018) to see the full range of high and low lake levels due to weather. We created two additional scenarios to help us determine the area contributing to any impacts from irrigated agriculture, and how long it takes those (potential) impacts to reach the lakes.

Scenario 1: No Irrigated Agriculture

In the no-irrigated-agriculture scenario, we replaced irrigated agriculture and its associated groundwater withdrawals with a mix of forest, grassland, non-irrigated agriculture and wetland land uses. This land use distribution map is not historical, and it is not a possible future, but it is a needed comparison point for the study. This scenario allows us to answer the question, how much would lake levels vary due to weather alone, in the absence of groundwater withdrawals?

Scenario 2: Current-Irrigated Agriculture

We based the current-irrigated-agriculture scenario on 2018 crop rotations, with crops assigned based on how frequently they appear in a crop rotation cycle, except for potato/vegetable irrigated crops that follow a 4-year crop rotation schedule. The difference in lake levels between this scenario and the no irrigated agriculture scenario is an estimation of the change in lake levels that can be attributed to current withdrawals.

Scenario 3: Potential-Irrigated Agriculture

In the potential-irrigated-agriculture scenario, we attempted to identify all land that might be converted to irrigated agriculture and assign reasonable crop rotations to that potentially irrigable land. This is unlikely to happen, but it represents a possible growth of irrigated agriculture within the regional model domain. The difference in lake levels between the potential-irrigated agriculture scenario and the no-irrigated agriculture scenario is an estimation of the amount of change in lake levels that could potentially occur if the amount of irrigated agriculture continues to increase in the region.

Scenarios 4 and 5 illustrate the connection between irrigation and land use near Long Lake and the responses in water levels at Long Lake.

Scenario 4: Distance

For the distance scenario we assessed what the role distance between a well and Long Lake might have on impacts to the lake (i.e. the distance between the lake and the well and impacts the wells have on the lakes levels). We started with the current-irrigated-agriculture scenario and then sequentially converted wells and land use from the current-irrigation land use to the no-irrigation land use. The distance scenario illustrates the cumulative effects of pumping on lake stages as a function of distance and helps us identify how many wells are contributing to differences in lake levels.

Scenario 5: Lag-Time

Through the lag-time scenario we assessed the of timing between pumping and changes in water levels at Long Lake. This scenario was similar to the distance scenario but agriculture wells were combined into groups of 16 wells at similar distances from Long Lake. We had to lump the wells together, because the individual well impacts were too small to discern. The lag-time scenario illustrates the magnitude and timing of effects from groups of wells at various distances from Long Lake.

All of the modeling scenarios are described in more detail in Appendix C.

DETERMINING SIGNIFICANCE OF LAKE LEVEL REDUCTIONS CAUSED BY GROUNDWATER WITHDRAWALS

To determine whether Pleasant, Long, and Plainfield Lakes lake levels have been reduced in a ‘significant’ way requires us to understand the sensitivity of lake resources and determine if lake levels are outside a range where impacts are not harmful. Just as understanding the geology, hydrology, water and land use, and climatic conditions support the understanding of groundwater flow through the modeling process, understanding and characterizing the lake resources help us evaluate the lake ecosystem response to changes in lake levels.

The statute directed the DNR to determine whether groundwater withdrawals are causing “significant reduction of average seasonal water levels” at Pleasant Lake, Long Lake, and Plainfield Lake. Wis. Stat. § 281.34(7m)(2)(b). The statute does not define “average seasonal water level” or “significant reduction.” For purposes of this study, the DNR defined “average seasonal water levels” to reflect not only the median levels, but include the entire hydrologic regime of high and low lake levels that occur on the study lakes. For purposes of this study, we defined "significant reduction" to be a deviation from this natural lake level pattern that is large enough to cause a significant impact to the ecosystems of Pleasant, Long, and Plainfield Lakes. The DNR used five components of flow patterns (magnitude, frequency, duration, rate of change, and timing) to develop metrics to assess whether modeled reductions in lake levels would cause significant impacts. The modeled scenarios showed us that groundwater withdrawals only affect one aspect of these lake levels: their magnitude. Magnitude refers to the size, or extent, of the water level changes. We provide additional information on the study lake hydrologic metrics in Appendix B.

We used water use, varied land use, and climate scenarios in the groundwater model to calculate lake level changes. We characterized the lakes and evaluated lake responses to determine if a reduction in lake levels from groundwater withdrawals is significant.

Lake Ecosystem Categories

To characterize the lakes, we considered four lake ecosystem categories: human use, fish, aquatic plants, and water chemistry. While these categories do not include all aspects of these lake ecosystems, such as amphibians or birds, we know that plant habitat is critical to these animals, so we considered our evaluation of aquatic plants to be a proxy for impacts to other categories not used in this study. We characterized the human uses (e.g. boating, fishing, observing wildlife), fish, aquatic plants, and water chemistry of each lake by collecting two years of field observations, analyzing historical data, reviewing historical lake reports and scientific literature, and surveying lake residents (Appendix B).

For each lake ecosystem category, we evaluated lake levels relevant to different ecosystem indicator criteria, such as ability to use a lake for docks and boating or extent of fish habitat. We determined criteria to use as ecosystem indicators based on other relevant studies, professional judgement, and the results of fieldwork. Some ecosystem indicators, such as changes in the plant community distribution, were applicable for all the study lakes, while others were only relevant for some of the lakes. For example, Pleasant Lake is the only lake deep enough to stratify, but it is shallow enough that lower lake levels could cause it to stay at a uniform temperature from top to bottom.

In our analyses, we found that the rise and fall of lake levels on Pleasant, Long, and Plainfield Lakes is important to the health of the lake ecosystems. For example, high lake levels help clear out upland vegetation, and low lake levels offer an opportunity for inland beach and emergent plants to germinate and survive (Figure 13).

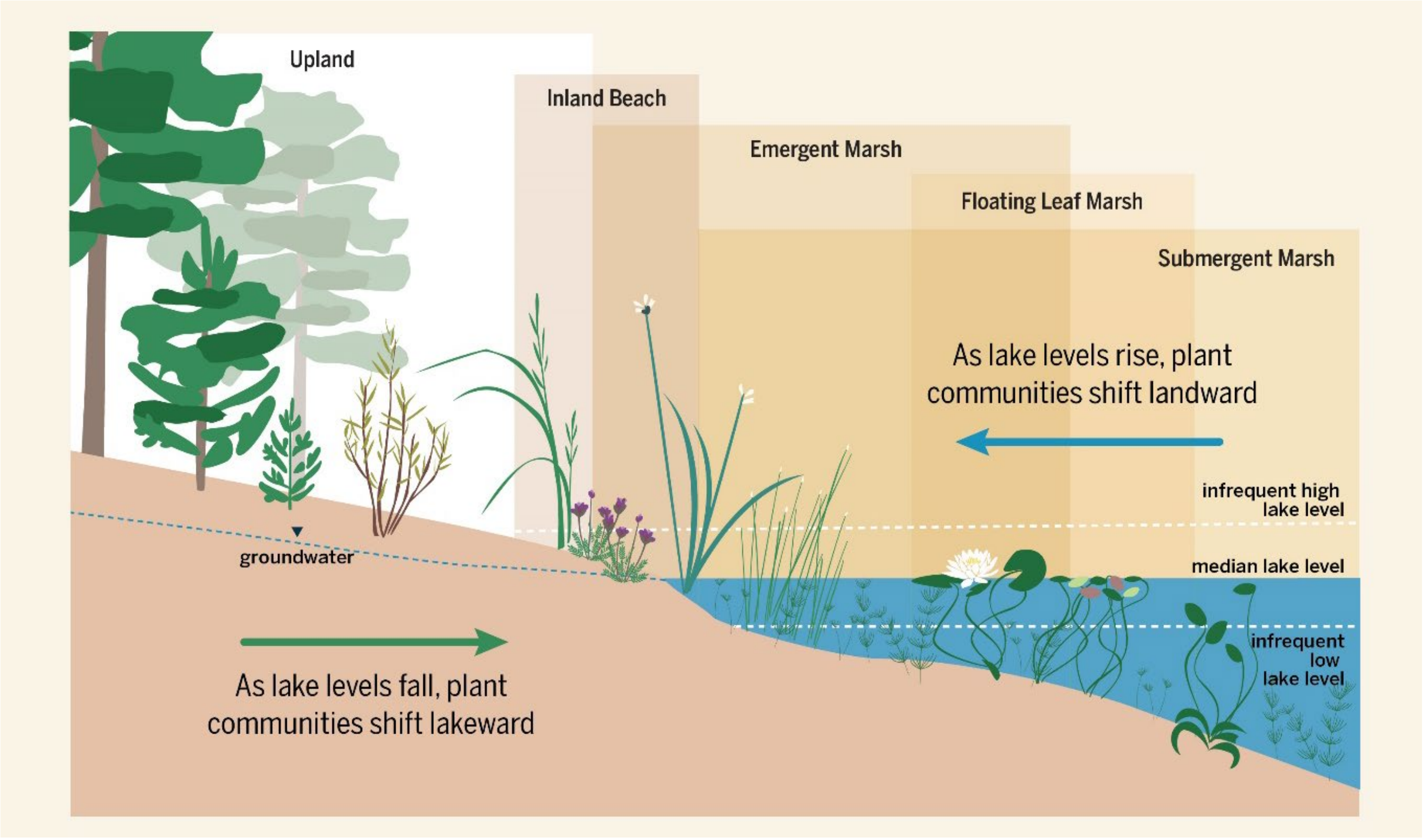


Figure 13 The rise and fall of lake levels in our study lakes are necessary for a healthy ecosystem. The primary goal of the study was to determine if groundwater withdrawals are causing a significant reduction of lake levels and impacting the lakes' ecosystems.

Lake Level Reductions

At all three study lakes, we concluded current groundwater withdrawals shift the water levels lower (Figure 14). Current irrigated agriculture causes lake level reductions across the entire suite of lake levels (low levels, median levels, and high water levels[1]), but by a different amount on each lake. For example:

- On Pleasant Lake, median levels drop by 0.4 feet.
- On Long Lake, median levels drop by 3.3 feet.
- On Plainfield Lake, median levels drop by 2.3 feet.

For each of the study lakes, we determined whether groundwater withdrawals alter the lake levels (high, median and low) enough to exceed a single ecosystem indicator. Then we used the most sensitive ecosystem indicator (human uses, fish, plants, or lake chemistry) to ultimately make the significance determination for each lake. As we explain below, most indicators for a given lake concluded the same significance determination as the most sensitive indicator.

We also concluded potential groundwater withdrawals from irrigated agriculture could cause lake level reductions across the entire suite of lake levels (high levels, median levels, and low water levels), but by a different amount on each lake. For example:

- On Pleasant Lake, median levels drop an additional 0.3 feet beyond reductions from current-irrigated agriculture.
- On Long Lake, median levels drop an additional 0.5 feet beyond reductions from current-irrigated agriculture.
- On Plainfield Lake, median levels drop an additional 0.4 feet beyond reductions from current-irrigated agriculture.

[1] In this document the terms "low levels" and "high levels" are the same as infrequent low levels and infrequent high levels, respectively, in Appendix B.

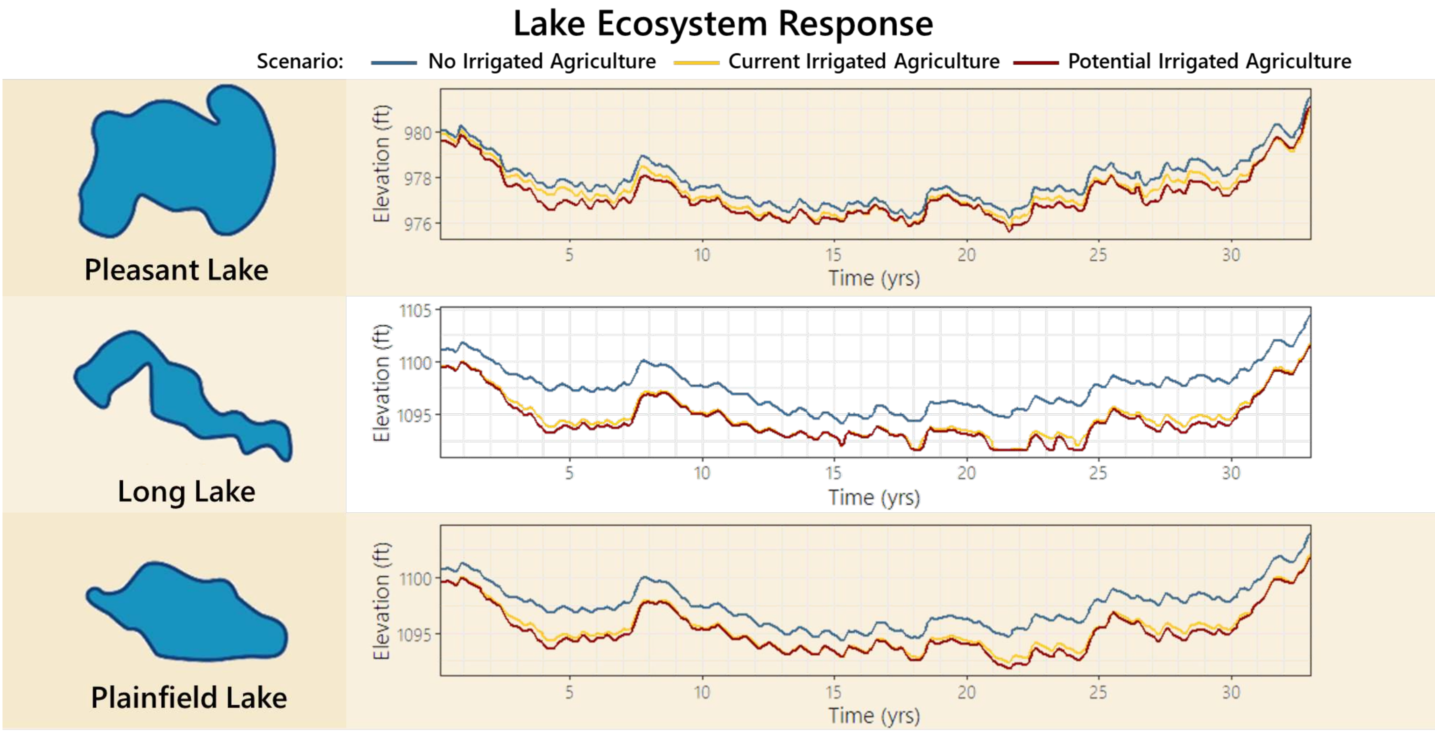


Figure 14 Lake level reductions based on current- and potential- irrigated agricultural modeling scenario results for Pleasant, Long and Plainfield Lakes.

Pleasant Lake Impacts

Our study showed that current groundwater withdrawals reduce Pleasant Lake levels up 0.4 to 0.5 feet. Our impact analysis found that this is not a significant reduction in lake level that causes impacts to any of our ecosystem indicator categories (human uses, fish, plants or water chemistry) (Figure 15). However, we note some ecosystem indicators are very close to their thresholds and/or could become impacted under our potential groundwater withdrawals (Appendix B).

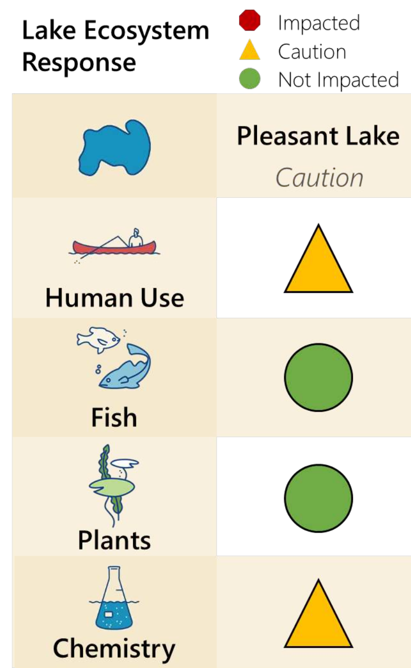


Figure 15 Pleasant Lake Ecosystem Response

We found dock use to be the most sensitive human use ecosystem indicator at Pleasant Lake. We do not tie dock use impacts to a specific lake level, so our impact assessment was based on metrics like the percent of time that docks were able to remain in place the entire season. Although natural lake level fluctuations often require dock owners to move their docks, we tested whether current groundwater withdrawals would make this more common. We found that the frequency of poor conditions for putting docks in place or for leaving them in place the entire season increased. This increase was not enough given model uncertainty to warrant a significant reduction of lake levels with current groundwater withdrawals, but it became significant under potential groundwater withdrawals. Thus, we labeled it with a caution flag.

At Pleasant Lake, the DNR found fish habitat to be the most sensitive ecosystem indicator at median and high levels. For example, fish habitat would become significantly impacted with a drop of approximately 1.5 feet from the median or high lake levels. We found the most sensitive ecosystem indicator for reductions to the low lake level was lake stratification. If low lake levels at Pleasant Lake drop 0.2 feet, Pleasant Lake would shift from a stratified to mixed lake, a key factor in lake ecology. Our model results indicate that current- and potential-irrigated-agriculture reduce low lake levels 0.4-0.5 feet, which is below the tipping point for stratification, a key factor in maintaining lake ecology (Figure 16). This change is within our model uncertainty, so we cannot definitively conclude that Pleasant Lake would lose stratification (become mixed) more often in the modeled irrigated agriculture scenarios versus the no-irrigated-agriculture scenario. As a result, we did not determine that this reduction is significant, but we note chemistry indicators with a caution flag on Pleasant Lake. Under the potential-irrigated-agriculture scenario, lake levels were not significantly reduced to impact fish, chemistry or plants.

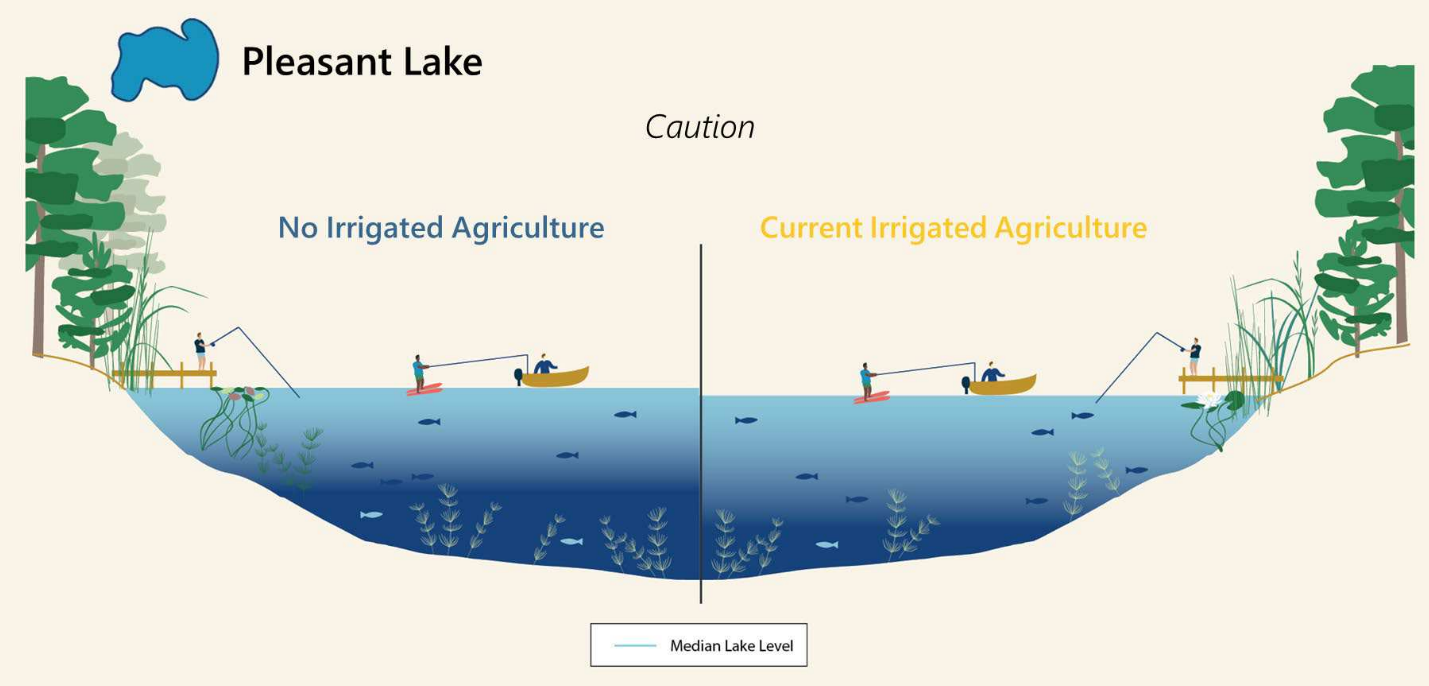


Figure 16 The image on the left shows Pleasant Lake in the no-irrigated-agriculture scenario. The image on the right shows lowering of lake levels from the current-irrigated-agriculture scenario. We did not find a significant reduction to lake levels on Pleasant Lake, but indicators related to water chemistry and human use warrant caution.

Long Lake Impacts

Our study showed that at Long Lake, current groundwater withdrawals reduce lake levels approximately 3 feet. Our ecosystem impact analysis found that this reduction in lake levels results in significant changes to all of our ecosystem categories (human uses, fish, plants and water chemistry) (Appendix B)(Figure 17). Long Lake is sensitive to lake level changes due to its shallow depth and small changes in lake levels can result in significant changes to the lake's ecosystem. The lake level reductions that we calculated from current groundwater withdrawals are considerably greater than the thresholds for seventeen of the nineteen ecosystem indicators we applied to Long Lake.

At Long Lake, we found fish habitat to be the most sensitive ecosystem indicator. Despite the presence of aerators at Long Lake, the calculated reductions in lake volume are expected to result in negative impacts to fishery. We determined a 0.4-foot lake level reduction in Long Lake would result in a significant impact. We observed the modeled reduction to the average lake level to be about 3.3 feet, exceeding this significance threshold.

We also observed that current groundwater withdrawals result in impacts to plants, human uses, and (to a lesser extent) lake chemistry (Figure 18). We found Long Lake shifts from a lake-state to a wetland-state much of the time. This shift involves loss of submergent and floating leaf plants, filling in by emergent plants, and encroachment of upland plants (Figure 13). In addition, we observed non-motorized boating, dock impacts and limited fishing opportunities. We found lake water chemistry to be impacted only during very low lake levels. We found all ecosystem indicators show increasing impacts with potential groundwater withdrawals and the most noteworthy change is that Long Lake would become dry >10% of the time.

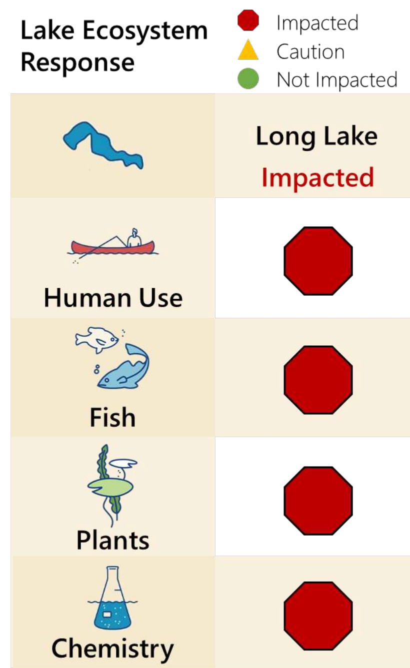


Figure 17 Long Lake Ecosystem Response

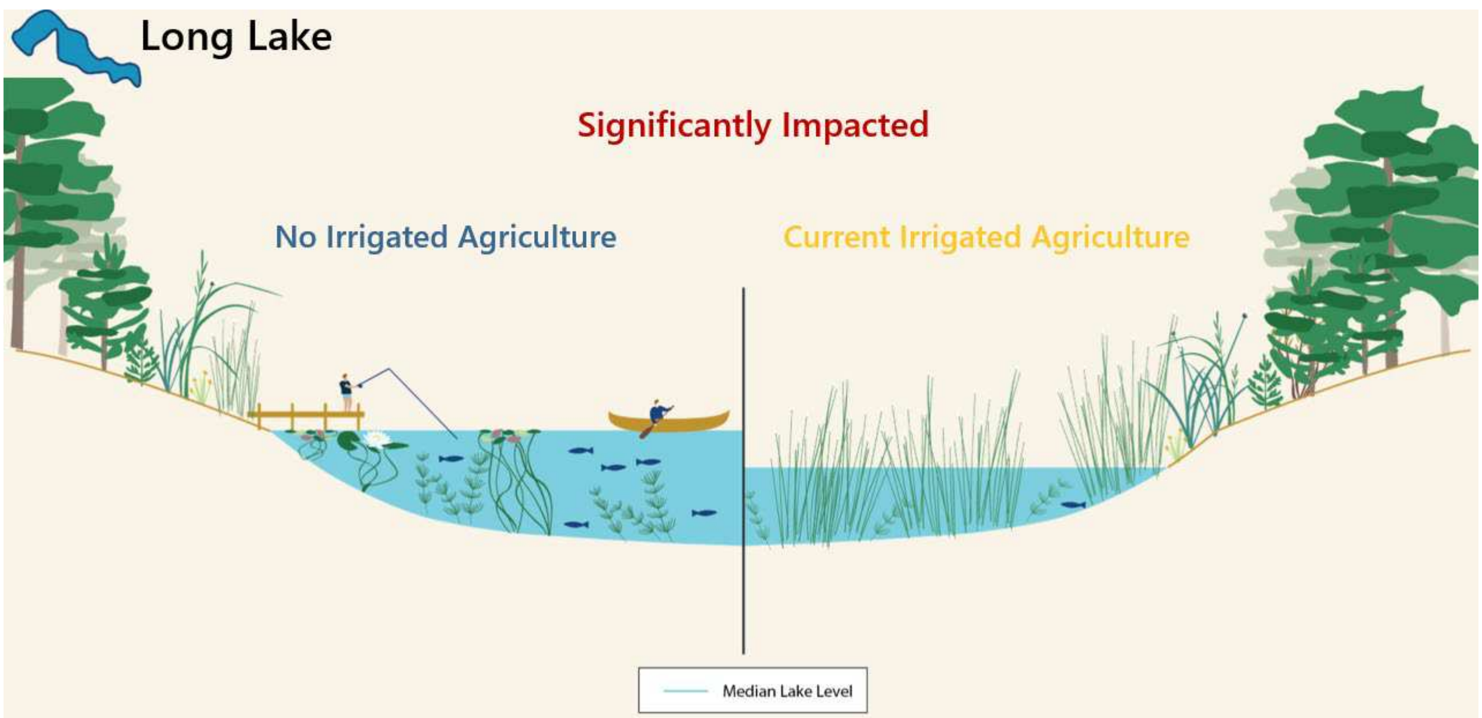


Figure 18 The image on the left shows Long Lake in the no irrigated scenario. The image on the right shows lowering of lake levels from current irrigated agriculture. Groundwater withdrawals significantly reduce lake levels, impacting human uses, plants, fish, and water chemistry.

Plainfield Lake Impacts

Our study showed that current groundwater withdrawals reduce Plainfield Lake levels by about 2 feet. Our ecosystem impact analysis found lake level reductions result in significant changes to the human use and plant ecosystem indicators, but not to water chemistry (Appendix B)(Figure 19). Plainfield Lake is sensitive to lake level changes due to its shallow depth, and small changes in levels can result in significant changes to the lake's ecosystem. We did not evaluate impacts to fish at Plainfield Lake because fish occur intermittently, and the lake is not managed to maintain a fishery. Nonetheless, Plainfield Lake provides high-quality habitat for fish and wildlife, and the plant indicators should serve to protect these aspects of the lake as well.

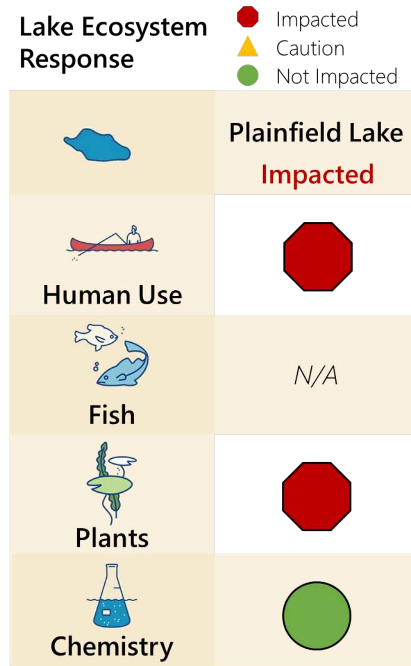


Figure 19 Plainfield Lake Ecosystem Response

We found the most sensitive ecosystem indicators for reductions to the low and high lake levels at Plainfield Lake are changes to its plant communities, including a state-endangered and federally threatened plant (Figure 20). This inland beach plant thrives on exposed sand when lake levels are low but requires periodic flooding to kill back competitors like shrubs and trees. Our study established that maintaining a similar average and range of lake level fluctuations as in the past is critical to its plant communities. We determined a 0.6-foot lake level reduction in Plainfield Lake would result in a significant impact to the threatened plant species. We observed the modeled reduction to the average lake level is about 2.3 ft, exceeding this significance threshold. We found Plainfield Lake moves toward an emergent wetland plant community rather than a floating-leaved and submergent plant community (Figure 13). Changes to the plant community would become more severe with potential groundwater withdrawals. In addition to the impacts to the plant communities themselves, we expect that changes in vegetation also result in changes to the wildlife communities that depend on those plants.

While Plainfield Lake has few homes along the shoreline, it is part of state natural area and has a public boat launch for non-motorized boating. We found that current groundwater withdrawals result in impacts to non-motorized boating by reducing the frequency at which Plainfield Lake is deep enough for paddle sports. We found potential groundwater withdrawals non-motorized boating remains impacted and the frequency that Plainfield Lake exhibits a lake state significantly declines.

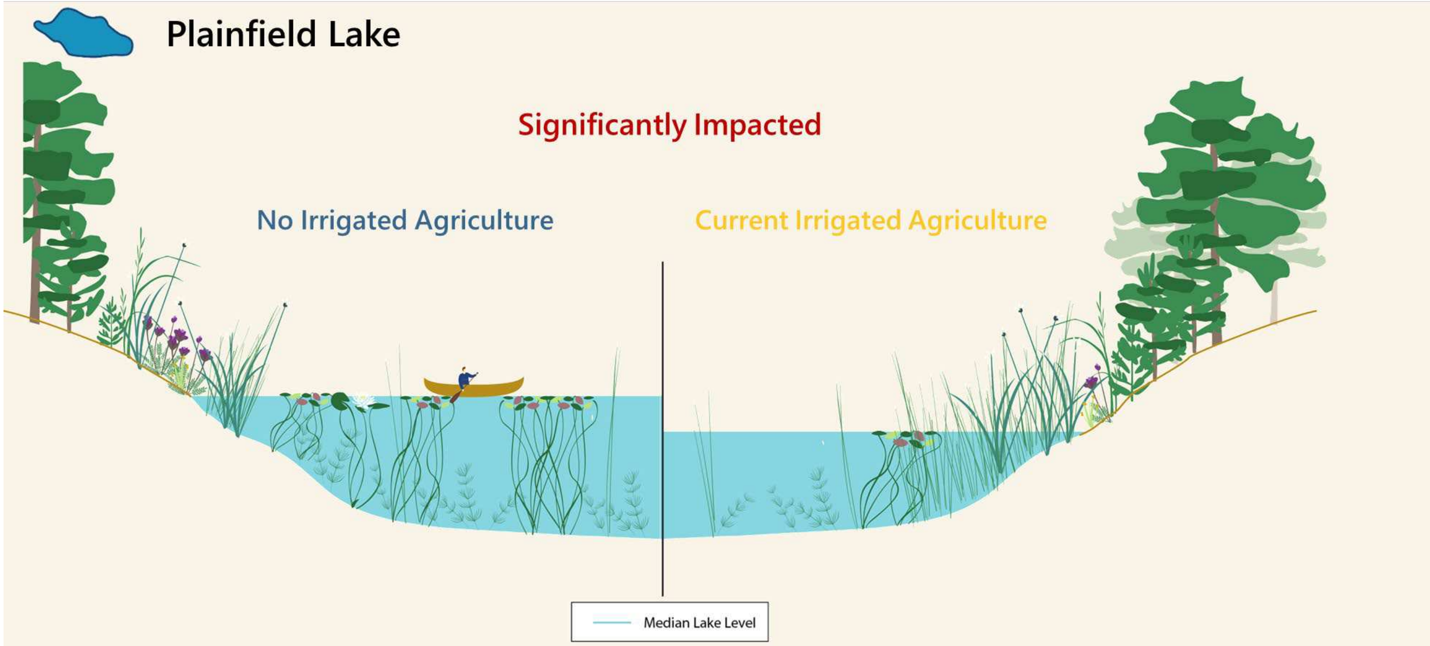


Figure 20 The left side of the graphic shows Plainfield Lake in the no-irrigated scenario. The right side of the graphic shows lowering of lake levels from current-irrigated agriculture. Groundwater withdrawals significantly reduce lake levels, impacting human uses and plants.

SOURCE OF IMPACTS

We discovered that Long and Plainfield Lakes are significantly impacted under the current-irrigated-agriculture scenario. So we asked the question: *where are those impacts coming from?* We ran Scenario 4 to delineate the area contributing to the significant reduction in lake levels at Long and Plainfield Lakes. This scenario helped us identify how many wells are contributing to significant lake level reductions.

A single well can result in groundwater drawdown and when more wells are added nearby it causes the water table to drop further. Our study shows that all three lakes are affected by a large number of wells spread over a large area. The significant reduction and resulting impacts to Long Lake are a result of the collective drawdown from about 200 nearby wells, or all the irrigation wells within about 5 miles of Long Lake. All of these wells would need to stop pumping to achieve water levels that do not result in significant reductions and related impacts. Using the same scenario, we found we would have to eliminate pumping from approximately 140 nearby wells, or all the irrigation wells within about 4 miles of Plainfield Lake, to prevent significant reductions to lake levels.

We also noted that 19 other lakes and 3 headwaters streams are within the same 5-mile radius area surrounding Long Lake. The same high capacity wells that are impacting Long and Plainfield Lakes may also be impacting the nearby water resources.

For example, we know groundwater withdrawals affect lakes differently than streams. Streams tend to be shallower and contain less water than lakes, so a relatively small water level decrease could cause a stream reach to go from average flows to much lower flows, or cause a stream to go dry (Figure 21). Our preliminary results indicate that the North Branch of Ten-mile Creek may be substantially depleted by groundwater withdrawals (e.g. modeled median August flows were depleted by over 20%). We did not evaluate stream impacts for significance as part of this study, but the estimated reductions exceed ecological thresholds defined in similar settings in other states. For example, Michigan law considers a 14% reduction to this type of stream significant (Hamilton and Seelbach, 2011).

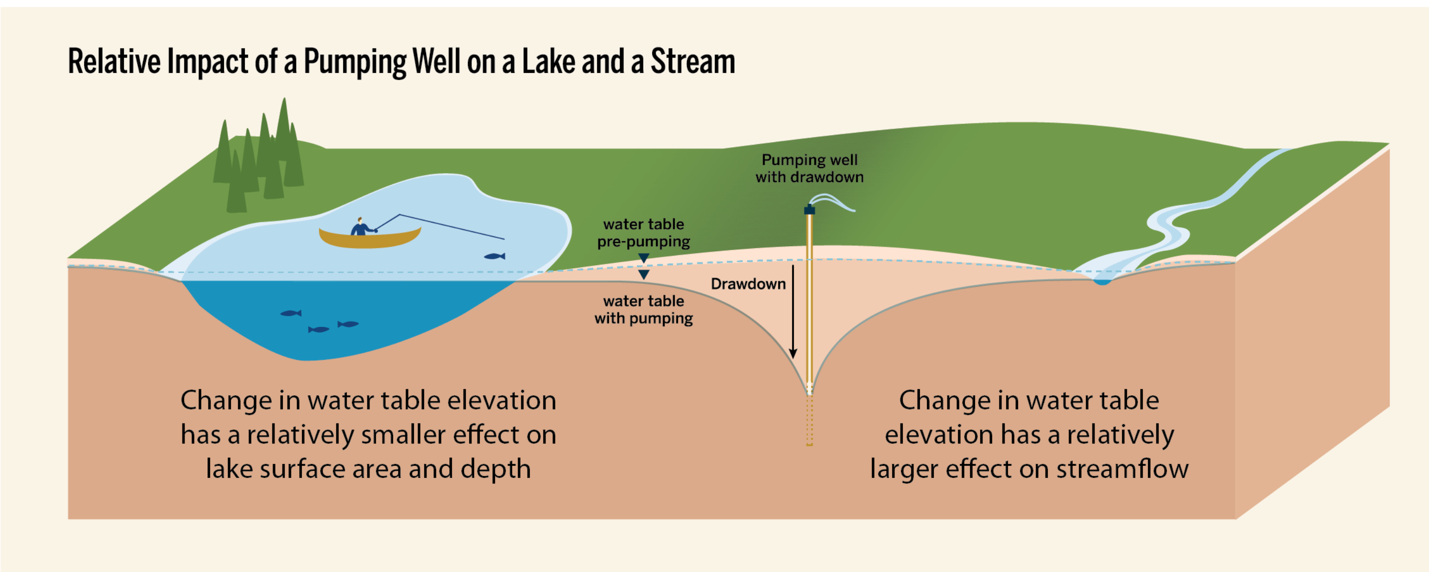


Figure 21 Relative Impact of High Capacity Well Pumping on Lakes vs. Streams

A similar drop in water levels on a lake is unlikely to reduce lake volume to the same extent. Evidence of single high capacity well pumping, causing reductions to a nearby stream in the Central Sands Region is well-documented (Weeks, 1965), but as noted in this study, it could take dozens of high capacity wells to cause impacts to a small lake. In the Central Sands Region, there are 3,100 high capacity wells, over 300 lakes and thousands of miles of streams. The results of this study strongly suggest the cumulative drawdown from high capacity well withdrawals within the Central Sands Region, have impacts on nearby water resources. Below, in the Recommendations Section, the DNR proposes a framework for addressing these impacts.

FINDINGS

Our study results are based on a substantial field data collection effort that improved our understanding of the hydrostratigraphy, hydrology, and ecology of the Central Sands. We applied that information to the groundwater flow model and characterization of the three lakes. We summarized the major findings of the study below.

- The geology in the region is mostly sand, with some intermittent clay, especially near Long Lake. These fine sediments do not create a confining unit separating portions of the sand and gravel aquifer.
- All three study lakes are well-connected to groundwater.
- Over 95% of the groundwater withdrawals in the study area are from irrigated agriculture.
- Water levels on these three lakes naturally rise and fall due to changes in weather more dramatically than other lakes largely because they are higher in the landscape and not connected to streams.
- The DNR defined "average seasonal water levels" to mean the range of high, median, and low lake levels that occur on the study lakes.
- The DNR defined "significant reduction" to mean a change from the natural pattern of lake level variations that is a large enough change to cause a significant impact or change to the lakes' ecosystems.
- The amount of groundwater recharge is a key driver of groundwater levels in the Central Sands. Our study found:
    - Precipitation has the largest effect on recharge, with more recharge in wetter years and less recharge in drier years.
    - Land use has a smaller, but persistent, impact on recharge.
    - Long-term differences between irrigated agricultural effective recharge and non-agricultural recharge are comparatively small. We observe larger differences in recharge in years with dry summers, when more water is pumped for irrigated agriculture.
- Precipitation is an important driver of the study lakes' levels and groundwater levels.
- Our groundwater modeling results indicate current-irrigated agriculture causes lake level reductions across the range of lake levels, but by a different amount on each lake. For example:
    - On Pleasant Lake, median levels drop 0.4 feet.
    - On Long Lake, median levels drop 3.3 feet.
    - On Plainfield Lake, median levels drop 2.3 feet.
- Our groundwater modeling results indicate potential-irrigated agriculture causes lake level reductions across the range of lake levels, but by a different amount on each lake. For example:
    - On Pleasant Lake, median levels drop an additional 0.3 feet.
    - On Long Lake, median levels drop an additional 0.5 feet.
    - On Plainfield Lake, median levels drop an additional 0.4 feet.
- On Pleasant Lake, current groundwater withdrawals do not cause a significant reduction in lake levels, but caution is warranted because low lake levels are very close to the significance thresholds. Furthermore, potential irrigation withdrawals may intensify impacts on human uses (dock usage).
- On Long Lake, current groundwater withdrawals cause a significant reduction in lake levels, resulting in impacts to human uses, fish, plants and lake chemistry. Potential groundwater withdrawals intensify these impacts and cause Long Lake to go dry >10% of the time.
- On Plainfield Lake, current groundwater withdrawals cause a significant reduction, resulting in impacts to the plant community, including a federally-threatened and state-endangered plant species, as well as human uses. Potential groundwater withdrawals intensify these impacts.
- The two main factors that affect how much influence wells have on the study lake levels, are the distance of the wells from the lake, and the pumping rates of the wells.
- To entirely remedy significant reductions in lake levels at Long and Plainfield Lakes, about 200 irrigation wells within 5 miles of the lakes would need to be shut off.

- The lag time between the groundwater withdrawals and the study lake level response varies greatly based on distance (see Scenario 5 in Appendix C), so it would be difficult to determine a specific lake level or elevation that would trigger management actions.
- The modeled area used to evaluate the study lakes included other nearby water resources including streams, lakes, and springs. Our preliminary results indicate that nearby streams are depleted by 20% or more due to groundwater withdrawals.

DNR RECOMMENDATIONS

This report describes the DNR's evaluation and modeling of the impacts of groundwater withdrawals from irrigated agriculture to the three study lakes' ecological and human uses. We provide well-documented scientific evidence that the water levels in Long and Plainfield Lakes are significantly reduced below average seasonal levels due to existing groundwater withdrawals, and water levels in Pleasant Lake have the potential to become significantly reduced. We share a key finding that the significant impacts to Long Lake are not caused by any one single well, but rather by the collective impacts from about 200 wells within about 5 miles or about 100 square miles. This area also includes the groundwater withdrawals that cause impacts to Plainfield Lake. Due to the lag time between pumping and lake level declines varying by distance from the well, identifying a specific lake level or elevation that would trigger management actions would not be practical.

The impact and the complexity of the issue only increases when we consider that there are 19 additional lakes and 3 streams within the vicinity of Long Lake, many of which are likely to be impacted by some of the same high capacity wells. This overlap of impacts becomes more complex when we consider that there are 3,100 high-capacity wells, over 300 lakes and many thousands of stream miles in the Central Sands Region.

For these reasons, the DNR is not recommending special measures that would address site-specific management measures. Rather, the DNR recommends addressing the impacts to all impacted water resources across the Central Sands Region by creating a mechanism for regional management to address the complicated problem of many wells impacting many water resources from substantial distances. The DNR will identify impacted resources, and we envision a flexible, economically reasonable and science-based approach to implementing groundwater withdrawal management strategies in the entire Central Sands Region.

Collectively Managing Water Use in the Central Sands

The DNR recommends water use management on a regional scale through the creation and implementation of a water use district for the entire Central Sands Region, defined as the contiguous area east of the Wisconsin River with sand and gravel deposits equal to or greater than 50 feet deep. The DNR would continue to work within its authority to review high capacity well applications and assist in targeting groundwater reductions to reduce impacts to impacted resources within the water use district. The DNR would also work with the water use district to balance conservation goals with economic concerns by providing technical and policy assistance.

Within the Central Sands Region, there are areas of greater and lesser concern over withdrawals, water levels, and significant impacts to surface waters. With further refinements to the groundwater flow model used for this study, the DNR would identify impacted water resources and set significant impact thresholds for waters that have not been assessed. The water use district could then develop strategies for efficient water use and impact reduction, identify and empower landowners whose withdrawals impact water resources to plan and implement measures to reduce water use near impacted resources.

The benefits of a water use district include:

- Having a structure to manage water use and related impacts to water resources in the Central Sands Region.
- District oversight and coordination of regional water use management to balance conservation and economic objectives.
- Including representation and planning input from local stakeholder groups such as: high capacity well owners, landowners, county land and water representatives, lake districts, natural resource groups and DNR.

Water use district roles in this regional framework could include:

- Developing strategies for efficient water use and impact reduction within areas nearby impacted waterbodies
- Identifying and empowering landowners whose withdrawals impact water resources to engage with each other to plan and implement measures to reduce water use near impacted resources
- Providing facilitation for analyses and modeling support
- Tracking management measures and progress toward water use goals
- Operating on a regular planning and implementation cycle (e.g. 5-year cycle)
- Providing regular updates to DNR

DNR's roles in this regional framework would include:

- Setting ecological thresholds and significance targets to protect water resources
- Providing technical support, through updates to the groundwater flow model
- Assisting the water use district in identifying management measures and reviewing management plans
- Collecting monitoring data including groundwater levels, lake levels, stream flow, evapotranspiration, and precipitation
- Implementing measures through high capacity well regulatory program as legal authority allows

Water Use Plans

Under regional coordination from the water use district, water users could develop water use plans to establish implementation goals to meet significance thresholds. Potential management mechanisms include:

- Installing totalizing flow meters for more accurate water use reporting
- Reducing water use voluntarily
- Withdrawal allocations with water or irrigated-land banking or water trading
- Water use reductions based on zones or distance from impacted resources
- Incentive structures for implementing water conservation and efficiency measures, such as irrigation scheduling and other more efficient irrigation processes
- Land retirement
- Per-property withdrawal limits

The regional approach to water use management recommended here is consistent with what we found in our Groundwater Quantity Programs Summary (Appendix G) of other states with programs that manage groundwater withdrawals with respect to surface water resources. Many of these states have implemented similar programs with all or some of the management measures proposed above.

Our recommendation requires additional monitoring, modeling, analysis, and research to implement the water use district. We recommend continued support for these efforts and describe them in the following section.

We recognize that implementing some of the suggested practices above may not eliminate the significant impacts from groundwater withdrawals on Long and Plainfield Lakes, but they may help it. For example, our modeled results indicate that even a 1.0-ft. increase of the median level at Long Lake would double the lake volume and improve the fishery, even though significance thresholds would still not be met.

Next Implementation Steps

This section identifies additional work needed to support the management of groundwater withdrawals in the Central Sands Region. We have many of the needed tools in place, but these tools require support for maintenance, refinement, and in some cases, research to improve methods.

This study used state-of-the-art groundwater flow modeling techniques and processes. These processes will continue to advance so the model we used for this study should be kept current. Part of that maintenance involves the DNR or the

USGS conducting periodic re-recalibration using additional field data including high-quality pumping rates, precipitation rates, evapotranspiration rates, and water levels.

We also need to refine the groundwater flow model to identify impacted areas, consider ecologic thresholds, and evaluate management measures and progress towards goals for water resources beyond the three study lakes, since results from other studies and our own analyses indicate that many streams are likely impacted by groundwater withdrawals. The groundwater flow model that we developed for the study is the appropriate tool to simulate these impacts but will require refinement and recalibration to do so accurately in the entire Central Sands Region.

With some further development, the process we used as part of this study to evaluate the impacts of reduced water levels on lakes can be applied to other seepage lakes within the Central Sands. By using the tools and lessons learned in this study, we can streamline methods for future lake evaluations. We can base a simple, first-cut approach on bathymetric maps and could conduct fish, plant, and human use surveys to tailor specific ecosystem indicators for other seepage lakes. We can also use this process for evaluating management options aimed at improving conditions on lakes impacted by groundwater withdrawals.

Additionally, we suggest more research on collecting and interpreting groundwater recharge and evapotranspiration data to continue to improve our models and knowledge of the groundwater system in the Central Sands, since recharge and evapotranspiration's temporal and spatial distribution are complex and hard to quantify.

Finally, we recommend more research on more efficient irrigation processes that can be used to reduce irrigation demand, withdrawals, and therefore, impacts to water resources.

OUTREACH

Over 30 scientists from various agencies (DNR, USGS, WGNHS, and UW) worked on the Central Sands Lakes Study. This study occurred during the COVID-19 pandemic and we found inventive ways to work with our partners and communicate in ways where traditional means (face-to-face and public meetings) were unavailable. We provided the best available science to the public at regular intervals throughout the study. DNR's outreach activities associated with this project included:

- Updating our website throughout the study period and creating a GovDelivery listserv for interested citizens
- Developing a Scope of Work that outlined our study purpose and scope for our partners
- Developing a Fact Sheet related to the study purpose
- Creating a unique email address dedicated to answer CSLS questions from the public
- Meetings with County Staff during project kick-off
- Monthly project management meetings with study partners
- Providing six-month updates (one page PDFs) from 2017 and 2020 to interested parties (posted on our website)
- Presenting to various organizations, agencies and interested parties upon request (over 35 presentations in the past 4 years)
- Developing methodology presentations with our partners in October 2020 with a 30-day public comment opportunity.
- Receiving 177 lake resident surveys from Pleasant and Long Lakes (177 received, approximately 60% response rate) and incorporating uses into our study.
- Receiving and responding to over 70 sets of comments during a public comment period from April 6 to May 7, 2021.
- Hosting a public hearing for oral comments on the *Draft Findings and Recommendations Report* on April 28, 2021.
- Developing a final presentation on the DNR Central Sands Lakes Study findings and recommendations.

ACKNOWLEDGMENTS

DNR's Water Use Program led the Central Sands Lakes Study and we would like to acknowledge our partners in this study, including: the Wisconsin Geological and Natural History, the United States Geological Survey Midwest Science Center, the University of Wisconsin – Madison and the University of Wisconsin – Stevens Point. We collaborated with Cricket Design Works on many of the graphics found in this report, appendices and presentations. We greatly appreciate the landowners in the Central Sands who granted the DNR and our partners access to collect field data and groundwater levels on their properties. Lastly, we acknowledge the many staff in various programs at the DNR that dedicated hours to this valuable study.

SUPPORTING DOCUMENTS

The Central Sands Lakes Study was complex and led by a multidisciplinary team of scientists and policy experts from the DNR, the USGS, the WGNHS, and the UWS. The DNR used the following appendices in writing this report:

Appendix A - Central Sands Lakes Study Technical Report: Data Collection and Hydrostratigraphy

Authors: WGNHS Staff - David Hart, Mike Parsen, J. Elmo Rawling III, Stephen Mauel, Peter Chase, and DNR staff - Rachel Greve. The purpose of Appendix A was to better understand the connection between groundwater and the three study lakes and define the hydrostratigraphy for use in the groundwater flow model. In addition, this report outlines data collection methods, results of work completed, interpretation of lake and groundwater interaction and the aquifer properties.

Cite: (Hart et al., August 2020)

Appendix B - Central Sands Lakes Study Technical Report: Lake Ecosystem Characterization and Response

Authors: DNR staff - Carolyn Voter, Catherine Hein, Justin Chenevert, Ian Anderson, Robert Smail, Melissa Gibson, Kevin Doyle, and Scott Bunde. The purpose of Appendix B was to characterize the current conditions of Pleasant Lake, Long Lake, and Plainfield Lake in the Central Sands Region and evaluate the impacts of groundwater withdrawals on each lake. This report covers data collection, defining terms such as "average seasonal water levels" and "significant reduction."

Cite: (Voter et al., April 2021)

Appendix C - Central Sands Lakes Study Technical Report: Modeling Documentation

Authors: US Geological Survey Upper Midwest Water Science Center in Middleton, Wisconsin, staff: Michael N. Fienen, Megan J. Haserodt, Andrew T. Leaf, and Stephen M. Westenbroek. The purpose of Appendix C was to outline the framework of models developed in support of the Central Sands Lakes Study. The USGS created three groundwater models were created: a regional Central Sands model and two smaller inset models, focused near the lakes.

Cite: (Fienen et al., April 2021)

Appendix D - Central Sands Lakes Study Technical Memorandum: Recharge

Authors: DNR – Aaron Pruitt, Rachel Greve, Adam Freihoefer, Jeff Helmuth. The purpose of Appendix D is to provide greater detail on how recharge estimates were calculated for the purpose of groundwater flow modeling.

Cite: (Pruitt et al., April 2021a)

Appendix E - Central Sands Lakes Study Technical Memorandum: General Lake Model

Author: DNR - Aaron Pruitt. The purpose of Appendix E is to explain how the DNR used a General Lake Model for verifying lake evaporation estimates used in the groundwater model.

Cite: (Pruitt, April 2021b)

Appendix F - Central Sands Lakes Study Technical Memorandum: Land Use in the Central Sands

Authors: DNR - Aaron Pruitt, Robert Smail, Rachel Greve. The purpose of Appendix F is to summarize the history of land use in the Central Sands and further explain the three different land use scenarios and modeled lake level regimes under each land use scenario.

Cite: (Pruitt, Smail and Greve, April 2021)

Appendix G - Groundwater Quantity Programs Summary

Author: DNR – Adam Freihoefer, Nicole Clayton, Jeff Helmuth, Rachel Greve, Shaili Pfeiffer. The purpose of Appendix G is to summarize what the DNR researched and learned from interviewing experts of other states' groundwater management programs.

Cite: (Freihoefer et al., April 2021)

References[2]

Bradbury, K.R., Fienen, M.N., Kniffin, M.L., Krause, J.J., Westenbroek, S.M., Leaf, A.T., and Barlow, P.M., 2017, Groundwater flow model for the Little Plover River Basin in Wisconsin's Central Sands,: Wisconsin Geological and Natural History Survey Bulletin 111, 82 p.

Fienen, M. N., Bradbury, K. R., Kniffin, M. and Barlow, P. M. (2017), Depletion Mapping and Constrained Optimization to Support Managing Groundwater Extraction. Groundwater. doi:10.1111/gwat.12536

Hamilton, D.A., and Seelbach, P.W., 2011, Michigan's Water Withdrawal Assessment Process and Screening Tool: Michigan Department of Natural Resources, Fisheries Special Report 55, Lansing, MI.

Kniffin, Maribeth (unpublished, 2014) A Hydrogeological Investigation of Long Lake – Oasis, Waushara County, Wisconsin. National Conservation Resource Service – CIG Grant Report

Kraft, G.J., Mechenich, D.J., 2010. Groundwater pumping effects on groundwater levels, lake levels, and streamflows in the Wisconsin Central Sands. Report to the Wisconsin Department of Natural Resources in completion of project: NMI00000247. Center for Watershed Science and Education, University of Wisconsin – Stevens Point / Extension. http://www.uwsp.edu/cnr/watersheds/Reports_Publications/Reports/gwpumpcentralsands2010.pdf

Weeks, E.P., and Stangland, H.G., 1971, Effects of irrigation on streamflow in the central sand plain of Wisconsin: U.W. Geological Survey Open-File Report 70-362, 113 p.

Weeks, E.P., and D.W. Ericson and C.L.R. Holt, Jr. 1965, Hydrology of the Little Plover River Basin Portage County, Wisconsin and the Effects of Water Resource Development: U.S. Geological Survey Water-Supply Paper 1811, 78 p.

[2] Note: We have complete references within each of the Central Sands Lakes Study technical appendices.