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

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Introduction

This report characterizes the current conditions of Pleasant Lake, Long Lake, and Plainfield Lake in the Central Sands region and evaluates the impacts of groundwater withdrawals on each lake. This report is part of the Wisconsin Department of Natural Resources (DNR) Central Sands Lakes Study (CSLS or "the study") in response to 2017 Wisconsin Act 10, which directs DNR to determine whether existing and potential groundwater withdrawals are causing or are likely to cause significant reduction of average seasonal water levels at Pleasant Lake, Long Lake, and Plainfield Lake (s. 281.34(7m)(2)(b), Wis. Stats.). This statute does not define "average seasonal water level" or "significant reduction"; therefore, we defined these terms in an effort to provide the most meaningful response to Act 10. For purposes of this study, we define "average seasonal water levels" to mean the pattern of high, normal, and low lake levels that naturally occur on the study lakes (which we refer to as the lake level regime), and "significant reduction" to be a deviation from this natural pattern strong enough to cause a significant impact to the ecosystem and/or human use of the study lakes. Note that since irrigated agriculture accounts for greater than 95% of groundwater withdrawals in the area of the lakes, we use the terms "groundwater withdrawals" and "irrigated agriculture" interchangeably.

We characterized the chemical, biological, and societal features (e.g. boating, observing wildlife) of each lake by conducting a 2-year field campaign, analyzing historical data, reviewing historical lake reports and scientific literature, and surveying lake residents. We characterized the hydrology and lake level regimes of these lakes using a 38-year climate dataset and the MODFLOW groundwater flow model (Fienen et al., 2021). Historic lake level observations result from a combination of climate factors and groundwater withdrawals and thus we cannot define average seasonal water levels based on observations alone; using MODFLOW allowed us to isolate the impacts of groundwater withdrawals and associated land use changes under a full range of climatic conditions.

We used three scenarios to evaluate whether existing and potential groundwater withdrawals are likely to cause a significant reduction in water levels: one that represents a landscape without groundwater withdrawals, a second with existing groundwater withdrawals, and a third with existing and potential groundwater withdrawals. All three scenarios featured identical climatic drivers (precipitation and air temperature records). This approach allowed us to simulate climatic variation under three levels of groundwater withdrawals and then compare average seasonal water levels between scenarios. Representing climatic variation is critical for defining average seasonal water levels. The purpose of modeling a 38-year climate record is not to recreate historical water levels; rather, this method simulates a broad range of climatic conditions to understand lake hydrologic and ecosystem response to groundwater withdrawals. We used available lake level data from the study lakes to quantitatively evaluate the error in MODFLOW lake level predictions and qualitatively verify reasonableness.

In this report, we first present results from our lake characterization and then evaluate whether groundwater withdrawals significantly impact the three lake ecosystems. We structured our evaluation of lake ecosystem response around four categories of indicators: water quality, plants, fish, and human use. Using relevant literature, professional judgement, and the results of recent and past fieldwork, we developed a suite of ecosystem indicators and protective thresholds and then used MODFLOW to evaluate whether irrigated agriculture and/or potential irrigation changes lake hydrology enough to exceed these thresholds. In some cases, we identified clear, unidirectional thresholds at which significant ecosystem impacts would be immediately apparent. For example, empirical equations can predict the elevation at which Pleasant Lake would no longer stratify, potentially impacting internal phosphorus loading and algal blooms. Other cases are more gradual and bidirectional (e.g., upland plants expanding and submergent plants contracting lakeward with declining lake levels). For these cases, we defined how much change in the ecosystem indicator would be significant (e.g., 10% change in submergent plant cover). For each lake, we determined whether groundwater withdrawals alter hydrology enough to exceed a single ecosystem indicator threshold. Thus, the most sensitive ecosystem indicator made the ultimate significance determination.

Lake Resource Characterization

Overview of the Study Lakes

Pleasant Lake, Long Lake and Plainfield Lake are located in Waushara County within the Central Sands region of Wisconsin (Figure 1). The geology in this area is characterized by thick (>50 ft) sand and gravel deposits with some interbedded fine-grained sediments overlying sandstone bedrock. The aquifer in the unconsolidated materials is well-connected to surface water bodies and is also the primary source of public and private water supplies in the region. All three study lakes are seepage lakes, meaning they have no streams or rivers flowing into or out of the lakes. Water levels in seepage lakes tend to fluctuate more dramatically than those in drainage lakes, where hydrology is more constant due to streamflow (Perales et al*.,* 2020).

The study lakes are located on glacial moraine deposits relatively high in the landscape, near the groundwater divide that separates groundwater flowing towards Lake Michigan and that flowing towards the Wisconsin River (Hart et al., 2020, Figure 9, page 18). Landscape position, or the elevation of a lake relative to the regional groundwater flow system, influences the character of the lake through the magnitude and direction of groundwater flow between the lake and surrounding geology (Kratz et al., 1997). Lakes situated low in the landscape receive greater and more constant fluxes of groundwater, as most areas of groundwater recharge are at higher elevation, placing the lake in the path of groundwater as it flows to lower elevation. In contrast, Pleasant,

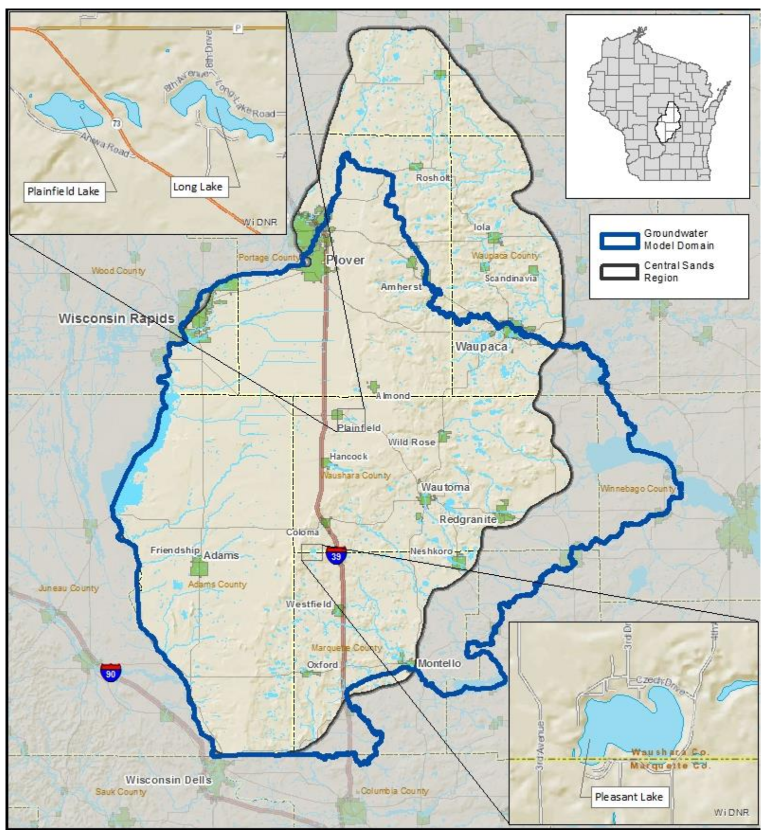

Figure 1. Map of study area in Wisconsin including the Central Sands Region, the groundwater model domain, and the three study lakes.

Long and Plainfield Lakes are high in the local topography, so there are fewer areas at higher elevation to potentially contribute groundwater. As a result, deficits and excesses of precipitation are quickly reflected in local groundwater, and then in lake levels (Webster et al., 1996; Ala-aho et al., 2013). This variation, plus the proximity of the groundwater divide, mean that the direction of local groundwater flow can change, and the study lakes (especially Plainfield and Long Lakes) can oscillate from receiving groundwater to supplying it to the surrounding aquifer. As a result of the relative contribution of groundwater in the water budget, lakes positioned high in the landscape like these tend to have lower cation, anion, and nutrient concentrations, higher water clarity, and lower fish diversity than lakes low in the landscape (Kratz et al., 1997).

Table 1. Lake and watershed characteristics derived from the DNR Register of Waterbodies, DNR's 1:24,000 scale hydrography database (Ruesch et al. 2013), and the 2018 Wiscland 2.0 Level 2 land cover data set. Land covers are reported as the percent of the total watershed area for each lake.

Parameter	Units	Pleasant	Long	Plainfield
Maximum depth	feet	24	14	12
Lake area	acres	120	40	29
Watershed area	acres	1,432	10,411	10,810
Developed, Low Intensity	%	2.0	0.5	0.6
Crop Rotation	%	1.9	70.9	68.3
Forage Grassland	%	3.9	4.2	4.0
Idle Grassland	%	1.3	2.4	2.9
Coniferous Forest	%	36.1	8.2	8.6
Broad-leaved deciduous forest	%	45.8	12.6	13.8
Mixed deciduous/coniferous forest	%	0.0	0.0	0.1
Open water	%	9.2	1.2	1.6
Emergent/wet meadow	%	0.0	0.0	0.1
Lowland scrub/shrub	%	0.0	0.0	0.0
Forested wetland	%	0.0	0.0	0.0
Barren	%	0.0	0.0	0.1

The study lakes vary in their size and watershed composition (Table 1). Some characteristics (e.g., maximum depth, lake area) vary with lake level, so different sources may report different values depending on the assumed lake level. Pleasant Lake is the largest of the three lakes, with a surface area of 120 acres and maximum depth of over 22 feet (Figure 2). Its watershed is the smallest and is dominated by forested land cover (Figure 3). The remaining land cover in the watershed consists of open water, grassland, crop rotation, and low-intensity development along the lake shoreline. Of the approximately 137 parcels adjacent to Pleasant Lake, two small parcels are in public ownership (Figure 4). There are additional access points around the lake, depicted on this map as breaks between the parcels (e.g., boat launch on the north shore, Figure 4). Most private parcels have homes and around 50 feet of water frontage, resulting in high housing density along the shoreline.

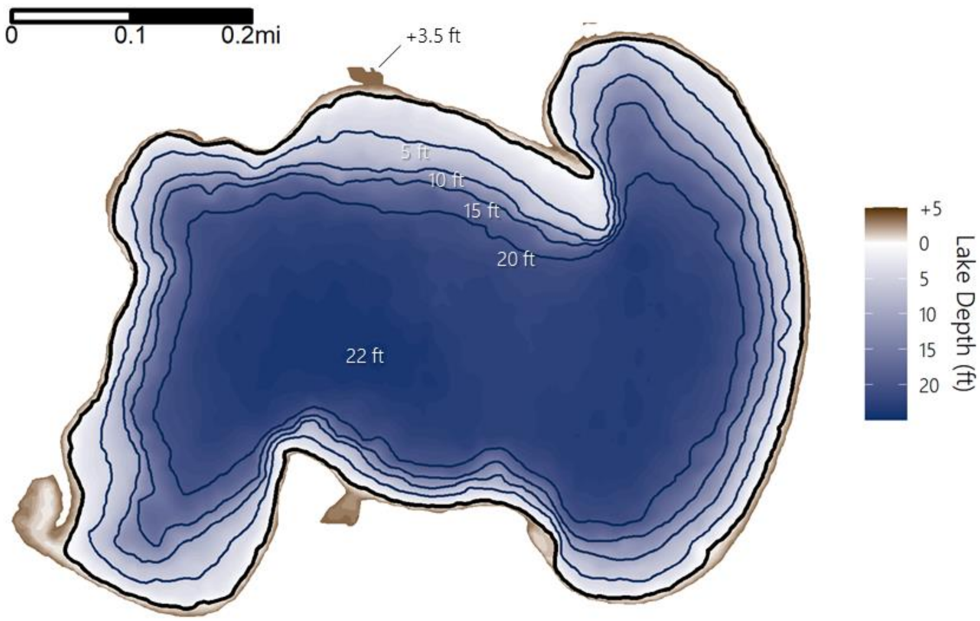

Figure 2. Pleasant Lake bathymetry. Black line denotes the lake shoreline at the modeled no-irrigated-agriculture median lake level (977.6 ft asl) with shades of blue indicating 0.5-ft contours of lake depth at this lake level, dark blue lines indicating 5-ft contours of lake depth, and shades of brown indicating 0.5-ft contours up to the maximum lake level observed in July 2020.

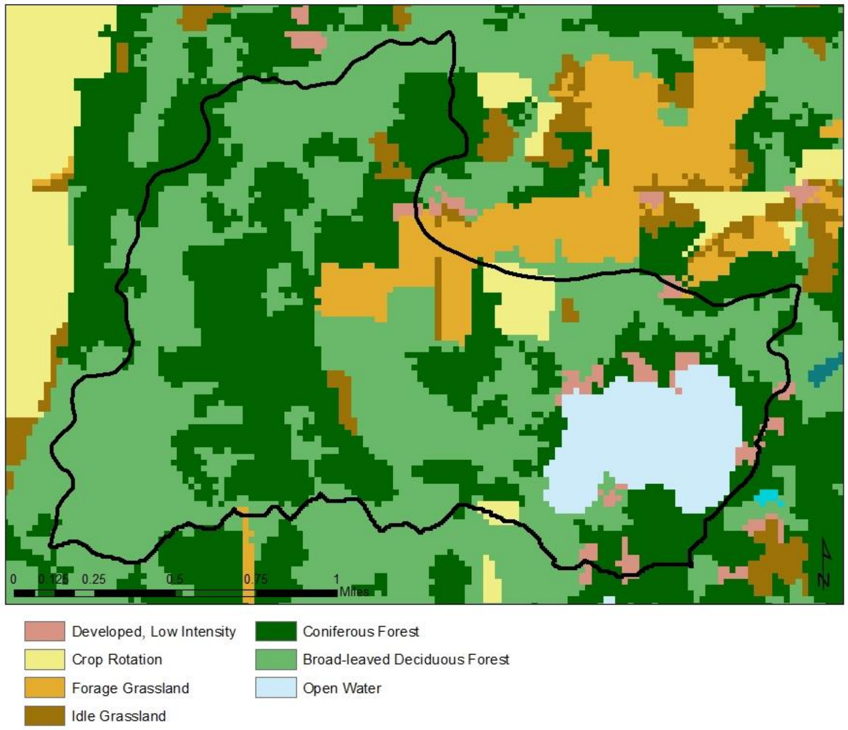

Figure 3. Pleasant Lake landcover. Landcover (2018 Wiscland 2.0, level 2) in the watershed of Pleasant Lake. Pleasant Lake is the open water area in blue, and the watershed is delineated with the solid black line.

Figure 4. Pleasant Lake parcels. Private (white) and public (yellow) parcels adjacent to Pleasant Lake. Additional access corridors are depicted as gaps between parcels.

Long and Plainfield Lakes are smaller and shallower (Figure 5, Figure 6). Their watersheds almost completely overlap, with Plainfield Lake less than 0.5 miles west of Long Lake (Figure 7). Over 68% of their watersheds are in crop rotations, followed by forested lands and forage or idle grassland (Table 1). Their watersheds extend approximately five miles east of Long Lake, which is where most of the cropland occurs. The area immediately surrounding Long and Plainfield Lakes is dominated by broad-leaved deciduous and coniferous forest. The Town of Oasis owns two of the approximately 87 parcels adjacent to Long Lake, and there is a public access point at the boat launch on the north shore (Figure 8). The rest of the parcels are privately owned and most have homes. Plainfield Lake is within a State Natural Area, with three of eight parcels in public ownership and only two houses near the lake shoreline (Figure 9). A county highway runs near the entire north shore of Plainfield Lake.

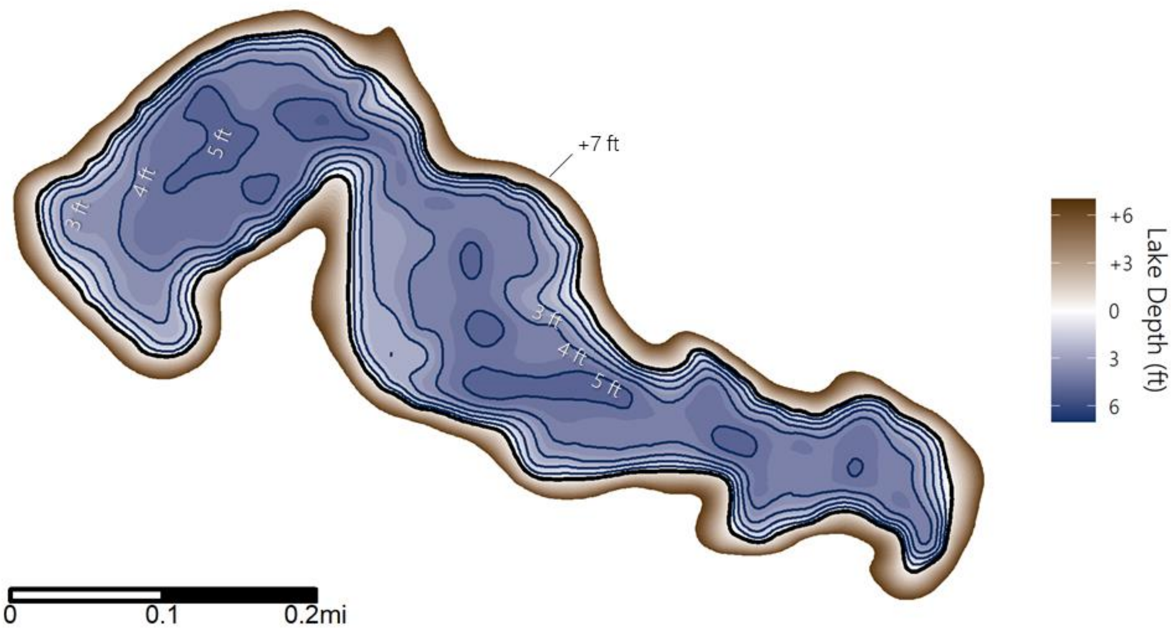

Figure 5. Long Lake bathymetry. Black line denotes the lake shoreline at the modeled no-irrigated-agriculture median lake level (1097.6 ft asl) with shades of blue indicating 0.5-ft contours of lake depth at this lake level, dark blue lines indicating 1-ft contours of lake depth, and shades of brown indicating 0.5-ft contours up to the maximum lake level observed in July 2020.

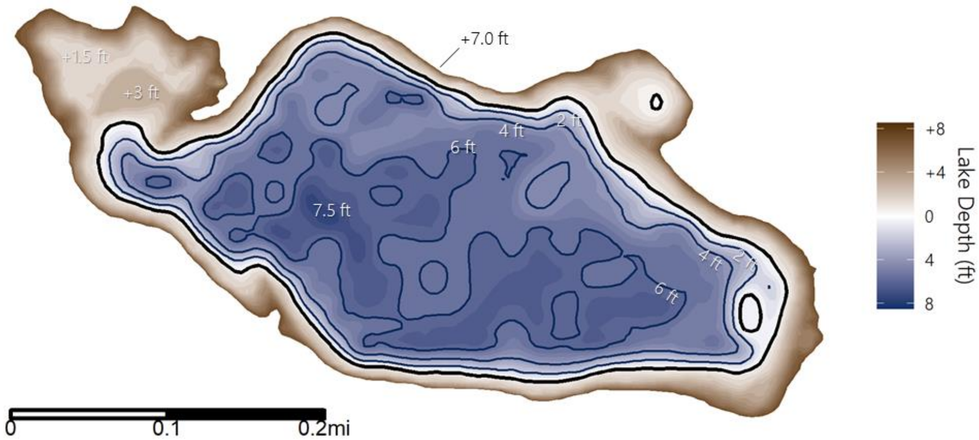

Figure 6. Plainfield Lake bathymetry. Black line denotes the lake shoreline at the modeled no-irrigated-agriculture median lake level (1097.3 ft asl) with shades of blue indicating 0.5-ft contours of lake depth at this lake level, dark blue lines indicating 2-ft contours of lake depth, and shades of brown indicating 0.5-ft contours up to the maximum lake level observed in July 2020

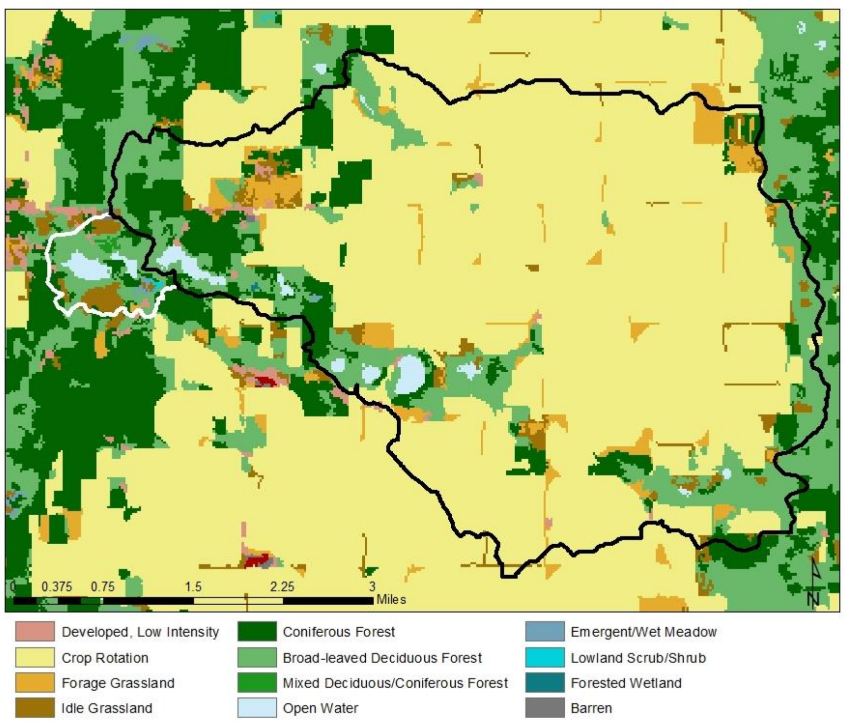

Figure 7. Long Lake and Plainfield Lake landcover. Landcover (2018 Wiscland 2.0, level 2) in the watersheds of Long Lake and Plainfield Lake. Long Lake's watershed is delineated with the solid black line. Plainfield Lake's watershed includes the entire Long Lake watershed and the area delineated with the solid white line.

Figure 8. Long Lake parcels. Private (white) and public (yellow) parcels adjacent to Long Lake. Additional access corridors are depicted as gaps between parcels.

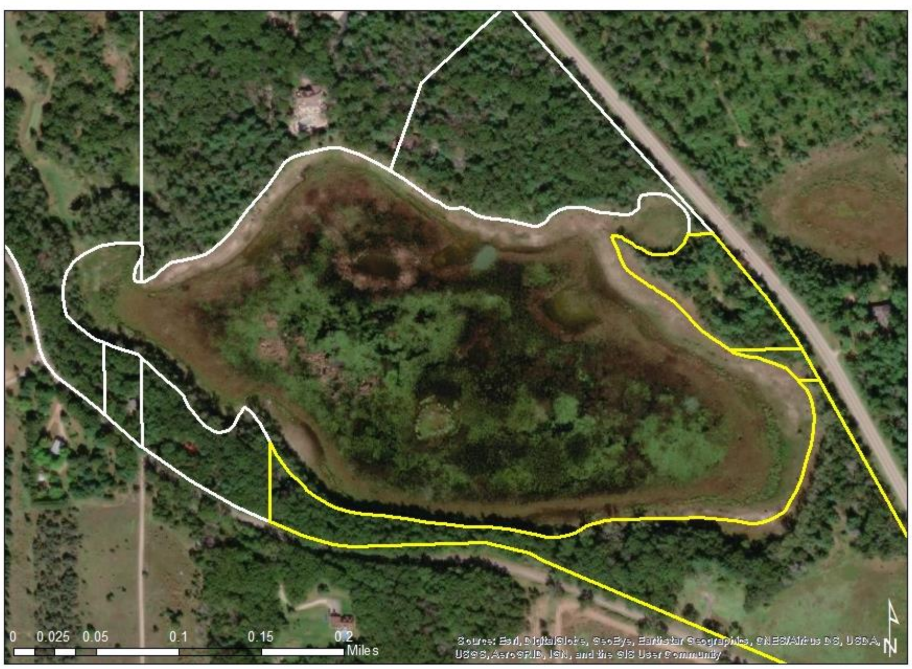

Figure 9. Plainfield Lake parcels. Private (white) and public (yellow) parcels adjacent to Plainfield Lake.

Methods

Hydrologic Characterization

Lake Levels

We gathered water level observations from four sources to develop a historical lake level dataset: 1) Waushara County lake monitoring records, 2) the United States Geological Survey (USGS) National Water Inventory System (NWIS), 3) DNR, and 4) estimates of shoreline elevations from USDA and DNR historical aerial photos. In the Summer 2017, DNR and partners from Waushara and Marquette counties began regularly measuring water level elevations on multiple lakes. In mid-2018, USGS installed continuously monitoring lake level gages on all three study lakes. However, prior to the CSLS, water level records are more sporadic. On Pleasant Lake, aerial photos provide the only information prior to 1964, when Waushara County records begin. We interpret Plainfield Lake levels solely from aerial photos until 2017. Waushara County and USGS records exist for Long Lake from 1961-1981 and then resume in 1995. The temporal distribution of the sampling record is highly skewed, with recent months (i.e., post-2017) sampled much more frequently than in the past. Thus, these lake level observations can give context, but are not sufficient for a detailed understanding of lake hydrologic regimes in the past.

Groundwater Flow Model

The CSLS team used MODFLOW-6, a finite difference numerical groundwater model, to investigate the responses of the study lakes to groundwater withdrawals. This model mathematically simulates groundwater movement in the area around the study lakes by partitioning an aquifer into a virtual grid of three-dimensional cells and solving the groundwater flow equation at each cell interface. Each cell is assigned parameters to replicate the physical characteristics of the study area. For instance, scientists from the Wisconsin Geological and Natural History Survey (WGNHS) retrieved sediment cores from several points around the study lakes and carefully investigated the properties of the different layers of material, including how easily water can pass through the aquifer materials. This information is then incorporated into the model which calculates how quickly groundwater moves through the cells that correspond to the core's location. Other pieces of information gathered in the field or from relevant literature that are simulated in the model include: how different crops extract and use groundwater, patterns of crop rotation, precipitation recorded in the study area, and properties of natural vegetation. In addition, the model is programmed to reflect well-understood principles of hydrogeology, such as conservation of mass and Darcy's Law.

USGS and DNR modelers calibrated the MODFLOW model using climate, land use, groundwater withdrawal, groundwater level, lake level, and streamflow data from 2012 to 2018. This time period afforded accurate data and a wide range of precipitation conditions. This calibration exercise results in a set of parameter values that best reproduce observations and are consistent with what we already know about the study area. The calibration also estimates uncertainty in the predicted lake levels.

The Soil Water Balance Model, which provides inputs to the groundwater flow model, requires daily, spatially-gridded precipitation and air temperature data. We selected PRISM (Parameter-elevation Regressions on Independent Slopes Model, PRISM, 2004) as the climate data source for the groundwater flow model because it provides daily data from 1981-2018 and includes the timeframe of groundwater model calibration data (2011-2018). Coverage from other data sources such as Daly et al., 2015, and Livneh et al., 2015, are limited to pre-2013, and thus do not include the MODFLOW calibration period.

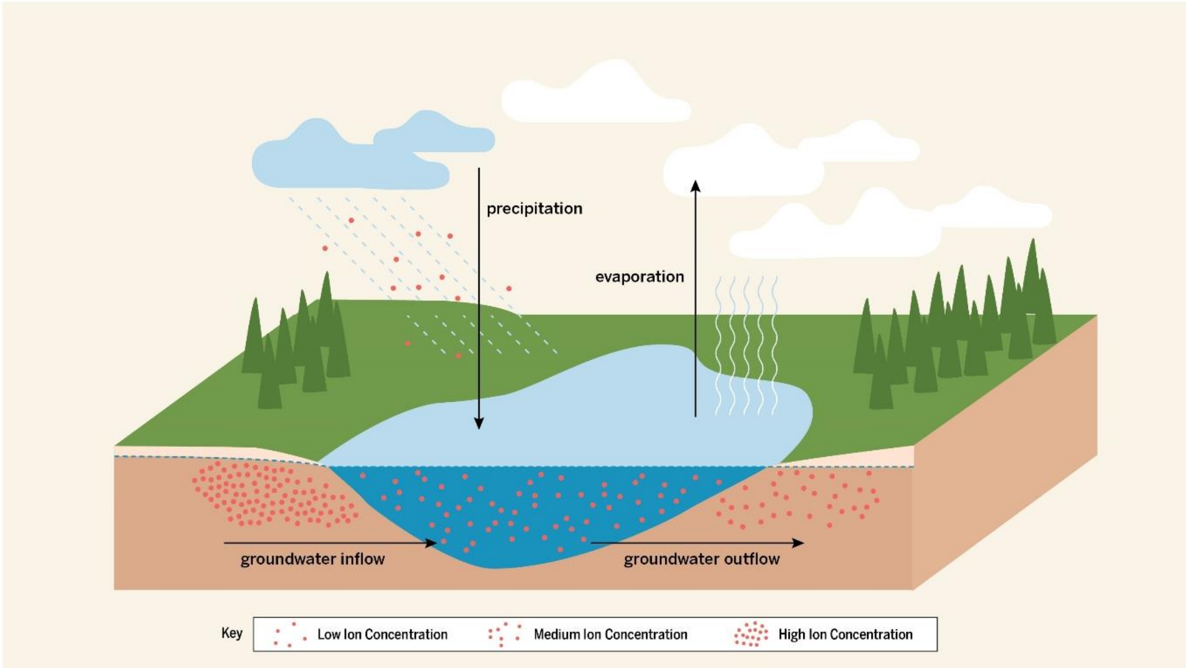

Figure 10. Water and solute budget for a seepage lake. Schematic of the inflows (precipitation, groundwater inflow) and outflows (evaporation, groundwater outflow) for seepage lakes, with relative contributions to solute budget shown via the concentration of ions.

Water Budget

The water budget for seepage lakes (e.g., the Central Sands study lakes) is as follows (Figure 10):

$$\frac{dV}{dt} = P - E + GW_{in} - GW_{out} \quad \text{(Eq. 1)}$$

where *dV/dt* is the change in lake volume (m^3), *P* is the precipitation (m^3), *E* is the lake evaporation (m^3), GW_{in} is the groundwater flowing into the lake (m^3), and GW_{out} is the groundwater flowing out of the lake (m^3).

Since a modeled approach is often essential for estimating groundwater flows (Anderson et al., 2015), we relied upon the numerical model of groundwater flow calibrated to match 2012-2018 conditions in order to determine the water budget at our study lakes. As a complementary and independent approach, we also explored use of conservative solute tracers and stable isotope tracers, where possible, to independently verify estimates of groundwater contributions to the lake water budget at each of the three lakes during water year 2019 (WY2019; Oct 2018-Sept 2019) (Kenoyer and Anderson, 1989; Krabbenhoft et al., 1990; Gurrieri and Furniss, 2004). We evaluated several major ions for use as conservative tracers to estimate the water balance at each lake: calcium, magnesium, sodium, potassium, chloride, and sulfate. We assumed magnesium is conservative and then compared each other solute to magnesium. Sodium, potassium, chloride and sulfate were poor fits when plotted against magnesium concentrations, but calcium had a linear relationship when compared to magnesium meaning calcium may be conservative as well. For stable isotopes, we explored the use of $\delta^{18}O$ and $\delta^{2}H$. Evaluation of WY2019 measurements indicate that Pleasant Lake and possibly Plainfield Lake did not have sufficiently strong evaporation signals in lake values for stable isotopes to be an appropriate approach (Gurrieri and Furniss, 2004), but that a stable isotope approach may be appropriate at Long Lake. All calculations for the chemical tracer approach are documented in the CSLSflux R package (https://github.com/WDNR-Water-Use/CSLSflux) but are also briefly described here.

When we refer to fluxes as a percent of the water budget, this represents the flux as a percent of incoming fluxes (including decreases in lake volume) or outgoing fluxes (including increases in lake volume). For example, precipitation as a percent of the water budget during a period of rising lake levels would be calculated as:

$$P_{pct} = 100 * \frac{P}{P+GW_{in}} = 100 * \frac{P}{P+GW_{in}+\Delta V} \qquad \text{(Eq. 2)}$$

Change in Lake Volume

The groundwater flow model calculates change in lake volume using model-predicted water level elevations (for details, see Fienen et al., 2021). For the chemical tracer approach, we obtained lake elevation data from water level sensors at USGS gages at all three lakes in the CSLS (USGS gages 5401065, 5401067 and 435857089325301). We used elevation-volume relationships derived from bathymetry information in ArcGIS (using the Storage Capacity tool within Spatial Analyst Supplement Tools) to convert daily lake elevations to daily lake volumes (detailed in the “Bathymetry” section of the Methods). The change in lake volume for a given year is then the difference between the lake volume at the end of the year from where it began on the first day of the year.

Precipitation

In the groundwater flow model, precipitation is an input derived from monthly gridded precipitation values from the PRISM dataset (Fienen et al., 2021; Pruitt et al., 2021a). For the chemical tracer approach, we obtained hourly precipitation depth (mm) from the Hancock Agricultural Research Station (Michigan State University station id: hck). The station is in Hancock, WI (location: 44.1188, -89.533, elevation: 791 ft), approximately 8 miles from Plainfield Lake, 8.5 miles from Long Lake, and 14.5 miles from Pleasant Lake. To derive precipitation as a volume, we used bathymetric maps to convert daily lake elevations to daily lake areas and then multiplied monthly precipitation as a depth by the mean monthly lake area and summed to annual totals.

Evaporation

The CSLS modeling team calculated lake evaporation using an air temperature-based approach as an input for the groundwater flow model (Fienen et al., 2021; Pruitt, 2021). For the chemical tracer approach, we calculated lake evaporation using a lake energy-budget approach (McJannet et al. 2008, McMahon et al. 2013). This approach uses measured incoming solar radiation, wind speed, relative humidity, and air temperature from a nearby weather station (Hancock), lake surface temperature from continuous temperature sensors at 3.3 ft depth, and daily values of lake area and lake depth derived from daily lake elevation measurements and elevation-area relationships. For complete documentation on these calculations, please refer to the CSLSevap R package documentation (https://github.com/WDNR-Water-Use/CSLSevap) as well as McMahon et al. (2013). We averaged evaporation as a daily depth at a monthly timestep, multiplied by the mean monthly lake area to convert evaporation to a volume, and summed to annual totals.

Groundwater Inflow

Using the groundwater flow model, we calculated groundwater inflow based on model-predicted water level elevations (Fienen et al., 2021). For the chemical tracer approach, we calculated annual groundwater inflow using a mass balance of chemical tracers (Gurrieri and Furniss, 2004):

$$GW_{in} = \frac{P(C_P - C_L) + E(C_L - C_E) - V(dC_L/dt)}{(C_L - C_{GWin})} \qquad \text{(Eq. 3)}$$

where GW_{in} is the groundwater inflow (m^3), P is precipitation (m^3), E is evaporation (m^3), V is the lake volume (m^3) and C_x is the solute concentration (for conservative solute tracers) or the relative isotopic composition in units of per mil relative to a known standard (for stable isotope tracers). All C_x values are median values from WY2019 with the exception of stable isotope precipitation and evaporation values, which we calculated on a monthly time step and weighted by monthly precipitation volumes (for δ_P) or monthly evaporation volumes (for δ_P) for a volume-weighted average annual value. C_L is measured at the lake, C_P is measured from precipitation, and C_{GWin} is measured at inflowing (i.e., upgradient) groundwater wells. We calculated the mean daily difference in groundwater and lake levels over the 30 days prior to a date of interest and considered a well upgradient if this mean daily difference was greater than 1 cm. C_E is zero for solutes, but must be estimated for stable isotopes ($\delta^{18}O$ or δ^2H). We estimated monthly δ_E as follows (Krabbenhoft et al., 1990, Eq. 5):

$$\delta_E = \frac{(1/\alpha) * \delta_L - h * \delta_A - \epsilon}{1 - h + 10^{-3}\Delta\epsilon} \qquad \text{(Eq. 4)}$$

We calculated the relative humidity of the surface water (unitless), h, as follows (Mook, 2000b, Eq. 1.8):

$$h = \frac{RH}{100} * \frac{es_A}{es_L} \qquad \text{(Eq. 5)}$$

where RH is the relative humidity (%), es_A is the saturated vapor pressure for the air (kPa), and es_L is the saturated vapor pressure for the lake (kPa). We calculated saturated vapor pressure based on Allen et al. (1998, Eq. 11) using air temperature (°C) or lake temperature (°C) as appropriate:

$$es = 0.6108 * exp\left(\frac{17.27T}{237+T}\right) \qquad \text{(Eq. 6)}$$

We calculated the equilibrium isotope fractionation factor (unitless), α, based on Mook (2000a, Eq. 2.11a), where T is the lake surface temperature (K). Note that this formulation represents the fraction of isotopes in liquid vs. the fraction in vapor (i.e., L/V form, α > 1). Others, including Krabbenhoft et al. (1990), use the inverse form of α (i.e., V/L form, α < 1) in their equations. In all equations presented in this report, we consistently use the L/V form for alpha. To use the V/L form of alpha, simply replace α with 1/α in the equations presented in this document.

$$\alpha = exp(2.0667 * 10^{-3} + 0.4156/T - 1137/T^2)^{-1} \qquad \text{(Eq. 7)}$$

We calculated the kinetic fractionation factor (unitless), Δϵ, based on Krabbenhoft et al. (1990, Eq. 6) where k = 14.3 for $\delta^{18}O$ and k = 12.5 for δ^2H:

$$\Delta\epsilon = k * (1 - h) \qquad \text{(Eq. 8)}$$

The total fractionation factor (unitless), ϵ, combines both the isotopic fractionation factor and the kinetic fractionation factor (Krabbenhoft et al., 1990, Eq. 5):

$$\epsilon = 1000 * (1 - 1/\alpha) + \Delta\epsilon \qquad \text{(Eq. 9)}$$

Lastly, we calculated the isotopic composition of the atmosphere, δ_A, based on Mook (2000b, Eq. 1.10):

$$\delta_A = (1/\alpha) * \delta_P + \epsilon^* \qquad \text{(Eq. 10)}$$

where ϵ* is defined as:

$$\epsilon^* = (1/\alpha - 1) * 1000 \qquad \text{(Eq. 11)}$$

Groundwater Outflow

In the groundwater flow model, groundwater outflow is calculated based on model-predicted water level elevations (Fienen et al., 2021). For the chemical tracer approach, we calculated groundwater outflow as the only remaining term of the water budget in Eq. 1.

Water Residence Time

Water residence time indicates the amount of time it takes to fully replace the entire volume of water in the lake and is equal to the lake volume divided by the inflow rate (here, precipitation and groundwater inflow). We calculated the water residence time on an annual time step by dividing the mean lake volume for the year by the sum of precipitation and groundwater inflow.

Physical and Chemical Characterization

Bathymetry

We surveyed the bathymetry of Pleasant Lake with a boat-mounted sonar system. Following the manufacturer's instructions, we drove the sonar unit across the entire lake area in evenly spaced transects (C-MAP, Inc., 2017). The BioBase software then combined the information from the sonar unit with the location of the boat to produce the depth of water at 18,371 points spaced approximately 16 feet apart (C-MAP, Inc., 2018). Using boat-mounted sonar was not feasible on Long and Plainfield Lakes because of dense floating-leaved plants and lack of boat access, respectively. We determined the bathymetry of Plainfield and Long Lakes during the aquatic plant point-intercept survey. The field crew measured the water depth using a marked pole or weighted rope on a grid of evenly spaced points across the entire surface of the lakes. On Plainfield Lake, the field crew measured depth at 212 points spaced 89 feet apart, and on Long Lake, the field crew measured depth at 232 points spaced 95 feet apart. We converted measured depths to lakebed elevations based on the lake elevation on the day of measurements (USGS gages 5401065, 5401067 and 435857089325301).

We used ArcGIS to convert point-based measurements into an elevation raster. We incorporated upland LiDAR measurements into our analysis to expand the footprint of our bathymetric map and account for water level fluctuations (DNR, 2019b). Before combining point shapefiles from measured lakebed elevations with upland LiDAR data, we used the Spatial Analyst toolbox to aggregate the point shapefile of LiDAR-derived upland elevations to match the resolution of measured lakebed elevations. We then performed kriging on the points using the Geostatistical Analyst toolbox, iteratively adjusting parameters to minimize scalloping of contour lines. We calculated elevation-volume and elevation-area curves using the Storage Capacity script within Spatial Analyst Supplement Tools (Noman, 2017).

Substrate Habitat

Fish and plant species vary in their preferred substrate for growth, spawning, and foraging. We mapped the locations of gravel and cobble habitat on Pleasant Lake using a modified version of the Critical Habitat Designations protocol (Cunningham, 2008). We drove around the perimeter of the lake nearshore, observing the substrate from 0 – 3 feet deep. We used a GPS unit to record points where the gravel/cobble began and ended along the shoreline and then established 2-5 transects perpendicular to shore spaced at approximately equal intervals. Each transect went from shore out to 3 feet deep or a 50-foot horizontal distance, whichever was nearer to shore. We identified bands of similar substrate running parallel to shore and recorded the depth of water at the start and end of each band and the total horizontal distance. We then placed a 2.68 square foot quadrat in the middle of each band and estimated the percent cover of detritus, clay, sand, and gravel to the nearest 5%. We also estimated the degree of embeddedness (amount of fine particles in the interstitial spaces of rocks) within the quadrat, on a scale from 1 (>75% of the substrate covered by sand, silt or clay) to 5 (<5% of the substrate covered by sand, silt or clay).

Lake Temperature and Dissolved Oxygen

We monitored water temperature (and dissolved oxygen concentration on Pleasant Lake only) at hourly intervals using data loggers at the deepest point of each study lake (installed on June 28, 2018; DNR, 2019a). Due to frequent changes in lake level, we measured logger positions from the lake bottom. We attached a sunken fishing float above the top-most logger to keep the line taut and maintain the loggers at constant distances from the bottom, even as the surface buoy moved up and down with the water level (Figure 11). We deployed two temperature loggers (ONSET HOBO Pro v2) on each of Plainfield and Long lakes at 1.5 and 3.0 feet above the lake bottom by attaching them to rope strung between a surface buoy and a cinder block. We deployed seven temperature loggers on Pleasant Lake at 3 to 5-foot intervals, capturing nearly the full extent of the water column starting at 1.5 feet above the lake bottom. On August 9, 2019, we added one temperature logger to each lake, suspended directly off the surface buoy. This additional logger, in contrast to the others, remained a constant distance from the surface. To capture the hypolimnetic and near-surface oxygen concentrations on Pleasant Lake, we installed two dissolved oxygen loggers (ONSET HOBO U26) on Pleasant Lake at 3.3 and 18.5 feet from the bottom, respectively.

Every few months during the ice-free season, we cleaned the data logger arrays and downloaded data. Field crews used a plastic brush and small amounts of vinegar to remove periphyton and debris from the loggers, checked that all equipment was in good condition, and then collected the data using a waterproof data shuttle. An antifouling protective guard made of copper wire also minimized biofouling on the dissolved oxygen sensors. We compared readings from the automatic loggers to those from the handheld multiparameter probe to check for accuracy. During January 2019, the dissolved oxygen sensor caps expired before they could be replaced, and the loggers ceased collecting data. Crews restored the top logger to normal operation in April and restored the bottom logger in June.

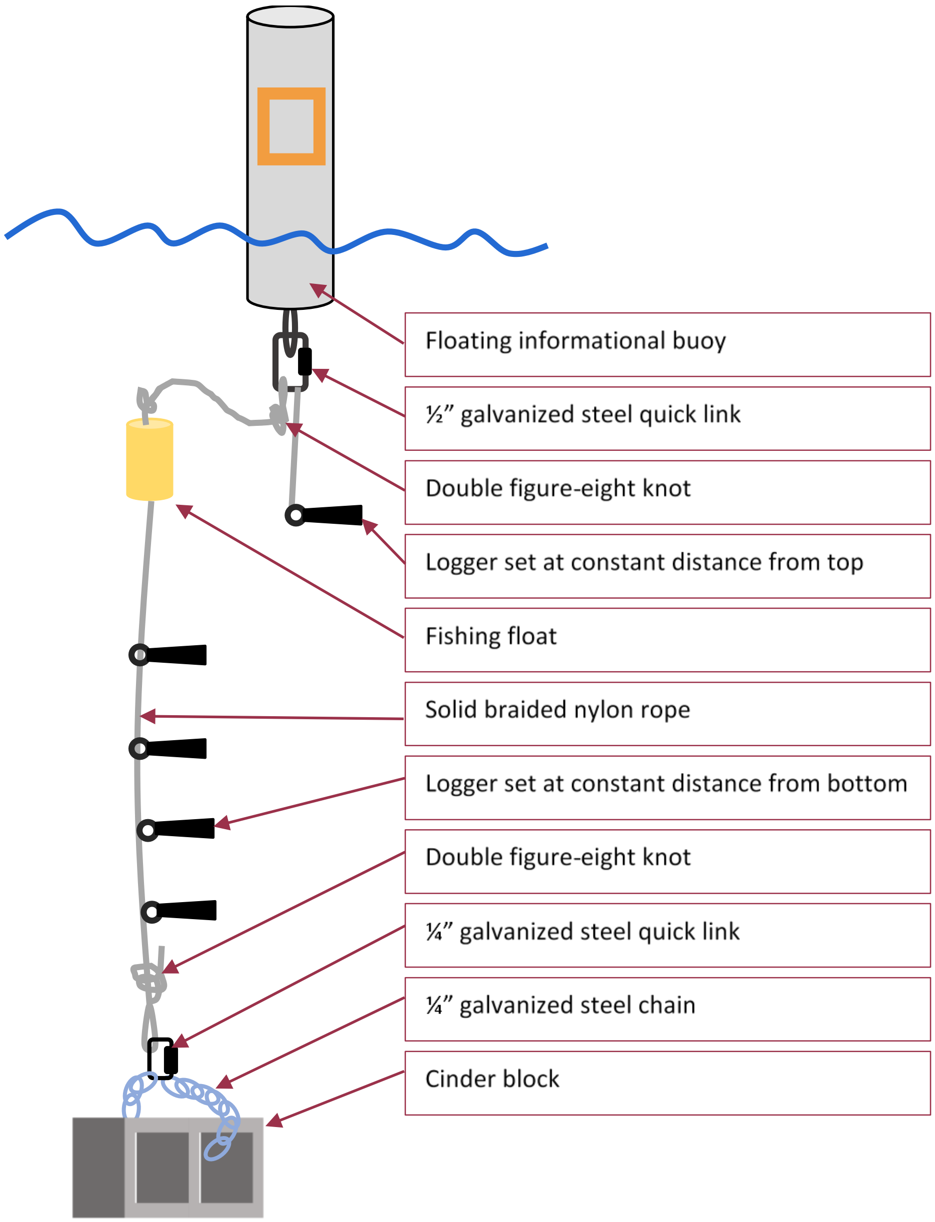

Figure 11. Automatic data logger array. Schematic of automatic data loggers used to collect continuous temperature and dissolved oxygen measurements at the deep hole of each lake.

Lake Water Chemistry

We collected water samples for analysis at the Wisconsin State Laboratory of Hygiene (SLH) and measured water quality parameters in the field with a hand-held multiparameter meter. We adapted the monitoring schedule and procedures for the surface water chemistry portion of the study from Wisconsin’s Long-Term Trend Lake Sampling Procedures (DNR, 2017) and the Wisconsin Consolidated Assessment and Listing Methodology (DNR, 2019c).

Each lake monitoring event took place at the deepest point of the lake. We first conducted visual observations (wind speed, cloud cover, water level); we then measured Secchi depth, total depth, and a water column profile of temperature, conductivity, dissolved oxygen, and pH; and we finally collected water samples for laboratory analysis (Table 2, Table 3). The visual observations included an estimate of the water color and "user perception", or rating of water quality, where a "1" corresponds to an aesthetically pleasing, clear body of water and "5" corresponds to an aesthetically displeasing water containing algae blooms, trash, or other blemishes that might cause a user to refrain from boating, fishing or swimming.

Table 2. Water quality parameters measured in the field biweekly 2018-2019.

Parameter	Instrument	Purpose
Secchi depth	Secchi disk	A measure of water clarity that is lowered by algae, sediments, and dissolved organic matter (e.g. tannins)
Total depth	Secchi disk	Measure of total depth at sampling location to nearest quarter-foot. Useful to know total depth before collecting profile with multimeter probe to avoid disturbing sediment.
Water color	Secchi disk	High concentrations of algae can make the water appear green. Tannins, sediment or other organic compounds can make the water appear brown or yellow.
Water appearance	Visual	User perception of water quality – are there floating scums, algae blooms or other obvious concerns that would cause a user to avoid boating, swimming, or fishing?
Water level	Visual	Water levels determine the amount of available habitat for aquatic and wetland plants and animals and can also influence chemical cycling and water column dynamics.
Wind speed	Estimate	Wind mixes the upper layers of lakes, more so at higher speeds.
Cloud cover	Visual	Can sometimes influence Secchi depth measurement
Water temperature	YSI DSS Pro Multimeter / In-Situ smarTROLL Multimeter	Temperature is the "master variable" in lake ecosystems, controlling the speed of biogeochemical processes, the degree of stratification of the lake, and the amount of oxygen the water can hold.
Dissolved oxygen		Aquatic organisms need oxygen dissolved in lake water to live. Dissolved oxygen is consumed by decaying organic matter and respirating organisms and replenished by aquatic plants, wind mixing, and inflowing water
pH		Relevant for many chemical and biological processes. High or low pH can also exclude some animals and plants from the ecosystem.
Conductivity		A measure of how well the lake water conducts electricity; conductivity increases with increasing concentration of cations/anions. A change from a lake's baseline conductivity can indicate a change in the water supplying the lake.

Table 3. Water quality monitoring events.

Monitoring Event	Medium	Parameters	Frequency
Baseline observations and water quality (field measured)	lake water	water appearance, clarity, color, and profiles of dissolved oxygen, temperature, conductivity, and pH.	Biweekly during ice-free season
Baseline water chemistry	lake water, integrated sample of top 0-6 ft	hardness (Ca & Mg) alkalinity, pH, conductivity	Biweekly during ice-free season
Nutrient and chlorophyll-*a* sampling	lake water, integrated sample of top 0-6 ft	baseline parameters, total P, chlorophyll-*a*	July and September, 2018 and 2019
Midsummer sampling	lake water, integrated sample of top 0-6 ft	baseline parameters, total P, SO_4^{2-}, K, Na, Al, Cl, chlorophyll-*a*, NH_4^+, NO_3^- + NO_2^-, total N, SiO_2, dissolved organic carbon, turbidity, color	Mid-August 2018 and 2019
Hypolimnetic sample (Pleasant Lake only)	lake water, Kemmerer sample (2 ft above bottom)	total P, SO_4^{2-}, Mn	Twice during mid-summer 2018 and 2019
Turnover sampling	lake water, integrated sample of top 0-6 ft	baseline parameters, total P, SO_4^{2-}, K, Na, Al, Cl, chlorophyll-*a*, NH_4^+, NO_3^- + NO_2^-, total N, SiO_2, dissolved organic carbon, color	Spring and fall when the water column is mixed (as determined by temp. profile)
Surface water stable isotope sampling	lake water, integrated sample of top 0-6 ft, surface waters of Chaffee and Tagatz creeks	^2H and ^{18}O stable isotopes	5 times from October 2018 to November 2019, one time in October 2018 for Tagatz and Chaffee creeks
Groundwater sampling	groundwater from shallow wells surrounding each lake	^2H and ^{18}O stable isotopes, baseline parameters, K, Na, Al, Cl, NH_4^+, NO_3^- + NO_2^-, total P, SiO_2, SO_4^{2-}, Mn, Fe	Bimonthly from August 2018 to December 2019
Precipitation sampling	precipitation collectors at Hancock ag. station	^2H and ^{18}O stable isotopes	8 times from October 2018 to November 2019
Precipitation sampling	precipitation collectors at Hancock ag. station	conductivity, pH, alkalinity, hardness, Ca, Mg, Na, Cl, SO_4^{2-}, K	November 5, 2019

We used a handheld multiparameter meter to collect measurements of temperature, conductivity, dissolved oxygen, and pH in the field. On Plainfield and Long lakes, the field crew measured these parameters every half meter from just below the lake surface to within one-half meter from the bottom. Because Pleasant Lake is deeper, they measured these parameters every meter. At each depth we waited for readings on the handheld multimeter to stabilize before recording the measurement. We calibrated the multiparameter probe each morning and recorded the calibration results in a notebook. On October 5, 2018, a YSI DSS Pro multimeter replaced the In-Situ smarTROLL multimeter, which we had used until that point.

We collected surface water samples for chemical analysis at SLH using a 1-in diameter, 6-ft long polyvinyl chloride integrated sampler. During some monitoring events, low water on Plainfield and Long lakes prevented the collection of a full 6-ft integrated sample, so the crew collected a 5-ft integrated sample instead and noted this discrepancy on the field data sheet. We collected hypolimnetic samples in late summer and late winter using a Kemmerer at 1.6 ft above the sediment.

We took steps to prevent the contamination of samples following established sampling protocols (DNR, 2017). Wearing nitrile gloves, we triple rinsed the sampling devices in lake water (surface water for the integrated sampler and bottom water for the Kemmerer) along with a 1-gallon plastic Rubbermaid container used for sample collection and homogenization. After rinsing, we sampled water from the opposite side of the boat and poured the water into the Rubbermaid container. To achieve the necessary volume, we homogenized surface water from two full integrated samples. We then poured the samples into standard 250 ml and 1-quart low-density polyethylene (LDPE) plastic bottles provided by SLH. We took a new sample if the sample water or container came into contact with an object or surface that had not been rinsed. We acidified metals and nutrient samples on shore and stored all samples on ice until delivered to the laboratory.

Groundwater Chemistry

The Wisconsin Geological and Natural History Survey (WGNHS) installed a total of 31 shallow groundwater wells around the perimeter of each of the three study lakes (Hart et al., 2020, Figure 17 and Figure 18). On September 5-6, 2018, we collected water samples from each well for ^{18}O and ^{2}H stable isotopes to determine wells that are upgradient and downgradient from the lake. Based on these preliminary results at each lake in concert with gradients as measured by water levels in wells, we selected two wells upgradient from each lake and two wells downgradient from each lake (three on Pleasant Lake) for more intensive water chemistry and stable isotope monitoring. In total, we recorded groundwater levels and collected groundwater samples for stable isotopes and chemistry from monitoring wells ten times from August 2018 to December 2019. On April 23, 2019, we slightly modified which wells to continue monitoring to better reflect groundwater quality upgradient and downgradient from the lakes. This switch was based on the groundwater levels, isotope, and chemistry data collected until that point, indicating that some wells had locally high concentrations of some parameters or were not clearly up or downgradient from the lake.

At each groundwater monitoring well, we followed a modified version of EPA's standard operating procedure for low-flow groundwater sampling (Reinhart, 2017). In wells less than 35 feet deep, we withdrew water from the well using a battery-powered peristaltic pump. This type of pump has an adjustable flow rate and detachable plastic tubing that can be fitted to the flow-through cell of a handheld multimeter. The water passes from the well, through tubing to the pump, through the flow-through cell where pH, specific conductance, dissolved oxygen and temperature are measured, and then into a collection bucket so that the total volume of water pumped can be measured. The peristaltic pump can only draw water up about 35 feet, so we used high-density polyethylene (HDPE) tubing with a foot valve to sample water in deeper wells. To sample water using the HDPE tubing, we surged it up and down by hand and collected water in a graduated cylinder to periodically take readings with the multiparameter meter.

During each groundwater sampling event, we removed the pressure transducer from the well and noted the time (to later remove any data recorded by the transducer while it was out of the well) and depth to water in the well. We pumped water from three to five feet above the bottom of the well, keeping flow rates below 500 milliliters/minute and measuring temperature, dissolved oxygen, conductivity, and pH every three minutes. After readings had stabilized or three times the initial well volume had been pumped, we recorded the final readings from the multiparameter, assuming they represent the ambient groundwater. We then collected water samples while wearing nitrile gloves. The sample collector sealed the glass isotope sample vial with parafilm, and acidified the water chemistry samples, mimicking procedures for collecting and preparing lake water chemistry samples (DNR, 2017). Before leaving the site, we measured the depth to water again and noted the time at which we replaced the pressure transducer.

Precipitation Chemistry

We installed two precipitation collectors at Hancock Agricultural Research Station, approximately seven miles southwest of Plainfield and Long lakes and nine miles north of Pleasant Lake. The precipitation collectors consist of a 5.5-inch diameter funnel attached to a 4-liter HDPE plastic collection jar, which is nested inside a 5-gallon bucket (Figure 12). A plastic ping-pong ball rests inside the funnel, allowing water to pass through but not evaporate from inside the bottle. Plastic mesh covers the top of the funnel to secure the ping-pong ball and prevent large debris from falling into the collection jar. A ½-inch layer of mineral oil in the precipitation collection jar

Figure 12. Precipitation collectors. Water passes through the plastic mesh and past the buoyant ping-pong ball to the 4-liter jug nested inside the bucket.

reduces evaporation, as the heavier water sits below the mineral oil layer. We anchored the entire precipitation collector with iron rebar sunk 1.5 feet into the ground and situated the collectors well away from any foliage or structures.

We collected eight monthly precipitation samples for stable isotope analysis, excluding winter, and one sample for water chemistry analysis from both precipitation collectors. During each sample collection event, we carefully removed the collection jar from the bucket and siphoned water from below the mineral oil layer, passing water through a coffee filter to remove any residual mineral oil. We then poured this filtered water into the appropriate sample container. Field staff wore nitrile gloves and cleaned the inside of the precipitation collectors after each sampling.

For chemistry tracer-based estimates of lake water budgets, we relied upon biweekly datasets from the closest National Atmospheric Deposition Program station at Devils Lake, WI (site id: WI31, lat: 43.4352, long: -89.6801). At the time of analysis, data was available for January 2014 through October 2019.

Stable Isotope Measurements

We sampled and analyzed two types of stable isotopes from various sources of water in and around the study lakes in order to create a water budget according to techniques described in Krabbenhoft (1990). Field staff collected stable isotope samples in a 20-ml glass scintillation vial, first filling the vial so that the meniscus extended above the rim and then stretching parafilm over the top before sealing to prevent any air from being included. Staff placed samples in a laboratory refrigerator before shipping them to the Iowa State Stable Isotope Laboratory in Ames, Iowa for analysis. We collected stable isotope samples from the precipitation collectors, the upper six feet of the three study lakes, groundwater from around each study lake, and once from two creeks whose headwaters are downgradient from Pleasant Lake. Chaffee Creek begins within 1500 ft of the eastern shore Pleasant Lake, while the headwaters of Tagatz Creek lie 0.6 miles south of Pleasant Lake.

Quality Control Results

We collected duplicate (two samples taken at the same time and place) and blank (deionized water poured through sample equipment after triple rinsing) samples on ~10% of lake and groundwater sampling events to document the accuracy and potential contamination of results (Table 4 and Table 5). Manganese, aluminum, and iron duplicate samples had the greatest maximum percent difference from the paired reference sample. Of 93 pairs of duplicate samples, 80 (86%) differed by less than 10%. Blank samples showed little evidence of contamination; 60 of 68 blank samples (88%) were below the limit of detection. Four of eight alkalinity blanks, three of eight calcium blanks, and one of two chlorophyll-α blanks returned concentrations above the detection limit. In each case, the maximum result was slightly above the detection limit and well below the median value of normal (non-blank) samples. All other blank samples were below the laboratory limit of detection.

Our two precipitation collectors at Hancock Agricultural Research Station were separated by approximately 200 yards. Assuming that differences in the precipitation reaching the two collectors were negligible, we considered paired samples to be duplicates. Differences in these paired samples reflect both the integrity of our sample collection devices and consistency in our collection methods. Isotope samples collected from the two precipitation collectors at Hancock Agricultural Research Station were nearly identical. The adjusted R^2 for paired deuterium (^2H) and heavy oxygen samples (^{18}O) were both greater than 0.99. We also gathered samples for chemical analysis from each precipitation collector on November 5th, 2019. Calcium concentration differed by 23% and hardness differed by 17%

between the two samples; all other analytes differed by less than 10%. In addition, we collected two sample blanks by slowly pouring deionized water into the precipitation collector, and then collecting the sample as normal. Both blank samples were found to contain sodium above the detection limit (0.326 mg/L and 0.271 mg/L, limit of detection 0.20 mg/L), and one was found to contain calcium (0.154 mg/L, limit of detection 0.10 mg/L). All other analytes were below the detection limit.

Table 4. Duplicate lake and groundwater chemistry samples.

Parameter	Number of duplicate sample pairs	R^2 value (for n > 5)	Max percent difference between paired samples
Alkalinity (total, $CaCo_3$)	9	1	1%
Aluminum	4		140%
Calcium	9	1	5%
Chloride	3		4%
Conductivity	9	1	1%
Hardness	9	1	4%
Iron	2		40%
Magnesium	9	1	4%
Manganese	2		148%
Nitrogen NH_3-N, dissolved	3		8%
Nitrogen NO_3 + NO_2, dissolved	3		1%
pH	9	0.98	2%
Phosphorus, total	4		32%
Potassium	4		17%
Silica	4		2%
Sulfate, total	4		3%
Chlorophyll-*a*	2		16%
Nitrogen, total	1		6%
Sulfate, dissolved	1		4%

Table 5. Blank lake and groundwater chemistry samples. ND is below the limit of detection.

Parameter	No. of non-detects / Total No. of blanks	Highest value	Limit of detection
Alkalinity	4 / 8	4.3 mg/L	2.55 mg/L
Aluminum	3 / 3	ND	10 ug/L
Calcium	5 / 8	0.17 mg/L	0.1 mg/L
Chloride	2 / 2	ND	0.93 mg/L
Chlorophyll-*a*	1 / 2	0.57 µg/L	0.26 µg/L
Conductivity	8 / 8	ND	10 ug/L
Hardness	8 / 8	ND	0.66 mg/L
Iron	1 / 1	ND	0.1 mg/L
Magnesium	8 / 8	ND	0.1 mg/L
Manganese	1 / 1	ND	1 ug/L
Nitrogen NH_3 + N	2 / 2	ND	0.015 mg/L
Nitrogen NO_3 + NO_2	2 / 2	ND	0.036 mg/L
Nitrogen, Total	1 / 1	ND	0.075 mg/L
Phosphorus, Total	3 / 3	ND	0.008 mg/L
Potassium	3 / 3	ND	0.2 mg/L
Silica	3 / 3	ND	0.10 mg/L
Sodium	3 / 3	ND	0.2 mg/L
Sulfate, Dissolved, as SO_4	1 / 1	ND	0.8 mg/L
Sulfate, Total	1 / 1	ND	2.3 mg/L

Biological Characterization

Aquatic Plants

Plant Point-Intercept Surveys

We conducted aquatic plant point-intercept surveys to determine the spatial distribution and relative abundance of species in the navigable portion of each lake (Hauxwell et al., 2010). Before going into the field, staff created a regularly-spaced grid of coordinates overlaid on the lake of interest. A field crew trained in aquatic plant identification navigated to each point using a GPS unit and collected a sample of vegetation using a retrievable rake. The crew recorded all species found on the rake, nearby visible species, and the depth and substrate. We conducted plant point-intercept surveys on all three study lakes in early August 2018 and 2019 (Table 6). Onterra LLC (2009) and UW – Stevens Point (2012) conducted plant point intercept surveys on Pleasant Lake in the past. We revised the survey grids on Long and Plainfield Lakes using current areal images to reflect the high water (Mikulyuk et al., 2010).

Plant point-intercept surveys generate metrics that describe the type and condition of the lake's aquatic plant community. Lake-wide statistics generated from the point-intercept surveys include the species richness, the mean coefficient of conservatism (C-value), the Floristic Quality Index (FQI), two bioassessment metrics (MAC-gen and MAC-P), and the maximum depth of colonization. The species richness is the total number of species encountered during the survey. The mean coefficient of conservatism calculates the average coefficient of conservatism (or C-value) of each species encountered and, is thus independent of species richness. C-values for each plant species are based on professionals' judgement of how likely a given species is to be found in pristine, undisturbed habitats. Non-native species and those tolerant of degradation have low C-values, whereas native species intolerant of habitat degradation have higher C-values, up to a maximum of 10. The FQI depends on both richness and C-values; it is calculated as the sum of all C-values divided by species richness and then multiplied by the square root of species richness (Nichols, 1999). The MAC-gen bioassessment metric rates a lake's condition in relation to general anthropogenic disturbance and the MAC-P metric in relation to phosphorus pollution by evaluating the relative abundance of species that are tolerant vs. sensitive to disturbance (Mikulyuk et al., 2017; Mikulyuk et al., 2019). Finally, the maximum depth of colonization is the deepest depth at which plants occur and reflects how deep into the water column light can penetrate.

Plant point-intercept surveys also generate plant-specific metrics. For each species, we calculated the littoral frequency of occurrence, which is the number of points at which the species occurs divided by the total number of littoral points (littoral points are all points shallower than the maximum depth of colonization).

Table 6. Biological and habitat monitoring events.

Monitoring Event	Method	Information Collected	Sample Dates
Electrofishing	stun fish with boat-mounted electrodes, targets bass and panfish	counts by species, length and weight for some fish	Long Lake – May 14, 2019 Pleasant Lake – May 28, 2019
Shoreline seining	gather fishes in net while wading, targets juveniles and near-shore fishes	counts by species	Pleasant Lake – Aug 29, 2018 Long Lake – Aug 28, 2018 Plainfield Lake – Aug 29, 2018 & Sep 9, 2019
Aquatic plant point-intercept survey	identify plants at gridded locations across entire lake	abundance of each species across the entire lake basin	Pleasant – Aug 8-9, 2018 & Aug 8-9, 2019 Long – Aug 6-7, 2018 & Aug 7-8, 2019 Plainfield – Aug 2 & 6, 2018 & Aug 6-7, 2019
Emergent and floating-leaved plant bed mapping	identify and delineate plant beds with GPS	areas and composition of plant beds visible at the surface	Long – Aug 7 & Sep 26, 2018 & Aug 20, 2019 Plainfield – Aug 7 & Sept 24, 2018 & Aug 20, 2019
Wetland plant timed-meander survey	identify plants along pseudo-random path	species composition and richness, estimate of % cover	Pleasant – Aug 21, 2018 Long – Aug 2, 2018 Plainfield – Aug 2, 2018
Pleasant Lake sonar mapping	boat-mounted sonar unit, sonar reflects off lake bottom and plants	% of water column occupied by plants across entire lake basin, water depth and substrate hardness	Pleasant – Aug 13, 2018
Shoreline substrate mapping	substrate composition around lake perimeter and along transects perpendicular to shore	% sand, gravel, muck etc. for each transect, degree of embeddedness	Pleasant – Sep 26 and Oct 4, 2018

Floating and Emergent Plant Bed Delineation

DNR staff delineated the extent of floating plants on August 7th, 2018 and the extent of emergent plants on September 24 and 26, 2018 on Plainfield and Long lakes, respectively. In 2019, DNR staff mapped floating and emergent plants on August 20th in both lakes. These surveys differed from the point-intercept surveys because staff mapped visible, contiguous stands of emergent or floating plants and identified the dominant species, rather than detailing every species present at pre-defined points. This methodology gives a more detailed view of the spatial extent of floating and emergent plants, especially nearshore. Field staff paddled a canoe or drove a motorboat around contiguous stands of plants, identifying dominant and secondary species. A GPS unit (Garmin GPSMAP 78) logged the path of the boat every 30 seconds as tracks, and we then converted these tracks to polygons. Next, we used ArcMap 10.4.1 to calculate the areas of floating and emergent plant beds.

Staff only delineated beds greater than ~100 square feet. Determining whether a group of plants was dense enough to qualify as a bed and identifying the bed boundaries were somewhat qualitative, but we attempted to maintain consistency by defining a minimum percent cover. For example, the *Brasenia schreberi* bed on the west side of Long Lake had almost 100% cover and was clearly defined, but there were dispersed *Nymphaea odorata* across most of Plainfield Lake in 2018, so we only delineated areas with ~50% cover or greater. Thus, it should be recognized that the density of floating and emergent plant beds varies to some degree. Still, a study from Minnesota found high repeatability in mapping bulrush beds between survey crews and estimated that it would be possible to detect whole-lake changes in coverage of 10% (Radomski et al., 2011).

Aquatic Plant Biovolume

On August 13, 2018, we mapped the biovolume of aquatic plants in Pleasant Lake using a boat-mounted sonar unit (C-MAP, Inc., 2017). During the survey, we piloted the boat around the lake following the shoreline, and then across the lake in approximately equally spaced east-west transects, except in the southwestern lobe, where the boat was driven predominantly north-south. The boat operator drove across the entire lake surface at a relatively constant speed while the sonar collected data. We used BioBase software (C-MAP, Inc., 2018) to translate the sonar data into a map of biovolume, which is the proportion of the water column taken up by plant biomass.

Wetland Plants

In August of 2018, DNR staff surveyed wetland communities not included in aquatic plant point intercept surveys using a “timed-meander” method (Trochlell, 2016; Table 6; Figure 13). In this survey method, wetland plant experts began by visually identifying an assessment area defined as an area of homogeneous vegetation based on dominant plant species. Assessment areas were consistent with Natural Heritage Inventory (NHI) natural communities (O’Connor, 2020; Epstein, 2017). A single wetland can contain a mosaic of several natural communities, so the biologist completed a survey for each natural community identified. The team searched each assessment area for as many species as possible, identifying all species encountered until one or zero new species are encountered in the last five-minute interval or until the number of new species is less than 5% of the total. We aimed to identify every species present in the pre-defined assessment area. Then we estimated the total percentage of the assessment area covered by each species. Similar to aquatic plants, each wetland species has a C-value which can be used to calculate a Floristic Quality Index (Bernthal, 2003; Marti & Bernthal, 2019).

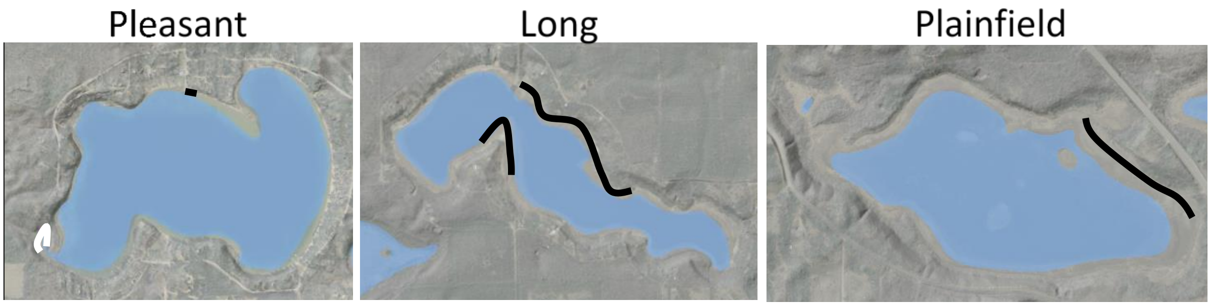

Figure 13. Timed-meander survey locations of Inland Beach plant community on each lake (black lines) and of the Southern Sedge Meadow on Pleasant Lake (white line).

Fish

To assess the state of the fish communities of the study lakes, we seined along shore and electrofished (Table 6). Used in combination, these two techniques produced an estimate of the number of fish species present, the abundance of each species, and the overall health of the fish community. Seining targeted small, non-game fish species and young-of-year that use shallow near-shore habitat, whereas electrofishing targeted adult game fish species.

Shoreline Seining

Shoreline seining is a sampling technique wherein a large net is dragged along the shore and then gathered to capture fishes in the near-shore littoral zone. We modified seining protocols from the Minnesota Division of Fisheries and Wildlife (2015) according to recommendations from experienced fisheries staff at DNR. We seined all three lakes on August 28-29, 2018 and seined Plainfield Lake a second time on September 10, 2019 after observing fish for the first time during ongoing monitoring activities in 2019.

On Pleasant Lake, we used the same stations that DNR staff sampled in 2013. We used ArcGIS to randomly select the first monitoring station and then select nine more equidistant stations around the perimeters of Long and Plainfield lakes. However, only five of ten stations in 2018 and four of ten in 2019 were sampled on Plainfield Lake due to high water and steep drop-offs. Nine of ten stations were sampled on Long Lake due to a thunderstorm. We navigated to sites using a GPS unit, measured the length and width of shoreline seined, and recorded substrate composition at each site. Two staff stretched the seine net (6 X 30 feet with a 6 X 6 X 6-foot bag and 1/8-inch mesh) perpendicular to the shore, extended the net either fully or until the water became too deep, and slowly walked the previously measured length. When the net reached the pre-determined sampling length, staff brought the two ends of the net together and up on shore. Staff counted the number of each species present, enumerating adults and young-of-year separately, and then returned the fish to the lake.

Electrofishing

DNR fisheries staff conducted electrofishing surveys on Long Lake on the night of May 14, 2019 and Pleasant Lake on the night of May 28, 2019. They did not sample Plainfield Lake due to lack of boat access. Fisheries staff followed the Spring Electrofishing II protocol (Lakes Assessment Team, 2008). This technique used a battery to run an electrical current between the two boom shockers (metal anodes) and the metal hull of the boat. The current momentarily stunned the fish, which allowed the crew to collect them in nets. In addition to counting game fish by species, fisheries staff measured a subset of the catch to estimate size structure for different fish species. Electrofishing in spring is most effective at sampling bass and panfish. DNR fisheries staff did not assess the walleye and muskellunge populations on Pleasant Lake, which would require additional survey methods.

Fish Metrics

Fisheries staff calculated several metrics based on the abundance and size of the fishes encountered during electrofishing. These metrics help summarize the state of the fishery when appropriately interpreted.

Catch Per Unit Effort (CPUE): Staff divided reported catch, or catch above a certain size, by a measure of fishing effort. Electrofishing surveys measure effort in miles or hours. We report abundances of fish in individuals per mile, individuals of adult size per hour, and individuals of preferred size (for anglers) per mile. Fisheries staff then compared the CPUE of similar lakes to determine the relative health of a fishery.

Proportional Stock Density (PSD): Fisheries experts commonly assign fish to categories of "stock" and "quality" based on length. Stock size fish are generally a few years old and not suitable for harvest. Quality size fish are at or approaching legal harvest size. PSD is the number of quality size fish divided by the number of stock size fish, expressed as a percent, and gives a general idea of the size structure of the population. Fisheries staff usually consider a PSD of 30 – 50% ideal.

Length Frequency Distribution (LFD): Fisheries staff often measure a subset of fish captured during a survey to investigate the size structure of the population. This can reveal which year classes have survived the best and how the fishery will change in the future. The LFD is displayed graphically as the number of fish that fall into 1-inch size intervals. The size structure of the LFD is dependent on the technique used to catch the fish, and so is not necessarily representative of the entire population in the water body.

Human Use Characterization

Survey Collection Methods

We conducted surveys by mail and email to better understand the ways in which property owners along Long and Pleasant Lakes interact with the lakes. We used the Wisconsin 2019 tax parcel database to identify riparian landowners on the two lakes. Pleasant Lake recipients also included several residential parcels within 1/4 mile of the lake because anecdotal evidence indicated some of these properties also had deeded access to the lake. On May 28, 2020 we sent letters to 277 recipients with properties located on Long Lake (n=70) and Pleasant Lake (n=207). The letter notified them of the study and that they would be sent a mail survey. The survey also asked respondents to call or email DNR staff to provide their email address if they would prefer to conduct the survey online. In total, respondents provided 72 email addresses, 17 for Long Lake and 55 for Pleasant Lake.

On June 9, 2020, we sent a mail survey with 33 questions to the 205 recipients that had not responded with a valid email address. We also sent an email with a link to a nearly identical online survey to those that responded with valid emails. On July 2, 2020, we sent a reminder letter or email to those who had not yet completed the survey. In total, there were 2 unreachable landowners on Long Lake and 10 on Pleasant Lake. We completed survey collection on August 20, 2020, with 41 responses for Long Lake and 136 for Pleasant Lake. The final response rate across both surveys was 66.8%. The response rate for

Long Lake (60.3%) was lower than Pleasant Lake (69.04%). The proportion of online respondents were nearly identical in the two survey with 31.7% of Long Lake respondents completing an online survey compared to 31.6% for Pleasant Lake.

Our survey contained questions on lake property ownership features, recreation and navigation, lake level variation, and the economic impact of lake tourism. The section on lake property ownership contained questions about the length of time residents had owned property on the given lake, and features of the property such as length of shoreline and number of watercraft owned. We used this section largely to provide context for the remainder of the survey. For the recreation and navigation sections, we asked respondents to indicate the frequency with which they participated in a list of outdoor recreation activities and the importance of these activities to their enjoyment of their lake property. Both questions used a Likert scale; the options for frequency included “Never”, “Rarely”, “Occasionally”, “Often” and “Very Often”, and the options for importance included “Not at all important”, “Slightly important”, “Moderately important”, “Very important”, and “Extremely important”. We used the section on lake level variation to understand how lake level variation had affected residents and their lake property, in particular asking respondents to think about the impacts of low or high levels to the various ways they enjoy the lake. Finally, the section focused on lake tourism informed our understanding of how lake residents support the local economy.

We used a paired T-test to compare differences in the mean responses between low and high lake levels and an ANOVA to test between types of activities, lake qualities, and damage at low lake levels and at high lake levels. Because respondents may differ in how they perceive the Likert scale (e.g., from strongly disagree to strongly agree), we report percentages of respondents in pooled categories. Summary percentages are based on the number of respondents to each individual question rather the total number of respondents.

Results

Hydrology

Lake Levels

Pleasant Lake levels range from 977.1 to 983.8 ft asl from 1937 through 2019 (Figure 14). Low water periods occurred in the mid-1960’s and again in the mid-2000’s. High water occurred from 1973 to 1997, but data gaps exist during this period. Lake levels are currently very high, with a rapid rise of 2.8 ft from 2016 to 2019. Current lake levels are near the peak observed in 1994. Our interpretation of the air photo approximations of lake levels are two to three feet lower than the Waushara County- and DNR-surveyed lake levels where the two records overlap (1973-1993). Waushara County, USGS, and air photo lake levels show greater agreement from 2003 to 2019. The full range of lake levels is less extreme according to the air photos, with a range of 3.6 feet versus 5.5 feet based on the survey data. The total range from all observations is 6.7 feet. We use caution interpreting the air photo records. Relative to themselves, the air photos corroborate surveyed lake levels, showing that lake levels oscillate over time with an additional high in 1940.

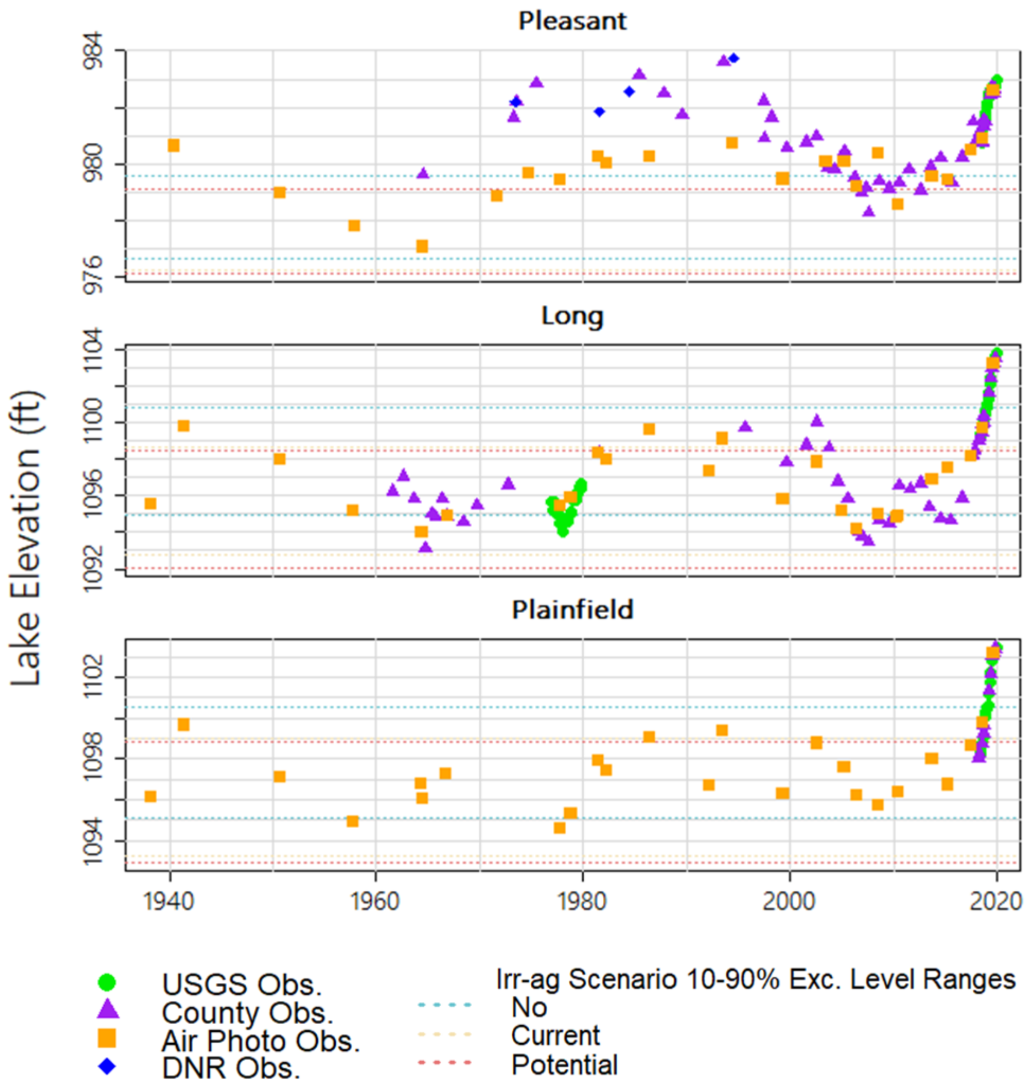

Figure 14. Historical observed lake levels. Historical observations derive from four data sources: United States Geological Survey (USGS), Waushara County, Wisconsin Department of Natural Resources, and inferred lake elevations from air photos. Overlaid are the 10 and 90% exceedance probability levels from the MODFLOW model under the no-irrigated-agriculture-scenario (No), current-irrigated-agriculture-scenario (Current) and potential-irrigated-agriculture-scenario (Potential).

Long Lake levels range from 1093.1 to 1103.8 ft asl from 1938 to 2019, a range of 10.7 feet (Figure 14). Low water periods occurred in the mid-1960's, late 1970's, and mid-2000's. The most recent low water period lasted for approximately 11 years. Low water might have extended for that long or longer in the 1960's to 1970's, but data gaps exist during this period. High water occurred *c.* 1940, 1986, 1995, and 2002. Again, data gaps occur, but existing records indicate lake levels were high during this entire period. Several historical reports that state maximum depth corroborate air photo and lake level records: the maximum depth was 5.5 ft in 1979 (Waushara County, 1981), 6 ft in 1980 (Waushara County, 1981), 5.5 ft in 1987 (Primising, 1987), 6 ft in 1997 (Neibur, 1998), and 5 ft in 2002 (Cason and

Chikowski, 2004). Assuming that the elevation of the lake bottom at the deepest point remained 1092 ft asl over time, lake level elevations were approximately 1097-1098 ft asl. There are several historical bathymetric maps indicating that the maximum depth reached 10-14 feet, which would translate to lake level elevations of 1104 ft asl in 1941 (DNR) and 1102 ft asl in 1983 (USGS). These elevations are higher than any other historical records but are similar to the high lake levels observed during this study. Long Lake rapidly increases beginning 2016, undergoing a 7.9-foot increase from 2016 to 2019. A similarly fast rise was observed from 1978 to 1979, but the data record does not continue. The air photos and surveyed data show good agreement on Long Lake, and Long Lake oscillates in coherence with the other two lakes.

Plainfield Lake levels range from 1094.6 to 1103.4 ft asl from 1938 to 2019, a range of 8.8 feet (Figure 14). Unlike Pleasant Lake and Long Lake, data prior to 2017 comes only from air photos. Still, the air photos show coherence with both of the other lakes. Historical fisheries reports state that Plainfield Lake levels were low from 1959 to 1962, causing winter fish kills and a lack of fish in the summer of 1960. They reported a max depth of 2.5 ft in 1959 and 6 ft in 1960 (Primising, 1961; 1962). Assuming the lake elevation at the deepest point was the same then as it is now at 1089.5 ft asl, this would correspond to lake level elevations of 1092 and 1095.5 ft asl. The latter elevation corresponds well with that inferred from an air photo in 1957, but 1092 ft asl is 2.9 ft lower. The report does not specify where the maximum depths were recorded. Still, the fisheries reports provide additional evidence that Plainfield Lake can experience very shallow water and fish kills and that Plainfield Lake levels were low *c.* 1960. The oscillation prior to the rapid rise of 5.2 feet from May 2018 to December 2019 ranges from 1094.6 to 1099.6 feet, a range of 5 feet. The recent high lake levels on both Plainfield Lake and Long Lake are unprecedented given the data records we have available.

Water Budget

Pleasant Lake

Groundwater accounts for around one third of annual inflows and over half of annual outflows on Pleasant Lake according to the MODFLOW calibration (2012-2018) (Table 7, Figure 15, Figure 16). Precipitation is always larger than groundwater inflow, and evaporation is always smaller than groundwater outflow. Change in lake volume is on average near-zero but can account for as much as 24% of outflows (when lake volume increases) and 14% of inflows (when lake volume decreases). Lake water residence time is on average 3.4 years, but ranges from 2.6 to 3.7 years (Table 8).

Table 7. Water budget from the MODFLOW calibration, as percent.

Flux	Minimum	Median	Maximum
Pleasant			
Precipitation (%)	50	61	69
Groundwater Inflow (%)	30	34	39
Evaporation (%)	32	40	43
Groundwater Outflow (%)	44	57	61
Δ Lake Volume (%)	-24	0	14
Long			
Precipitation (%)	50	61	64
Groundwater Inflow (%)	21	36	39
Evaporation (%)	32	37	42
Groundwater Outflow (%)	15	52	63
Δ Lake Volume (%)	-53	-9	28
Plainfield			
Precipitation (%)	61	74	84
Groundwater Inflow (%)	6	16	27
Evaporation (%)	38	45	54
Groundwater Outflow (%)	9	43	55
Δ Lake Volume (%)	-53	-3	34

Figure 15. Water budget from the MODFLOW calibration, as percent. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

We used magnesium as a chemical tracer to calculate the Pleasant Lake water budget for WY2019. While magnesium-based WY2019 values are unlikely to perfectly match the groundwater flow model budget for WY2018 (the last full water year modeled during the calibration period) due to the difference in dates, values should be close. Groundwater inflow values are extremely similar between the two approaches, and groundwater accounts for a similar percent of all inflows (Table 9). Lake water residence time is also similar between the two estimates. Groundwater outflow is substantially lower in the magnesium-based WY2019 estimate compared to the MODFLOW-based WY2018 estimate, but this is not surprising for two reasons. First, Pleasant Lake levels were substantially higher in WY2019 than they were in WY2018, and groundwater outflow tends to be slightly lower in the study lakes when lake levels are high and rising higher (Table 8). Second, the WY2019 energy balance-based estimate of lake evaporation is substantially higher than the WY2018 air temperature-based estimate. Since groundwater outflow is calculated as the residual of the water balance in the magnesium-based approach, this acts to lower the magnesium-based estimate of groundwater outflow relative to the MODFLOW-based estimate. The fact that groundwater inflow and lake water residence time values are so similar to one another despite these confounding factors increases our confidence in the groundwater flow model water budget.

Figure 16. Water budget from the MODFLOW calibration, as volumes (ac-ft). Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

Long Lake

Groundwater accounts for around one third of inflows and around half of outflows (Table 7, Figure 15, Figure 16) at Long Lake according to the MODFLOW calibration (2012-2018). However, there is more variability in this range than at Pleasant Lake; as a volume, groundwater inflow ranges from 25 acre-ft/yr to 114 acre-ft/year and groundwater outflow ranges from 46 acre-ft/year to 108 acre-ft/year (Table 8). Precipitation is always larger than groundwater inflow, accounting for 50%-64% of all inflows. Evaporation is smaller than groundwater outflow at lower lake levels (from 2012-2015) but becomes larger than groundwater outflow at higher lake levels (from 2016-2018), overall accounting for 32%-42% of outflows. Change in lake volume is on average near-zero, but can be substantial, accounting for up to 53% of outflows (when lake volume increases) and 28% of inflows (when lake volume decreases). Lake water residence time is relatively short at just 0.6 years (Table 8). The chemical tracer approach is not computationally stable at Long Lake and cannot be used to independently check groundwater flow model values.

Plainfield Lake

At Plainfield Lake, the groundwater flow model calibration (2012-2018) indicates groundwater plays a smaller role in the lake water budget. Groundwater accounts for 6%-27% of annual inflows and 9%-55% of annual outflows (Table 7, Figure 15, Figure 16). As at Long Lake, groundwater flow can be highly variable; as a volume, groundwater inflow ranges from 9 acre-ft/yr to 58 acre-ft/year and groundwater outflow ranges from 17 acre-ft/year to 75 acre-ft/year (Table 8). Precipitation is always larger than groundwater inflow. Evaporation is approximately equal to groundwater outflow at lower lake levels (from 2012-2015) but becomes larger than groundwater outflow at higher lake levels (from 2016-2018), overall accounting for 38%-54% of outflows. As at Pleasant and Long Lakes, change in lake volume is on average near-zero, but can be substantial, accounting for up to 53% of outflows (when lake volume increases) and 34% of inflows (when lake volume decreases). Lake water residence time is relatively short at just 0.9 years (Table 8). We found the chemical tracer approach not to be computationally stable at Plainfield Lake and cannot use it to independently check groundwater flow model values.

Table 8. Water budget from the MODFLOW calibration, as volumes (ac-ft).

Flux	Minimum	Median	Maximum
Pleasant			
Precipitation (ac-ft/yr)	338	395	586
Groundwater Inflow (ac-ft/yr)	190	239	260
Evaporation (ac-ft/yr)	257	269	292
Groundwater Outflow (ac-ft/yr)	351	378	393
Δ Lake Volume (ac-ft/yr)	-206	-2	94
Residence Time (yr)	2.6	3.4	3.7
Long			
Precipitation (ac-ft/yr)	51	96	200
Groundwater Inflow (ac-ft/yr)	25	41	114
Evaporation (ac-ft/yr)	35	59	101
Groundwater Outflow (ac-ft/yr)	46	55	108
Δ Lake Volume (ac-ft/yr)	-165	-9	53
Residence Time (yr)	0.4	0.6	0.8
Plainfield			
Precipitation (ac-ft/yr)	81	89	162
Groundwater Inflow (ac-ft/yr)	9	21	58
Evaporation (ac-ft/yr)	54	65	84
Groundwater Outflow (ac-ft/yr)	17	44	75
Δ Lake Volume (ac-ft/yr)	-117	-3	49
Residence Time (yr)	0.6	0.9	1.3

Table 9. Comparison of modeled and calculated water budget at Pleasant Lake.

Flux	Calculation Type	Value
Water Budget as Percent (%)		
Precipitation	MODFLOW WY2018	71
	Magnesium WY2019	66
Groundwater Inflow	MODFLOW WY2018	29
	Magnesium WY2019	34
Evaporation	MODFLOW WY2018	36
	Magnesium WY2019	56
Groundwater Outflow	MODFLOW WY2018	53
	Magnesium WY2019	16
Δ Lake Volume	MODFLOW WY2018	11
	Magnesium WY2019	27
Water Budget as Volume (acre-ft)		
Precipitation	MODFLOW WY2018	534
	Magnesium WY2019	461
Groundwater Inflow	MODFLOW WY2018	223
	Magnesium WY2019	242
Evaporation	MODFLOW WY2018	273
	Magnesium WY2019	396
Groundwater Outflow	MODFLOW WY2018	403
	Magnesium WY2019	116
Δ Lake Volume	MODFLOW WY2018	82
	Magnesium WY2019	191
Residence Time (yr)	MODFLOW WY2018	2.9
	Magnesium WY2019	3.4

Water Chemistry

Acidity

The pH of water is a critically important parameter for lake ecosystems because it controls the solubility and bioavailability of dissolved solutes (Wetzel, 2001). Aquatic life typically does best at a pH between 6.5 and 8.5, and all three study lakes fall within this optimal pH range (Figure 17). Most Wisconsin lakes have a pH between 6.5 and 8, with Central Wisconsin lakes typically less acidic (mean pH 7.9) (Lillie and Mason, 1983; Figure 17). Pleasant Lake is more basic than most central Wisconsin lakes (mean pH 8.5), while Plainfield Lake is more typical of central Wisconsin lakes (mean pH 8.0) and Long Lake is more acidic (mean pH 7.6).

Alkalinity is a measure of how much base is present and is determine by adding strong acid to a water sample until all hydroxyl, carbonate, and bicarbonate ions are neutralized. Lakes with high alkalinity (> 100 mg/L $CaCO_3$) are resistant to changes in pH, tend to support more aquatic life, and are known as hard water lakes (Wetzel, 2001). Lakes with a low alkalinity (<30 mg/L) are more susceptible to changes in pH and are known as soft water lakes. An alkalinity of 20 mg/L is the minimum recommended threshold for aquatic life in the United States (US EPA, 2020). Wisconsin lakes have a mean alkalinity of 50 mg/L with central Wisconsin lakes typically much higher (mean alkalinity 120 mg/L) (Lillie and Mason, 1983; Figure 17). Both Pleasant Lake and Plainfield Lake are hard water lakes with very high alkalinity, while Long Lake is closer to a soft water lake but still moderate compared to other Wisconsin lakes. The high lake alkalinities are a result of the high carbonate content of the sands and gravels in the area (Syverson et al., 2011).

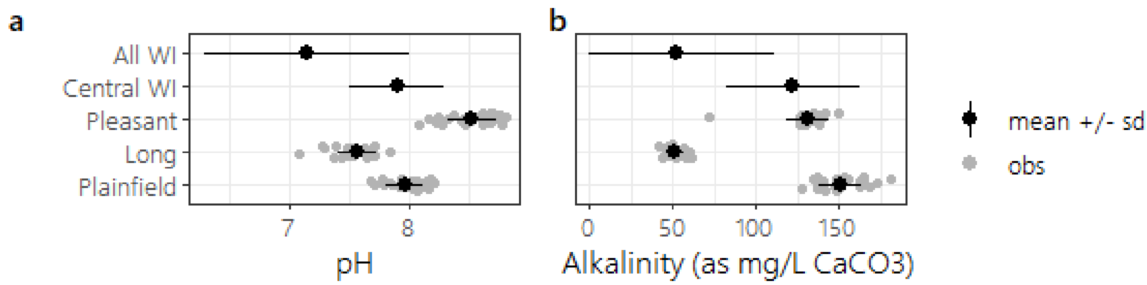

Figure 17. Acidity at Pleasant, Long, and Plainfield lakes. pH (a) and Alkalinity (b) measured at Pleasant, Long, and Plainfield lakes compared to the mean and standard deviation for lakes in all of Wisconsin and in central Wisconsin measured by Lillie and Mason (1983).

Salinity

The total concentration of all dissolved ions represents the salinity of water bodies, often measured as specific conductance, or conductivity (Wetzel, 2001). Dissolved ions can be toxic to freshwater life if concentrations are too high and water becomes too saline, but moderate concentrations are necessary for maintaining an appropriate pH and supporting biological processes. High conductivity (> 50 µS) is strongly correlated with high richness and diversity of aquatic life including fish, snails, invertebrates, and aquatic plants (Hrabik et al., 2005). However, very high conductivity (>1,000 uS/cm) can be a sign of contamination (McGinley and Sisk, 2015) and several Great Lakes states set an upper limit of 2,400 µS/L to protect aquatic life from dehydration and other salinity-related stresses (Bodkin et al., 2007). Of the Central Sands study lakes, Plainfield Lake has the highest specific conductivity (mean of 328 uS/cm), followed by Pleasant Lake (272 uS/cm), then Long Lake (109 uS/cm, Table 10). This indicates all three lakes have sufficiently high salinity to support abundant and diverse aquatic life but are well below values at which contamination or salinity stresses become a concern.

In lakes and groundwater, salinity is largely controlled by the dissolved concentrations of four major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and four major anions (HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-) (Wetzel, 2001; Schwartz and Zhang, 2002). In hard water lakes, calcium, magnesium, bicarbonate, and carbonate (i.e., alkalinity) dominate lake water chemistry. These ions are derived from calcium-rich rocks such as limestone or glacial outwash derived from those rocks such as occurs in the Central Sands. Alkalinity measures HCO_3^- and CO_3^{2-} and is therefore strongly correlated with conductivity in calcium bicarbonate systems like the study lakes (Wetzel, 2001; Schwartz and Zhang, 2002). Sodium, potassium, sulfate, and chloride typically occur in groundwater and hard water lakes at much lower concentrations, though they can be a major component of salinity in soft water lakes (Kalff, 2002; Wetzel, 2001). Although minor ions (e.g., Al, Fe, Mn, SiO_2, N, P) typically play a small role in overall salinity (Wetzel, 2001), they can be important biologically and most come from groundwater (Hurley et al., 1985; Vanek, 1991; Lewandowski et al., 2015; Nisbeth et al., 2019).

Table 10. Mean (standard deviation) of water quality parameters measured at 0-6 ft depth or less, 2018-2019.

Parameter	Units	Pleasant	Long	Plainfield
Acidity				
pH	SU	8.5 (0.2)	7.6 (0.2)	8.0 (0.2)
Alkalinity (as mg/L CaCO3)	mg/L	131 (12)	51 (6)	151 (13)
Salinity				
Specific Conductance	uS/cm	272.2 (22.6)	108.6 (11.7)	328.4 (27.1)
Calcium	mg/L	28.1 (1.8)	11.1 (1.4)	36.2 (4.4)
Magnesium	mg/L	18.4 (0.7)	5.9 (0.6)	16.5 (1.2)
Potassium	mg/L	0.4 (0.1)	0.9 (0.2)	1.6 (0.4)
Sodium	mg/L	1.9 (0.1)	0.8 (0.2)	7.6 (1.1)
Sulfate	mg/L	9.2 (8.7)	0.8 (1.3)	1.5 (1.6)
Chloride	mg/L	4.0 (0.2)	1.6 (0.3)	11.9 (1.8)
Aluminum	ug/L	2.5 (5.0)	4.9 (7.5)	0.0 (0.0)
Iron	mg/L	0.0 (NA)	0.9 (NA)	0.2 (NA)
Manganese	ug/L	9.8 (13.9)	23.0 (NA)	103.0 (NA)
Silica (mg/L as SiO2)	mg/L	2.6 (1.5)	0.7 (0.7)	5.2 (3.4)
Trophic State				
Chlorophyll-*a*	ug/L	3.2 (2.1)	4.7 (4.6)	4.7 (9.9)
Total Nitrogen	mg/L	0.8 (0.1)	1.0 (0.2)	0.8 (0.2)
Total Phosphorus	mg/L	0.012 (0.003)	0.022 (0.011)	0.015 (0.004)
Water Clarity				
Turbidity	NTU	1.6 (0.2)	3.4 (1.4)	1.5 (0.4)
Color	SU	5.0 (5.0)	35.0 (22.9)	18.3 (10.4)
Secchi Depth	ft	14.6 (5.6)	6.6 (1.2)	8.1 (2.1)
Secchi Hit Bottom	-	1/23 times	10/23 times	18/23 times

Calcium and magnesium, the dominant major cations in groundwater and hard water lakes, are both micronutrients. There is typically less in-lake uptake of magnesium, but calcium has special importance for snails, crustaceans, and other aquatic life (Capelli and Magnuson, 1983; Lodge et al., 1987; Jeziorski et al., 2008). Calcium can also play a role in photosynthesis-related water chemistry (McConnaughey et al., 1994) and can be critical to nutrient and productivity dynamics in hard water lakes (Håkanson et al., 2005). Minimum calcium thresholds for aquatic life range from 2.5 mg/L to 5 mg/L (Capelli and Magnuson, 1983; Lodge et al., 1987; Jeziorski et al., 2008) and lakes with calcium > 10 mg/L function as hard water lakes in terms of nutrient dynamics (Håkanson et al., 2005). While calcium is generally not thought to have a toxic upper limit, lakes become borderline suitable for invasive zebra mussels when lake calcium is 10 mg/L – 21 mg/L and are considered suitable for zebra mussels if lake calcium is above 21 mg/L (Papeş et al., 2011). Lakes in central Wisconsin tend to have more calcium and magnesium than the overall average for Wisconsin (Lillie and Mason, 1983; Figure 18). Pleasant Lake and Plainfield Lake have higher concentrations than even the central Wisconsin average for calcium but are similar or slightly below the central Wisconsin average for magnesium. Long Lake has much lower concentrations of both and is near or slightly below the overall averages for Wisconsin. This indicates that high levels of calcium are likely important to Pleasant and Plainfield lake photosynthesis and nutrient dynamics. Calcium may be less important to these dynamics at Long Lake, but all three lakes have suitably high calcium to support diverse aquatic life. The other major cations, potassium and sodium, are within the expected range for north temperate surface waters and do not show signs of contamination due to road salt, fertilizer, or manure (McGinley and Sisk, 2015).

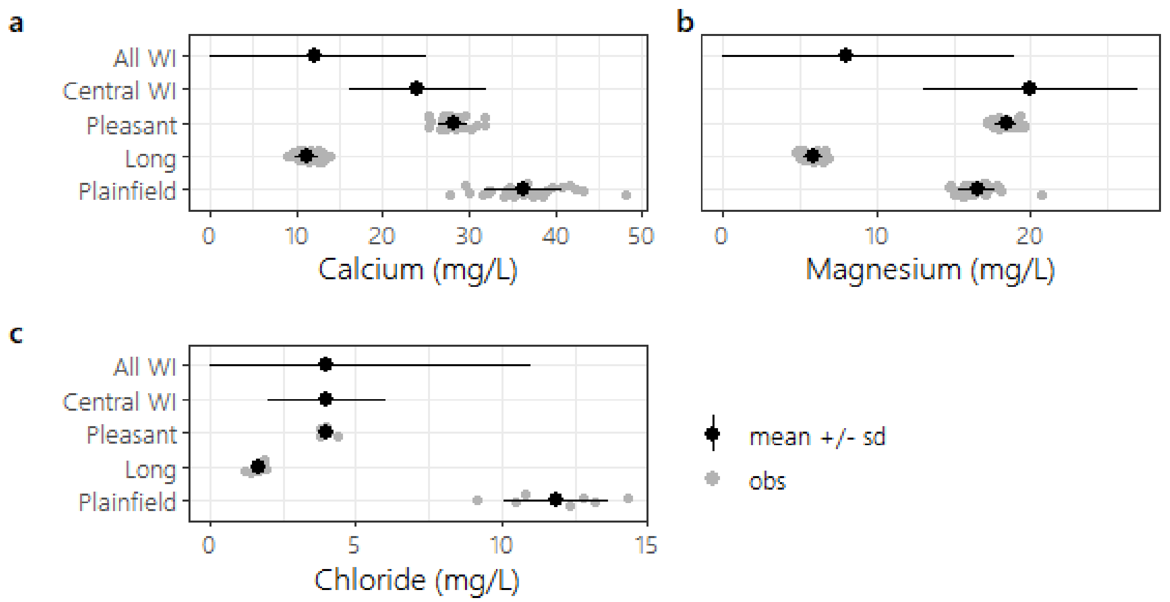

Figure 18. Major ions at Pleasant, Long, and Plainfield Lakes. Calcium (a), Magnesium (b), and Chloride (c) measured at Pleasant, Long, and Plainfield lakes compared to the mean and standard deviation for lakes in all of Wisconsin and in central Wisconsin measured by Lillie and Mason (1983).

In terms of major anions, chloride concentrations in all of Wisconsin, including central Wisconsin, tend to be very low (mean Cl 4 mg/L in central WI and all of WI) (Lillie and Mason, 1983; Figure 18). Pleasant Lake has similarly low chloride concentrations and Long Lake has even lower chloride, but Plainfield Lake has much higher chloride. High chloride concentrations indicate that road salt from a nearby road (WI-73) may be making its way to Plainfield Lake, but even at Plainfield Lake, chloride levels are far below the concentrations at which chronic (395 mg/L) or acute (757 mg/L) toxicity effects would occur. Compared to other lakes in Wisconsin, sulfate is very low in Long Lake, low in Plainfield Lake and moderate in Pleasant Lake (Table 10, National Lakes Assessment 2017, unpublished data). Although sulfate concentrations in Pleasant Lake are comparable to lakes that experienced high sulfate deposition due to acid rain in the past (Nichols and McRoberts, 1986), Pleasant Lake also has high alkalinity and pH which indicates acidity is not a concern.

As expected, minor ions (aluminum, iron, manganese, and silica) are present at low concentrations (Table 10). Nitrogen and phosphorus are discussed below.

Trophic State

In most lakes, plant and algae growth is limited by the availability of either phosphorus or nitrogen. High levels of these nutrients can lead to eutrophication, which can reduce water clarity, increase the likelihood of harmful algae blooms, and negatively affect aquatic organisms including plants and fish (Smith, 2003). In Wisconsin lakes, the limiting nutrient is typically phosphorus (90% of lakes), though nitrogen can be the limiting nutrient if N:P is less than 15:1 (Shaw et al., 2004). As the ratio of N:P is over 100:1 at all Central Sands study lakes, phosphorus is the limiting nutrient for all three lakes (Table 10, Figure 19).

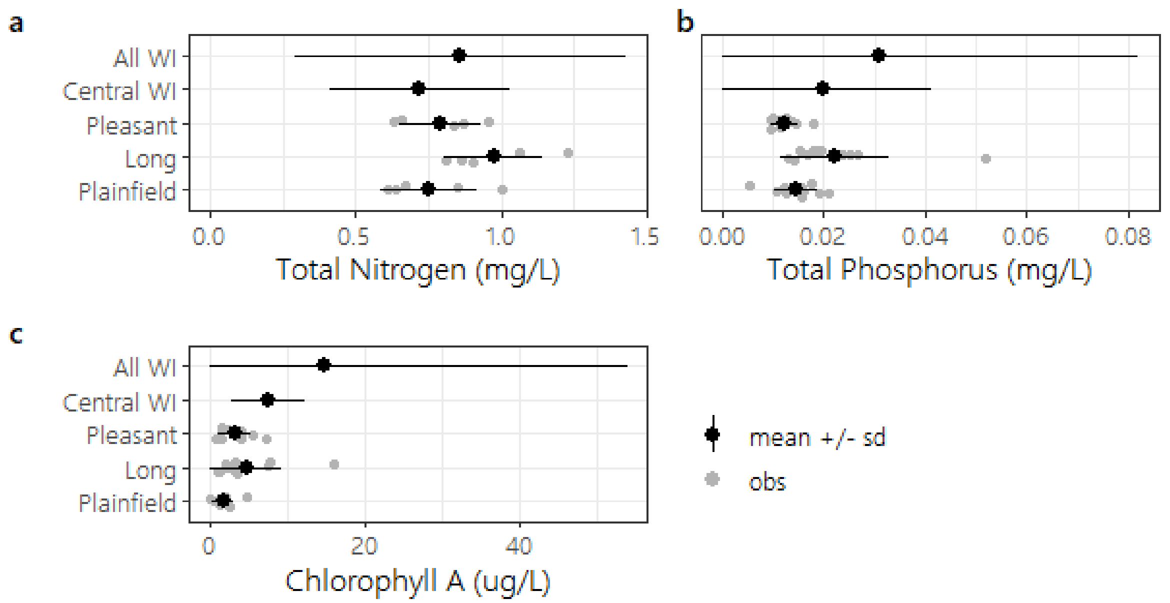

Figure 19. Nutrients at Pleasant, Long, and Plainfield Lakes. Total Nitrogen (a), Total Phosphorus (b), and Chlorophyll-*a* (c) measured at Pleasant, Long, and Plainfield lakes compared to the mean and standard deviation for lakes in all of Wisconsin and in central Wisconsin measured by Lillie and Mason (1983).

Based on the total phosphorus and chlorophyll-*a* samples we collected, these three lakes are classified as mesotrophic or oligotrophic and are clearly below Wisconsin's nutrient impairment thresholds for aquatic life and/or recreation (DNR, 2019c). For Pleasant Lake, a deep seepage lake, total phosphorus must be below 20 ug/L and chlorophyll-*a* must be below 27 ug/L. For Long and Plainfield Lakes, shallow seepage lakes, total phosphorus must be below 40 ug/L and chlorophyll-*a* must be below 27 ug/L. In terms of total phosphorus, the 80% confidence intervals for Pleasant Lake (10.4-12.7 ug/L), Long Lake (15.2-28.4 ug/L), and Plainfield Lake (14.2-20.4 ug/L) indicate that all three lakes are classified as mesotrophic lakes. In terms of chlorophyll-*a*, the 80% confidence intervals for Pleasant Lake (1.5-4.0 ug/L), Long Lake (1.9-7.2 ug/L), and Plainfield Lake (0.7-1.8 ug/L) indicate that Pleasant Lake falls at the lower end of mesotrophic, Long Lake is mesotrophic, and Plainfield Lake is oligotrophic. In general, chlorophyll-*a* is considered a more direct measurement of lake productivity and trophic status (DNR, 2019c).

Water Clarity

Water clarity is a function of dissolved and suspended substances in the lake and affects both water temperature and light availability for vegetation (Wetzel, 2001). Low water clarity is an indicator that a lake has excessive algae production or sediment inputs, but water clarity can naturally be low in highly stained lakes. Three metrics of water clarity include: turbidity, color, and Secchi depth (Table 10).

Lakes in central Wisconsin have similar patterns in water clarity as in all of Wisconsin (Lillie and Mason, 1983; Figure 20). Mean turbidity is 2.5-3 NTU, mean color is 40 SU, and mean Secchi depth is 7.5-8 ft. Pleasant is much clearer than these average values, with very low turbidity (1.6 NTU), low color (5 SU), and deep Secchi depths (14.3 ft). Plainfield Lake is also very clear, with very low turbidity (1.5 NTU) and moderate color (18 SU). At Plainfield Lake, the Secchi disk typically hits lake bottom (18/23 measurements hit bottom; mean depth all measurements 7.8 ft). Long Lake is not as clear, but still shows signs of deep light penetration. On Long Lake, turbidity is near-average (3.4 NTU), color is moderate (35 SU), and mean Secchi depth is 6.4 ft with the Secchi disk hitting lake bottom about half of the time (10/23 measurements). None of the study lakes have a discernible seasonal pattern with water clarity (Figure 21).

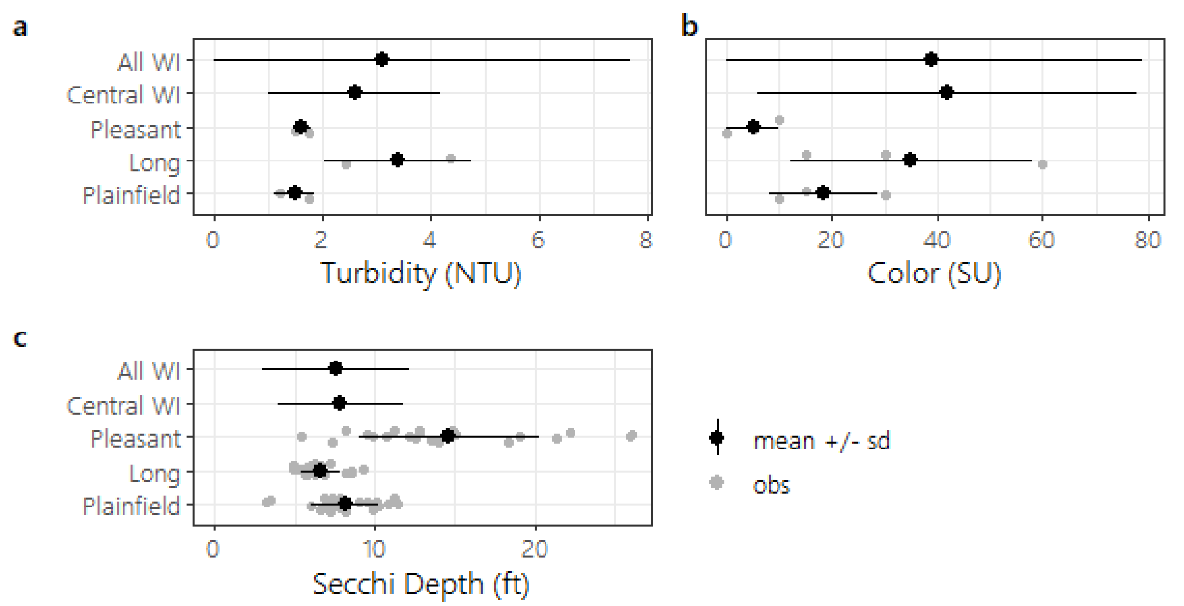

Figure 20. Water clarity at Pleasant, Long, and Plainfield Lakes. Turbidity (a), Color (b), and Secchi depth (c) measured at Pleasant, Long, and Plainfield lakes compared to the mean and standard deviation for lakes in all of Wisconsin and in central Wisconsin measured by Lillie and Mason (1983). When Long and Plainfield Lakes were so clear that the Secchi disk hit the lakebed, the depth to the lakebed is displayed on the plot.

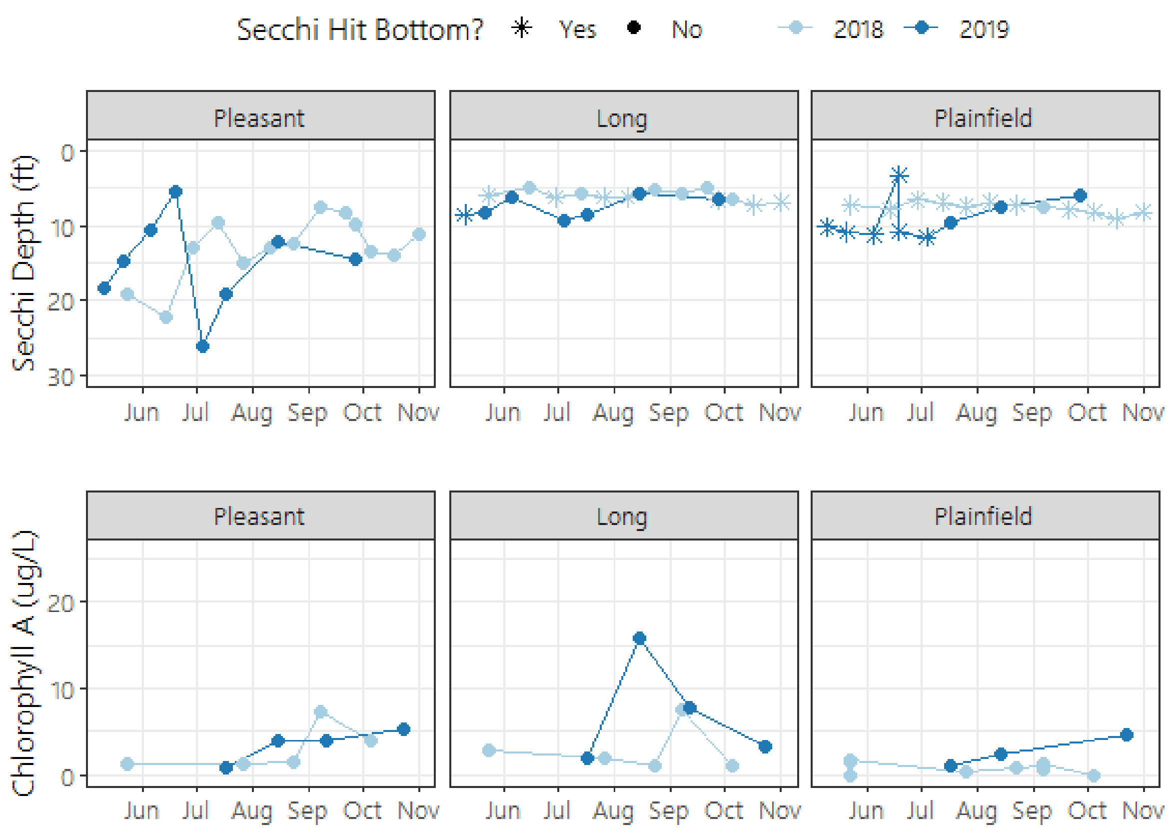

Figure 21. Time series of water clarity at Pleasant, Long, and Plainfield Lakes. Time series of Secchi depth (top) and chlorophyll-*a* (bottom) for 2018 (light blue) and 2019 (dark blue) at all three lakes. Dates when Secchi disk hit the lake bottom are noted with asterisks.

Temperature and Dissolved Oxygen

The spatial and temporal patterns of temperature and dissolved oxygen (DO) are important to lake ecosystems because they affect physical and chemical processes as well as how much of the lake is habitable for fish and other aquatic life (Wetzel, 2001). These spatiotemporal dynamics are largely controlled by whether a lake remains well-mixed throughout the year or instead stratifies during the summer and/or winter due to differences in water density at different temperatures (Wetzel, 2001; DNR, 2019a). Since water density peaks at 39.2°F, in summer stratification the shallowest part of the lake (epilimnion) is warmer than the deepest part of the lake (hypolimnion) while in winter stratification the epilimnion is colder than the hypolimnion. This temperature differential can be especially important for aquatic life in summer, when cooler bottom waters can become refugia for temperature-sensitive fish. In a well-mixed lake, there is no difference in temperature from surface to bottom in any season. Most of the fishes native to the study lakes are warm-water species that are less dependent on these cool temperature refugia.

Lake mixing regimes are also a critical control on DO and nutrient dynamics in lakes (Wetzel, 2001). Under stratified conditions, very little mixing of solutes or DO occurs between the

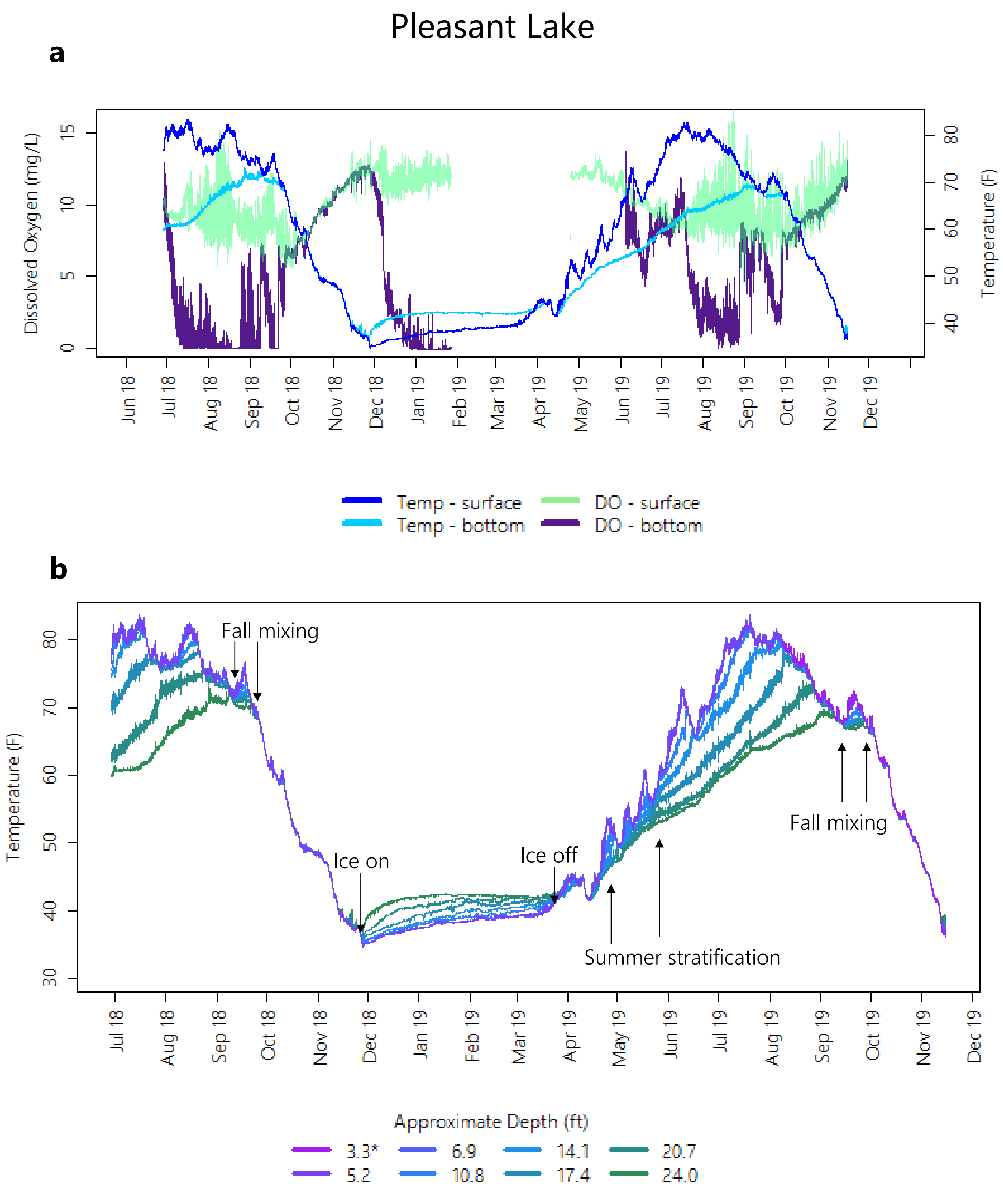

Figure 22. Temperature and dissolved oxygen at Pleasant Lake from automatic data loggers. Depths in (b) are approximate because of changing lake levels, except for logger at 3.3 ft, which remained at that depth because it was attached directly to the surface buoy. All other loggers were attached to the lakebed.

epilimnion and the hypolimnion, but lake water chemistry is more uniform under well-mixed conditions. In a stratified lake, lack of diffusion often leads to low DO conditions in the hypolimnion while DO remains quite high in the epilimnion. By contrast, when low DO occurs in well-mixed lakes it affects the entire lake, with no refugia for sensitive fish species. Most of the fishes native to the study lakes prefer DO greater than 5 mg/L and cannot survive prolonged exposure to levels below 2 mg/L, but DO tolerance varies by fish species and depends on water temperature and duration of exposure (Inskip, 1982; Krieger et al., 1983; Stuber et al., 1982a; Stuber et al., 1982b). Additionally, under well-oxygenated conditions most lakebed sediment retains phosphorus bound to redox-sensitive species containing metals like iron and manganese, but these species release phosphorus under anoxic conditions. When release of phosphorus due to low DO occurs in well-mixed lakes, phosphorus concentrations increase throughout the lake, immediately increasing the risk for eutrophication. When this release occurs in stratified lakes, most phosphorus remains trapped in the anoxic hypolimnion throughout much of summer, which limits the impact to surface water quality until the fall. Stratified lakes can therefore be more resistant to some of the harmful effects (e.g., algae blooms) of eutrophication.

Of the Central Sands study lakes, only Pleasant Lake experienced summer stratification (Figure 22, Figure 23). During the summer, the lake surface was 9-18 °F warmer than the bottom of the lake and the lake surface maintained higher levels of DO than the lake bottom. The lake became well mixed during fall turnover when temperature (within 0.5°C) and DO were the same throughout the water column (September 9 – November 27, 2018 and September 8 - November 13, 2019). After ice cover, reverse stratification occurred with the lake surface colder but higher in DO than the lake bottom. The DO at the lake bottom rapidly declined after ice on (the point in time when the temperatures between the surface and bottom diverged: November 27, 2018) and remained below 4 mg/L after December 8. At ice off (c. March 29, 2019), temperature and DO were once again similar throughout the water column and this spring turnover period lasted for several weeks until summer stratification occurred again on April 21, 2019. Temperature gradients in the water column increased through the spring until the thermocline appeared at a depth of about 16.5 feet in early June. By July the thermocline had expanded, stretching from 9 – 22 feet below the surface. As waters near the surface warmed in late summer, the thermocline contracted and deepened until disappearing in early September. Historical data also show that Pleasant Lake generally stratifies in summer. Of 72 temperature profiles taken in June, July, and August from 1993 to 2020, less than 20% (only 13 profiles) indicated the lake was mixed (less than 1.8°F temperature difference from top to bottom). Most of these summer mixing events (10 of 13) occurred at the end of the summer in August. In all years except 2009, for which there are only two profiles available, the lake stratified at some point in the summer. We conclude that Pleasant Lake is a stratified lake which occasionally experiences late summer mixing events.

Given Pleasant Lake's low concentration of chlorophyll-*a*, decomposition rates at the bottom of the lake were likely low, with sustained oxygen concentrations above 8 mg/L through July 2 in 2018 and July 19 in 2019. At that point, oxygen concentration rapidly declined (within 3 days) and varied from 0 – 4 mg/L until fall mixing occurred. Note that we observed spikes in hypolimnetic oxygen concentrations during stratification, indicating either some diffusion of oxygen down from the epilimnion or direct oxygen production via photosynthesis in the hypolimnion. Given the occurrence of macroalgae on the lake bottom across the entire lake (Figure 32) and a photic zone that extended below the thermocline during most of the summer, the latter source of oxygen is possible.

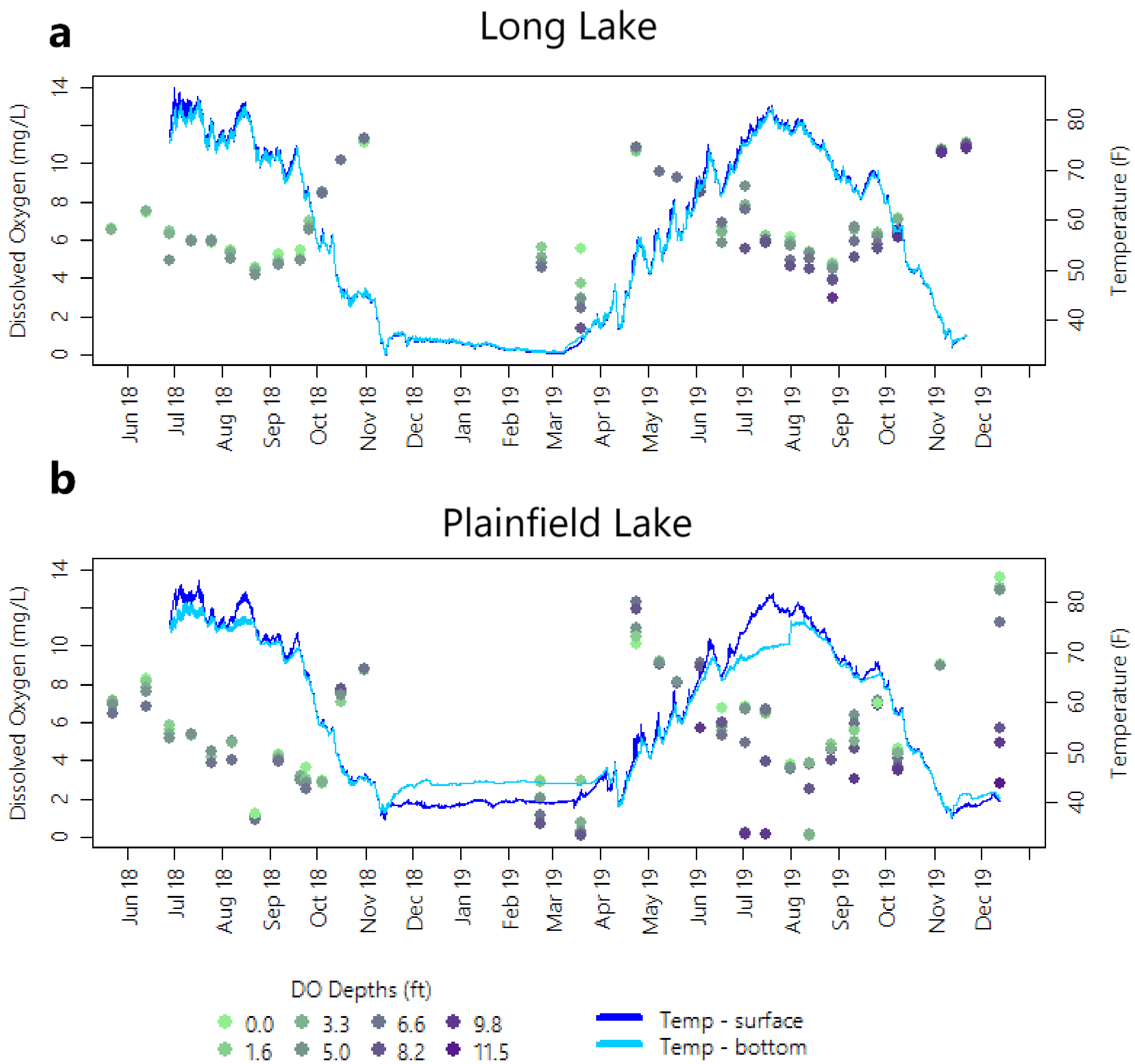

Figure 23. Temperature and dissolved oxygen at Long and Plainfield Lakes. Dissolved oxygen measurements are from a multiparameter probe, while temperature measurements are from automatic data loggers.

Both Long Lake and Plainfield Lake are shallow enough that they remain fully mixed year-round. Both lakes sometimes experience DO concentrations that can be low enough to cause fish kills, but this can be expected on shallow lakes. Long Lake has mechanical aerators to prevent hypoxia, and field crews detected fewer instances of low DO (<4 mg/L) compared to Plainfield Lake (Figure 23). Surface DO at Long Lake peaked at 12 mg/L during November and May, dropping to 4-5 mg/L during August and March. Low oxygen at the interface with the sediment is expected at times due to decomposition of organic matter. DO near the lakebed generally followed the same pattern as the surface and remained above 4 mg/L but reached minimums of 1.36 mg/L and 2.96 mg/L on March 19 and August 27, 2019, respectively. On March 19, only the top 1.6 feet of the water column had DO > 3.7 mg/L. Dissolved oxygen was above 4 mg/L in the top 6.6 feet of the water column on August 27. Although we observed areas of the lake with oxygen low enough to threaten fish, the aerators provided enough oxygen to prevent fish kills. The mixing action of the aerators keeps circular areas around each aerator ice-free throughout the winter. We had to sample well away from the aerators in winter for safety, but there would have been higher oxygen concentrations immediately surrounding the aerators. Because we only sampled twice during the winter, we do not know how long low DO persisted in March, but we do know that the entire water column was greater than 4.5 mg/L DO two weeks prior to and after the low oxygen observed on August 27, 2019. Of 26 epilimnetic DO measurements during the ice-free season, 5 (19%) were below 5 mg/L. Although DNR's assessment criteria specify that DO should go below 5 mg/L no more than 10% of the time (DNR, 2019c), the aerators are successfully keeping DO above 4 mg/L and preventing fish kills. Water temperatures peaked at 80° F during mid-July and then fell until ice-on, which occurred from November 13, 2018 until March 9, 2019.

Plainfield Lake experienced several periods of hypoxia throughout the water column. Dissolved oxygen declined through summer 2018 and remained at or below 5 mg/L for consecutive biweekly measurements from July 25 through October 4, 2018 (Figure 23). On August 22nd, field crews measured a maximum of 1.26 mg/L DO. By October 16, the entire water column was above 7 mg/L. During winter monitoring on February 21 and March 19, 2019, field crews again measured oxygen below 5 mg/L through the entire water column, reaching below 1 mg/L just above the sediment. Oxygen levels recovered during the spring before falling throughout

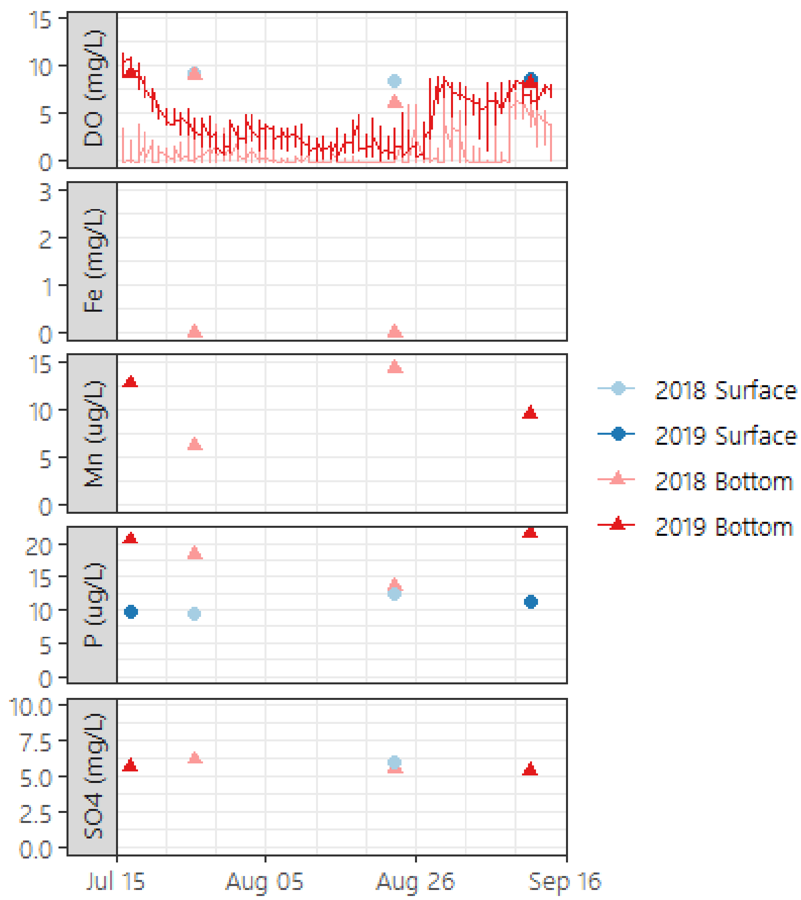

Figure 24. Hypolimnion water chemistry at Pleasant Lake, summer 2018 and 2019. Measurements of dissolved oxygen (DO), iron (Fe), manganese (Mn), total phosphorus (P), and sulfate (SO4) collected on four dates in summer 2018 (lighter shades) and summer 2019 (darker shades) at the lake bottom (red/triangles) and at the lake surface (blue/circles). Continuous DO loggers indicate the lake bottom was hypoxic at the time of 2018 samples, but not at the time of 2019 samples. Field DO measurements indicate lake bottom was oxygenated at the time of all lake bottom samples.

summer as in 2018. In 2019, DO was < 5 mg/L in the entire water column for the month of August, but remained > 3.7 mg/L. Dissolved oxygen just above the lakebed was < 1 mg/L on July 16 and August 13, 2019. Overall, oxygen in the epilimnion of Plainfield Lake was low on 7 of 13 occasions in 2018, and 4 of 13 occasions in 2019. Although both years exceed the state criterion of 10% of dates with DO < 5 mg/L (DNR, 2019c), low oxygen might have been prevalent in recent years due to the flooding and subsequent senescence and decomposition of vegetation. Given the wetland-like characteristics of this lake, DNR does not propose listing Plainfield Lake as impaired for low dissolved oxygen.

Internal Nutrient Loading (Pleasant Lake)

Internal nutrient loading in lakes occurs when sediment-bound nutrients are released back to the water column. In lakes, the amount of DO is one of the strongest controls on whether solutes remain bound to sediment or are dissolved in the water. Under oxidized conditions, dissolved concentrations of solutes such as iron, manganese, and sulfate are typically very low; most of these solutes remain bound to sediment (Wetzel, 2001). However, if the lake becomes anoxic, these solutes can be released to the water column. Anoxic conditions can also trigger the release of phosphorus since phosphorus often co-precipitates with iron, manganese, and carbonates (Wetzel, 2001). When anoxic conditions trigger phosphorus release from the sediment in the hypolimnion of stratified lakes, phosphorus typically stays trapped near the lake bottom; stratification prevents mixing with the near-surface epilimnion waters.

Algal blooms that occur in fall often occur just after fall mixing, when the phosphorus from the sediments that was stored in the hypolimnion mixes to the surface and can be used by algae near the surface. In mixed lakes, nutrients released from internal loading are distributed throughout the water column, which can increase algae concentrations and reduce water clarity. Lake stratification can therefore play an important role in maintaining water clarity.

At Pleasant Lake (the only study lake that stratifies), the hypolimnion is occasionally anoxic (Figure 22). Although our sampling design intended to capture hypolimnetic chemistry during anoxia, the hypolimnion was well-oxygenated and similar to surface DO on three of four dates that we collected lake-bottom water chemistry samples (Figure 24). Hypolimnetic concentrations of iron were 0 mg/L and manganese were low at 6.17 – 12.7 µg/L. Total phosphorus concentrations were approximately equal in the epilmnion and hypolimnion on August 22, 2018. They were approximately doubled, but still relatively low, in the hypolimnion on the other three dates (Figure 24). Although the hypolimnion was oxygenated on the sample dates, DO was low from mid-July through August and some anoxia in surficial sediments could spur phosphorus release. Still, water clarity decreased only slightly just after fall turnover in 2018 and not at all in 2019, a phenomenon we would expect to see if phosphorus had built up in the hypolimnion over summer and was then released at fall turnover, fueling algal growth (Figure 21). This indicates that though there may be a small degree of internal nutrient loading in Pleasant Lake, it is not likely a large component of the lake's nutrient budget. Pleasant Lake likely has a high rate of marl formation, which can bind and retain phosphorus even under anoxic conditions.

Groundwater Chemistry

During the measurement period (2018-2019), nearby groundwater monitoring wells typically had higher concentrations of major and minor ions than the lake (Figure 25 to Figure 30). Spatial variability in groundwater chemistry measurements was more substantial than temporal variability. At all three lakes, alkalinity, conductivity, all major ions (calcium, magnesium, sodium, potassium, chloride, sulfate), and several minor ions (aluminum, iron, manganese, silica) were typically higher in nearby groundwater than in the lake. Exceptions to this include potassium and iron at Long Lake and sodium, potassium, chloride, and manganese at Plainfield Lake, where lake values were similar to or higher than nearby groundwater values. In terms of nutrients, ammonia-nitrogen was higher in all three lakes than in nearby groundwater, but nitrate/nitrites and total phosphorus were typically higher in nearby groundwater.

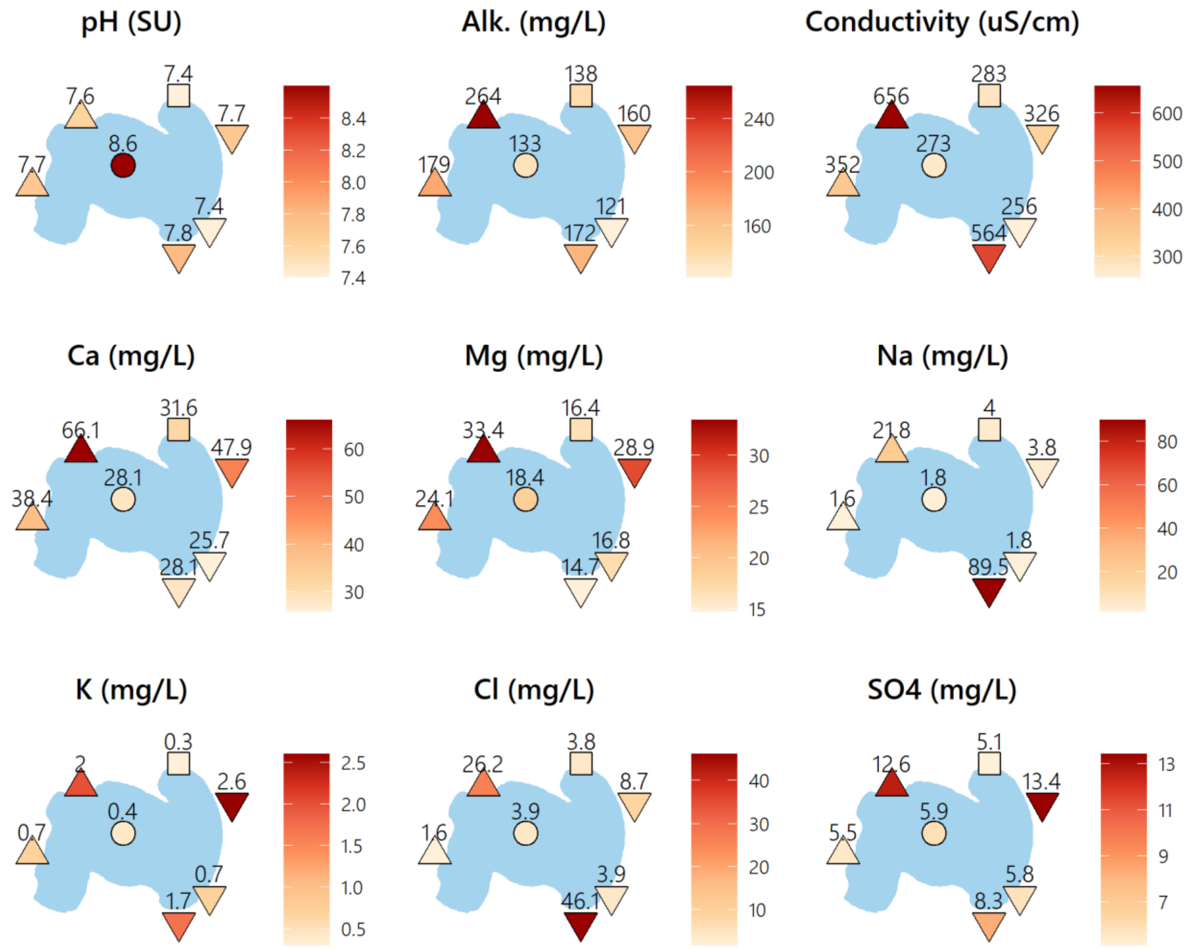

Figure 25. Pleasant Lake groundwater chemistry – acidity and major ions. Median values measured at upgradient (triangles pointed up), downgradient (triangles pointed down), and side gradient (squares) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

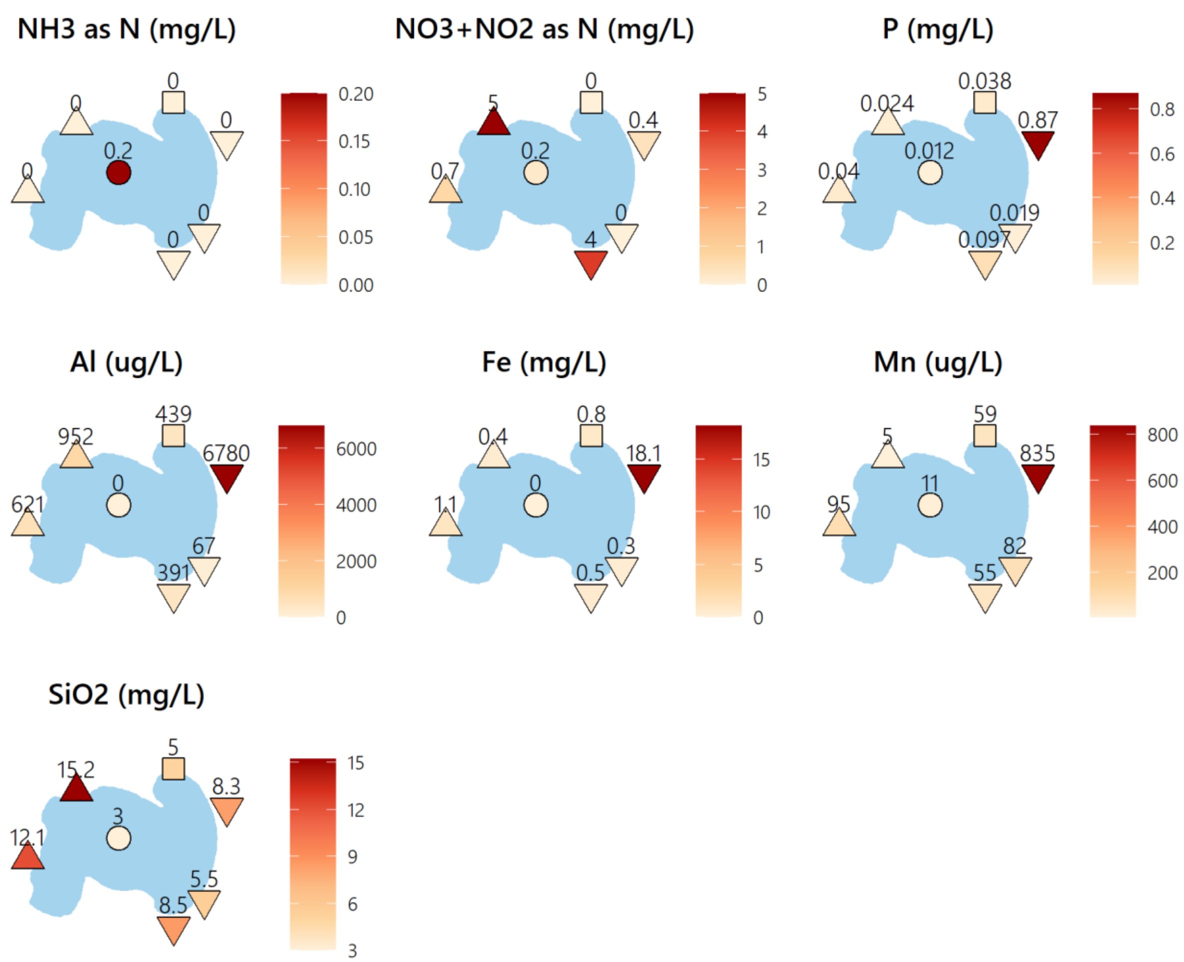

Figure 26. Pleasant Lake groundwater chemistry – nutrients and minor ions. Median values measured at upgradient (triangles pointed up), downgradient (triangles pointed down), and side gradient (squares) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

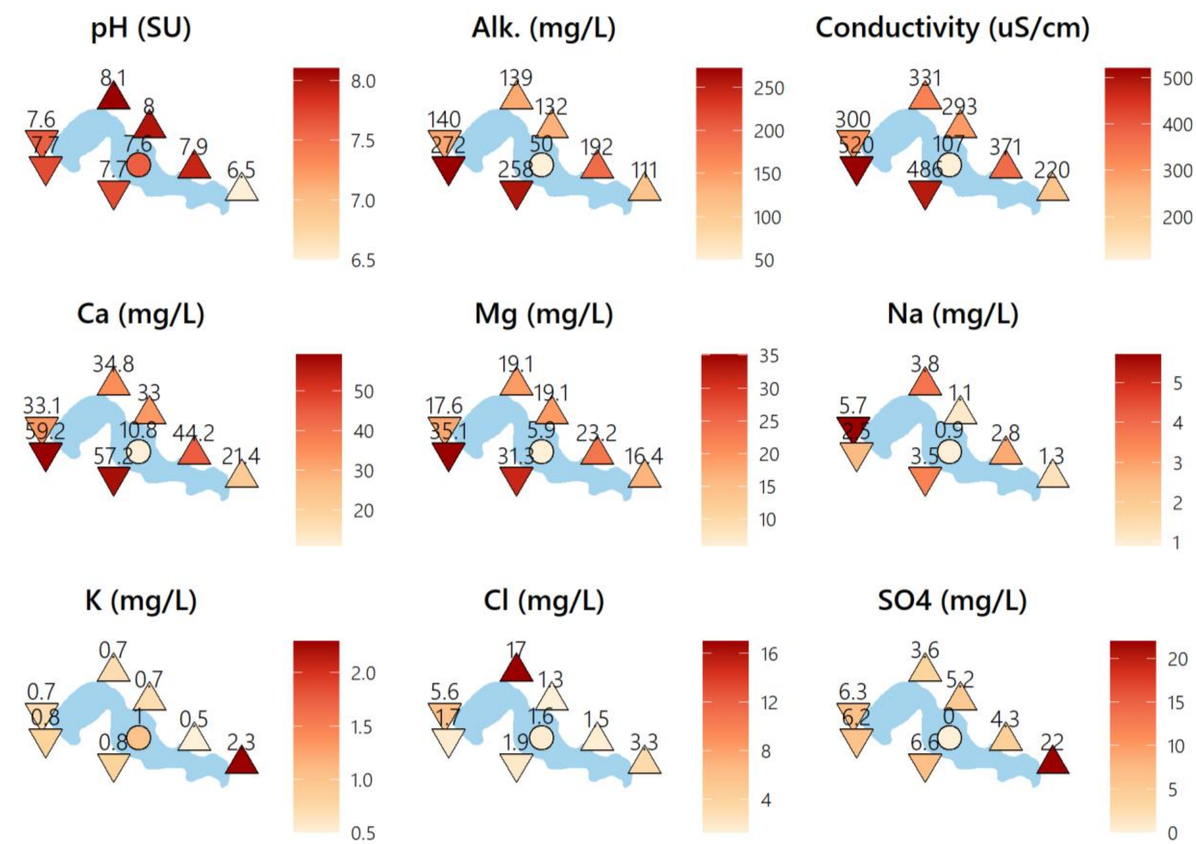

Figure 27. Long Lake groundwater chemistry – acidity and major ions. Median values measured at upgradient (triangles pointed up) and downgradient (triangles pointed down) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

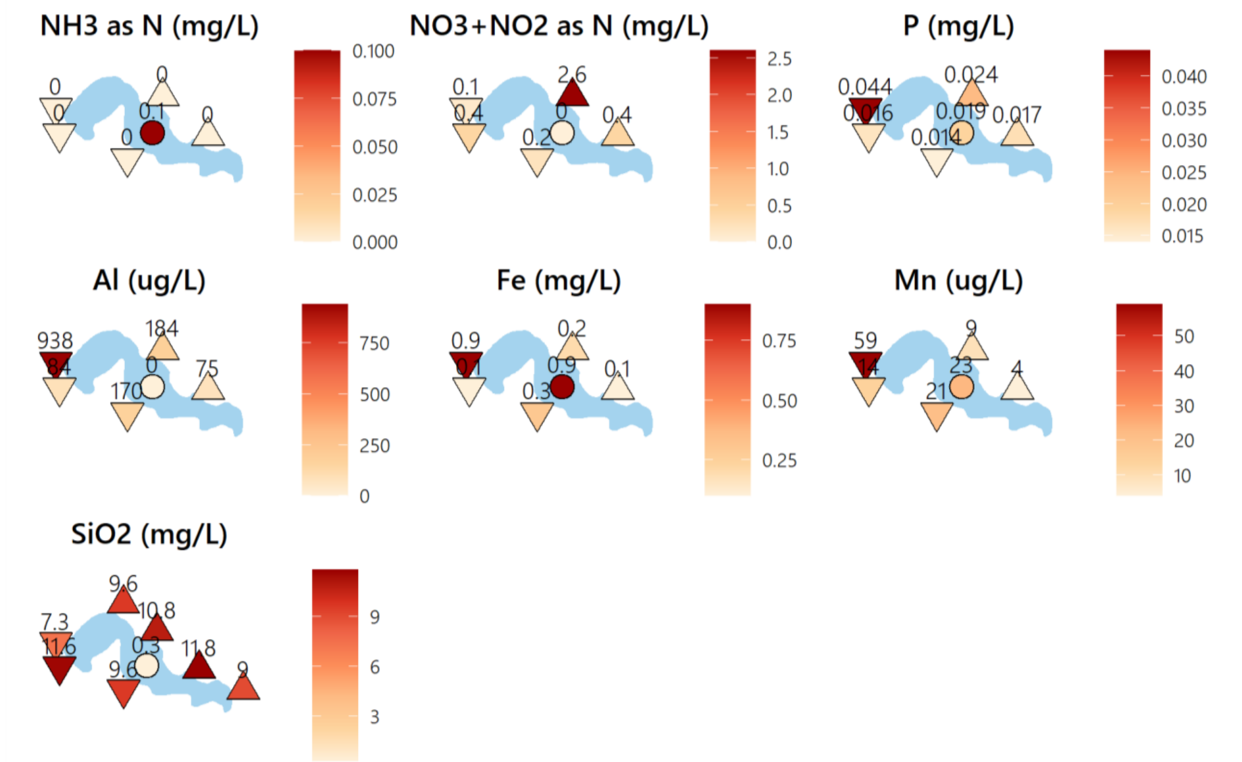

Figure 28. Long Lake groundwater chemistry – nutrients and minor ions. Median values measured at upgradient (triangles pointed up) and downgradient (triangles pointed down) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

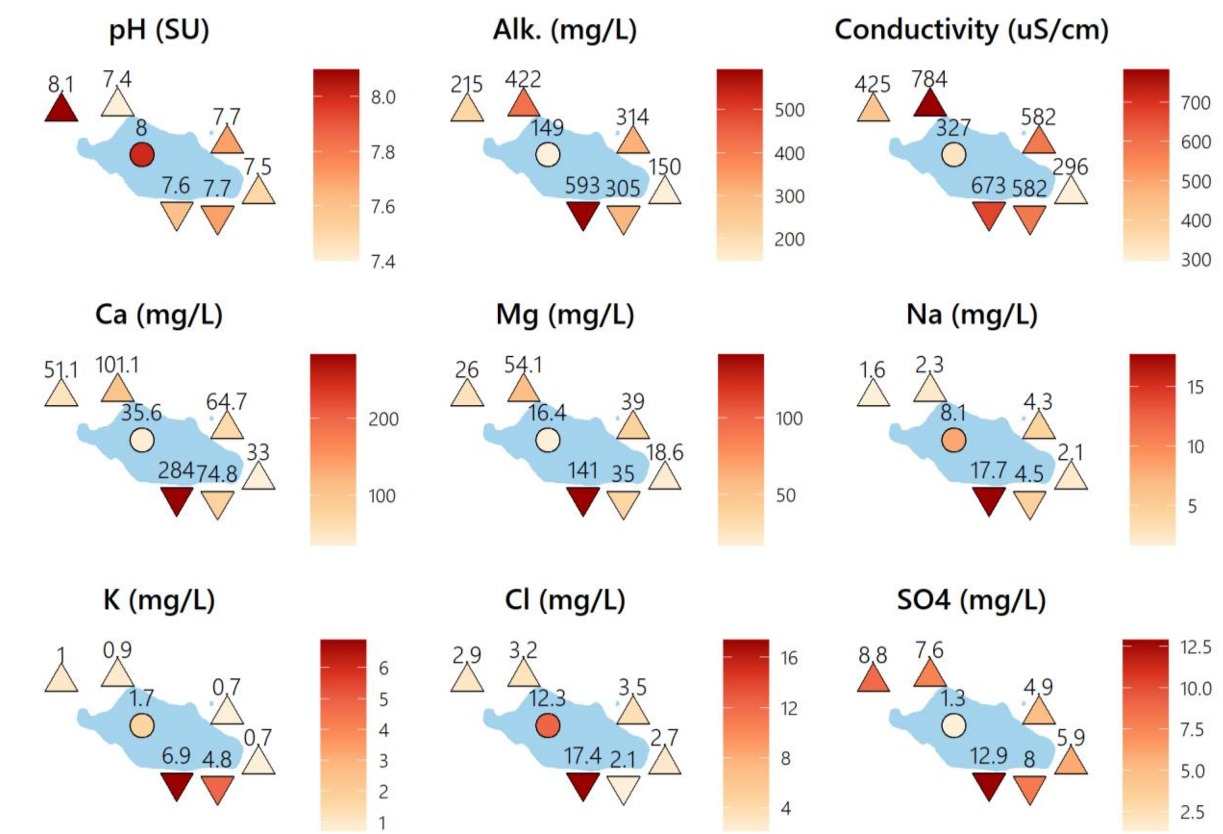

Figure 29. Plainfield Lake groundwater chemistry – acidity and major ions. Median values measured at upgradient (triangles pointed up) and downgradient (triangles pointed down) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

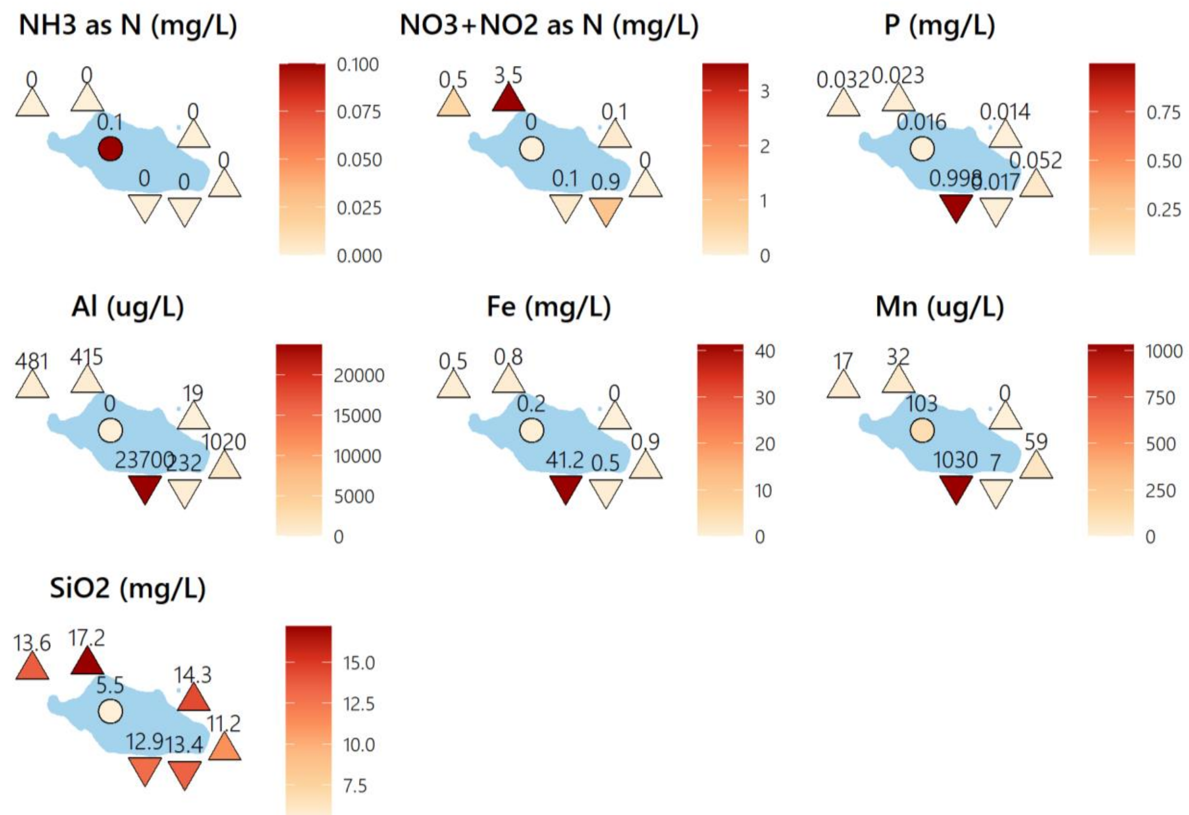

Figure 30. Plainfield Lake groundwater chemistry – nutrients and minor ions. Median values measured at upgradient (triangles pointed up) and downgradient (triangles pointed down) groundwater monitoring wells compared to at the lake (circle) from 2018-2019.

Aquatic and Wetland Plant Communities

Pleasant, Long, and Plainfield Lakes support generally high quality, diverse aquatic and wetland plant communities that form the base of a healthy lake and wetland ecosystem. While we may characterize the condition of some plant communities as "poor" or "fair" due to a moderate degree of non-native cover, we did not see significant degradation due to nutrient pollution or invasive species. Most wetland and aquatic communities that we surveyed host at least some sensitive species and have high species richness. In turn, these diverse communities provide cover and forage for fishes and other aquatic organisms while also stabilizing lake bottom sediment, taking up nutrients like phosphorus and nitrogen, and releasing oxygen into the water column. Wetland plants stabilize sediment and provide cover and forage along the margins of the lake, colonizing areas that are inundated too frequently for terrestrial vegetation to grow.

There are not distinct, spatial boundaries between aquatic and wetland ecosystems. Instead, many different plant community types exist on a gradient from dry Upland to deep Submergent Marsh (Hudon, 2004, Figure 31). In this report, we share results that offer a lake-wide perspective on all plants that occur within or along the margins of the lake. We also provide a more detailed characterization of the various plant community types that occur within each lake. These plant communities often overlap in space but still exhibit unique characteristics in terms of species assemblage, growth forms and their habitat preferences. We used two methods to survey the plant communities: 1) plant point-intercept (PI) surveys cover the entire navigable area of the lake and record all plant species encountered at each point, 2) wetland timed-meander surveys evaluate contiguous areas along the lake margins and include areas without standing water.

The aquatic plant communities in Pleasant, Long, and Plainfield Lakes are “Mixed Characid” communities, which generally have high abundance of *Chara* species as well as *Potamogeton gramineus*, *Potamogeton amplifolius*, *Nymphaea odorata*, and *Brasenia schreberi* (Poinsatte et al., 2019). Mixed Characid lakes also have moderate alkalinity and low nutrient levels, accommodating emergent, floating-leaved, and submergent species at different depths. Mixed Characid lakes have the highest diversity of the lake-wide plant community types in Wisconsin (Poinsatte et al., 2019). *Chara* species help to maintain low nutrient levels by efficiently removing phosphorus and nitrogen from the water column, which might otherwise spur algal growth and reduce clarity (Scheffer and van Ness, 2007).

The aquatic plant communities of all three lakes are in good condition. In all survey years, the lakes attained both biocriteria used to evaluate Wisconsin Lakes: one that signifies general disturbance and one that is responsive to phosphorus pollution (Table 11). The lakes have moderately high mean coefficient of conservatism (mean-C) values, indicating that these lakes harbor more plants associated with intact ecosystems than those associated with disturbed or altered ecosystems. Their mean-C values (~ 6) are similar to the median of all other Southern Seepage lakes that attain the biocriteria (Hein et al., 2019). Species richness and Floristic Quality Index values are also on the high end of the range observed in other Mixed Characid lakes (Poinsatte et al., 2019), Southern Seepage lakes (Hein et al., 2019), and other lakes in the North Central Hardwood Forest ecoregion (Nichols, 1999).

Littoral habitat occurs across nearly the entire surface area of all three lakes, as evidenced by the fact that aquatic plants occur out to the deepest points of the lakes (Figure 32, Figure 35, Figure 40). Plants grew at the deepest point of Plainfield Lake: 9.0 feet in 2018 and 13.5 feet in 2019, and plants were present at more than 90% of the points surveyed (Table 11). The maximum depth of Long Lake in 2018 was 7.5 feet and in 2019 was 11.0 feet and plants colonized most of the lake (Table 11). At a maximum depth of 28 feet in 2018 and 29 feet in 2019, Pleasant Lake is deeper, but also has very clear water, allowing *Chara globularis* and *Nitella flexilis* to grow in the deepest areas of the lake (Table 11, Figure 32). In 2009 and 2012, the percent littoral area of Pleasant Lake was slightly less than 100% at 92% and 85%, respectively. Most of Pleasant Lake is vegetated in all years, but to a lesser extent than Plainfield and Long Lakes (Table 11).

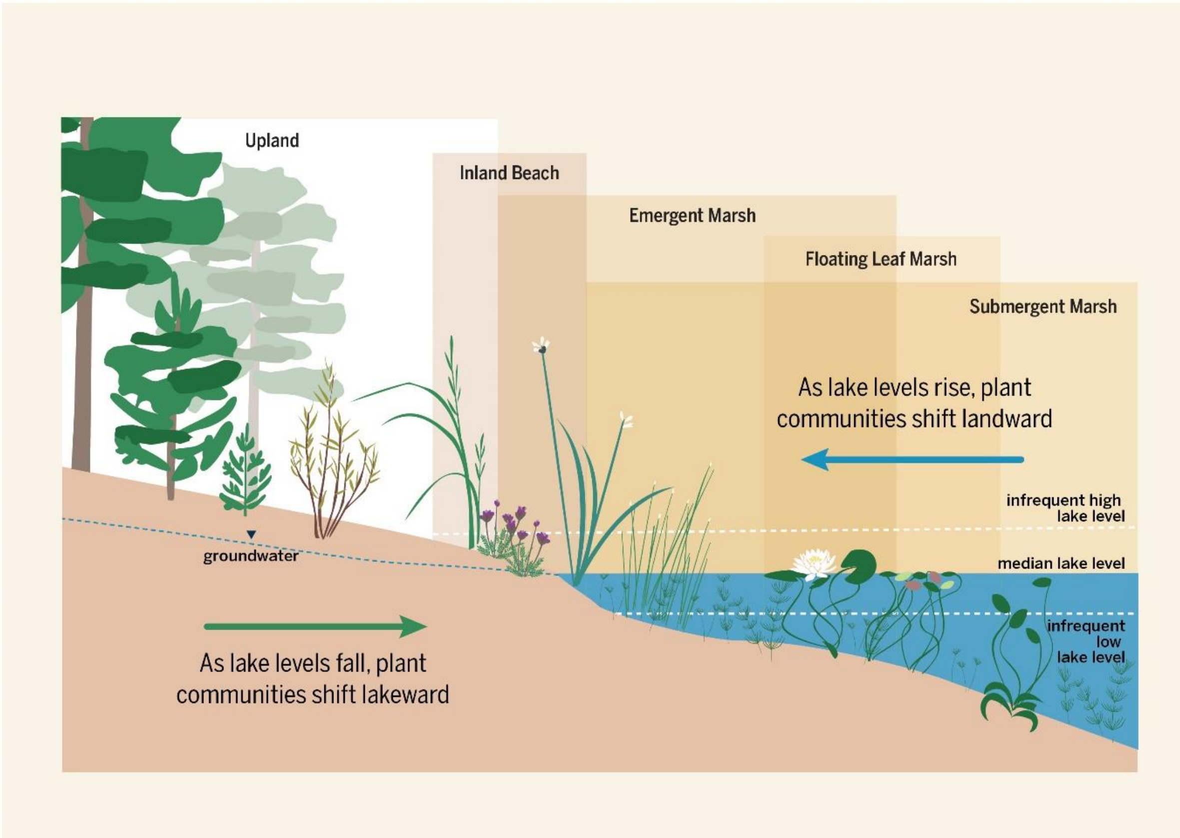

Figure 31. Gradation of plant communities. Diagram depicting the gradation of plant communities from upland plants on the lake shore to submergent aquatic plants in the lake.

Plant Communities Found on Pleasant, Long, and Plainfield Lakes

The ability to accommodate several different growth forms contributes to the relatively high species richness of Mixed Characid lakes. In addition, the gently sloping, irregular basins of Plainfield and Long Lakes, combined with their lake level fluctuations of several feet, create a constantly shifting mosaic of habitats. These habitats range from infrequently flooded inland beaches to Submergent Marshes that are only desiccated during the most extreme droughts. Many of the species found are adapted to yearly changes in available habitat.

Submergent Marsh, often referred to as an aquatic plant bed, is the deepest habitat found on the study lakes and is defined as "an assemblage of permanently inundated aquatic macrophytes where the majority of plant biomass occurs beneath the surface" (Epstein, 2017; O'Connor, 2020). This community occurs where there is permanent standing water of at least 1.5 feet but can extend to greater depths when the water is clear. Submergent plants occupy the deepest waters that can support rooted macrophytes and can occur anywhere there is shallow standing water except where either Emergent Marsh or Floating-leaved Marsh plants outcompete them for light and space.

Submergent Marsh provides an important food source for waterfowl and aquatic invertebrates and requires long periods of flooded conditions with regular water level fluctuations. Infrequent periods of low water levels are necessary for some species to reproduce by seed. More general conservation requirements include prevention of sedimentation, exclusion of common carp and other causes of turbidity, maintenance of current nutrient and calcium concentrations, and protection from herbicide application, dredging, mining for marl, and powerboats (Epstein, 2017).

Table 11. Aquatic plant summary statistics for each lake and year that a plant point intercept survey was conducted. MAC-General is an aquatic plant condition metric for general disturbance, MAC-Phosphorus is an aquatic plant condition metric for phosphorus pollution, and A means that plant biocriteria was attained.

Statistic	**Plainfield**		**Long**		**Pleasant**			
	2018	2019	2018	2019	2009	2012	2018	2019
Maximum depth of plants	8.5	13.5	7.5	11.0	22	29.0	28.0	29.0
Number of littoral points	202	209	230	227	386	349	416	419
% of littoral points vegetated	99%	91%	88%	95%	67%	73%	80%	74%
MAC-General	A	A	A	A	A	A	A	A
MAC-Phosphorus	A	A	A	A	A	A	A	A
Mean C	6.6	6.4	6.9	6.9	5.8	5.8	6.2	6.0
Species richness	28	24	21	20	18	26	28	24
Floristic Quality Index	35	31.4	31.4	30.9	24.7	29.8	32.7	29.6

Floating-leaved Marshes are dominated by free-floating or rooted species with leaves that rest on and cover the water's surface (Epstein, 2017). Floating-leaved Marshes generally occur in areas with deeper standing water than Emergent Marshes, but water clarity and hardness also affect where this community can establish. Floating-leaved species must grow through the entire water column to reach the surface and are therefore more likely to be limited by water depths than submergent species. Once beds of floating-leaved species are established, they can inhibit the growth of other macrophytes by shading the lakebed. However, floating-leaved species often co-occur with emergent or Submergent Marsh species. This community type is found at intermediate depths, with 7 - 8 feet of water during the growing season considered optimal. Emergent vegetation dominates when water levels fail to reach optimal levels, while consistently high water levels favor submergent vegetation.

Floating-leaved Marsh communities provide important foraging, resting, and hiding areas for fish, amphibians, and invertebrates which in turn support bird and mammal populations. Like other marsh habitats, Floating-leaved Marshes are negatively impacted by turbidity, and so the continued absence of carp and motorized boat traffic is crucial to the survival of floating-leaved plants (Epstein, 2017).

Emergent Marsh species such as cattails, bulrushes and sedges are rooted, grow past the water surface and often form dense, clonal stands (Epstein, 2017). Emergent Marshes occur in permanent standing water of less than 6.6 feet in depth but are almost always inundated. Like other marsh types, Emergent Marshes are important habitat for many kinds of waterfowl and especially provide excellent duck and coot breeding and foraging habitat. This is especially true in Emergent Marshes interspersed with open water (Quinlan and Mulamoottil, 1987; Mortsch, 1998). Factors important to the survival of Emergent Marsh habitat are the absence of carp and motorized boat traffic, which can resuspend sediment and damage plants. Low nutrient and high calcium concentrations are also important for Emergent Marshes. Changes in nutrient or calcium levels could create conditions more favorable for highly productive species, including invasives, and lead to overall degradation of the habitat (Epstein, 2017).

Table 12. Condition metrics for the vascular plants in each wetland plant community type by lake. C is the coefficient of conservatism.

	Species Richness	Non-Native % Cover	Mean C	Weighted Mean C	Weighted FQI
Plainfield Lake					
Submergent Marsh	15	0	6.9	6.9	21.9
Emergent Marsh	10	9	4	5.4	13.1
Floating-leaved Marsh	10	0	5.3	5.6	14.9
Inland Beach	25	4	4.6	4.9	24.3
Long Lake					
Submergent Marsh	15	0	7.6	7.6	22.7
Floating-leaved Marsh	7	0	5.3	5.9	14.4
Inland Beach	27	13	3.7	4.1	21.2
Pleasant Lake					
Submergent Marsh	20	1	5.6	5.9	22.3
Inland Beach	29	18	2.2	2.9	15.5
Southern Sedge Meadow	67	4	3.9	3.5	28.9

An Inland Beach wetland community consists of short, often rare, specialized plants adapted to recently exposed sandy shoreline of fluctuating lakes (Epstein, 2017). The extent of this community varies with annual lake level fluctuations and is maintained by alternating high and low water levels, which effectively reduce competition from less specialized plants. Inland Beach is ranked "S3" within Wisconsin, meaning that the community is considered "vulnerable in Wisconsin due to a fairly restricted range, relatively few populations or occurrences, recent and widespread declines, threats, or other factors." (DNR, 2016). Inland Beach habitat supports rare plants and can be of value for migrating shorebirds and nesting turtles.

The Inland Beach community requires variable water levels to clear the sandy beach of upland vegetation in some years and expose bare sandy substrate for seed germination in other years. The magnitude of water level fluctuation and slope of the beach combine to determine the area of available habitat; thus, many inland beaches exist only on narrow strips along the shore of seepage lakes. Activities that reduce the range of water level variability, such as groundwater withdrawals or the addition of upland runoff, also reduce the amount of Inland Beach habitat. Sedimentation, nutrient pollution, and the introduction of invasive species can also degrade this sensitive community. Because Inland Beach lacks surface water and has a firm substrate, other threats include soil compaction from livestock and equipment and removal of vegetation by humans or herbivores (Epstein, 2017).

Southern Sedge Meadows are herb-dominated wetlands on usually alkaline peat or muck soils often associated with lake and stream margins (Epstein, 2017). They tend to exist in areas where the soil is normally saturated to the surface and surface water is present seasonally. Southern Sedge Meadows are most frequently dominated by *Carex stricta* and *Calamagrostis canadensis* in southern Wisconsin.

Southern Sedge Meadows require natural seasonal fluctuations in water levels with flooded conditions peaking in spring (Epstein, 2017). Severe, prolonged droughts could threaten Southern Sedge Meadows, causing trees and shrubs to encroach. Eutrophication and subsequent invasion by *Phalaris arundinacea*, *Typha* X *glauca*, and *Phragmites australis* ssp. *australis*, all of which are currently present in the area at low levels, pose additional threats to this plant community.

Table 13. Littoral frequency of occurrence of all Submergent Marsh species in Pleasant Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
Nitella flexilis	Slender nitella	33.5	36.8
Chara globularis	Globular stonewort	30.1	31.0
	Filamentous algae	18.7	4.3
Vallisneria americana	Water-celery	15.8	16.2
Chara contraria	Fetid stonewort	13.9	11.0
Najas flexilis	Slender naiad	12.4	9.1
Potamogeton sp.	Pondweed	9.6	9.5
Potamogeton gramineus	Variable-leaved pondweed	8.1	8.4
Potamogeton zosteriformis	Flat-stem pondweed	6.5	5.0
Chara aspera	Rough stonewort	5.5	3.8
Stuckenia pectinata	Sago pondweed	5.3	3.3
Najas guadalupensis	Southern naiad	3.8	4.3
Ceratophyllum demersum	Coontail	2.4	1.9
	Aquatic moss	1.7	1.0
Myriophyllum spicatum	Eurasian water milfoil	1.7	2.1
Potamogeton praelongus	White-stemmed pondweed	1.7	2.6
Heteranthera dubia	Water star-grass	1.0	1.2
Chara braunii	Braun's stonewort	0.5	0.2
Chara sp.	Muskgrass	0.5	0.5
Myriophyllum sibiricum	Common water-milfoil	0.2	0.0
Potamogeton foliosus	Leafy pondweed	0.2	0.2
Ranunculus aquatilis	White water crowfoot	0.2	0.0
Elodea canadensis	Common waterweed	0.0	0.2
Potamogeton illinoensis	Illinois pondweed	0.0	1.2

Pleasant Lake

We identified three wetland community types at Pleasant Lake in 2018 and 2019: Submergent Marsh, Southern Sedge Meadow, and Inland Beach. A few species from Emergent Marsh and Floating-leaved Marsh were represented but rare. Water levels during these years were higher than usual so these may not be typical wetland conditions. Furthermore, water levels increased by approximately 1.6 ft from August 2018 to August 2019. Submergent Marsh was surveyed by point-intercept survey in both 2018 and 2019; Inland Beach and the Southern Sedge Meadow were surveyed in 2018 by timed-meander survey. Emergent Marsh was mostly absent in 2018 and 2019. However, records from 2012 show that 5 species of emergents were found with combined frequency of 1.1%. These species were *S. acutus*, *E.*

palustris and *E. acicularis* and *Typha* spp. No emergents were found in an earlier 2009 survey but in 2018, wetland surveys additionally found *Schoenoplectus pungens* on the lake edge, with sparse cover. This community type likely benefits from lower water levels than those in 2018 and 2019.

Submergent Marsh

Submergent Marsh is the largest wetland type at Pleasant Lake. Pleasant Lake's steeply sloped, deep basin and relatively high water clarity create large areas favorable to submergent vegetation. Submergent Marsh in Pleasant Lake gives way to Floating-leaved Marsh or Emergent Marsh only in shallower water where members of these other communities can compete for light and space.

The Submergent Marsh community was dominated by *Chara* spp., with combined frequency in point intercept surveys of more than 75%. The macroalgae community was diverse with 6 species identified. Dominance was shared by *N. flexilis* and *C. globularis*. Other vascular submergent species included *Vallisneria americana* and several species of *Potamogeton*. In total, 20 species of vascular plant and macroalgae were found in the Submergent Marsh in addition to filamentous algae and aquatic moss (Table 12, Table 13, Figure 32). *Utricularia vulgaris* was observed visually

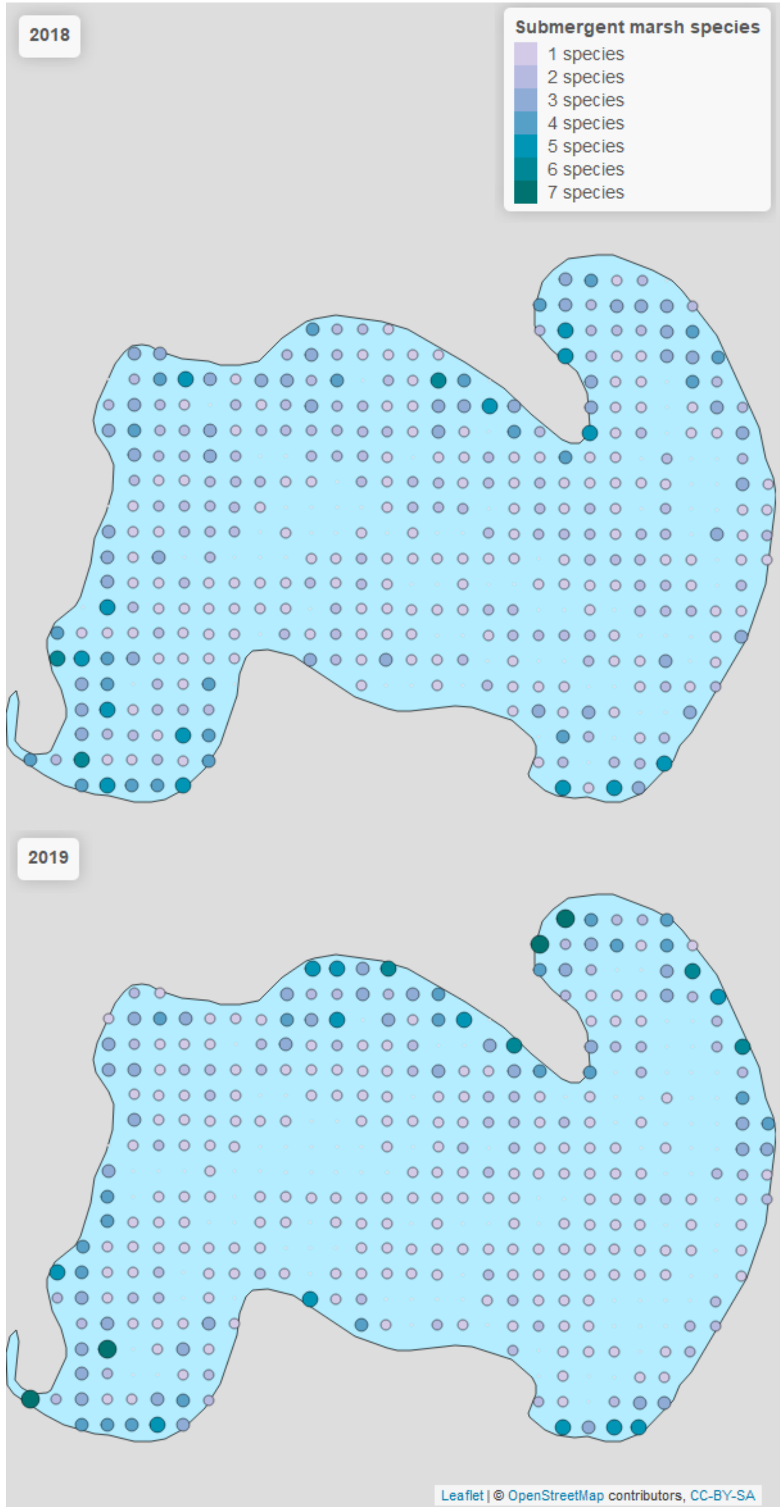

Figure 32. Submergent Marsh at Pleasant Lake, 2018-2019. Distribution of Submergent Marsh species richness in Pleasant Lake, 2018 and 2019. *Chara globularis* and *Nitella flexilis* were the two species growing in the deep areas of the lake.

during the plant point intercept survey. Submergent Marsh species had a weighted mean coefficient of conservatism of 5.9. There is not a condition benchmark for Submergent Marsh in the North Central Hardwood Forest ecoregion based on the weighted mean coefficient of conservatism, but Pleasant Lake was in good condition according to whole-lake biocriteria (Table 12).

While about three-quarters of Pleasant Lake's lakebed is occupied by plants, near-shore areas have higher plant biovolumes. Biovolumes are above 60% in large areas of the northwest, southwest, and northeast corners of the lake, and to a lesser extent, the southeast (Figure 33). Lower biovolumes occur along the eastern edge of the lake. The areas of high biovolume largely coincided with areas of high species richness (Figure 32, Figure 33), particularly species with tall growth forms like *Potamogeton zosteriformis* and *Potamogeton strictifolius*. The sonar did not detect the extensive beds of submergent plants found across the deep basin, likely due to the short growth forms of *C. globularis* and *N. flexilis*.

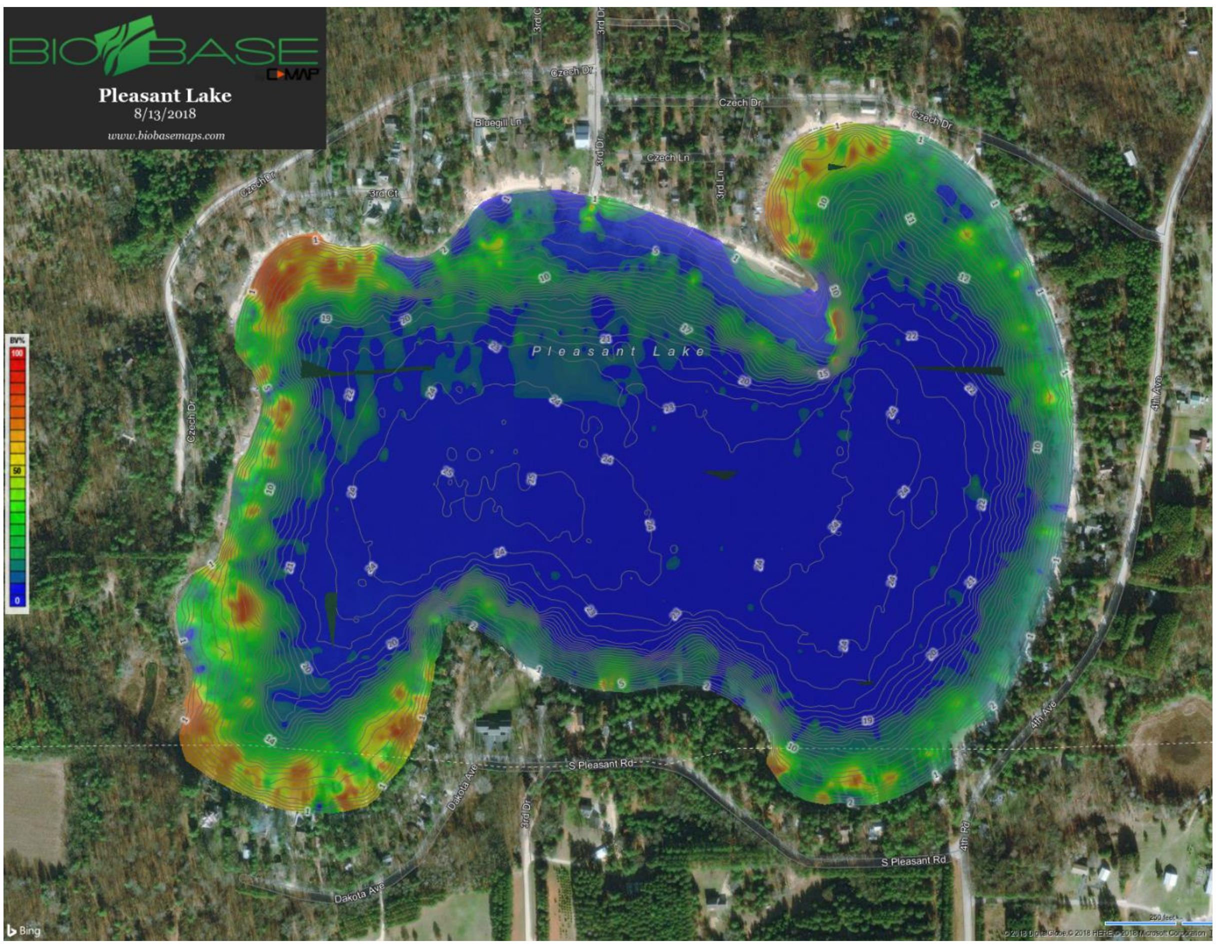

Figure 33. Sonar biovolume survey at Pleasant Lake, 2018. Warmer colors indicate that a greater percent of the entire water column is occupied by aquatic plants.

The aquatic plant community on Pleasant Lake was relatively stable from 2018 to 2019. The frequency of occurrence of Submergent Marsh declined from 83.0% in 2018 to 76.4% in 2019, and emergent and floating leaf species were rare in 2018 to begin with (Table 14). The average submergent species richness was stable (2 in 2018 and 1.9 in 2019), and only showed slight variations in the hotspots of diversity around the lake margin (Figure 32). Filamentous algae declined by 14.4% frequency of occurrence and only remained in the west in 2019, but no other species' occurrence changed by more than 5% (Table 14, Figure 34). The median depth of the Submergent Marsh distribution decreased from 15.2 to 13 feet deep, but the median depth of occurrence for common individual species increased by 1 to 2 feet (Table 14). In both years, the defining characteristic of Pleasant Lake remained the extensive coverage of submergent plants at impressive depths, with *C. globularis*, *N. flexilis* and filamentous algae at depths up to 30 feet in both years (Figure 34).

Table 14. Observed changes in the littoral frequency of occurrence (FOO) and the median depth (ft) of plant species in each lake. The difference in littoral FOO or median depth was calculated as the value in 2018 subtracted from the value in 2019. Thus, negative numbers indicate a lower littoral FOO or shallower depth in 2019 than in 2018. Plant species that did not occur in a lake are indicated as "NP" for not present. Changes in littoral FOO are listed in bold if the change was ≥ 5%. Changes in depth were only calculated for plants with at least 20 observations in each of 2018 and 2019.

	Plainfield Lake		**Long Lake**		**Pleasant Lake**	
Plant Species	**FOO**	**Depth**	**FOO**	**Depth**	**FOO**	**Depth**
Emergent	**-45.2**	5	**-5.7**	3.2	-0.72	-0.8
Schoenoplectus acutus	**-11.7**	4.0	NP		-0.2	
Floating-leaved	**-11.2**	4	3.5	3.5	-1.0	3
Nymphaea odorata	**-9.2**	4.5	**-14.0**	4.0	-0.2	
Brasenia schreberi	-0.2		**9.6**	4.0	NP	
Wolffia columbiana	**-5.1**		NP		NP	
Submergent	**-14.5**	4	**20.2**	4	**-6.6**	-2.2
Aquatic moss	**-5.8**		-4.4		-0.7	
Filamentous algae	**-62.8**		**-5.7**		**-14.4**	
Potamogeton gramineus	-0.5	5.3	**17.1**	4.0	0.2	2.0
Potamogeton illinoensis	**-24.5**	4.0	-0.4		1.2	
Utricularia gibba	**-15.2**		**44.7**	5.0	NP	
Utricularia minor	**9.8**		2.2		NP	
Utricularia vulgaris	**8.1**	4.0	**7.0**		0.0	
Chara contraria	3.6	2.0	0.4		-2.9	1.5
Potamogeton zosteriformis	2.2				-1.4	1.0
Chara globularis	-1.2	4.0	-4.4	3.5	0.9	-3.0
Najas flexilis	-2.6		0.9		-3.4	2.0
Nitella flexilis	NP		-0.4		3.3	2.0
Vallisneria americana	NP		NP		0.4	2.0

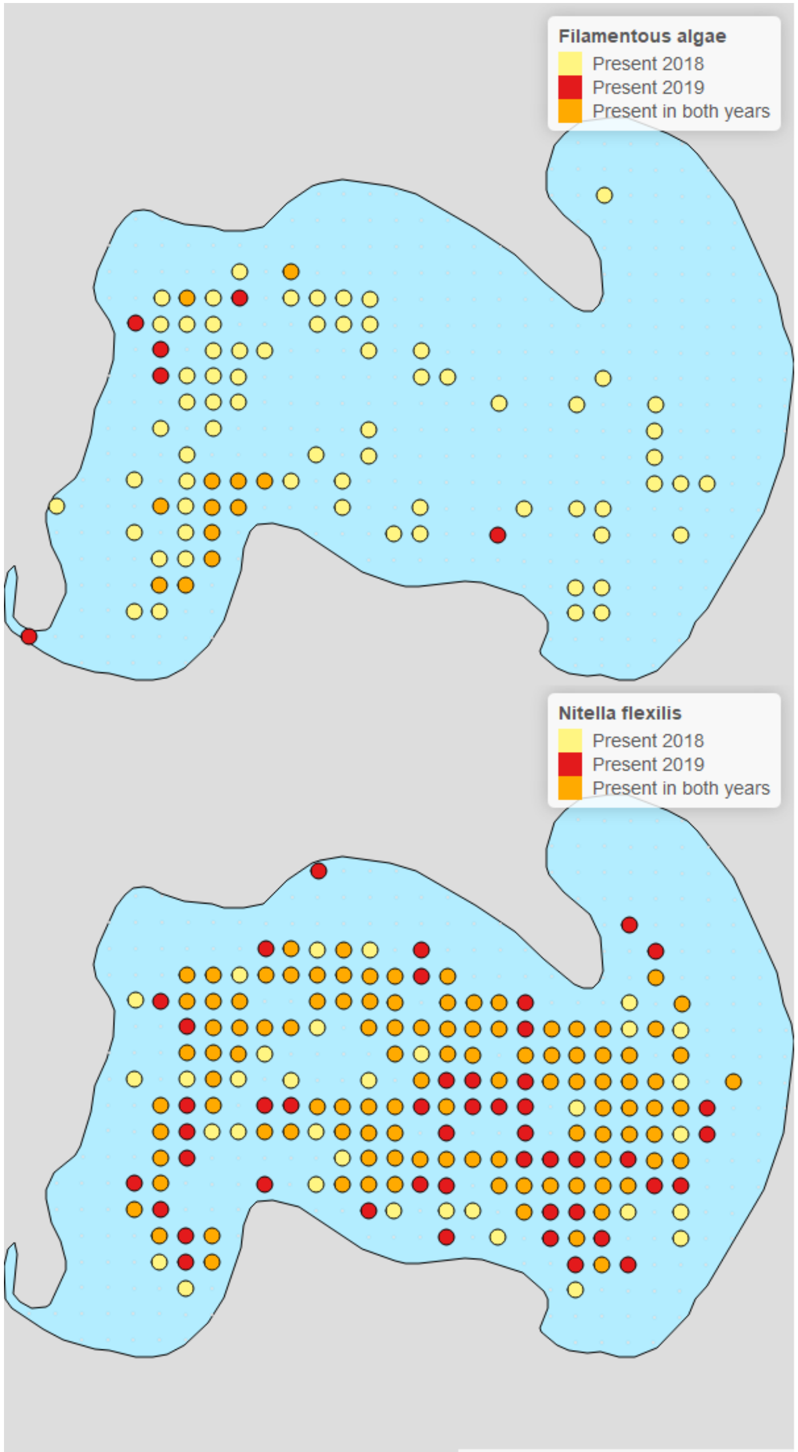

Figure 34. Change in Submergent Marsh at Pleasant Lake, 2018-2019. Distribution change of two Submergent Marsh species in Pleasant Lake from 2018 to 2019. Filamentous algae occurred less frequently in 2019. The distribution of the most common species, *Nitella flexilis*, did not change between years.

Emergent Marsh

Although Emergent Marsh was not extensive in Pleasant Lake, there were a few small patches of emergent species near the boat launch and the public swim area. *Eleocharis acicularis* and *Schoenoplectus acutus* were observed (on the west and northwestern shores), as well as sparse stands of *Schoenoplectus pungens*. These plants may have been more prevalent prior to shoreline development.

Floating-leaved Marsh

Floating-leaved Marsh was also essentially absent on Pleasant Lake, but the following species were observed: *P. natans*, *N. odorata*, and *Lemna minor.* They mostly occurred in the southwest and northwest bays with a few stray observations along the western shoreline.

Table 15. Percent cover of all Inland Beach Marsh species in Pleasant Lake in 2018 from timed meander survey.

Scientific Name	Common Name	2018
Cyperus bipartitus	slender flat sedge	10
Lobelia siphilitica	great blue lobelia	10
Lycopus uniflorus	northern bugleweed, northern water-horehound	3
Schoenoplectus pungens	chair-maker's rush, common three-square bulrush	2
Melilotus albus	white sweet-clover	2
Eupatorium perfoliatum	boneset, common boneset, thoroughwort	2
Bidens frondosa	common beggar-ticks, Devils beggar-ticks	2
Echinochloa muricata	barnyard grass, cockspur grass, rough barnyard grass	2
Cyperus strigosus	false nut sedge, straw-colored cyperus	2
Salix interior	sandbar willow	2
Agalinis purpurea	purple false foxglove, smooth agalinis	1
Plantago lanceolata	English plantain, narrow-leaved plantain, plantain	1
Asclepias incarnata	swamp milkweed	1
Impatiens capensis	orange jewelweed, orange touch-me-not	1
Bidens connata	purple-stem beggar-ticks, purple-stemmed tickseed	1
Salix eriocephala	diamond willow, Missouri River willow	1
Salix X fragilis	brittle willow, crack willow	1
Carex viridula	green yellow sedge, little green sedge	1
Persicaria maculosa	heart's-ease, spotted lady's-thumb	1
Ambrosia artemisiifolia	annual bur-sage, common ragweed, short ragweed	1
Juncus dudleyi	Dudley's rush	1
Euphorbia maculata	milk-purslane, spotted sand-mat, wart-weed	1
Taraxacum officinale	common dandelion	1
Trifolium hybridum	alsike clover	1
Populus deltoides	eastern cottonwood	1
Robinia pseudoacacia	black locust	1
Oenothera biennis	bastard evening-primrose, common evening-primrose	1
Plantago major	broad-leaved plantain, common plantain, plantain	1
Digitaria ischaemum	smooth crabgrass	1

Inland Beach

Pleasant Lake's Inland Beach community, likely the rarest plant community found on Pleasant Lake, was limited by the unusually high water but still contained 29 species (Table 12) The presence of tree and shrub species in standing water along the shore indicates that water levels were lower before 2018 and allowed several weedy shrubs and trees to take hold, including the invasive *Robinia pseudoacacia*, and *Salix X fragilis* (Table 15). These species are unlikely to survive the flood state in 2018 and 2019, however if lake levels go down and remain down, these species would be expected to colonize in addition to *P. deltoides* and *Salix interior* (sandbar willow). The Inland Beach community surveyed at Pleasant Lake had a weighted mean coefficient of conservatism of 2.9. Compared to the 4.9 weighted mean coefficient of conservatism on Plainfield Lake indicating good condition, the plant community in Pleasant Lake is in poor condition (Table 12). This low score can be attributed to the estimated 18% non-native plant cover and the fact that the few species with C-values of 6 or above (*E. perfoliatum*, *Agalinis purpurea*, and *Carex viridula*) combined for an estimated cover of only 4%.

Southern Sedge Meadow

Southern Sedge Meadow occurs in Turtle Bay. The area known as Turtle Bay appears to be an artificially dug pond, as we did not observe open water there in 1930's aerial imagery. The 2018 timed-meander survey focused on the wetland surrounding the open water and made only casual observations of the open water area. The area surrounding the pond was difficult to classify into community type. Although it was dominated by native vegetation and had several species that might be seen in a Southern Sedge Meadow at the lowest elevations, early successional species were most abundant: *Impatiens capensis*, *Epilobium coloratum*, and *Apios americana* (Table 16). Shrub cover was estimated at 12% relative cover and tree cover at 6% relative cover. The ground layer also had many wet forest species. Some areas are succeeding to shrub-carr. Species with high C-values included *C. stricta*, *Salix bebbiana*, *Juncus brachycephalus*, and *Rumex brittanica*. Three invasive species were found at low cover: *P. arundinacea* at 3% cover, *Lonicera X bella*, and *Salix X fragilis*.

The weighted mean coefficient of conservatism of plants in the Southern Sedge Meadow area was 3.5, falling into the "Fair" condition category for this community type (Table 12). The small area was quite diverse with 67 plant species found and relative cover of non-native species was low, at 4% (Table 12). However, due to the dominance of plants with low conservatism values the overall floristic quality was only moderate. Overall, this was a very mixed community, lacking the more conservative dominants found in intact sedge meadow, and it may indicate that the area is still recovering from disturbance. Turtle Bay was likely dredged as evidenced by the lack of open water in 1930's aerial imagery, the rectangular shape after it appears in later aerial imagery, and the lack of a typical soil profile, indicating dredge material. Further investigation could help clarify Turtle Bay's origins. Although the floristic quality assessment indicates disturbance, the Southern Sedge Meadow at Pleasant Lake still harbors high plant diversity, and Southern Sedge Meadows generally provide habitat for a variety of birds, amphibians, reptiles, and rare invertebrates.

Table 16. Percent cover of all Southern Sedge Meadow species in Turtle Bay of Pleasant Lake in 2018 from timed meander survey.

Scientific Name	Common Name	2018
Impatiens capensis	orange jewelweed, orange touch-me-not	20
Epilobium coloratum	cinnamon willow-herb, eastern willow-herb	12
Apios americana	common groundnut, Indian-potato, potato-bean	10
Solidago canadensis	Canadian goldenrod	8
Calamagrostis canadensis	blue-joint grass	6
Carex stricta	tussock sedge	4
Phalaris arundinacea	reed canary grass	3
Lemna minor	common duckweed, lesser duckweed, small duckweed	2
Carex hystericina	bottlebrush sedge, porcupine sedge	2
Solidago gigantea	giant goldenrod	2
Persicaria punctata	dotted smartweed	2
Lycopus uniflorus	northern bugleweed, northern water-horehound	2
Carex bebbii	Bebb's oval sedge, Bebb's sedge	2
Rubus occidentalis	black-cap, black raspberry	2
Onoclea sensibilis	sensitive fern	2
Salix bebbiana	beaked willow, Bebb's willow	2
Cornus sericea	red osier dogwood	2
Salix petiolaris	meadow willow	2
Symphyotrichum firmum	glossy-leaved aster	1
Stachys palustris	hedge-nettle, marsh hedge-nettle, woundwort	1
Iris versicolor	harlequin blue flag, northern blue flag	1
Lobelia siphilitica	great blue lobelia	1
Hackelia virginiana	beggar's-lice, stickseed, wild comfrey	1
Urtica dioica	stinging nettle	1
Juncus dudleyi	Dudley's rush	1
Geum aleppicum	yellow avens	1
Ludwigia palustris	marsh purslane, marsh seed-box, water-purslane	1
Eleocharis intermedia	matted spike-rush	1
Hypericum ascyron	giant St. John's-wort, great St. John's-wort	1
Rumex britannica	great water dock	1
Asclepias incarnata	swamp milkweed	1
Cirsium vulgare	bull thistle	1
Sambucus canadensis	American elder, elderberry	1
Eupatorium perfoliatum	boneset, common boneset, thoroughwort	1
Persicaria amphibia	water heart's-ease, water smartweed	1
Galium trifidum	northern three-lobed bedstraw, small bedstraw	1
Juncus brachycephalus	short-headed rush, small-headed rush	1

Lycopus americanus	American water-horehound, common water-horehound	1
Poa palustris	fowl meadow grass, marsh bluegrass	1
Cyperus bipartitus	slender flat sedge	1
Juncus tenuis	path rush, poverty rush, roadside rush	1
Circaea canadensis	broad-leaf enchanter's-nightshade	1
Ribes americanum	American black currant, eastern black currant	1
Scutellaria galericulata	common skullcap, marsh skullcap	1
Ulmus americana	American elm, white elm	1
Symphyotrichum lanceolatum	eastern lined aster, panicled aster, white panicle	1
Pilea fontana	bog clearweed, lesser clearweed	1
Rhus typhina	staghorn sumac	1
Lonicera X bella	Bell's honeysuckle, showy bush honeysuckle	1
Equisetum arvense	common horsetail, field horsetail	1
Galium triflorum	fragrant bedstraw, sweet-scented bedstraw	1
Erechtites hieraciifolius	American burn-weed, fireweed	1
Parthenocissus quinquefolia	Virginia creeper, woodbine	1
Juncus canadensis	Canadian rush	1
Thelypteris palustris	eastern marsh fern, marsh fern	1
Potentilla norvegica	Norwegian cinquefoil, rough cinquefoil, strawberry	1
Schoenoplectus tabernaemontani	great bulrush, soft-stem bulrush	1
Geum canadense	white avens	1
Utricularia vulgaris	Common bladderwort, great bladderwort	1
Salix discolor	pussy willow	1
Rubus idaeus	wild red raspberry	1
Asclepias syriaca	common milkweed, silkweed	1
Corylus americana	American hazelnut	1
Erigeron strigosus	daisy fleabane, prairie fleabane, rough fleabane	1
Vitis riparia	frost grape, river bank grape	1
Stuckenia pectinata	comb pondweed, sago pondweed	1
Salix X fragilis	brittle willow, crack willow	1

Long Lake

Long Lake’s wetland communities (Inland Beach, Submergent Marsh, Emergent Marsh, and Floating-leaved Marsh) are healthy. Only one emergent species with a very limited range was observed on Long Lake. The gently sloping topography and dynamic water levels on Long Lake have encouraged colonization by many wetland plants from different communities and created a patchwork of habitats across this relatively small lake. Unlike many wetlands across the state, these wetlands have benefitted from high water quality and low sedimentation and show minimal signs of degradation or invasion by non-natives. Water levels were especially high on Long Lake during the survey and rose an additional 3.4 ft from August 2018 to August 2019.

Submergent Marsh

Submergent Marsh is the largest wetland type at Long Lake, covering nearly the entire lakebed where semi-permanent surface water occurs (Figure 35). *Chara globularis* is the most frequently occurring member of this community, found at more than one-third of all points (Table 17). Other *Chara* spp. are also present in large numbers during lower-water years. *Potamogeton gramineus*, *P. pusillus*, *P. illinoensis Najas flexilis*, and *N. gracillima* are also abundant. Other common community members include three species of bladderworts, *Utricularia. gibba*, *U. minor*, and *U. vulgaris*.

Table 17. Littoral frequency of occurrence of all Submergent Marsh species in Long Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
Chara globularis	Globular stonewort	40.8	36.4
Chara sp.	Muskgrass	20.6	0.0
Potamogeton gramineus	Variable-leaved pondweed	20.2	37.3
Utricularia gibba	Creeping bladderwort	14.0	58.8
Najas flexilis	Slender naiad	7.9	8.8
Filamentous algae	Filamentous algae	5.7	0.0
Utricularia minor	Lesser bladderwort	5.7	7.9
	Aquatic moss	4.4	0.0
Najas gracillima	Slender water-nymph	4.4	1.8
Potamogeton pusillus	Small pondweed	3.9	5.3
Utricularia vulgaris	Common bladderwort	2.2	9.2
Schoenoplectus subterminalis	Water bulrush	0.9	0.9
Nitella flexilis	Slender nitella	0.4	0.0
Potamogeton illinoensis	Illinois pondweed	0.4	0.0
Chara contraria	Fetid stonewort	0.0	0.4
Juncus pelocarpus f. submersus		0.0	0.4
Potamogeton amplifolius	Large-leaved pondweed	0.0	0.4
Potamogeton praelongus	White-stemmed pondweed	0.0	3.9

Long Lake's Submergent Marsh has 15 vascular plant species plus filamentous algae and aquatic moss (Table 12). Wisconsin does not currently have condition standards for Submergent Marsh, but the Long Lake community is healthy and has several conservative species. Four species with coefficient of conservatism values of 9 or 10 are especially notable: *U. gibba, U. minor* and *Schoenoplectus subterminalis*. In addition, *Najas gracillima* is a species of special concern associated with clear, soft water lakes. All species are native to Wisconsin.

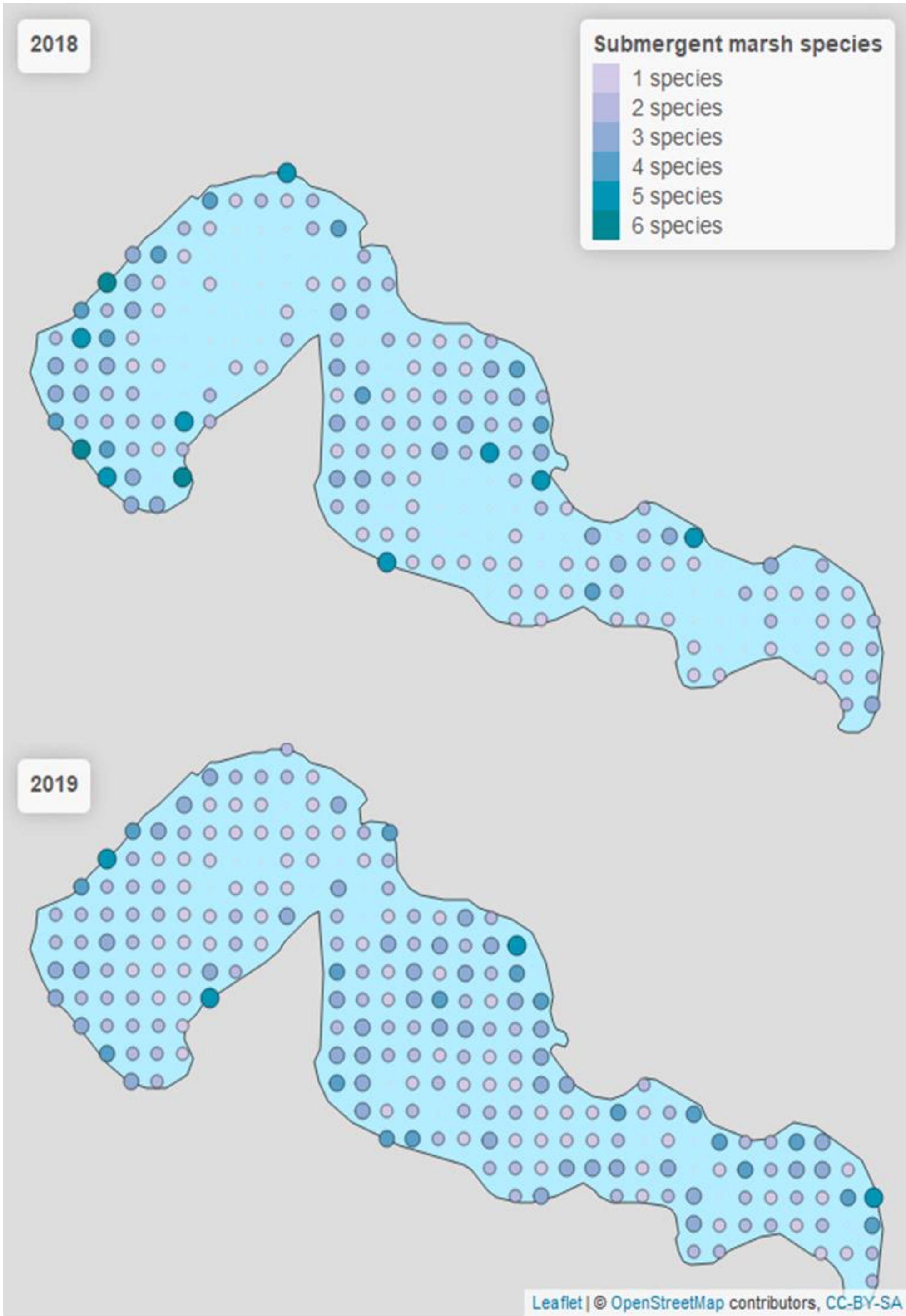

Figure 35. Submergent Marsh at Long Lake, 2018-2019. Distribution of Submergent Marsh species richness in Long Lake, 2018 and 2019.

The extent of Submergent Marsh increased from a frequency of occurrence of 73.7% in 2018 to 93.9% in 2019, and average species richness at individual points stayed the same at 2.1 species (Table 14, Figure 35). There was spatial heterogeneity in species richness responses, with declines in the southwest bay and increases in the north and east (Figure 35). In contrast to Plainfield Lake, the occurrence of *U. gibba* dramatically increased, suggesting that species' responses to increasing water levels are dependent on lake-specific factors. The increases mostly occurred in the central areas of the lake where *N. odorata* became less abundant, suggesting that competition with floating-leaved plants limited its extent in 2018 (Figure 36). The occurrence of *P. gramineus* and *U. vulgaris* also increased in 2019, whereas filamentous algae declined (Table 14). *Potamogeton gramineus* increased its extent along the lake margins, particularly in the eastern lobe, and to some degree in the central areas of Long Lake, and *U. vulgaris* became more extensive in the eastern lobe (Figure 36). Most species, including those that suffered some declines, demonstrated their ability to grow at a variety of depths, even as lake levels changed rapidly. The depth distribution of Submergent Marsh increased from a median depth of 5 to 9 feet, and the median depth where individual species occurred increased by 3.5 – 5 feet (Table 14).

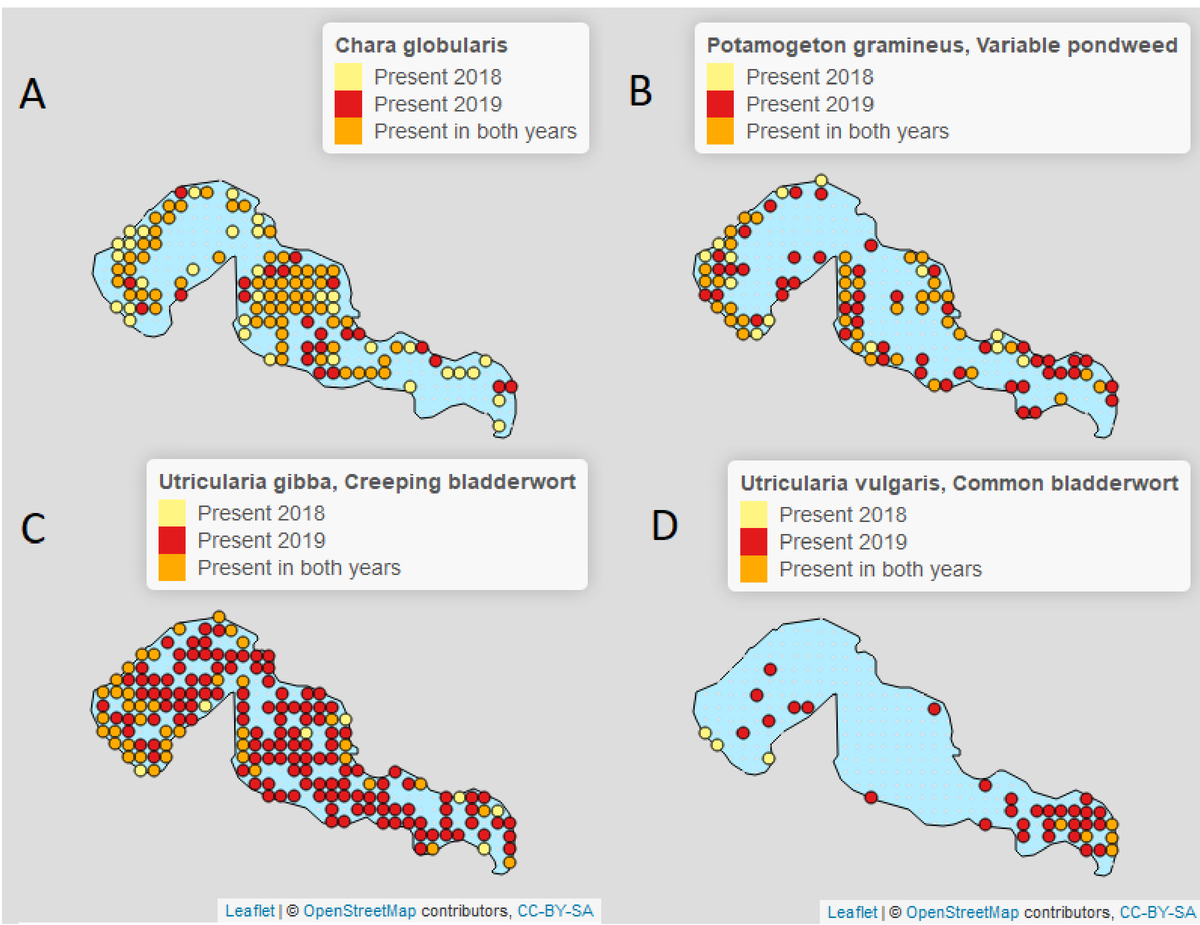

Figure 36. Change in Submergent Marsh at Long Lake, 2018-2019. Distribution change of 4 Submergent Marsh species in Long Lake from 2018 to 2019. *Utricularia gibba* (C), *U. vulgaris* (D), and *Potamogeton gramineus* (B) occurred more frequently in 2019, whereas the distribution of *Chara globularis* (A) changed very little.

Emergent Marsh

Long Lake only had one small bed of *Juncus effusus* on the north central shore to represent Emergent Marsh (Figure 37). This plant was not observed during the timed meander surveys, but it was observed as a visual during the plant point intercept surveys and was delineated as an emergent plant bed in 2018. In 2019, the entire *J. effusus* bed was flooded, resulting in a loss of 0.2 acres (Table 18). The depth at the point where *J. effusus* was observed increased from 2 feet in 2018 to 7 feet in 2019. Other emergent species encountered as visuals during the plant point intercept surveys were *Salix* spp. and *Sparganium* spp.

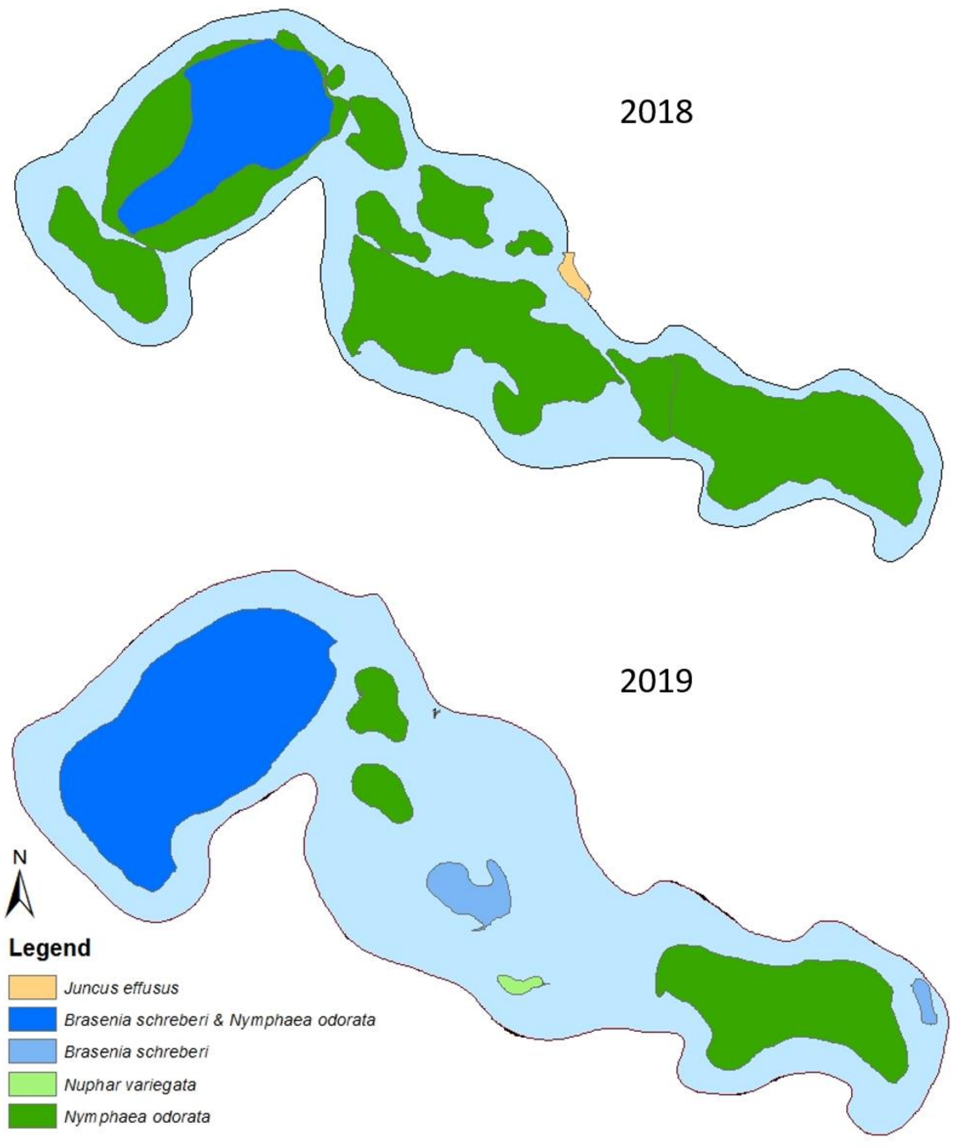

Figure 37. Change in Emergent and Floating-leaved Marsh at Long Lake, 2018-2019. Areal change in the Emergent and Floating-leaved plant beds in Long Lake from 2018 to 2019. *Juncus effusus* is the only emergent species, and *Nymphaea odorata* and *Brasenia schreberi* were the most common floating-leaved species.

Floating-leaved Marsh

The second most abundant wetland community type at Long Lake was Floating-leaved Marsh. The Floating-leaved Marsh areas at Long Lake were dominated by *Nymphaea odorata* and *Brasenia schreberi* (Figure 37). While this community contains fewer species than the Submergent Marsh, it is still in good condition (Table 12). The most common species, *N. odorata*, *B. schreberi*, and *N. variegata* all have coefficient of conservatism values of 6, bringing the weighted mean coefficient of conservatism of this community to 5.6. Additional species observed visually during the plant point intercept survey are *Potamogeton natans* and *Ricciocarpus natans.*

The net areal change of the Floating-leaved Marsh decreased by 8 acres from 2018 to 2019, and the frequency of occurrence increased slightly from 81.6% in 2018 to 85.1% in 2019. Average species richness was stable at 1.9 species, but the points with highest diversity shifted from the central areas of the lake to the lake margins (Figure 38). The median depth of the Floating-leaved Marsh increased from 5 feet in 2018 to 9 feet in 2019 and increased by 4 feet for both *N. odorata* and *B. schreberi*. During the 2018 survey, *N. odorata* occupied much of the lake surface area, posing a navigational difficulty for watercraft. Several other floating-leaved species were observed with *N. odorata*, including: *B. schreberi*, *Persicaria amphibia*, and *Nuphar variegata*. *Nymphaea odorata* declined most dramatically, with a loss of 16 acres and 14% decrease in frequency of occurrence (Table 14, Table 18). This loss mostly occurred at the central portion of the lake, where it is deepest (9 – 12 feet). The large area formerly colonized by *N. odorata* was bare of floating-leaved vegetation except for a small patch of *B. schreberi* occurring near the center of the lake (Figure 37). The western and eastern lobes remained relatively unchanged, though *B. schreberi* became more extensive and dominant in the west as evidenced by both the plant point intercept surveys and the floating-leaved plant bed delineations (Table 18, Table 19, Figure 37). *Persicaria amphibia* occurred along the lake margins in both years, with a 4.4% increase in frequency of occurrence from 2018 to 2019 (Table 19, Figure 38). We delineated 4.5 acres of *P. amphibia* and 1.6 acres of *P. amphibia* mixed with *B. schreberi* in 2019 (Figure 39). However, because we did not delineate these beds in 2018, it is difficult to say how much the extent of *P. amphibia* changed.

Table 18. Littoral frequency of occurrence of all Floating-leaved Marsh species in Long Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
Nymphaea odorata	American white water-lily	28.1	14.0
Brasenia schreberi	Water-shield	23.2	32.9
Nuphar variegata	Bull-head pond-lily	7.0	10.5
Persicaria amphibia	Water smartweed	3.9	8.3
Lemna minor	Common duckweed	1.8	3.9
Potamogeton natans	Floating pondweed	0.0	0.0
Ricciocarpus natans		0.0	0.0

Table 19. Areal change (acres) in emergent and floating-leaved plant beds in Long Lake from 2018 to 2019. Plant beds were delineated using a GPS unit.

	2018	2019	Change
Emergent			
Juncus effusus	0.2	0.0	-0.2
Floating-leaved			
Brasenia schreberi	0.0	1.2	1.2
Brasenia schreberi & Nymphaea odorata	5.5	12.1	6.6
Nuphar variegata	0.0	0.2	0.2
Nymphaea odorata	23.4	7.4	-16.0

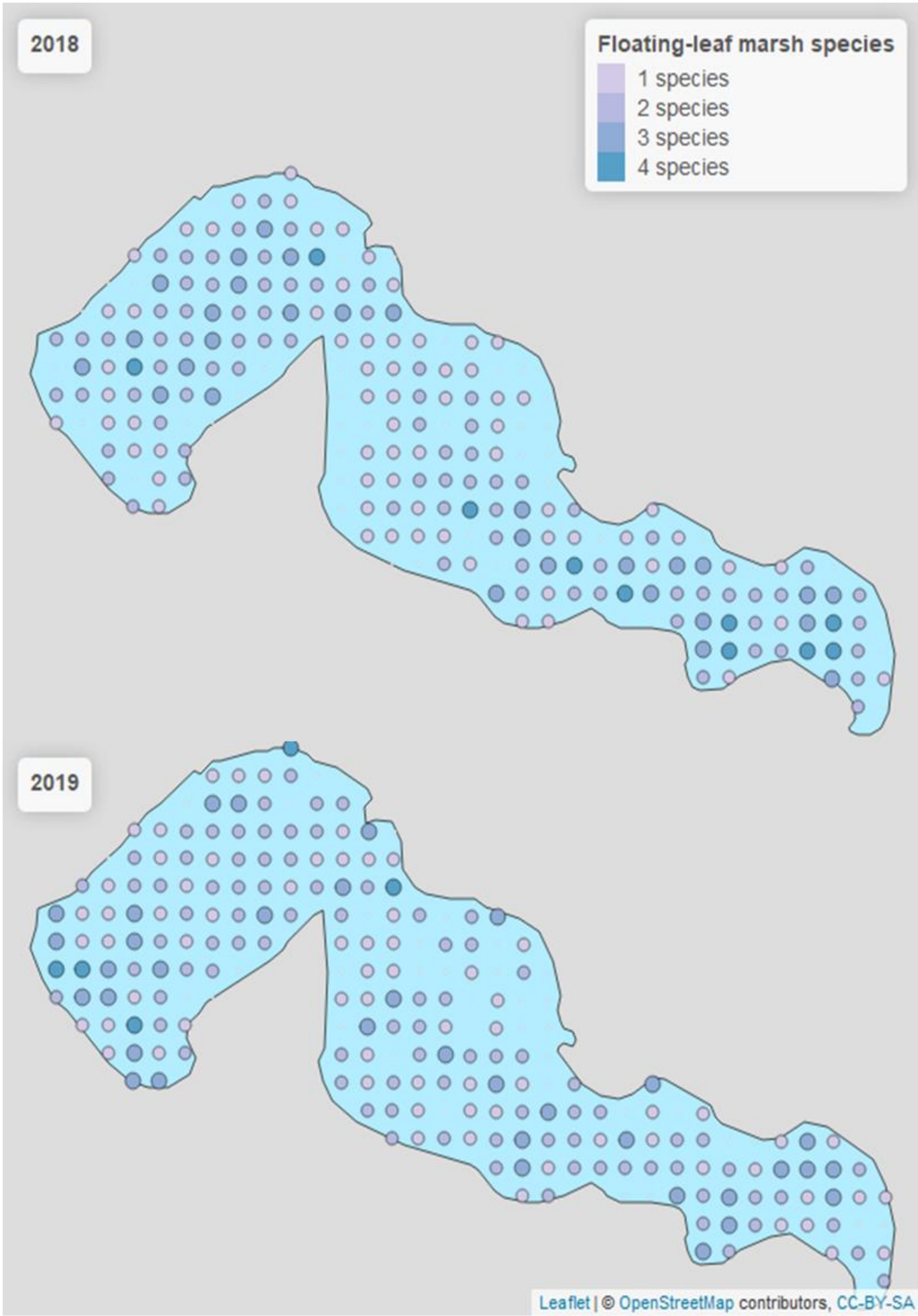

Figure 38. Floating-leaved Marsh at Long Lake, 2018-2019. Distribution of Floating-leaved Marsh species richness in Long Lake 2018 and 2019.

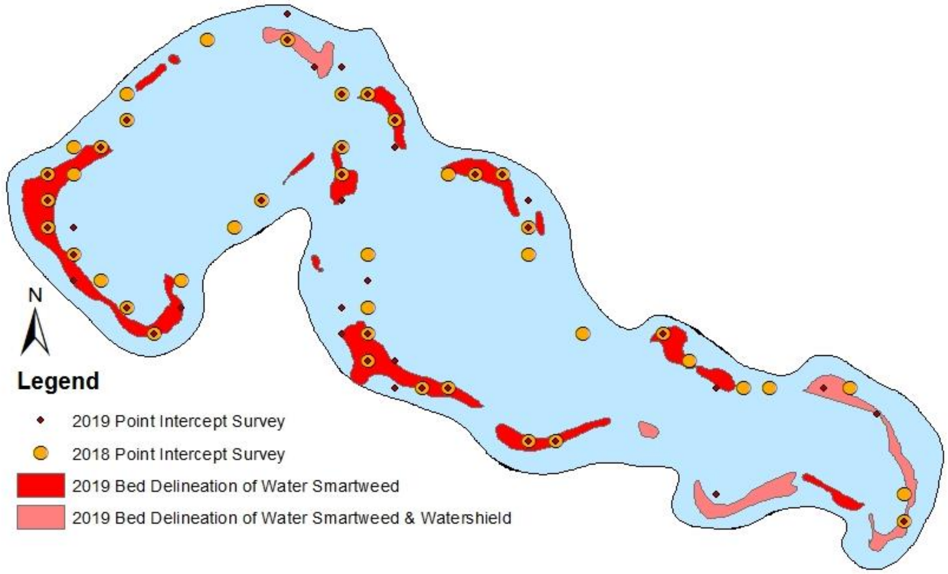

Figure 39. *Persicaria amphibia* at Long Lake, 2018-2019. Distribution of *Persicaria amphibia* in Long Lake according to plant point intercept surveys conducted in 2018 and 2019 and a plant bed delineation conducted in 2019.

Inland Beach

High water in 2018 and 2019 limited the extent of Long Lake's Inland Beach community. Nevertheless, we found 27 species and calculated a weighted mean coefficient of conservatism of 4.1 (Table 12). This is considered a stratified community, with sparse, short-statured, short-lived annuals growing in the wet, recently exposed sandy/gravelly shoreline, and denser, taller perennials inhabiting the drier area farther up on the shore. We found a few specialists of sandy, fluctuating lakes on the exposed, wet sandy shore: the diminutive annuals, *Lipocarpha micrantha* and *Fimbristylis autumnalis*, both with C-values of 8 (Table 20). Other areas of the beach, perhaps representing less recently exposed areas, have denser vegetation reminiscent of wet prairie. Dominants include *Eupatorium perfoliatum*, *Hypericum majus*, *Carex pellita*, and *Calamagrostis canadensis*. Historical photos suggest that at times this vegetation covers large areas of the beach and extends into the lakebed when water levels are lower than they were in 2018. While dominated by native plants, non-natives comprise 13% relative cover in this community, including *Frangula alnus*, *Poa pratensis*, and *Ambrosia artemisiifolia*. This community should be re-surveyed once water levels decline to determine if members of the imperiled Coastal Plain Marsh are also present.

Table 20. Percent cover of all Inland Beach Marsh species in Long Lake in 2018 from timed meander survey.

Scientific Name	Common Name	2018
Carex pellita	broad-leaved woolly sedge	8
Hypericum majus	larger Canadian St. John's-wort	8
Calamagrostis canadensis	blue-joint grass	5
Eupatorium perfoliatum	boneset, common boneset, thoroughwort	5
Poa pratensis	Kentucky bluegrass	4
Hudsonia tomentosa	false heather, woolly beach-heather	2
Agrostis hyemalis	southern hair grass, tickle grass, winter bentgrass	1
Ambrosia artemisiifolia	annual bur-sage, common ragweed, short ragweed	1
Cyperus bipartitus	slender flat sedge	1
Cyperus houghtonii	Houghton's flat sedge	1
Cyperus odoratus	flat sedge, fragrant cyperus	1
Dichanthelium acuminatum var. fasciculatum	hairy panic grass	1
Elymus repens	couchgrass, creeping quackgrass, quackgrass	1
Epilobium coloratum	cinnamon willow-herb, eastern willow-herb	1
Erechtites hieraciifolius	American burn-weed, fireweed	1
Fimbristylis autumnalis	autumn sedge, slender fimbry, slender fringe-rush	1
Fragaria virginiana	thick-leaved wild strawberry, Virginia strawberry,	1
Frangula alnus	European alder buckthorn, glossy buckthorn	1
Lipocarpha micrantha	small-flowered hemicarpha	1
Lycopus americanus	American water-horehound, common water-horehound	1
Lycopus uniflorus	northern bugleweed, northern water-horehound	1
Lysimachia quadriflora	narrow-leaved loosestrife, smooth loosestrife	1
Persicaria amphibia	water heart's-ease, water smartweed	1
Rumex acetosella	common sheep sorrel, field sorrel, red sorrel, she	1
Sagittaria latifolia	broad-leaved arrowhead	1
Solidago gigantea	giant goldenrod	1
Symphyotrichum ericoides	heath aster	1

Plainfield Lake

Plainfield Lake wetlands (Submergent Marsh, Emergent Marsh, Floating-leaved Marsh, and Inland Beach) are healthy and exceptionally dynamic. The constantly changing water levels and gently sloping topography create dynamic and diverse plant communities, which in turn support invertebrate populations important to wildlife. All wetlands at Plainfield Lake depend on fluctuating water levels to some extent to support their life-cycle: low water levels support seed germination and establishment of emergent plants and allow rare sandy beach specialists to expand; high water levels remove competition from generalists and prevent emergent vegetation from taking over the lakebed. For example, emergent vegetation that presumably established during low water conditions was flooded in 2018, creating high interspersion of submergent and Emergent Marsh ideal for waterfowl (Quinlan and Mulamoottil. 1987, Mortsch 1998). Plainfield Lake levels increased by 4.3 feet from August 2018 to August 2019.

Water quality also maintains the high quality of these wetlands. Unlike wetlands across much of the state, these wetlands do not yet show signs of degradation due to sedimentation and nitrogen and phosphorus additions. The water is naturally nutrient-poor due to the sandy geology and dominance of groundwater inflows. Typical invasive species, reed canary grass (*Phalaris arundinacea*), non-native cattail (*Typha angustifolia*) and giant reed grass (*Phragmites australis* ssp. *australis*) are present, but not abundant.

Submergent Marsh

Submergent Marsh is the largest wetland type at Plainfield Lake, covering nearly the entire lakebed where semi-permanent surface water occurs (Figure 40). Fifteen vascular plant species plus filamentous algae and aquatic moss were observed in this community (Table 12). *Chara* spp. dominated with combined frequency in point intercept surveys of 88% in 2018 and 66% in 2019 (Table 21). Five species of macroalgae were found, but *C. globularis* dominated (Table 21). *Potamogeton* species (especially *P. illinoensis and P. gramineus*) were also abundant with a combined frequency in PI surveys of 53%. Other dominants are *Utricularia*, with a combined cover of 33%, including *U. gibba*, *U. vulgaris*, and *U. minor*.

The frequency of occurrence of all Submergent Marsh species combined decreased from 98.5% in 2018 to 84.0% in 2019. Species richness at all points where Submergent Marsh plants occurred declined from an average of 3.1 to 2.1. The distribution of submergent species increased from a median depth of 6.5 to 10.5 feet. Though the occurrence of most submergent plant and algal taxa did not change between years, some taxa like filamentous algae changed by as much as 63% (Table 21, Figure 41). The occurrence of two other species of bladderwort (*U. minor* and *U. vulgaris*) increased in 2019. Whether their abundance largely stayed stable or declined, most species

Table 21. Littoral frequency of occurrence of all Submergent Marsh species in Plainfield Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
	Filamentous algae	62.8	0.0
Chara globularis	Globular stonewort	49.7	48.6
Potamogeton illinoensis	Illinois pondweed	37.2	12.7
Chara sp.	Muskgrass	22.1	0.0
Utricularia gibba	Creeping bladderwort	17.1	1.9
Potamogeton gramineus	Variable-leaved pondweed	15.1	14.6
Utricularia vulgaris	Common bladderwort	14.1	22.2
Chara contraria	Fetid stonewort	10.1	13.7
	Aquatic moss	9.5	3.8
Chara aspera	Rough stonewort	5.5	1.9
Najas flexilis	Slender naiad	4.0	1.4
Utricularia minor	Lesser bladderwort	2.5	12.3
Potamogeton zosteriformis	Flat-stem pondweed	2.0	4.2
Chara hydropitys		1.0	0.0
Myriophyllum sibiricum	Common water-milfoil	1.0	0.9
Nitella tenussima		0.5	0.0
Potamogeton pusillus	Small pondweed	0.5	0.0
Myriophyllum heterophyllum	Various-leaved water-milfoil	0.0	0.5

exhibited some ability to cope with higher water levels, as evidenced by the increase in their depth distribution. Among the submergent species with at least 20 occurrences in either year, the median depth at which they occurred increased by 3.9 feet on average (Table 14). For example, *Chara globularis* occurred at depths of 3 - 8 feet in 2018 and 6 - 12.5 ft in 2019. The maximum depth where submergent plants were found was 9 ft in 2018 and 13.5 feet in 2019.

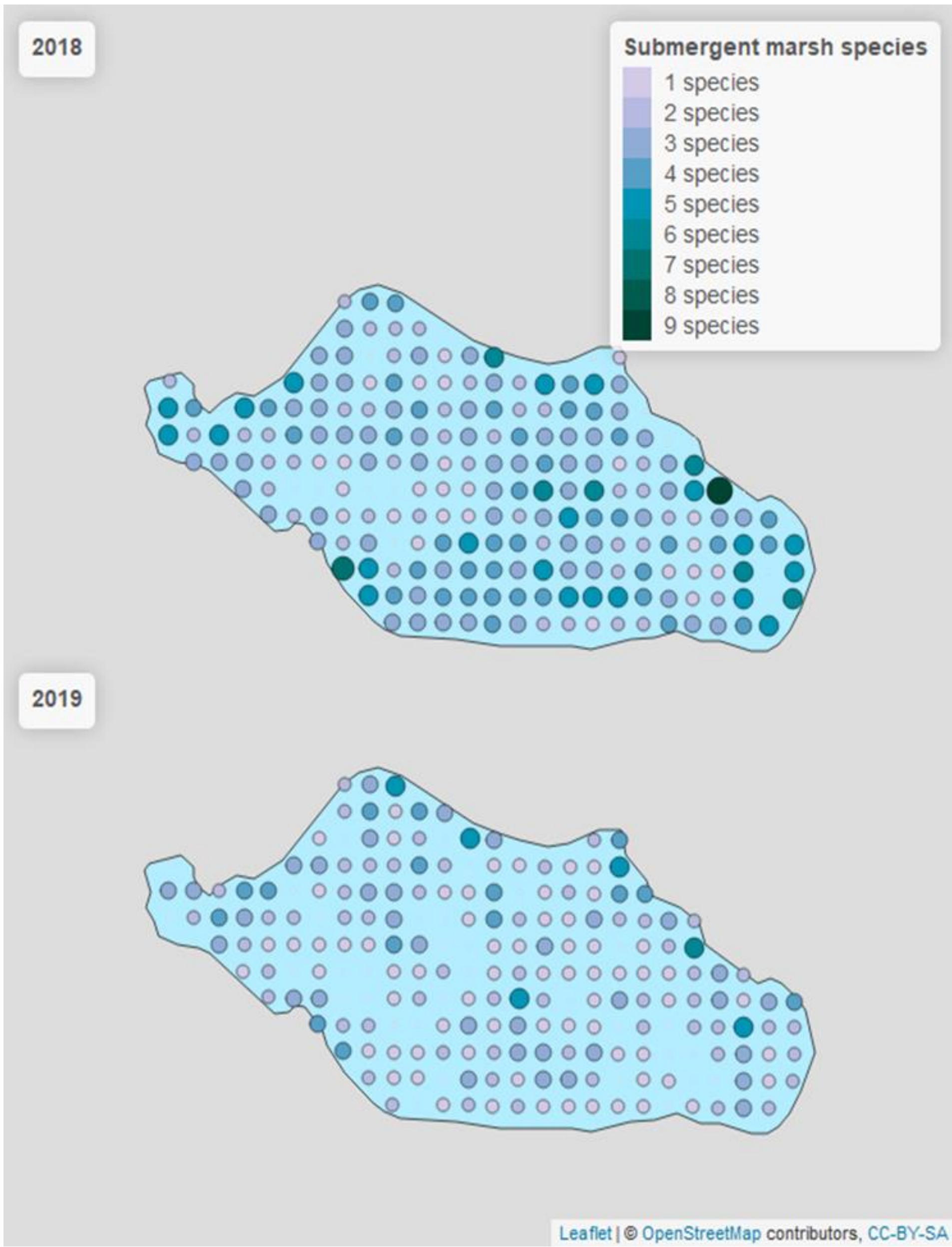

Figure 40. Submergent Marsh at Plainfield Lake, 2018-2019. Distribution of Submergent Marsh species richness in Plainfield Lake, 2018 and 2019.

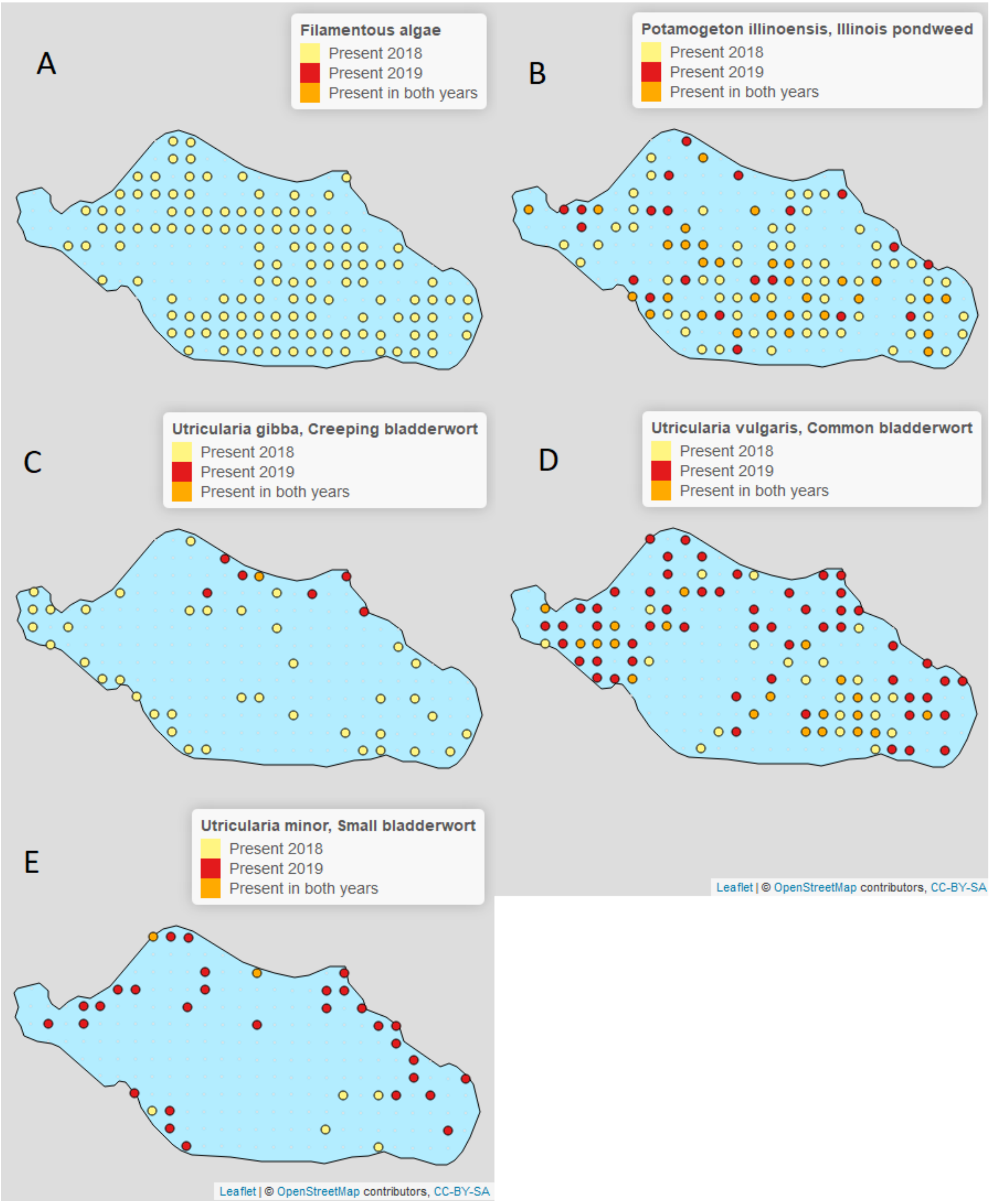

Figure 41. Change in Submergent Marsh at Plainfield Lake, 2018-2019. Distribution change of five Submergent Marsh taxa in Plainfield Lake from 2018 to 2019. *Filamentous algae* (A), *Potamogeton illinoisensis* (B), and *Utricularia gibba* (C) occurred less frequently in 2019, whereas *U. vulgaris* (D), and *U. minor* (E) were more frequent in 2019.

Emergent Marsh

On Plainfield Lake, Emergent Marsh is intermixed with the Submergent Marsh areas. Emergent Marsh areas in Plainfield lake were dominated by *Schoenoplectus acutus* and minor amounts of *Carex atherodes*, *Phragmites australis* ssp. *australis*, and *Typha angustifolia* (Table 22). Emergent species that were observed during the plant point intercept survey but not collected on the rake include: *Eleocharis palustris, Juncus balticus*, and *Spartina pectinata.* In addition, flooded *Populus deltoides* and *Salix* spp. were observed. Using Floristic Quality Benchmarks for Emergent Marsh in the North Central Hardwoods Forests Ecoregion based on weighted mean coefficient of conservatism scores, this Emergent Marsh is in "Good" condition (scores of 5.2-6.6, Table 12). "Good" condition Emergent Marshes have proved to be difficult to restore in Wisconsin, judging from studies of condition in restored wetlands. Emergent Marshes dominated by *S. acutus* tend to be more diverse and are indicative of higher water quality than those dominated by *Typha spp.*, but they are on the decline in Wisconsin (Barrick et al., 2007). The loss of *S. acutus* is a concern because of its value to fish, birds, and insects (Tilley, 2012). The frequency of occurrence of Emergent Marsh as determined from the plant point intercept survey declined from 82.9% in 2018 to 37.7% in 2019, and the species richness at individual points remained unchanged at an average of 1.3 in 2018 and 1.1 in 2019. The median depth of Emergent Marsh increased from 6 feet in 2018 to 11 feet in 2019. The biggest change was an overall reduction of *S. acutus* in 2019 when water levels were higher. The areal coverage of *S. acutus* decreased by 12 acres according to our plant bed delineations, and the frequency of occurrence decreased from 30% to 18% according to the plant point intercept surveys (Table 22, Table 23). *Schoenoplectus acutus* beds stretched across the middle of the lake in 2018 but were primarily limited to rings at intermediate depths around the perimeter of the lake in 2019 (Figure 42, Figure 43). The median depth of its occurrence increased from 7 feet in 2018 to 11 feet in 2019, and some *S. acutus* persisted at the deepest parts of the lake, up to 12.5 feet deep. The western lobe of the lake contained stands of *C. atherodes* along the lake margins in 2018 (Figure 43). *Carex atherodes* was too rare to delineate in 2019, but it was still observed at one of the

Table 22. Areal change (acres) in emergent and floating-leaved plant beds in Plainfield Lake from 2018 to 2019. Plant beds were delineated using a GPS unit.

	2018	2019	Change
Emergent			
Schoenoplectus acutus	16.8	4.8	-12.0
Carex sp.	1.0	0.0	-1.0
Typha sp.	0.6	0.1	-0.5
Phragmites sp.	0.4	0.3	-0.1
Floating-leaved			
Nymphaea odorata	19.7	10.5	-9.3

Table 23. Littoral frequency of occurrence of all Emergent Marsh species in Plainfield Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
Schoenoplectus acutus	Hard-stem bulrush	29.6	17.9
Carex atherodes	Wheat sedge	2.5	0.0
Phragmites australis ssp. australis	Non-native common reed	2.5	1.4
Typha angustifolia	Narrow-leaved cattail	1.5	0.0
Calamagrostis canadensis	Blue-joint grass	1.0	0.0
Sagittaria sp.	Arrow-head	0.5	0.0
Sparganium sp.	Bur-reed	0.5	0.0
Carex sp.	Sedge	0.0	0.5
Panicum virgatum	Switchgrass	0.0	0.9
Spartina pectinata	Prairie cordgrass	0.0	0.5

plant point intercept survey sites. Small patches of *Typha* spp. and *P. australis.* occurred at the margins of the large swaths of *N. odorata* and *S. acutus* in 2018. These small patches persisted in 2019 but were flooded and reduced in extent (Table 23, Figure 43).

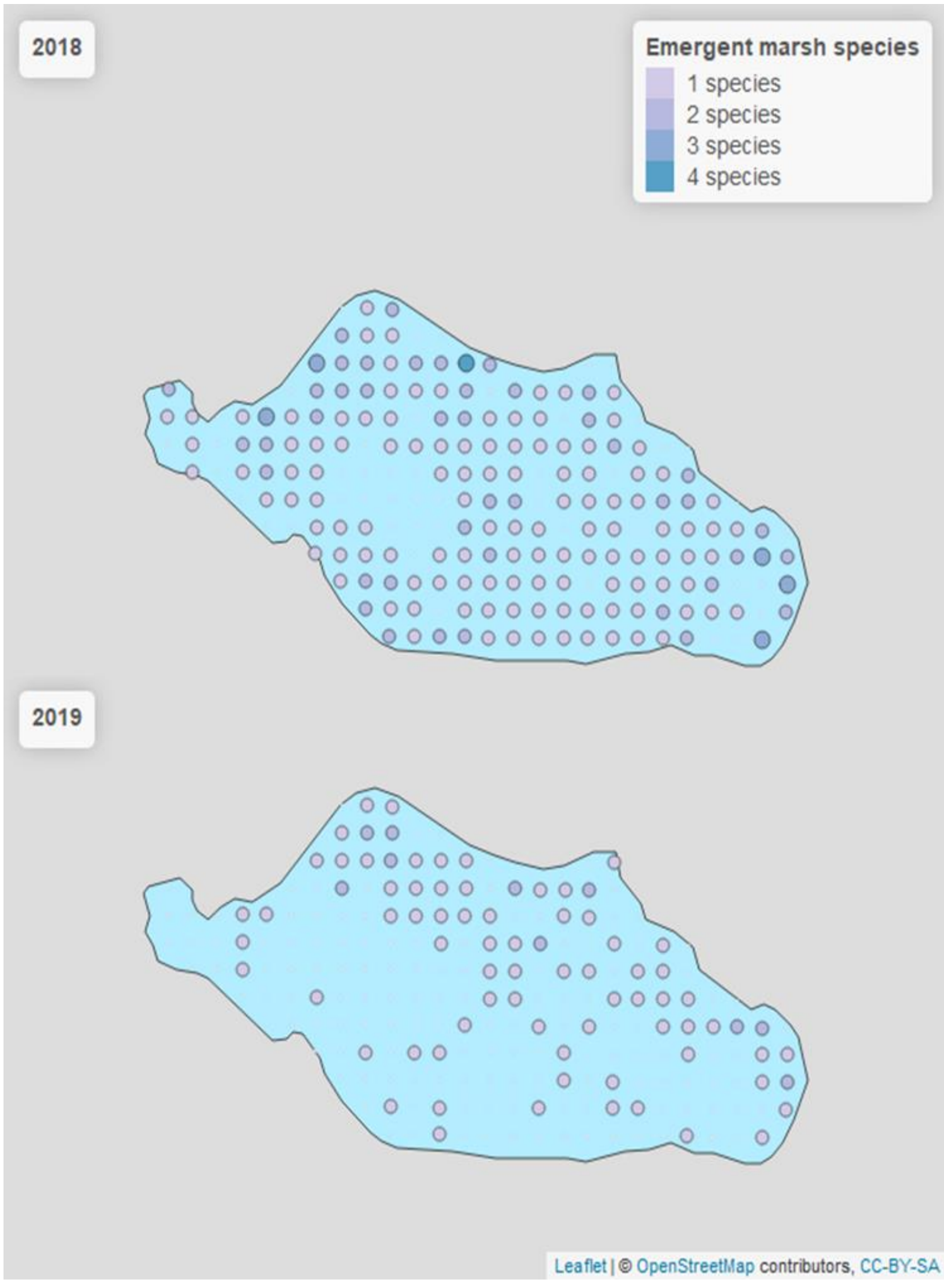

Figure 42. Emergent Marsh at Plainfield Lake, 2018-2019. Distribution of Emergent Marsh species richness in Plainfield Lake, 2018 and 2019.

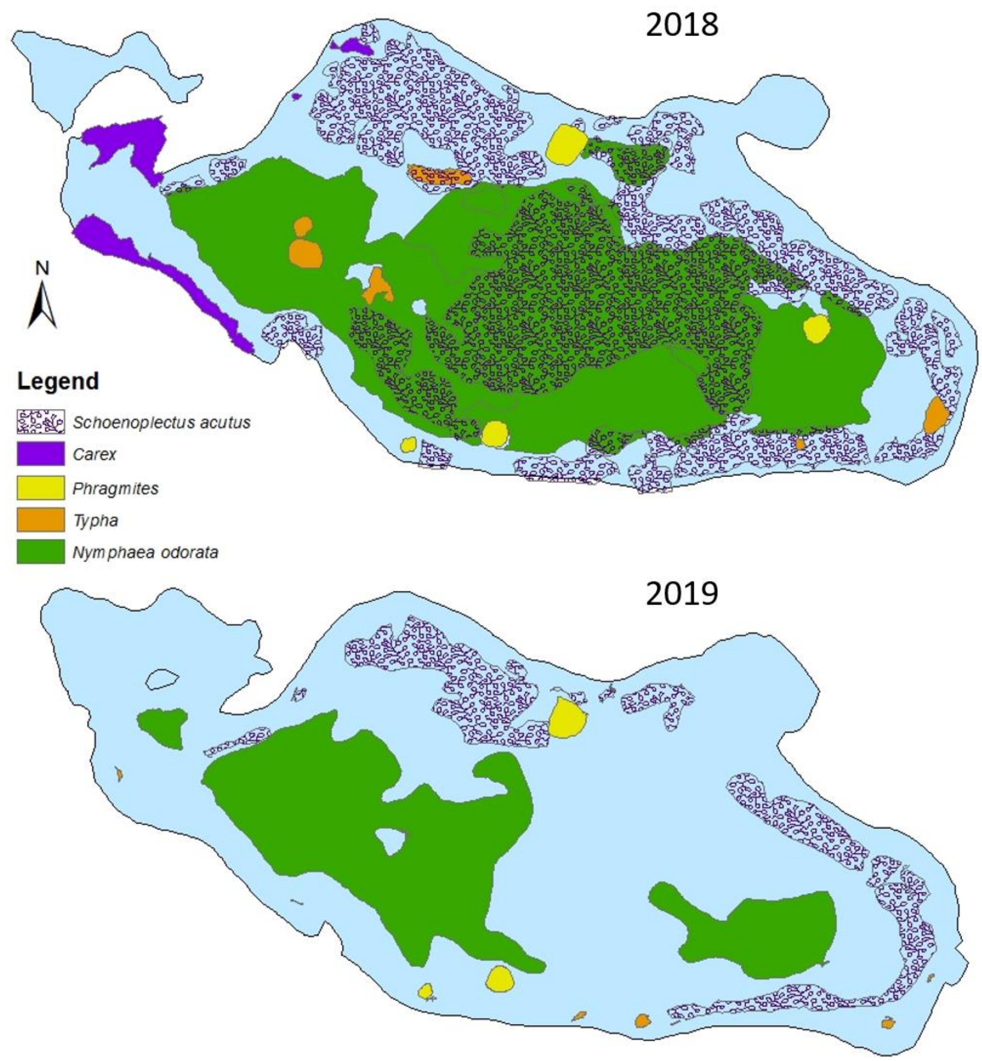

Figure 43. Change in Emergent and Floating-leaved Marsh at Plainfield Lake, 2018-2019. Areal change in the Emergent and Floating-leaved plant beds in Plainfield Lake from 2018 to 2019. Emergent species include: *Schoenoplectus acutus*, *Carex* sp., *Phragmites* sp., and *Typha* sp. *Nymphaea odorata* was the dominant floating-leaved species.

Water level fluctuations are important for Emergent Marsh to persist into the future, but sustained highs and lows are detrimental. For example, *Schoenoplectus acutus* can reproduce clonally through rhizomes while inundated but tend to disappear without regular germination of seeds, which require low water periods every few decades. However, *Schoenoplectus acutus* tends to be replaced with *Typha* spp. if water levels remain less than a few feet for too long and, conversely, does not tolerate extended periods of deep water (> 6 ft) either.

Floating-leaved Marsh

The Floating-leaved Marsh at Plainfield Lake is intermixed with the predominantly Submergent Marsh community (Figure 44). This community is quite diverse with 10 species and is dominated by *N. odorata*

(Table 24). *Persicaria amphibia* and *Wolffia columbiana* were found at more than 5% of points, while *Nuphar variegata* and *B. schreberi* were encountered less frequently.

The frequency of occurrence of Floating-leaved Marsh decreased from 83.4% to 72.2% (Figure 44, Table 14). The species richness at individual points increased from an average of 1.8 to 2.8, and the median depth of Floating-leaved Marsh increased from 7 to 11 feet (Table 14). *Nymphaea odorata* extent declined most dramatically in 2019, with a loss of 9.3 acres and a reduction in occurrence from 27.6% to 18.4% (Table 23, Table 24, Figure 43). In 2018, large beds of *N. odorata* were observed around the deep hole of the lake, off the southern shore, and at the eastern lobe. Much of the area lost in 2019 was in the center of the eastern side, but *N. odorata* persisted in deep areas. The median depth where it occurred increased from 7 to 11.5 feet. The occurrence of *W. columbiana* also declined in 2019 (Table 23). *Persicaria amphibia* occurred along the lake margins in both years, with a slight decline in frequency of occurrence in 2019 according to the plant point intercept surveys (Table 24, Figure 45). Several elongated patches of *P. amphibia* were delineated in 2019, often sharing space with *S. acutus*, *N. odorata,* and *B. schreberi* (Figure 45). However, *P. amphibia* beds were not delineated in 2018, so a direct measure of the areal change cannot be determined.

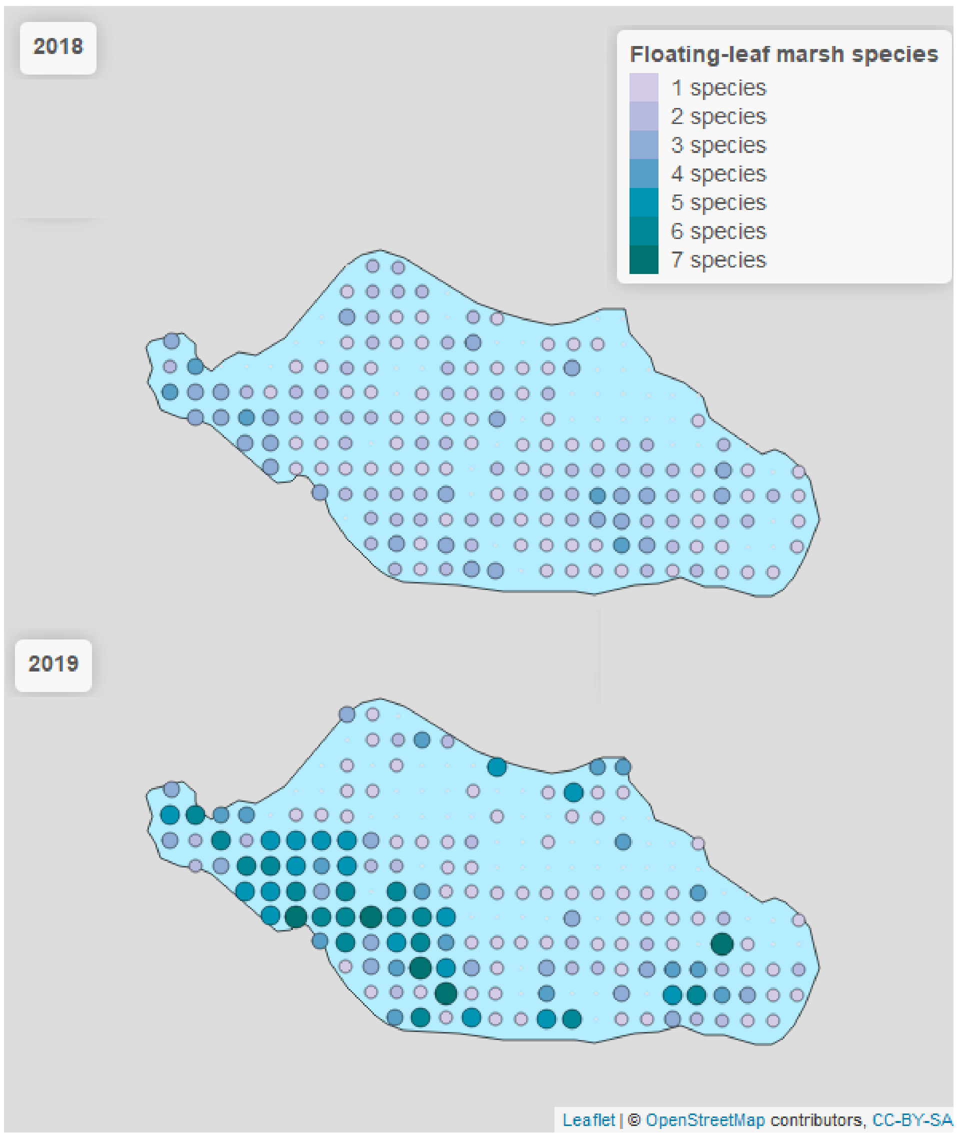

Figure 44. Floating-leaved Marsh at Plainfield Lake, 2018-2019. Distribution of Floating-leaved Marsh species richness in Plainfield Lake 2018 and 2019.

Table 24. Littoral frequency of occurrence of all Floating-leaved Marsh species in Plainfield Lake, 2018 and 2019.

Scientific Name	Common Name	2018	2019
Nymphaea odorata	American white water-lily	27.6	18.4
Persicaria amphibia	Water smartweed	10.1	5.2
Wolffia columbiana	Common water-meal	6.0	0.9
Nuphar variegata	Bull-head pond-lily	3.5	3.3
Brasenia schreberi	Water-shield	3.0	2.8
Potamogeton natans	Floating pondweed	2.0	1.4
Lemna minor	Common duckweed	1.5	0.0
Riccia fluitans	Slender riccia	1.0	3.3
Spirodela polyrhiza		0.5	1.9
Wolffia borealis	Northern water-meal	0.0	0.5

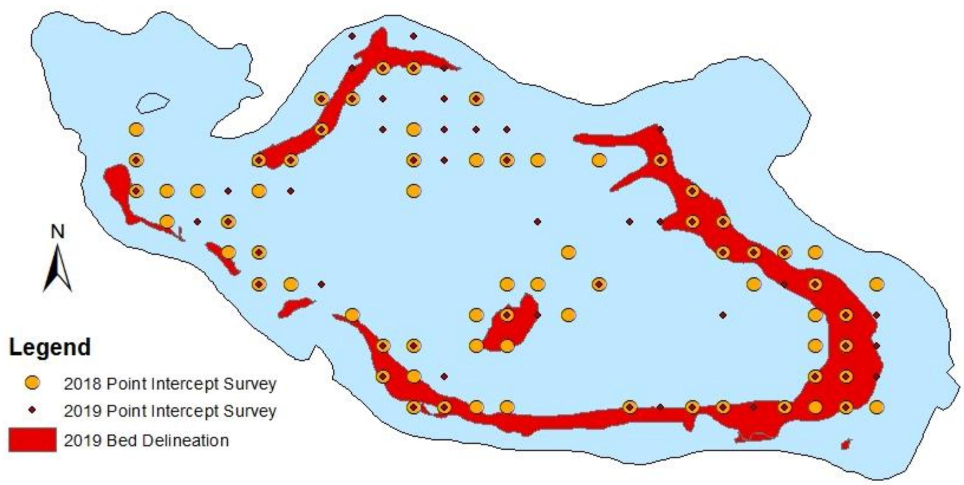

Figure 45. *Persicaria amphibia* at Plainfield Lake, 2018-2019. Distribution of *Persicaria amphibia* in Plainfield Lake according to plant point intercept surveys conducted in 2018 and 2019 and a plant bed delineation conducted in 2019.

Inland Beach

In 2018, the band where this community occurs in Plainfield Lake was very narrow due to rising water levels and was almost non-existent in 2019. In 2018 this community was dominated by low-growing rushes, *J. balticus* and *Juncus alpinoarticulatus* near the water, and *S. pectinata* higher up on the shore (Table 25). The DNR's Bureau of Natural Heritage Conservation tracks high quality examples of natural plant communities in Wisconsin and ranks the Inland Beach on Plainfield Lake as B, meaning it has "good estimated viability" with minimal but some signs of anthropogenic disturbance. However, 2018 was not an ideal year to sample this community given the high water levels. The most conservative species are probably most abundant during periods of recently lowered water levels. For example, this Inland Beach community hosts the world's largest population of a federally threatened, state endangered, and

Wisconsin endemic plant (DNR, 2016), but this species was not found in the 2018 survey. This plant depends on recently lowered water levels to expand its population and flooding to eliminate competition (U.S. Fish and Wildlife Service, 1991).

Table 25. Percent cover of all Inland Beach Marsh species in Plainfield Lake in 2018 from timed meander survey.

Scientific Name	Common Names	2018
Spartina pectinata	prairie cord grass, slough grass	50
Juncus balticus	Arctic rush, Baltic rush, wire rush	7
Juncus alpinoarticulatus	northern green rush	3
Poa compressa	Canada bluegrass, wiregrass	2
Eleocharis elliptica	elliptic spike-rush	2
Lobelia kalmia	bog lobelia, brook lobelia, fen lobelia, Kalm's lobelia	1
Wolffia columbiana	common water-meal	1
Hudsonia tomentosa	false heather, woolly beach-heather	1
Asclepias verticillata	whorled milkweed	1
Dichanthelium acuminatum var. fasciculatum	hairy panic grass	1
Equisetum hyemale	common scouring rush, pipes, scouring rush horsetail	1
Leersia oryzoides	rice cut grass	1
Utricularia vulgaris	Common bladderwort, great bladderwort	1
Calamagrostis canadensis	blue-joint grass	1
Euthamia graminifolia	common flat-topped goldenrod, grass-leaved goldenrod	1
Cyperus bipartitus	slender flat sedge	1
Lemna minor	common duckweed, lesser duckweed, small duckweed	1
Schoenoplectus acutus	hard-stem bulrush	1
Melilotus albus	white sweet-clover	1
Juniperus communis	common juniper	1
Salix eriocephala	diamond willow, Missouri River willow	1
Schizachyrium scoparium	broom beard grass, little blue-stem, prairie beard	1
Solidago missouriensis	Missouri goldenrod	1
Juncus nodosus	joint rush, jointed rush, knotted rush	1
Najas flexilis	nodding water-nymph, northern water-nymph, slender	1

Fish Communities

The three study lakes support different fish communities, largely due to differences in volume and the threat of low oxygen conditions (hypoxia). Pleasant Lake supports a permanent diverse fishery that includes large predatory game fish, panfish, and small non-game species. Long Lake supports a limited bluegill and largemouth bass fishery which is sometimes threatened by hypoxia despite mechanical aerators. Plainfield Lake supports fish intermittently and is at the greatest risk for hypoxia.

Wisconsin lakes can be classified into two simple types of fish communities: those dominated by cyprinids (such as carp, shiners, and minnows) with high tolerance for low oxygen conditions and those dominated by *Esox spp.* and centrarchids (sunfish, bass and crappie), fishes that have low tolerance for low oxygen conditions (Tonn and Magnuson, 1982). The latter community occurs in lakes with sufficient oxygen year-round or, if winter anoxia occurs, lakes that are connected to streams or other lakes that can serve as a winter refuge (Tonn and Magnuson, 1982). This dichotomy is helpful for understanding the historical and current fish communities found in Long, Plainfield, and Pleasant Lakes.

In general, the factors that determine whether a lake will have winter fish kills include lake morphometry, productivity, altitude, latitude, winter severity, and snow depth (Greenbank 1945, Mathias and Barica, 1980; Magnuson et al., 1998; Meding and Jackson, 2003). Oxygen consumption rates have an inverse relationship with mean depth and with the ratio of the surface area of sediment to lake volume (Mathias and Barica, 1980). In Wisconsin lakes, winter kill often occurs in lakes ranging from ~4-11 feet maximum depth (Magnuson et al., 1998). Oxygen depletion is greater in more productive lakes, which can be measured in terms of total phosphorus concentrations, chlorophyll-*a*, or macrophyte biomass (Mathias and Barica, 1980; Magnuson et al., 1998; Meding and Jackson, 2003). Once lakes freeze, gas exchange between the water and atmosphere ceases. Photosynthesis replenishes oxygen and can occur under the ice, but rapidly declines as snow cover accumulates and limits light penetration (Greenbank, 1945).

Pleasant Lake is less productive than the shallow lakes and deep enough to consistently provide sufficient oxygen for a more diverse fish community that includes top predators. Long and Plainfield Lake are more productive, shallower, and have more macrophytes as a proportion of lake volume. Both lakes have histories of low oxygen conditions and winterkills interspersed with stocking events and are at higher risk for winter kills when low lake levels coincide with long ice cover and snowfall.

Another important difference between Pleasant Lake and the other study lakes is the amount of pelagic or open-water habitat. While Pleasant Lake's entire lake basin can be considered littoral because of the presence of macroalgae at even the deepest points, low-growing *Chara* and *Nitella* provide poor cover for prey fish compared to the submergent and floating leaved plants growing along the shallower margins. The unvegetated areas of Pleasant lake, which make up a majority of the volume (Figure 33), provide open-water habitat, whereas this type of habitat is rare on Plainfield and Long Lakes.

Pleasant Lake

Historical Reports

Pleasant Lake has historically supported a diverse fish community. A spring electrofishing survey in April 1999 found abundant largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochirus*), bluntnose minnows (*Pimephales notatus*), and yellow perch (*Perca flavescens*). Other species captured included northern pike (*Esox lucius*), rock bass (*Ambloplites rupestris*), shiners, emerald shiners (*Notropis atherinoides*), warmouth (*Lepomis gulosus*), white suckers (*Catostomus comersonii*), and pumpkinseed (*Lepomis gibbosus*). Less than ten walleye (*Sander vitreus*), white bass (*Morone chrysops*), black crappie (*Pomoxis nigromaculatus*), brown bullhead (*Ameiurus nebulosus*), yellow bullhead (*Ameiurus natalis*), Iowa darter (*Etheostoma exile*), banded darters (*Etheostoma zonale*), and banded killifish (*Fundulus diaphanus*) were caught. Banded killifish is a potentially vulnerable species in Wisconsin (DNR Natural Heritage Program, 2016). Because spring electrofishing surveys primarily target adult game fish and panfish, the number of individuals caught is not necessarily a reflection of population size. On October

Table 26. Abundance and length index of fish caught during spring electrofishing on Pleasant Lake, 2012 and 2019.

Species	Total 2012	Total 2019	No. per mile (No. per hour) 2012	No. per mile (No. per hour) 2019	Percentile Rank 2019	Overall Abundance Rating 2019	Length Index	Length Index CPUE \ mile 2012	Length Index CPUE \ mile 2019	Percentile Rank 2019	Abundance Rating 2019
Bluegill	211	62	211 (348 ≥ 3 in)	62 (131 ≥ 3 in)	41st	Moderate	≥ 7.0	90	37	90th	High
Largemouth bass	234	197	102 (192 ≥ 8 in)	88 (187 ≥ 8 in)	95th	High	≥14.0	2	9	84th	Moderate-High
Northern pike	17	12	7.4	5.2	85th	Moderate-High	≥ 26.0	0.9	0	58th	Moderate
Black Crappie	19	2	19	2	21st	Low	≥ 8.0	13	2	41st	Moderate
Yellow perch	4	10	4	10	53rd	Moderate	≥ 8.0	0	0	-	-
Pumpkinseed	9	3	9	3	30th	Low	≥ 7.0	4	3	81st	Moderate-High
Rock bass	5	5	5	4	-	-	≥ 8.0	1	2	-	-

12, 1999, DNR staff electrofished again to assess the lakes' potential for natural reproduction of walleye and muskellunge (*Esox masquinongy*). DNR captured abundant bluegill, yellow perch, largemouth bass, and brown bullhead and some northern pike, but not walleye or muskellunge.

A more recent 2012 electrofishing survey found a similar assemblage of species, including one banded killifish. Bluegill and largemouth bass again dominated the catch (Table 26). Spring fyke netting was also conducted on Pleasant Lake on March 12, 2012 and found almost equal numbers of black crappie and bluegill as well as 24 northern pike, the target of spring fyke netting.

Table 27. Fish stocking on Pleasant Lake, from DNR permit records.

Year	Species
1972	Northern pike
1974	Northern pike
1975	Northern pike
1980	Northern pike
1981	Northern pike
1982	Northern pike
1983	Northern pike
1984	Northern pike
1985	Northern pike
1986	Northern pike
1987	Northern pike
1991	Northern pike
1992	Northern pike
2010	Walleye

Field crews conducted shoreline seining on August 6th, 2013 to assess the strength of the spring hatch and small, nearshore-dwelling species. Iowa darter and bluntnose minnow, two species not encountered during the previous year's electrofishing, appeared in the catch, as well as abundant juvenile and young-of-year bluegill and largemouth bass. The field crew found banded killifish adults at 9 of 11 sites around Pleasant Lake and young-of-year at 4 sites. The discovery of banded killifish young-of-year at four nearshore areas in August 2013 suggests that they successfully spawned at multiple locations earlier that spring. According to historical observations and air photos, Turtle Bay had only recently reconnected to the lake after a long period of disconnection going back to at least summer 2008, indicating that the killifish population persisted even while this habitat was inaccessible for five years.

Regular stocking of northern pike occurred during the 1980s and early 1990s but has since ceased. A small number of walleye fingerlings were stocked in 2010 (Table 27).

Current Fish Community

Fisheries staff conducted the most recent electrofishing survey on May 28, 2019 and found 298 fish among 11 species. Bluegill and largemouth bass were the most abundant, with moderate to low densities of northern pike, black crappie, yellow perch, and pumpkinseed (Table 26). The crew also counted a handful of rock bass, brown bullhead and yellow bullhead, one bluntnose minnow and one white sucker. The size distribution of largemouth bass was heavily skewed towards larger individuals (> 12 inches), a change from the previous electrofishing survey in 2012 when larger individuals were less common (Table 28, Figure 46). This is reflected in the proportional stock density (PSD) for largemouth bass, which at 92% is higher than desired. Largemouth bass growth rates were below average, taking 7.2 years to reach 14 inches. Bluegill catch declined from 211 individuals in 2012 to 62 individuals in 2019 (Table 26, Figure 47), while PSD increased from 82% to 97% (Table 28). Bluegill growth rates improved from the 2012 survey; in 2012, bluegill had reached 6 inches over five summers of growth, whereas in 2019 they had reached this size in four summers.

Although electrofishing is not the preferred technique for assessing northern pike populations, during this survey the field crew found 5.2 per mile, placing Pleasant Lake in the 58th percentile for northern pike density among lakes in Wisconsin (Table 26). Lengths ranged from 17.4 – 23.8 inches, below the legal harvest size of 26 inches (Table 28).

All species found during the 2012 fish surveys were also encountered in 2019, except warmouth. Stocking was not recorded during this time, indicating that these species were able to reproduce naturally in Pleasant Lake. Warmouth may still exist in Pleasant Lake at lower densities.

A field crew conducted shoreline seining on August 28th, 2018 (Table 29, Figure 48). As with the electrofishing survey, bluegill and largemouth bass were plentiful. The shoreline seining also revealed the presence of several non-game species not encountered during the electrofishing survey: Iowa darter, mimic shiner, and banded killifish. Young-of-year bluegill, largemouth bass, pumpkinseed, and yellow perch were all present. Compared to the shoreline seining conducted at the same sites on August 6, 2013, field crews found young-of-year yellow perch, young-of-year largemouth bass and adult bluntnose minnow at much higher densities in 2019, but the densities of other species declined. Crews counted 183.2 adult banded killifish and 27.8 young-of-year per nearshore acre in 2013 and only 4.8 adults and 0 young-of-year per acre in 2019. Densities of adult and young-of-year bluegill, young-of-year bluntnose minnow, and adult bass and pumpkinseed also declined. In total, 14 species of fishes were found on Pleasant Lake in 2019.

Table 28. Size structure of fish caught during spring electrofishing on Pleasant Lake, 2012 and 2019.

Species	Average Length (inches)	Length Range (inches)	Stock and Quality Size (inches)	Stock No	Quality No	PSD 2012	PSD 2019	Percentile Rank 2019	Size Rating 2019
Bluegill	8.1	2.8 - 9.0	3.0 & 6.0	61	59	82%	97%	99th	High
Largemouth bass	13.0	4.7 - 15.3	8.0 & 12.0	193	177	30%	92%	94th	High
Northern pike	19.5	17.4 - 23.8	14.0 & 21.0	12	1	-	-	-	-
Black crappie	10	9.5 - 10.4	5.0 & 8.0	2	2	-	-	-	-
Yellow perch	3.6	2.8 - 6.1	5.0 & 8.0	1	0	-	-	-	-
Pumpkinseed	7.9	7.4 - 8.4	3.0 & 6.0	3	3	-	-	-	-
Rock bass	7.5	4.4 - 9.8	4.0 & 7.0	5	3	-	-	-	-

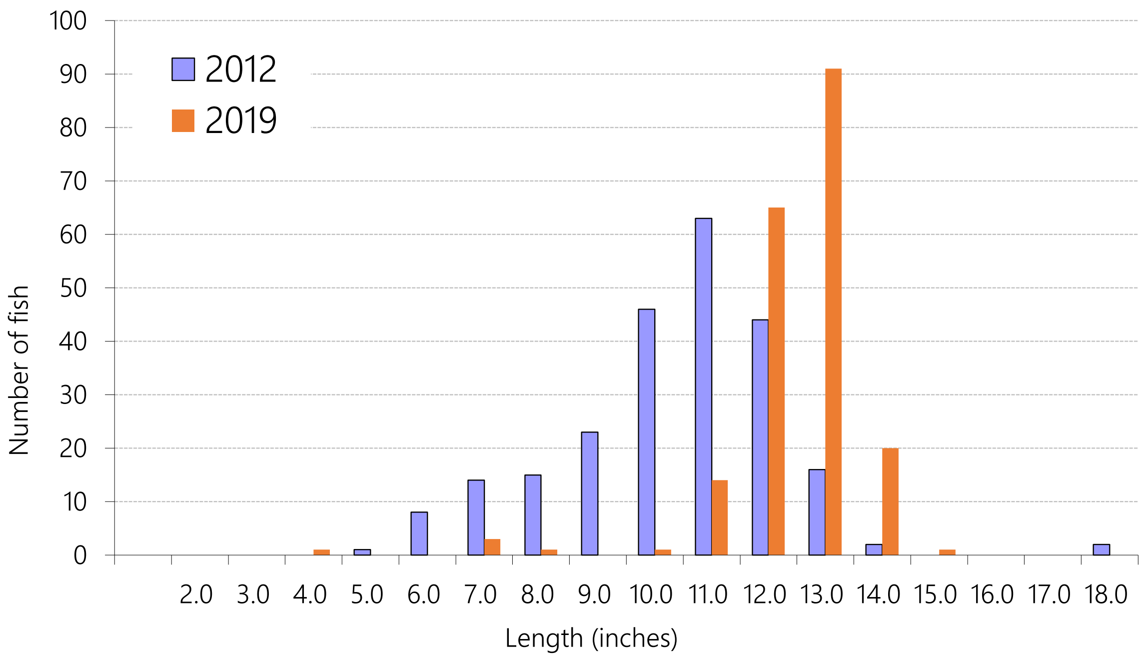

Figure 46. Largemouth bass at Pleasant Lake, 2012 and 2019. Lengths of largemouth bass caught during spring electrofishing on Pleasant Lake, 2012 and 2019.

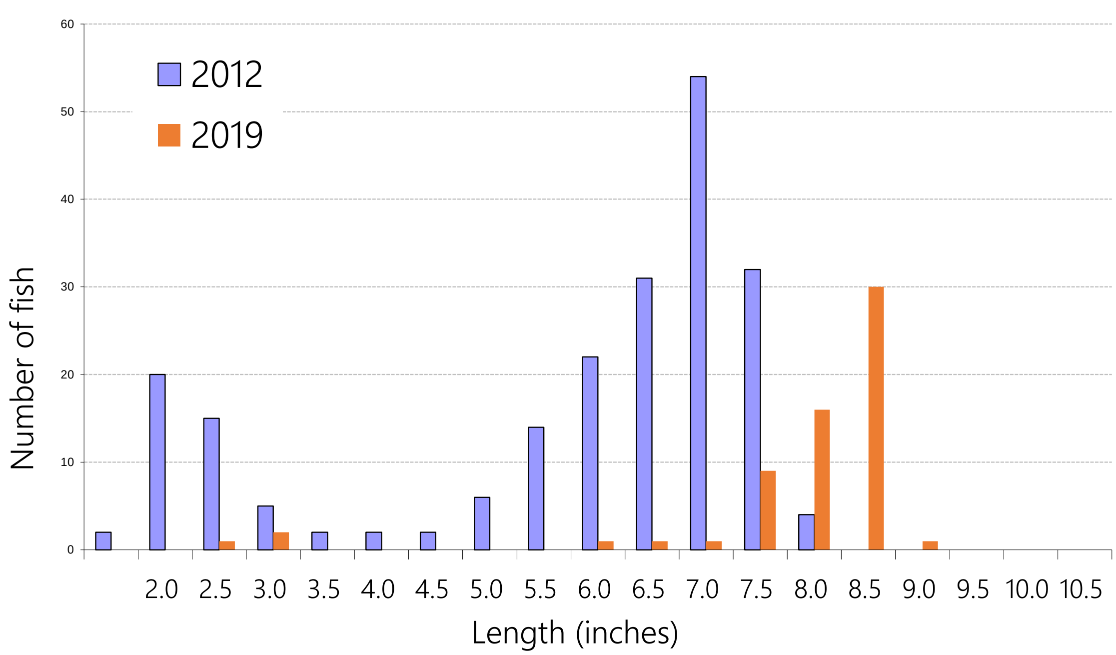

Figure 47. Bluegill at Pleasant Lake, 2012 and 2019. Lengths of bluegill caught during spring electrofishing on Pleasant Lake, 2012 and 2019.

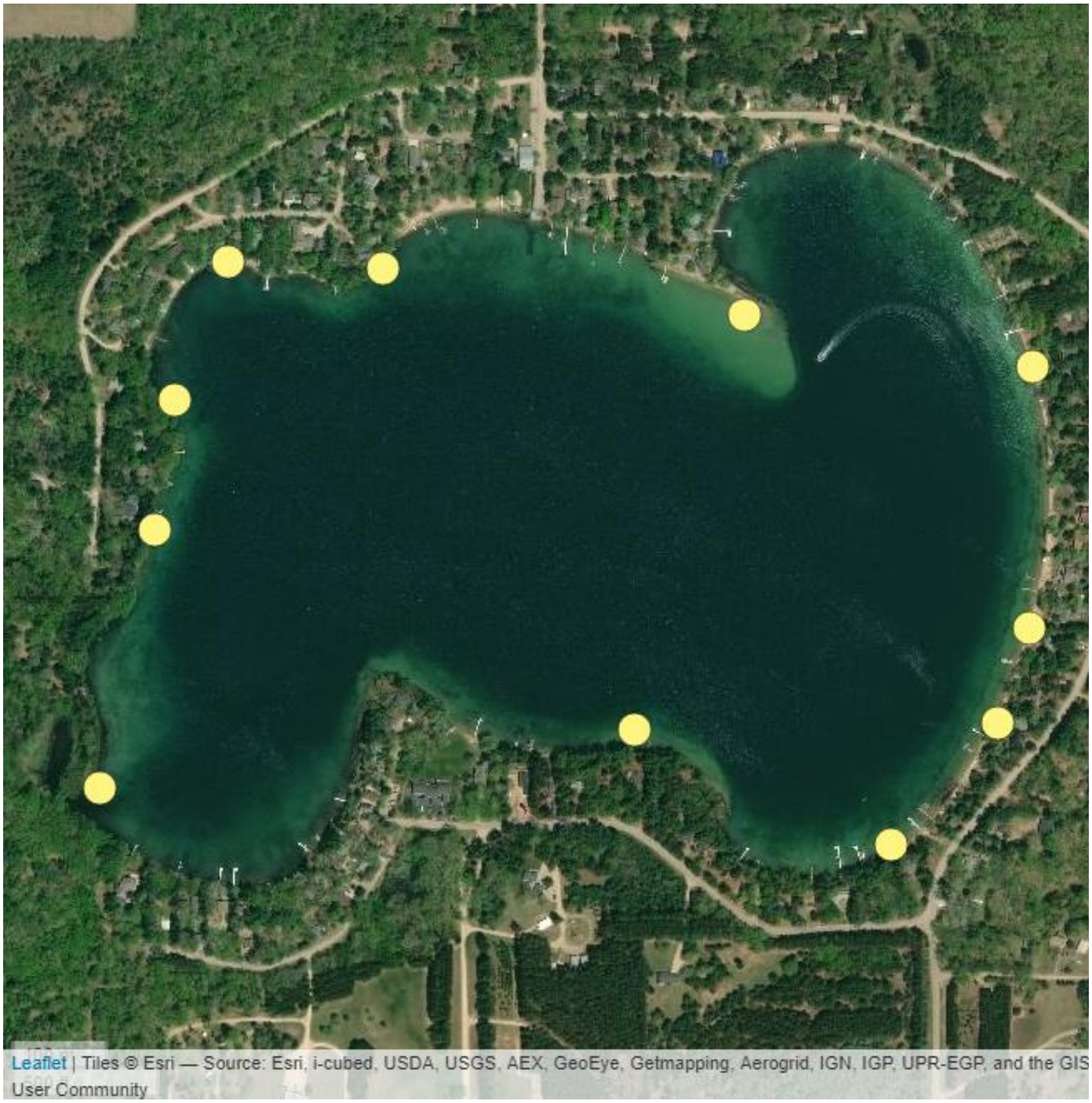

Figure 48. Seining locations on Pleasant Lake, 2013 and 2018.

Expectations for Fish Community

The size structure and density of the bluegill population is consistent with high predation pressure from largemouth bass and insufficient nearshore habitat. Currently, the proportion of stock size bass (> 8 inches) is higher than ideal, while the bluegill population is low overall. Removing the current bass size limit of 14 inches could address these problems by allowing anglers to remove more bass, reducing predation pressure upon the bluegill population. Ideally, the CPUE of stock size bass should fall to 22 – 66 per hour (currently 88), while the CPUE of bass greater than 14 inches should increase slightly to 10 – 15 per hour (currently 9). Bluegill greater than three inches should be found at densities of 300-400 per hour (currently 131), and the proportion of quality to stock bluegill should fall to 40-50% (currently 97%) (Bartz and Bunde, 2020b). Despite these concerns, Pleasant Lake currently sustains moderate or high densities of several popular species among anglers, as well as stable populations of several non-game species and minnows, including one species of special concern, the banded killifish.

Of the three study lakes, Pleasant Lake has the most developed shoreline. We surveyed the shoreline of Pleasant Lake for downed trees, logs, and other woody debris on October 4, 2018 and found very low abundances of this type of habitat. Anthropogenic alteration of nearshore habitat, such as removing submerged coarse woody habitat and replacing natural shoreline vegetation with lawns, can have adverse effects on fish communities (Jennings et al., 1999; Sass et al., 2006). Protecting nearshore vegetation and coarse woody habitat will continue to be important for the future of the Pleasant Lake fishery.

Table 29. Densities of fishes caught during seining of 10 nearshore sites on Pleasant Lake, 2013 and 2018. We calculated density for each seine haul (n = 13) as the number of individuals in the seine net divided by the area of the haul and expressed here as mean (minimum – maximum) density.

Species - age	Number / nearshore acre 2013	Number / nearshore acre 2018
Banded killifish - adult	183.2 (0 – 702)	4.8 (0 – 45)
Banded killifish - YOY	27.8 (0 – 180)	-
Bluegill - adult	111.2 (0 – 504)	6.4 (0 – 225)
Bluegill - YOY	137.4 (0 – 702)	91.9 (0 – 465)
Bluntnose minnow - adult	143.9 (0 – 1008)	211.2 (0 – 3734)
Bluntnose minnow - YOY	2877.4 (0 – 9753)	-
Iowa darter	1.6 (0 – 18)	3.2 (0 – 112)
Largemouth bass - adult	39.3 (0 – 234)	1.6 (0 – 56)
Largemouth bass - YOY	361.5 (0 – 1278)	783.6 (0 – 4993)
Mimic shiner	-	9.7 (0 – 337)
Pumpkinseed - adult	8.2 (0 – 54)	1.6 (0 – 56)
Pumpkinseed - YOY	-	1.6 (0 – 56)
Rock bass - adult	1.6 (0 – 18)	1.6 (0 – 45)
Rock bass - YOY	8.2 (0 – 72)	-
Yellow perch - YOY	24.5 (0 – 144)	93.5 (0 – 2418)
Unidentified Centrarchid	8.2 (0 – 36)	-

Pleasant Lake's aquatic plant community supports the fish community by providing shelter and supporting prey such as invertebrates and small fish. Aside from the low-growing *Chara* spp. that dominate the deeper portions of the lake, Pleasant Lake plants have a variety of architectures, from the long leaves of water celery (*Vallisneria americana)* to more densely-growing variable-leaved pondweed (*Potamogeton gramineus*). Bluegill, largemouth bass, black crappie, northern pike, and yellow perch are all dependent on submerged aquatic vegetation for the majority of their life cycles (Inskip, 1982; Krieger et al., 1983; Havens et al., 2005; Johnson et al., 2007). Adult bass and pike use the edge of submerged macrophyte beds or CWH to ambush smaller fishes that stray from cover (Sass et al., 2006). Bass forage more efficiently in intermediate densities of vegetation and less efficiently in monocultures of canopy-forming invasives such as Eurasian water-milfoil (Valley and Bremigan, 2002).

Shallow macroalgae could provide good habitat for non-game species in Pleasant Lake. Valley et al. (2010) found that banded killifish were associated with beds of *Chara* and macrophyte biovolumes above 20%, while Morgan and Godin (1985) observed schools in shallow water. Other authors support the affinity for *Chara* but suggest that banded killifish can also use rock or mud in shallow water (Pratt and Smokoworski, 2003). In any case, *Chara aspera* and *Chara contraria* also appear across shallower areas of Pleasant Lake.

Long Lake

Historical Reports

Long Lake's shallow average depth makes it prone to fish kills. During the late 1970s, consecutive winterkills provided some of the impetus to form the Long Lake District (Cason and Chikowski, 2004), which has since actively engaged in lake protection and restoration. They installed aerators in 1983-84 to prevent winter kills.

During spring 1987, DNR staff set fyke nets on Long Lake to evaluate the effectiveness of stocking activities from 1984-86 (Table 30). The survey found variable survival of northern pike fingerlings, with an estimated 18.4% surviving from the 1985 class and 44.8% surviving from the 1984 class. The biologist recommended stocking northern pike in alternate years during the fall, and stocking perch and bass in the next few years (Primising, 1987). Other fish species sampled in the fyke nets included walleye, perch, bluegill, bullhead (*Ameiurus spp.*), rock bass, and crappie (*Pomoxis spp.*). Walleye, perch, and crappie were stocked with little or no

Table 30. Fish stocking on Long Lake, from DNR permit records.

Year	Species
1937	Yellow perch
1940	Yellow perch, Smallmouth bass, Largemouth bass
1941	Yellow perch, Northern pike, Largemouth bass
1942	Largemouth bass, Bluegill
1943	Walleye, Smallmouth bass, Largemouth bass
1946	Largemouth bass
1952	Northern pike, Walleye
1956	Bluegill, Largemouth bass, Walleye
1957	Yellow perch, Walleye, Suckers, Northern pike, Crappie, Bullhead, Bluegill
1960	Yellow perch, Walleye, Northern pike
1961	Yellow perch, Walleye, Largemouth bass
1962	Largemouth bass, Bluegill, Northern pike
1963	Yellow perch
1974	Bluegill, Largemouth bass, Northern pike
1977	Yellow perch, Northern pike, Bluegill
1978	Yellow perch, Largemouth bass, Northern pike, Bluegill
1979	Largemouth bass
1984	Northern pike, Largemouth bass, Yellow perch, Bluegill
1985	Northern pike, Yellow perch, Largemouth bass
1986	Walleye, Largemouth bass, Northern pike
1987	Largemouth bass, Northern pike
1988	Largemouth bass
1989	Largemouth bass, Walleye, Muskellunge
1990	Muskellunge
1998	Largemouth bass
2000	Largemouth bass
2003	Yellow perch
2004	Largemouth bass
2019	Yellow perch, Golden shiner, Black crappie

evidence of natural reproduction. Bluegills were common and naturally reproducing but were small and in poor condition. Black bullhead (*Ameiurus melas*), tolerant of low oxygen conditions, was the most abundant fish species present. Fyke nets are not effective for sampling largemouth bass, so no conclusions were made about this fish species.

The next available survey data comes from an electrofishing effort on October 9th of 1997, which was motivated by Long Lake Association's concerns over summer fish-kills. Greater than 95% of the total catch was composed of largemouth bass (24%) and bluegill (72%). While bluegills were abundant, biologists concluded that the population had poor size structure and was slow growing, likely due to the ubiquity of submerged vegetation, which would inhibit predation by largemouth bass and increase intraspecific competition among bluegills for limited food. Several age classes of largemouth bass were identified; the fact that neither largemouth bass nor bluegill had been stocked for at least nine years indicates that both species successfully reproduced in Long Lake. For reference, three historical water levels observations occurred between 1992 and 1995 and indicated maximum water depths of 4.6 to 7.7 feet. Other species encountered in low numbers during this survey included northern pike, walleye, pumpkinseed, black crappie, yellow perch, white bass, and white sucker. Some of these species might have been present from undocumented stocking efforts. Fisheries biologists suggested encouraging catch and release of bass to maintain a high-quality bass fishery and help control the overabundant bluegill (Niebur, 1998).

No further records of the Long Lake fish community exist until the time of the current study, though another fish kill was noted in 2006.

Current Fish Community

Fisheries biologists conducted the most recent electrofishing survey on May 14, 2019 and found 142 bluegill and 138 largemouth bass (Table 31). The size structure of the bluegill population displays several year classes (2.5 - 3.0 and 4.5-5.5 inches, Figure 49). Most of the largemouth bass were 11 inches long and probably two years old (Figure 50). We do not know whether these bluegill and bass are the result of natural reproduction or undocumented stocking. Relatively little opportunity for recreational fishing currently exists in Long Lake at this time, as none of the bass had reached legal size (14 inches), and only 29% of bluegill were 6 inches or larger (Table 32). We seined at nine stations around Long Lake on August 28, 2018 (Figure 51). The densities of juvenile bluegill and largemouth bass were 12,000 and 830 per acre, respectively, and we also encountered a handful of adults of each species (Table 33). The large numbers of young-of-year suggest that adequate spawning habitat currently exists in Long Lake, but these high densities of bluegill also point to the same issues of ineffective predation and stunting as highlighted by historical reports. We did not find any other fish species.

Table 31. Abundance of fish caught during spring electrofishing on Long Lake, 1997 and 2019.

Species	Total 1997	Total 2019	No. per mile (No. per hour) 1997	No. per mile (No. per hour) 2019	Percentile Rank 2019	Overall Abundance Rating 2019
Bluegill	217	142	145 (288 ≥ 3 in)	79 (131 ≥ 3 in)	48th	Moderate
Largemouth bass	16	138	11 (25 ≥ 8 in)	77 (159 ≥ 8 in)	94th	High

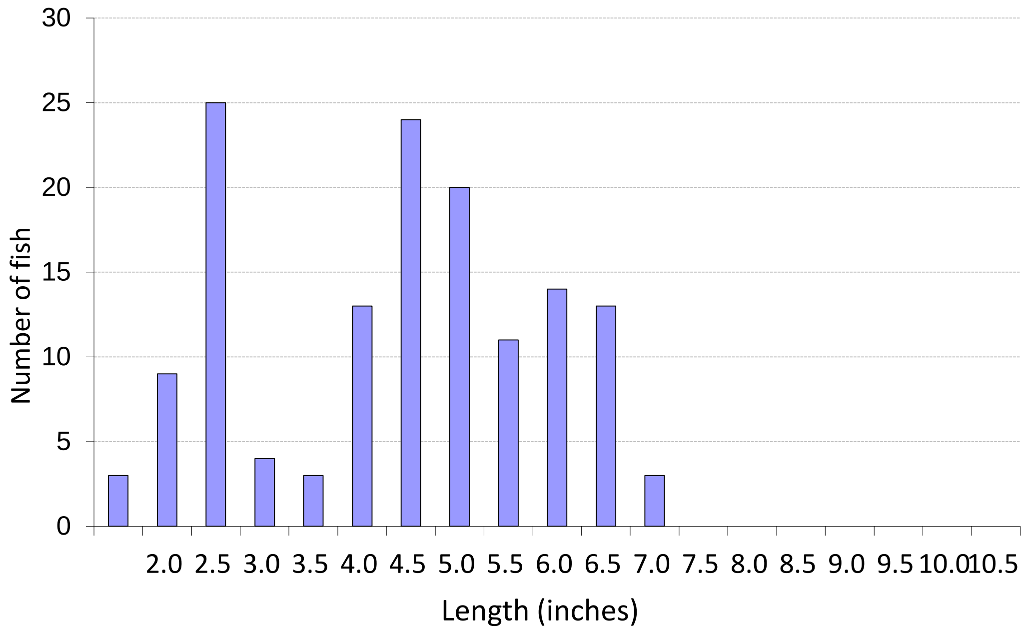

Figure 49. Bluegill at Long Lake, 2019. Lengths of bluegill caught during spring electrofishing on Long Lake, 2019.

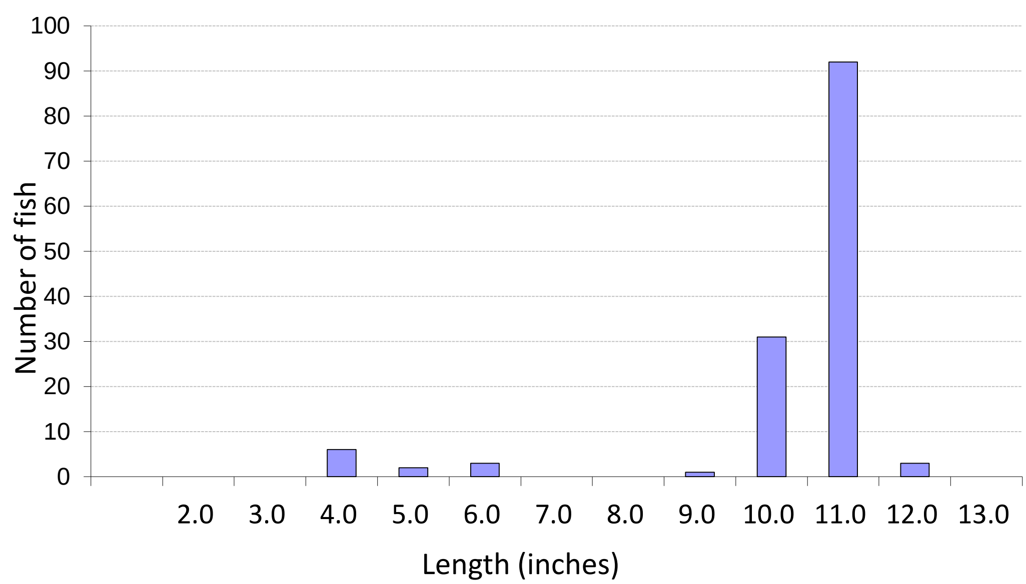

Figure 50. Largemouth bass at Long Lake, 2019. Lengths of largemouth bass caught during spring electrofishing on Long Lake, 2019

Table 33. Sizes of fish caught during electrofishing on Long Lake, 2019.

Species	Average Length 1997	Average Length 2019	Length Range (in) 1997	Length Range (in) 2019	Stock and Quality Size 1997	Stock and Quality Size 2019	Stock No. 1997	Stock No. 2019	PSD 1997	PSD 2019	Percentile Rank 2019	Size Rating 2019
Bluegill	5	4.6	2.6 – 7.0	2.0 - 7.2	2.6 and 7.0	3.0 and 6.0	215	105	30%	29%	44th	Moderate
Largemouth bass	10.7	10.8	5.2 – 19.5	4.0 - 12.8	8.0 and 12.0	8.0 and 12.0	-	127	-	2%	1%	NA

Table 32. Densities of fish captured during shoreline seining on Long Lake, 2018. We calculated density for each seine haul (n = 10) as the number of individuals in the seine net divided by the area of the haul and expressed here as mean (minimum – maximum) density.

Species – age	Number per nearshore acre
Bluegill - adult	15.6 (0 – 90)
Bluegill - YOY	12,000.4 (0 – 33,438)
Largemouth bass - adult	31.2 (0 – 135)
Largemouth bass - YOY	829 (0 – 1856)

Figure 51. Seining locations on Long Lake, 2018.

Expectations for Fish Community

The aerators on Long Lake should be kept in continuous operation to keep the water well oxygenated, especially as vegetation flooded from recent high water levels decays. To establish a successful largemouth bass fishery (5-10 bass per mile at >14.0 inches long and legal-sized fish comprising 40-50% of the population), largemouth bass stocking should cease and the population should be reassessed in 2027 to determine the strength of natural reproduction and growth rates (Bartz and Bunde, 2020a). Similarly, increasing the proportion of quality-size (> 6 inches) bluegill to at least 40% would improve the fishery. The abundance of stock size bluegill should ideally reach 300-400 per hour. Periodic stocking of bluegill, yellow perch, and black crappie should be allowed (Bartz and Bunde, 2020a). Protecting important habitat will also continue to be important for successful management of the fishery. Trees and shrubs colonized the dry lakebed during low water years and died with the recent high water levels. The flooded and dead trees provide good cover and should be left in the lake wherever possible. Currently, the Long Lake fishery is not mature enough to provide good recreational opportunities for most anglers. If water levels drop and another kill occurs, the fishery will need several years to recover.

Plainfield Lake

Historical Reports

Relatively little information exists on Plainfield Lake's fish community prior to the present day. In fall 1960, the DNR electrofished to evaluate the success of stocking walleye fry the previous spring. The survey found no fish of any species despite shocking nearly the entire lake. The maximum water depth at the time of the survey was 6 feet deep. During summer of 1959, the maximum depth of Plainfield Lake was noted to be 2.5 feet, shallow enough to cause widespread hypoxia the following winter (Primising, 1961). Another winterkill was reported during the winter of 1961 – 1962, with 14- to 16-inch long northern pike and up to 10-inch long perch dead along shore. Nevertheless, 400 adult bluegill, 25,000 northern pike fry, and 5,000 largemouth bass fingerlings were stocked in 1962 (Table 34). The bluegill and largemouth bass appeared to grow and survive well in Plainfield Lake, as DNR captured many during an electrofishing survey on August 8, 1962. DNR caught only three northern pike, but the individuals exhibited rapid growth. DNR also encountered pumpkinseed during the survey even though DNR had not stocked them. The biologist at the time noted that Plainfield Lake will likely continue to experience winterkills (Primising, 1962). Stocking of popular panfish and game species continued in Plainfield Lake through the 1970s.

Current Fish Community

We did not observe fish during our routine monitoring activities in 2018 despite abundant aquatic vegetation and habitat. We observed large-bodied *Odonata* larvae, vulnerable to fish predation, swimming through the water, further suggesting that Plainfield Lake had very low densities of fish or none at all. Regular monitoring at Plainfield Lake's deepest point during 2018 and 2019 found instances of hypoxia (less than 4 mg/L dissolved oxygen) in the entire water column during late summer and late winter (Figure 23). Shoreline seining on August 29th, 2018 yielded abundant aquatic macroinvertebrates but no fish.

Table 34. Fish stocking on Plainfield Lake, from DNR permit records.

Year	Species
1962	Bluegill, Northern pike, Largemouth bass
1973	Bluegill, Largemouth bass
1976	Northern pike, Largemouth bass
1977	Bluegill, Northern pike, Yellow perch
1979	Northern pike

When a second seining survey was conducted on September 10, 2019, staff found bluegill and pumpkinseed (Table 35, Figure 52). Bluegill young-of-year, hatched a few months earlier, made up the majority of the catch, accompanied by a handful of adult bluegill and pumpkinseed. Some of the adult bluegill were 3 inches in length and likely hatched the previous spring. It is likely that a relatively small number of adults were present in Plainfield in 2018, evaded the seining conducted that year, and produced a year class in 2019. Although we did not estimate ages from scales or other structures, these fish could possibly reach a length of 3 inches in productive habitat with little competition.

Table 35. Densities of fish caught during seining of Plainfield Lake, 2019.

Species – age	Number per nearshore acre
Bluegill - adult	82.0 (0 – 298)
Bluegill - YOY	6084.5 (0 – 10,717)
Pumpkinseed - adult	95.7 (0 – 270)

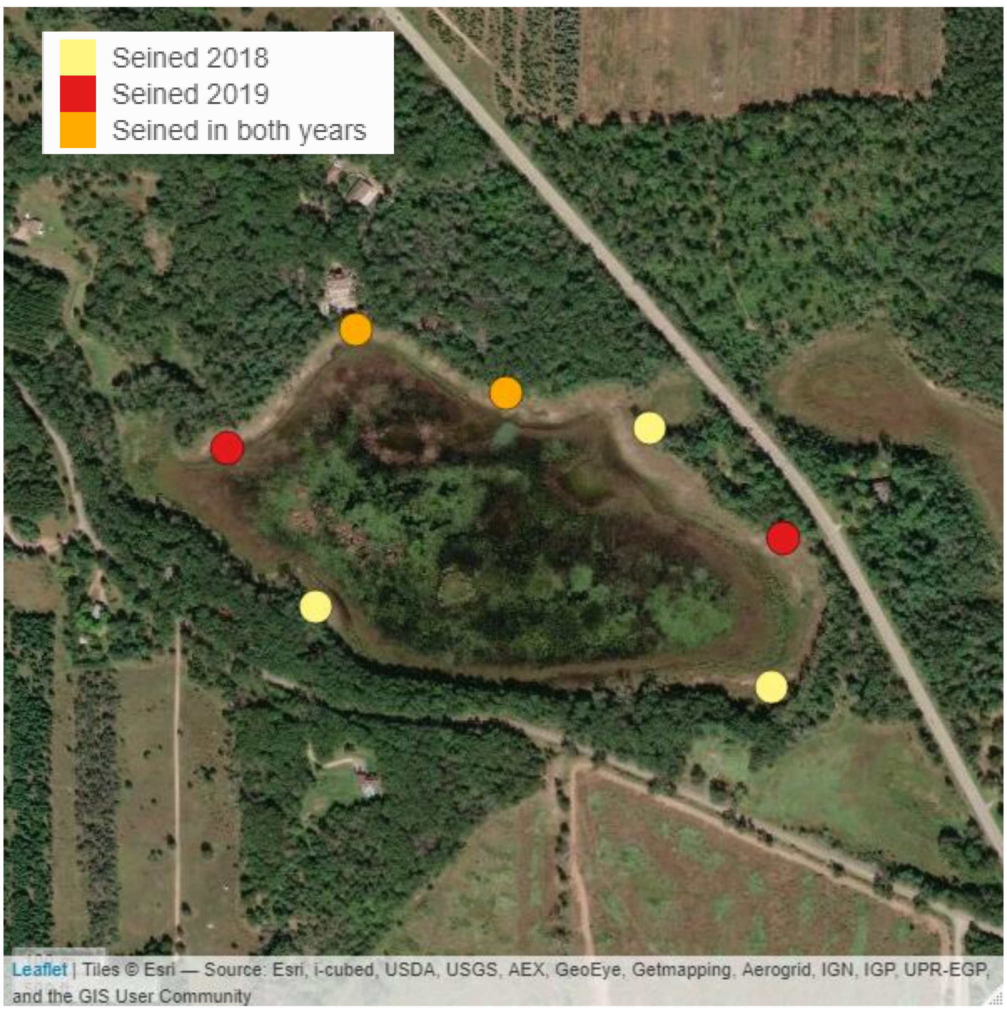

Figure 52. Seining locations on Plainfield Lake, 2018 and 2019.

We expect Plainfield Lake to have intermittent fish communities. The shallow average depths, large fluctuations in lake levels, high biomass of aquatic plants, and severe winters combine to place Plainfield Lake at high risk for hypoxia. We estimate that at the onset of a winter kill reported in 1962, lake levels were only about 2 inches below the 1981 – 2018 median (1097.3 ft above sea level). Plainfield Lake has remained below this level on several occasions since 1981. No other fish kills have been reported on Plainfield Lake, but this is not surprising considering that recreational fishing on Plainfield Lake is limited by the lack of a boat ramp, and fish must recolonize the lake after one winterkill before another can be observed and reported. Our DO measurements during 2018 and 2019 suggest that the fish community could be stressed by hypoxia in high-water years following low water.

In the near term, due to the absence of piscivores, bluegill growth rates will slow as the population expands and competition intensifies. When the fish population collapses again, Plainfield Lake will still provide good habitat for aquatic macroinvertebrates, waterfowl, and other wetland taxa.

Human Use

Pleasant Lake

Pleasant Lake Property Owners

According to the 2019 Wisconsin tax parcel database, there are 207 residential parcels with access to Pleasant Lake. Residents of 136 of these 207 parcels (69%) responded to our survey either online or by mail.

More than half (56%) of survey respondents have owned their Pleasant Lake property for more than 20 years, and a large majority (74%) have owned their property for more than 10 years. Only 19% of respondents consider their Pleasant Lake property to be their primary residence, and most of those respondents also own a secondary property. These primary residents spend an average of 10.9 months of the year at Pleasant Lake. The 81% of survey respondents whose Pleasant Lake residence is a second home own primary residences across southeast Wisconsin and northern Illinois (Figure 53), except for one respondent whose primary residence is in Washington State and another in Florida.

Respondents who consider Pleasant Lake to be their secondary residence vary widely in the amount of time they spend there. These property owners are most likely to visit from May to September, and 95% visit regularly during July. Still, almost one third (31%) indicated they regularly visit during December and January (Figure 54). Secondary residents most commonly make weekend or weeklong visits to their Pleasant Lake property; only 15% regularly stay for an entire season. On average, these residents bring 3.6 other friends or family members with them, ranging from 0 to 10. Altogether, secondary residents spend a mean of 78 days per year at Pleasant Lake, though there is substantial variation among respondents (SD = 55 days).

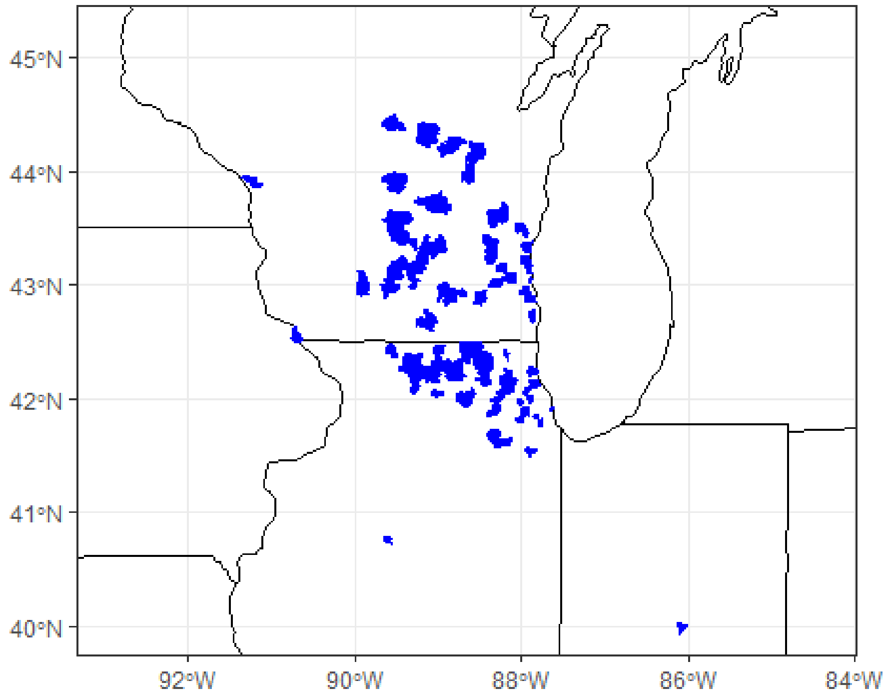

Figure 53. Pleasant Lake, secondary residence locations. Zip codes (blue) of primary residences for Pleasant Lake property owners who consider their lake house to be their secondary residence. Not shown: one zip code in Washington State and one in Florida.

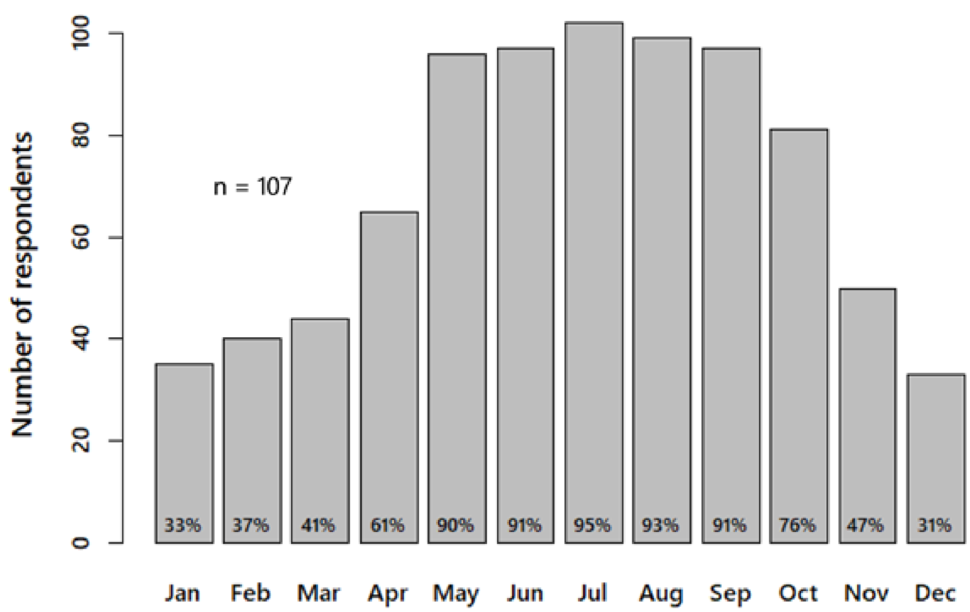

Figure 54. Pleasant Lake, secondary residence timing. Number and percentage of secondary Pleasant Lake residents (107 in total) who regularly visit Pleasant Lake by month.

Access to Pleasant Lake

Pleasant Lake property owners access and use the lake in a variety of ways. Property owners we surveyed reported a wide range in the amount of shoreline included in their parcel. The average respondent's property has 93 feet of shoreline, but answers ranged from 9 to 700 feet. For 80% of respondents, their shoreline also includes a beach for swimming and wading during average water level conditions. Sixteen percent of respondents have a boathouse, 92% have at least one watercraft, with a mean of 2.47 watercraft per property. Canoes and speedboats are the two most popular types of watercraft, owned by 65% and 49%, respectively, of those who own a boat. Other watercraft that Pleasant Lake respondents own include pontoon boats, rowboats, fishing boats, jet skis, sailboats, paddleboats, and stand-up paddleboards, in order of decreasing popularity. The most common type of dock among our respondents was a rolling dock, owned by 43% of respondents. Lift docks and pipe docks provide lake access for 17% and 18% of property owners, and only one respondent owns a floating dock. The average respondents' dock is 39 feet long, with a minimum of 12 feet and maximum of 90 feet. Twenty-one percent of Pleasant Lake respondents do not own a dock. In addition, 33% of respondents own a swimming raft.

Pleasant Lake Recreation

We asked Pleasant Lake property owners how often they take advantage of common outdoor recreation opportunities on the lake, and how important those activities are to their enjoyment of their lake property (Figure 55). Swimming or wading was the most popular activity; 71% of respondents said they swam or waded often or very often. Large proportions of respondents also often or very often enjoy motorized (61%) and non-motorized (47%) boating. Respondents also frequently engage in bird or wildlife watching (50% selecting "often" or "very often"), while fishing for anything, panfish, and gamefish are each slightly less popular (37%, 34%, and 29%). Twice as many respondents reported waterskiing often or very often as did jet skiing (26% and 14%).

In general, ordering the activities by frequency of participation produced the same results as ordering activities by degree of importance to our respondents' enjoyment of the lake (Figure 55). Across all lake recreation activities included in the survey, the proportion of respondents reporting an activity was "Very" or "Extremely important" was greater than the proportion reporting they participated in this activity "Often" or "Very often", except for bird and wildlife watching, for which the proportions were essentially the same. Thus, some occasional or infrequent participants still view a given activity as important to their enjoyment of Pleasant Lake. This gap was greatest across all types of fishing, for example 34% of respondents frequently (often or very often) panfish, but 57% of respondents consider panfishing to be important or very important to their enjoyment of their lake property.

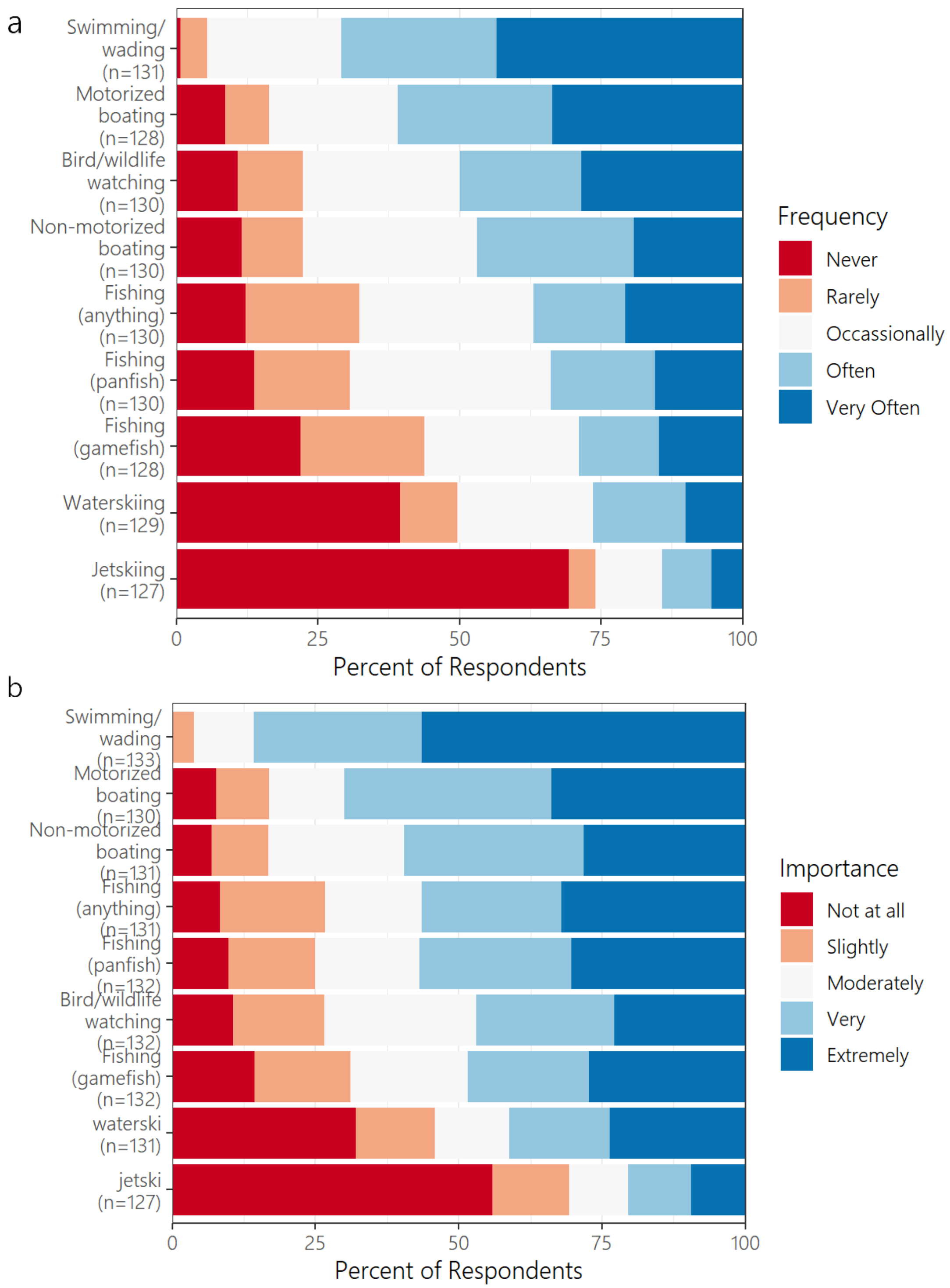

Figure 55. Pleasant Lake activity frequency and importance. Pleasant Lake respondents' frequency of participation in (a) and importance of (b) common lake recreation activities.

Pleasant Lake Levels

Pleasant Lake property owners who participated in our survey are aware of the natural fluctuations in lake level (i.e. variation apart from the influences of human activity). A plurality of respondents (43%) believe that lake levels naturally varies up to three feet, selecting from among “<1 foot”, “up to 3 feet”, “up to 5 feet”, “up to 10 feet”, “> 10 feet” and “not at all”. The next most popular response was “up to 5 feet” (30%), with many fewer respondents believing lake levels naturally varied by up to 10 feet (8%) or more than 10 feet (6%). Eight percent of property owners we surveyed believe that lake levels vary by less than one foot, and 5% believe they do not vary at all. For comparison, we found that Pleasant Lake levels have varied by at least 5.5 ft; the maximum elevation ever recorded was 983.75 ft asl in 1994 and the minimum (excluding air photos, see p. 35) was 978.27 ft asl in 2007. According to the no-irrigated-agriculture scenario from the groundwater flow model described below, lake levels should remain within a range of 2.9 feet 80% of the time (Table 39). At the time this survey was distributed to residents in the summer of 2020, Pleasant Lake had steadily risen more than 2 feet since the summer of 2018.

Most respondents stated that lake levels did not limit or only slightly limited their recreational activities (Figure 56). There were some differences between recreational activities (ANOVA, $F=12.2$, $p<0.001$) and between low and high lake levels (paired t-test, $T=6.97$, $df=416$, $p< 0.001$). Activities that were most limited by low and high lake levels were waterskiing and motorboating and the least limited activity was bird and wildlife watching. Recreational activities were more impacted at low lake levels than high, with on average 16.5% of respondents listing recreational activities severely or completely limited at low levels and 7% of respondents listing the same at high lake levels. The mean of the response across respondents and all recreational activities was 1.74 at low lake levels and 1.3 at high lake levels. One signifies “no limitation” and two signifies “slight limitation”, so respondents leaned more toward slight limitation at low lake levels and more toward no limitation at high lake levels.

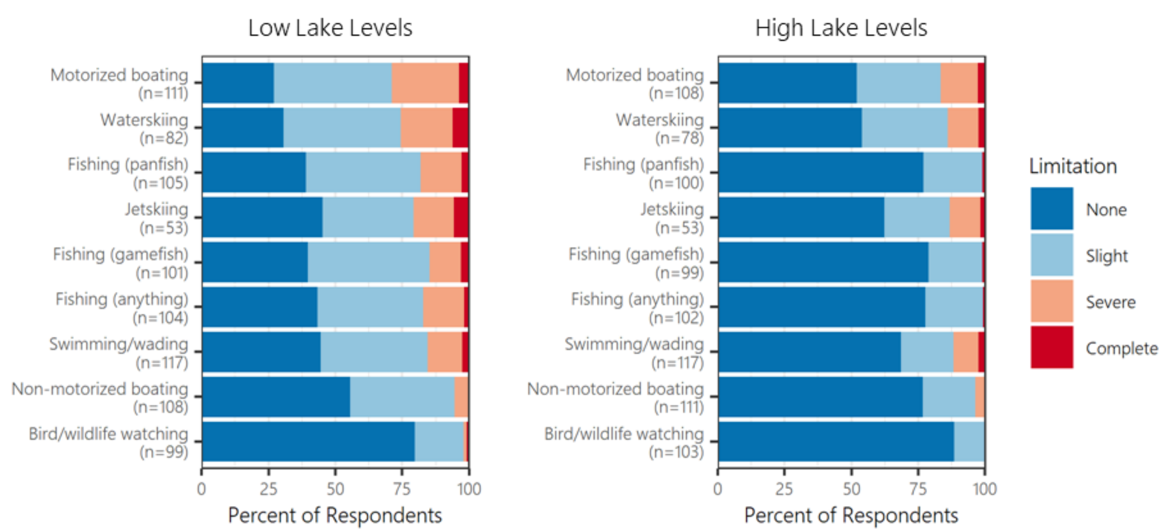

Figure 56. Pleasant Lake recreation limitations. The percent of respondents from Pleasant Lake who selected the degree to which their recreational activities are limited by low versus high lake levels. The number of people who responded to each recreational activity is listed in parentheses.

Most respondents agreed or strongly agreed that low lake levels decrease a variety of Pleasant Lake's intrinsic values, but high lake levels do not (Figure 57; paired t-test, T=16.98, df=561, p<0.001). The values that were impacted by low lake levels according to the most respondents were water quality, property value, and aesthetic appeal with 68.3 to 72.4% agreeing or strongly agreeing that low lake levels decrease their value (ANOVA testing differences between all values, F=2.91, P=0.008). Slightly more than half (56.5 – 57.4%) of respondents agreed or strongly agreed that low lake levels decrease fish populations, the enjoyment of their property, and lake safety. Only 41.2% agreed or strongly agreed that low lake levels decreased bird and wildlife watching opportunities. Most respondents disagreed or strongly disagreed that high lake levels decrease the value of Pleasant Lake, but there were some differences between values in respondents' level of concern at high lake levels (ANOVA, F=6.59, p<0.001). The values most impacted by high lake levels were enjoyment of their property, lake safety, property value, and aesthetic appeal (29.2 – 39.5% agreed or strongly agreed that high lake levels decreased these values). Fourteen percent agreed or strongly agreed that high lake levels decreased water quality, and only 4.5 and 5.2% agreed or strongly agreed that high lake levels decreased fish and wildlife populations, respectively.

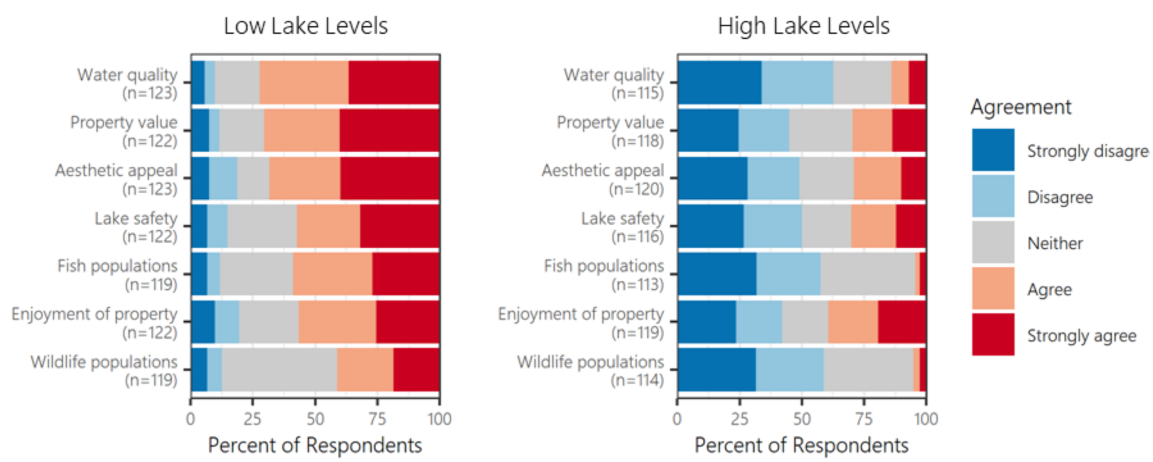

Figure 57. Pleasant Lake perception of value. Percent of respondents from Pleasant Lake who disagree, agree, or neither disagree/agree that low or high lake levels decrease a variety of lake values. The number of people who responded to each lake value is listed in parentheses.

Some types of property damage or modifications caused by low and high lake levels were of more concern than others to respondents (ANOVA at low lake levels, F=22.8, p<0.001; ANOVA at high lake levels, F=19.1, p<0.001) with more agreeing that costs were incurred at high lake levels than low (Figure 58; paired t-test, T=-8.7, df=458 p<0.001). More than half of respondents agreed/strongly agreed that low (60.4%, 60.7%) and high (74.1%, 69.2%) lake levels caused them to move or modify their dock. Neither low nor high lake levels have damaged most peoples' homes (only 5.5% and 12.6% agreed/strongly agreed at low and high lake levels, respectively). High lake levels were more problematic for landscaping costs and structural repairs: 53.8% of respondents agreed/strongly agreed that high lake levels incurred landscaping costs as compared to 24% at low lake levels, and 52.5%

agreed/strongly agreed that high lake levels incurred structural repair costs compared to 16.3% at low lake levels.

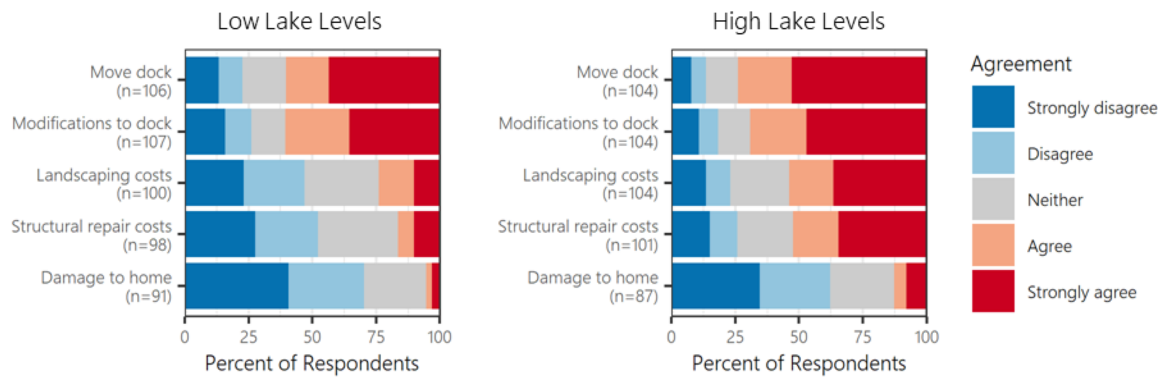

Figure 58. Pleasant Lake perception of cost. Percent of respondents from Pleasant Lake who disagree, agree, or neither disagree/agree that low or high lake levels incur a variety of costs or modifications to their properties. The number of people who responded to each item is listed in parentheses.

Long Lake

Long Lake Property Owners

According to the 2019 Wisconsin tax parcel database, there are 70 parcels with access to Long Lake. Residents of 41 (60%) of these parcels responded to our survey by mail or by email. The high response rate gives us confidence that survey responses are generally representative of the total population of Long Lake property owners.

A large proportion of respondents have owned their Long Lake properties for more than 20 years (48%), and a majority (78%) have owned their property for more than 10 years. Respondents who consider their Long Lake property to be their primary residence made up 33% of the total; these residents spent an average of 10.4 months per year at Long Lake. Many of the 67% of survey respondents who consider their Long Lake property to be a secondary property own primary residences around the Milwaukee metro area and Chicago (Figure 59). One respondent travels to Long Lake from Arizona and one visits from Kansas.

Property owners whose Long Lake property is not their primary residence largely make weekend (85%) and weeklong (63%) trips to Long Lake; only two respondents indicated that they regularly visit for a month or longer. These secondary residents also spent a mean of 72 days per year at Long Lake, indicating that many are making multiple short-term trips per year. May through September was the most popular time of year to visit, but some respondents (30-33%) regularly visit during December, January, or February (Figure 60). On average, respondents who consider their Long Lake property to be their secondary residence bring two visitors with them on each occasion.

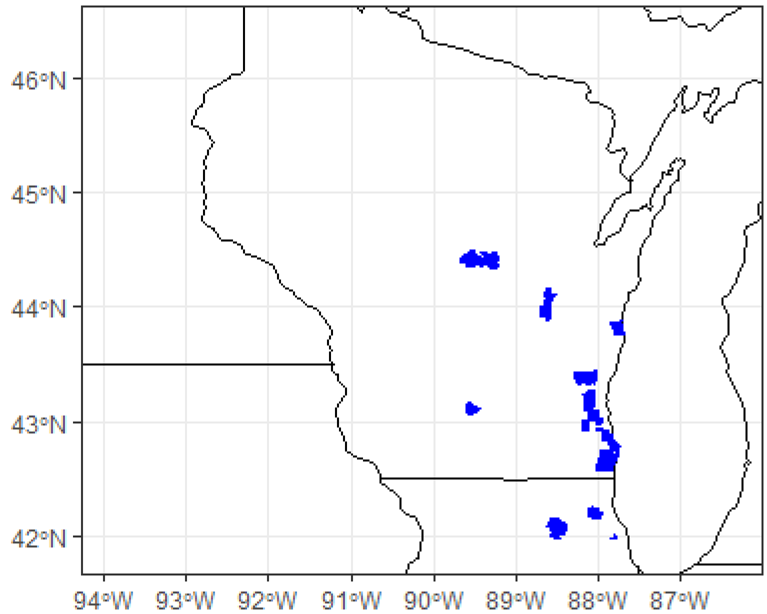

Figure 59. Long Lake, secondary residence locations. Zip codes (blue) of primary residences for Long Lake property owners who consider their lake house to be their secondary residence. Does not show one zip code in Arizona and one in Kansas.

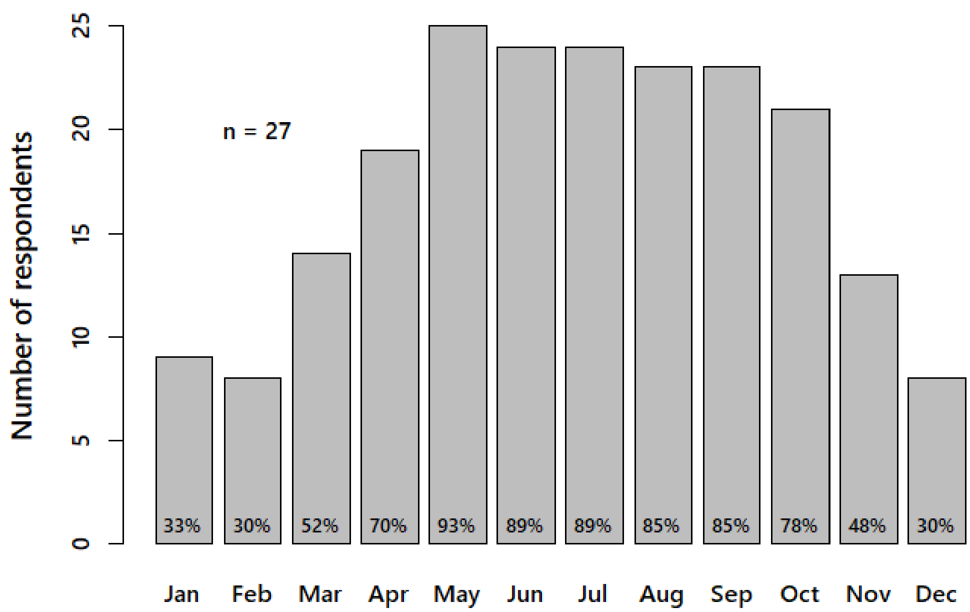

Figure 60. Long Lake, secondary residence timing. Number and percentage of secondary Long Lake residents (27 in total) who regularly visit Long Lake by month.

Access to Long Lake

Most property owners along Long Lake have made additional investments to access and enjoy the lake. The survey respondents' properties have an average of 107 feet of shoreline, ranging from 20 to 200 feet. When asked if their property has a beach or area at which they can swim or wade during average water level conditions, 78% responded yes. Most respondents own at least one watercraft (90%), but do not have a boathouse (93%). Those who indicated that they own a boat on Long Lake own a mean of 1.47 boats. Canoes are the most popular type of watercraft on Long Lake (owned by 57% of all respondents), closely followed by rowboats, (49% of all respondents). Paddleboats (29% of respondents) are the next most prevalent, followed by pontoons (20%), and fishing boats (14%). One respondent owns a sailboat, and another does not use watercraft at the lake due to low levels.

Almost two-thirds of respondents on Long Lake (65%) have some sort of dock. Rolling docks were the most popular, but some residents also own pipe docks, permanent docks, or lift docks. On average, our survey respondents' docks are 23 feet in length, with a range from 6 to 40 feet. Swimming rafts are not common on Long Lake; only one respondent owns one.

Long Lake Recreation

We asked Long Lake property owners how often they take advantage of common outdoor recreation opportunities on the lake, and how important those activities are to their enjoyment of their lake property (Figure 61). Bird and wildlife watching was the most popular recreation activity; 65% of respondents indicated that they engaged in this activity often or very often when weather permits. Fishing is also popular on Long lake; 38% of respondents fish often or very often without targeting a particular species, while 30% often fish for panfish and 29% often fish for game species. A similar proportion of the Long Lake property owners we surveyed (30%) often access the lake for non-motorized boating.

In general, the most popular activities were also important to our respondents' enjoyment of their Long Lake properties. Roughly half of the property owners we reached indicated that bird and wildlife watching (55%), fishing for any species (53%), panfishing (49%), and non-motorized boating (51%) were "very important" or "extremely important". Large proportions of our respondents also rated these four activities as "moderately important". The percentages of respondents who said these activities are at least moderately important are each greater than 84%. Fishing for game fish was described as very or extremely important by 34% of respondents. The least popular activities, swimming/wading and motorboating, are also the least important to surveyed property owners, with only 28% and 23% respectively rating these activities as very or extremely important to their enjoyment of Long Lake.

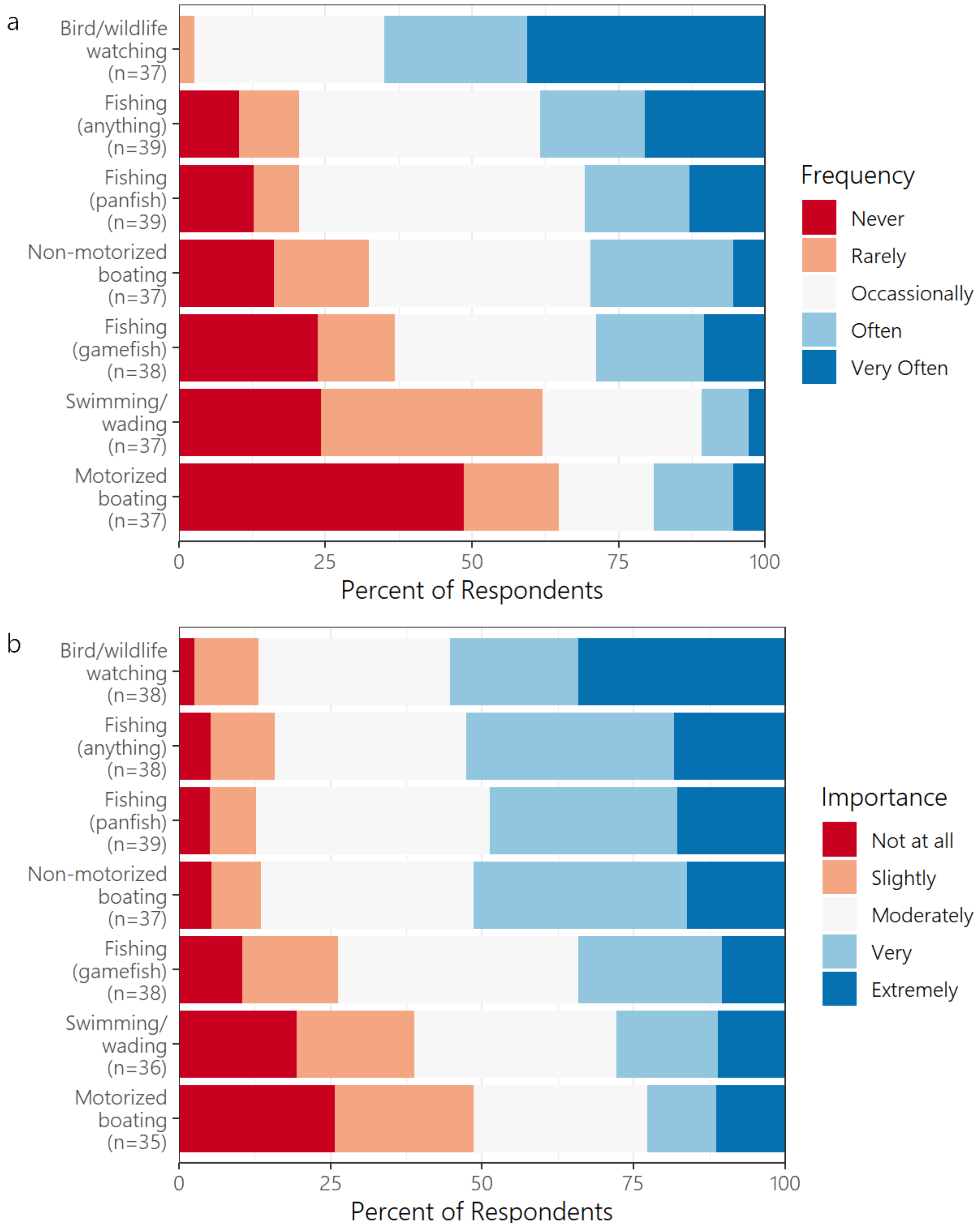

Figure 61. Long Lake activity frequency and importance. Long Lake respondents' frequency of participation in (a) and importance of (b) common lake recreation activities.

Long Lake Levels

We also asked property owners on Long Lake how much they believe water levels would naturally vary if there were no impacts from high capacity wells or land cover change. Three in ten (31%) respondents indicated that natural lake level variation on Long Lake is less than one foot. Only 13% of respondents believe that lake levels naturally vary up to 3 feet, while approximately equal proportions believe that lake levels naturally vary up to 5 feet (21%), up to 10 feet (18%), or more than 10 feet (18%). Observed lake levels range 10.7 feet from a minimum of 1093.1 feet in 1964 to a maximum of 1103.8 feet in 2019. During the previous three years alone, Long Lake has risen eight feet, from near historic lows to all-time highs. According to the no-irrigated-agriculture scenario of the groundwater flow model, lake levels range 5.9 feet 80% of the time (Table 39).

Recreational activities were generally perceived to be impacted by low lake levels, but not by high lake levels (Figure 62, paired t-test, T=19.86, df=145, p<0.001). There were differences in the degree to which low lake levels limited recreational activities (ANOVA, F=3.08, p=0.006), but not high lake levels (ANOVA, F=1.53, p=0.169). More than 75% of respondents stated that low lake levels severely or completely limit the majority of recreational activities we listed, including: fishing, swimming/wading, non-motorized boating, and motorized boating. The only activity that was less impacted by low lake levels was bird and wildlife watching, severely or completely limiting only 25.8% of respondents. This was in sharp contrast with how respondents perceived high lake levels. Almost all respondents stated that high lake levels did not limit any of their recreational activities; only 2.9% – 4.3% stated that high lake levels severely limited fishing for panfish, fishing for any fish, motorized boating, and swimming/wading.

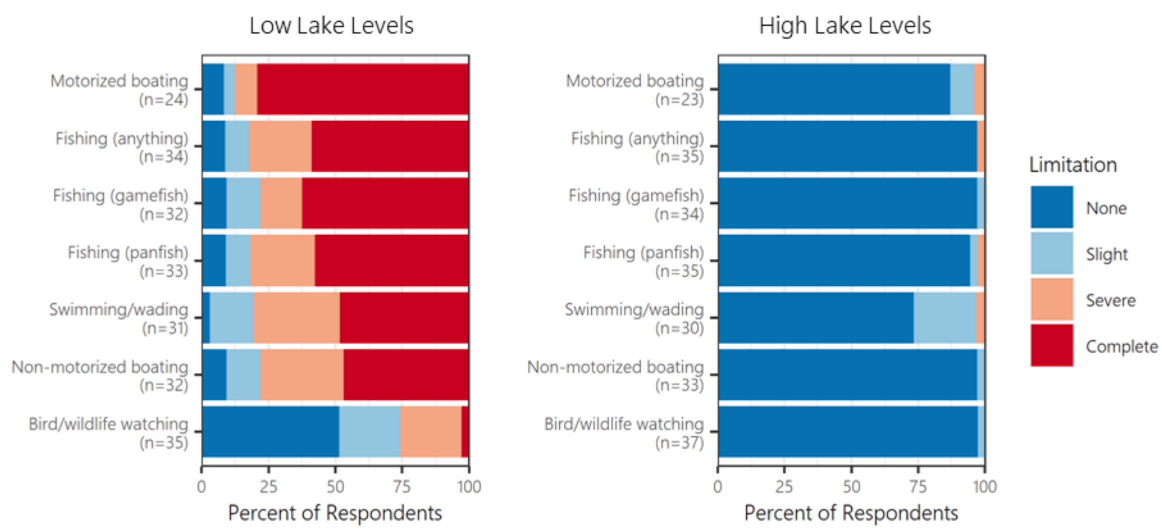

Figure 62. Long Lake recreation limitations. The percent of respondents from Long Lake who selected the degree to which their recreational activities are limited by low versus high lake levels. The number of people who responded to each recreational activity is listed in parentheses.

Respondents agreed or strongly agreed that low lake levels negatively impact a variety of intrinsic values of Long Lake, but not high lake levels (Figure 63, paired t-test, T=26.56, df=181, p<0.001). The degree to which lake values were impacted by low lake levels varied (ANOVA, F=3.42, p=0.003), but not at high lake levels (ANOVA, F=1.04, p=0.4) Most respondents (89.5 – 94.8%) agreed or strongly agreed that low lake levels decrease fish populations, water quality, the aesthetic appeal of the lake, their enjoyment of their lake property, and their property value. Sixty-eight percent of respondents agreed or strongly agreed that low lake levels decrease wildlife populations. Slightly more than half (54%) agreed that low lake levels make the lake less safe. This is in stark contrast with high lake levels. At high lake levels, most respondents (66.7% - 84.6%) disagreed or strongly disagreed that high lake levels decrease all of the above intrinsic values of Long Lake.

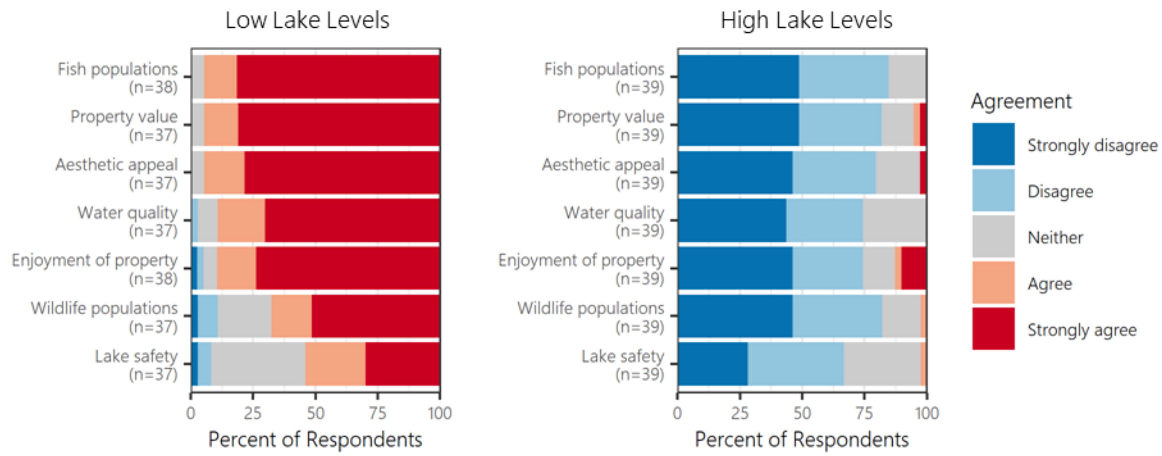

Figure 63. Long Lake perception of value. Percent of respondents from Long Lake who disagree, agree, or neither disagree/agree that low or high lake levels decrease a variety of lake values. The number of people who responded to each lake value is listed in parentheses.

Fewer respondents had problems with property damage overall, but responses varied by the type of impact at both low lake levels (ANOVA, F=8.59, p<0.001) and high lake levels (ANOVA, F=4.58, p=0.001). Slightly more respondents agreed that high lake levels damage their property than low, but the effects were similar (Figure 64; paired t-test, T=-2.49, df=140, p<0.001). Over half of respondents agreed or strongly agreed that they need to move their dock when lake levels are low (63.9%) and high (75%). Though not a majority, 45.2% of respondents agreed/strongly agreed that they modify their dock at low lake levels, and 63.3% modify their dock at high lake levels. Only 9.7% and 6.2% agreed/strongly agreed that low and high lake levels damaged their home, respectively. However, high lake levels impacted landscaping and structures more than low lake levels. 55.9% of respondents agreed/strongly agreed that high lake levels incurred landscaping costs compared to 25.8% at low lake levels. Structural repair costs were more problematic at high lake levels: 45.1% agreed/strongly agreed that high lake levels incurred costs vs. 10.7% at low lake levels.

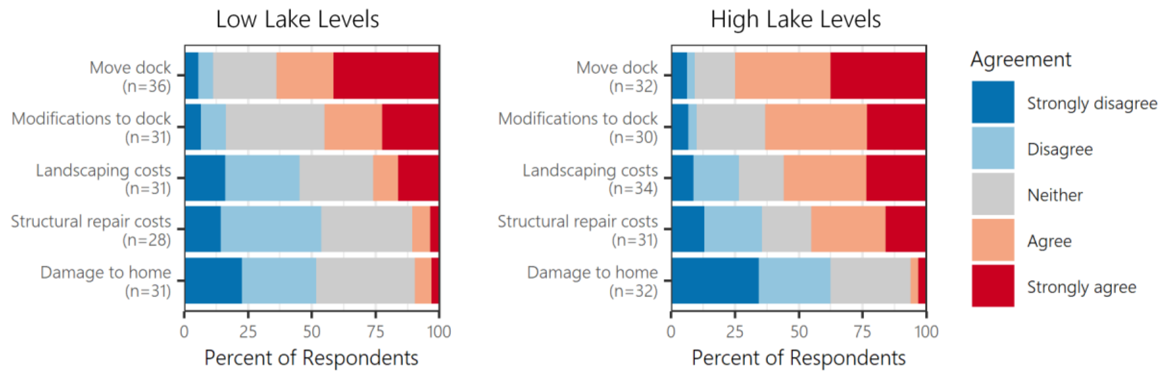

Figure 64. Long Lake perception of cost. Percent of respondents from Long Lake who disagree, agree, or neither disagree/agree that low or high lake levels incur a variety of costs or modifications to their properties. The number of people who responded to each item is listed in parentheses.

Significant Impacts of Groundwater Withdrawals on Lake Ecosystems

To determine whether groundwater withdrawals may significantly impact Pleasant, Long, and Plainfield Lakes, we first evaluated how groundwater withdrawals affect the hydrology of the study lakes. We then assessed how changes in hydrology would impact four ecosystem components of these lakes: water chemistry, aquatic plants, fish, and human use. Given that this study occurred during a period with the highest lake levels on record (2018-2019), we could not directly observe how the lake ecosystems respond to low water levels. Thus, we used literature reviews, historic data and reports, and field surveys to understand how lake hydrology interacts with and affects lake ecosystems. We developed a suite of ecosystem metrics and protective thresholds representing the four ecosystem components and then used a groundwater flow model (MODFLOW) to evaluate whether groundwater withdrawals are contributing or will contribute to a significant reduction of lakes levels. We refer to groundwater withdrawals as “irrigated agriculture” as over 95% of the pumping within the inset models is used for irrigated agriculture, and the model takes into consideration the changes in pumping, land use and recharge associated with irrigation. We use the groundwater flow model to evaluate whether current and/or potential irrigated agriculture could change lake hydrology enough to exceed the ecosystem thresholds compared to a scenario without irrigated agriculture. Using the groundwater flow model allowed us to evaluate the effect of irrigated agriculture on lake levels while accounting for climatic variation, which drives lake level fluctuations at decadal time scales (Watras et al., 2014). Historical lake level observations represent a combination of both drivers and therefore, cannot be used to isolate the effect of groundwater withdrawals.

Ecosystems are tightly linked and changes to hydrology will likely cascade through multiple indicators. For example, plant community changes may in turn affect fish, which rely on aquatic plants for food and shelter. Water quality largely determines which species reside in a lake and also influences how humans use the resource. Although we do not directly evaluate ecosystem interactions, we recognize that a significant impact on one ecosystem metric affects others. Therefore, if irrigation alters hydrology enough to exceed a single ecosystem indicator threshold, we concluded that the lake is significantly impacted by groundwater withdrawals. Some ecosystem indicators are unidirectional in nature whereas

Table 36. Summary of ecosystem indicators and their significance thresholds.

Indicator	Significance Threshold	Pleasant	Long	Plainfield
Chemistry				
Stratification[1]	lake level of a given magnitude (e.g., median) falls from above 976.6 ft asl in the no-irrigated-agriculture scenario to below 976.6 ft asl	x		
Median Mg (mg/L)[2]	change in concentration beyond the 80% range in the no-irrigated-agriculture scenario	x	x	x
Maximum Mg (mg/L)	increase by more than two times the maximum Mg concentration in the no-irrigated-agriculture scenario	x	x	x
Plants				
Upland area	area increases by an increment > 10% of the lake footprint	x	x	x
Inland beach area	area changes by an increment > 10% of the lake footprint	x	x	x
Emergent area	area changes by an increment > 10% of the lake footprint	x	x	x
Floating-leaved area	area changes by an increment > 10% of the lake footprint	x	x	x
Submergent area	area changes by an increment > 10% of the lake footprint		x	x
Submergent pondweed area	area changes by an increment > 10% of the lake footprint	x		
Submergent macroalgae area	area decreases by an increment > 10% of the lake footprint	x		
Range from infrequent low to infrequent high	change beyond uncertainty in the estimate	x	x	x
Federally threatened plant	change in the median lake level beyond uncertainty in the estimate			x
Fish				
Area	greater than 10% decline in area from that in the no-irrigated-agriculture scenario	x	x	
Volume	greater than 10% decline in volume from that in the no-irrigated-agriculture scenario	x	x	
Littoral habitat	mean substrate hardness at centrarchid spawning depth (0.5 - 5 ft) drops below 0.4	x		
Spawning (%)	decrease in the percent of good spawning years beyond the uncertainty in the estimate	x		

*uncertainty in estimates are defined as ± 1 SD of the metric being evaluated, which is calculated using the runs from the no-irrigated-agriculture scenario. If the SD is zero, a significant change is defined at > 1%. Specific thresholds are reported in each lake table summarizing significant impacts.

[1]Stratification applies the uncertainty in the estimate concept when evaluating whether the lake level drops below 976.6 ft asl. The change is not significant if it is within 1 SD of the metric being evaluated.

[2]Median Mg applies the uncertainty in the estimate concept to both the lower and upper bound of the 80% range in Mg concentrations.

Table 36 (cont.) Summary of ecosystem indicators and their significance thresholds.

Indicator	Significance Threshold	Pleasant	Long	Plainfield
Human Use				
Motorboat crowding	greater than 10% decline in lake area from that in the no-irrigated-agriculture scenario	x		
Motorized boating (%)	lake area drops below 62.5 acres	x		
Non-motorized boating (%)	decrease in the percent of time lake level exceeds 1096.8 ft asl on Long Lake and 1096.3 ft asl on Plainfield Lake beyond uncertainty in the estimate		x	x
Open water (%)	decrease in the percent of time lake level exceeds 1100.84 ft asl beyond uncertainty in the estimate		x	
Good Dock Install & Season	decrease in the percent of time lake is deep enough to install dock in spring and keep in place over summer beyond uncertainty in the estimate	x	x	
Good Dock Install	decrease in the percent of time lake is deep enough to install dock in spring (water depth of 2 ft on Pleasant and 1 ft on Long at end of average dock) decreases beyond uncertainty in the estimate	x	x	
Good Dock Season	decrease in the percent of time lake remains deep enough in summer for dock to remain in place decreases beyond uncertainty in the estimate	x	x	
Meets Lake Definition (%)	decrease in the percent of time lake has at least 0.25 acres area > 3.28 ft deep decreases beyond uncertainty in the estimate		x	x

others are bidirectional (Table 36). For example, loss of lake area with declining water levels adversely impacts fish and boating. In contrast, declining lake levels will favor upland and wetland plants over submergent aquatic plants, but no single plant community is desired over another. Rather, maintaining a diverse and dynamic plant community is the goal. For indicators like plant cover and magnesium concentration, we evaluated whether groundwater withdrawals significantly change the ecosystem indicator in either direction. We conclude this report with our determination of whether existing and potential groundwater withdrawals significantly reduce the water levels in each of the three study lakes and, if so, how the ecosystems are impacted.

Hydrology

Literature Review

In general, lake water levels can naturally fluctuate by five vertical feet or more, with the magnitude of fluctuation increasing as the time scale increases from days to tens of years or more (Hofmann et al., 2008; Watras et al., 2014). Given this dynamic nature of lake water levels, a single lake level estimate is insufficient to describe the full lake level regime for this study. In addition to capturing how a single, static average lake level is affected by groundwater withdrawals, our description of lake level regimes must also allow us to answer ecologically relevant questions like:

- How do groundwater withdrawals affect the highest and lowest lake levels?
- Do groundwater withdrawals reduce the duration of flooded periods?
- Do groundwater withdrawals increase the duration of low water periods?

The natural flow regime is a paradigm in stream ecology which recognizes that natural variations in streamflow are vital to the health and character of aquatic ecosystems (Poff et al., 1997). This concept has been used to understand how regulated rivers are impacted by an altered flow regime and to better manage altered flow regimes to improve ecosystem function (e.g. Chen and Olden, 2017). There are five components of the natural flow regime for streams, all of which can also be used to statistically describe the hydrology of lakes: magnitude, frequency, duration, rate of change, and timing.

We used all five hydrologic components to fully characterize the study lakes' hydrologic regimes and evaluate the impacts of lake hydrology on lake ecosystems. Within each component, we defined multiple ecologically relevant hydrologic metrics (Table 37). Hydrologic metrics related to lake level "magnitude" capture the range of elevations of a lake's water levels from high to low. Lake levels climb above the infrequent high in 10% of all months and dip below the infrequent low in 10% of all months. Similarly, they rise above the frequent high in 25% of all months and fall below the frequent low in 25% of all months. Florida establishes minimum lake levels by applying this concept of exceedance probabilities to lakes (Alley et al., 1999; Chapter 40D-8). However, the pattern of very high and very low levels within the time series can be quite variable; extreme levels can occur many times for very short durations or fewer times for longer durations. Metrics related to "frequency" capture how many times a lake level reaches a certain elevation and those related to "duration" capture how long lake levels exceed that elevation. Metrics related to "rate of change" capture how quickly lake levels rise or fall over a month, season, or year, which can impact how well aquatic organisms can adapt to water level fluctuations. Lastly, "timing" metrics capture the regularity or predictability with which a given magnitude is exceeded. For example, in many stream ecosystems it is common for low flows to predictably occur in late summer.

Table 37. Lake level regime hydrologic metrics.

Metric	Definition	Question Answered
Magnitude		
Median lake levels	Median lake levels for: - Entire time series - Each season	What is the average lake level?
High and low lake levels	Lake levels that are exceeded X% of the time. Includes: - Infrequent high (10% exceedance probability) - Frequent high (25% exceedance probability) - Frequent low (75% exceedance probability) - Infrequent low (90% exceedance probability)	What is a typical high or low lake level?
Ranges in lake levels	Range between the: - 25%-75% exceedance probability levels - 10%-90% exceedance probability levels	What is the typical range of lake levels?
CV of maximum lake depth	Coefficient of variation in maximum lake depth for: - Entire time series - Each season	What is the variability in maximum lake depth?
Frequency		
Count of high and low lake levels	Number of times lake levels spend 1+ months: - At/above the 10%, 25%, or 50% exceedance probability level - At/below the 50%, 75% or 90% exceedance probability level	How often do lake levels reach high and low levels?
Count of prolonged high and low lake levels	Number of times lake levels spend 2+ years: - At/above the 10%, 25%, or 50% exceedance probability level - At/below the 50%, 75% or 90% exceedance probability level	How often do lake levels remain at high and low levels for prolonged periods of time?
Duration		
Median duration	Median number of months lake levels are: - At/above the 10%, 25%, or 50% exceedance probability level - At/below the 50%, 75% or 90% exceedance probability level	For how long do lake levels typically stay very high or very low?
CV of duration	Coefficient of variation in the number of months lake levels are: - At/above the 10%, 25%, or 50% exceedance probability level - At/below the 50%, 75% or 90% exceedance probability level	What is the variability in the length of time lake levels stay very high or very low?
Rate of Change		
Median rise/fall rate	Median rate of rise and rate of fall in lake levels over: - 1 month - 3 months (i.e., a season) - 12 months (i.e., a year)	How quickly do lake levels typically rise or fall over a month, season, or year?
CV of rise/fall rate	Coefficient of variation in the rate of rise and rate of fall in lake levels over: - 1 month - 3 months (i.e., a season) - 12 months (i.e., a year)	What is the variability in how quickly lake levels rise or fall over a month, season, or year?
Timing		
Relative seasonal levels	Frequency at which the median seasonal level is higher than the previous season's median level for: - Each season (e.g., summer vs. prior spring) - Spring vs. prior growing season	Are there consistent seasonal patterns in relatively high vs. low lake levels?

For the purposes of this study, the average seasonal lake level is most analogous to the median lake level in the “magnitude” category of metrics, or the lake level that is exceeded 50% of the time. The term “average” is sometimes interpreted as the mean value, but when lake levels have high variability, the mean greatly depends on how many samples are taken and when they are taken. In this study, we use the median rather than the mean lake level to define “average” but use all five components described above to fully characterize lake level regimes.

Methods

Groundwater Flow Model Scenarios

Using the groundwater flow model, USGS and DNR modelers created three scenarios to help disentangle the effects of climate and irrigated agriculture on the lake hydrologic regime. In the first scenario, no irrigated agriculture takes place in the study area; areas of cropland that rely upon groundwater withdrawal are replaced with forest, grasslands, wetlands, or other crops that do not require irrigation. In the second scenario, current levels of irrigated agriculture are simulated based on crop rotations from 2018 in the Wiscland 2.0 dataset (Pruitt et al., 2021b). In the final scenario, a complete build-out of potentially irrigable lands within the study area is simulated, maximizing the possible amount of irrigated cropland while maintaining reasonable crop rotation schedules and land use. We refer to these scenarios as: “no-irrigated-agriculture”, “current-irrigated-agriculture” and “potential-irrigated-agriculture”. These three scenarios are constructs that allow us to decouple climate and groundwater withdrawal and answer the legislatively mandated question of whether groundwater withdrawals are significantly impacting water levels in lakes. We note that the no-irrigated-agriculture scenario is not intended to replicate actual past conditions and that the potential-irrigated-agriculture scenario represents an end-member case of full irrigation build-out.

Each scenario runs for 38 years, uses the same parameter values determined for the calibration period, and experiences identical climatic conditions. Even though the model uses historical precipitation and air temperature data from 1981 to 2018 as an input, corollary data like crop rotations and groundwater withdrawals are not available over that time period. Thus, the scenarios are not an attempt to re-create the past and are not expected to precisely align with observed lake level records. Instead, the scenarios allow us to examine how lake levels on Pleasant, Long and Plainfield Lakes respond to different land management schemes while accounting for climatic variation. The period from 1981-2018 includes a full range of climatic conditions and reflects more recent shifts in Wisconsin’s precipitation toward wetter conditions (Figure 65, Figure 66). In Waushara County, annual precipitation has increased at a rate of 0.87 in/decade since 1950 (Kucharik et al., 2010).

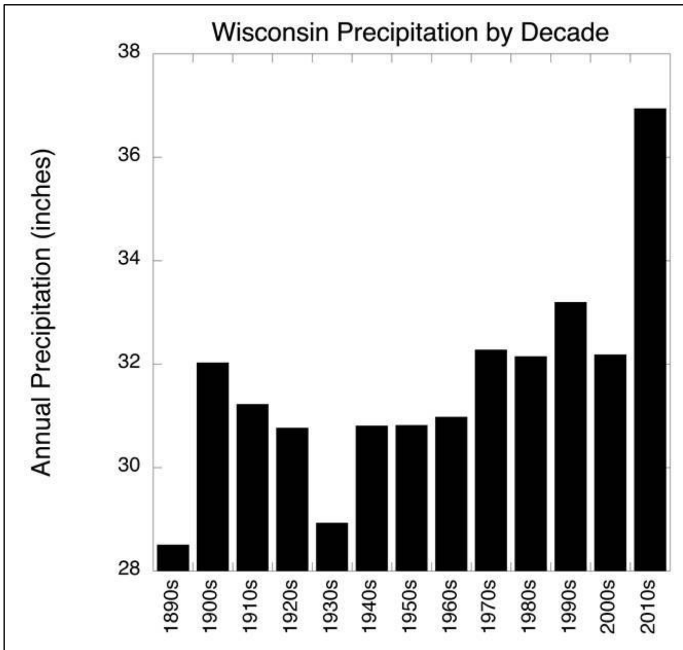

Figure 65. Average annual precipitation (inches) in Wisconsin by decade. Courtesy of Stephen Vavrus.

The MODFLOW groundwater flow model outputs a monthly time series of lake levels, from which we calculate a series of hydrologic metrics that describe the lake level regime for each scenario. We consider the first 5 years to be a model equilibration period, so we exclude them from our analysis and only evaluate the last 33 years. The model also estimates groundwater fluxes in and out of the study lakes, and water gained and lost due to precipitation and evaporation. This information is important for evaluating potential changes to lake water and chemistry budgets.

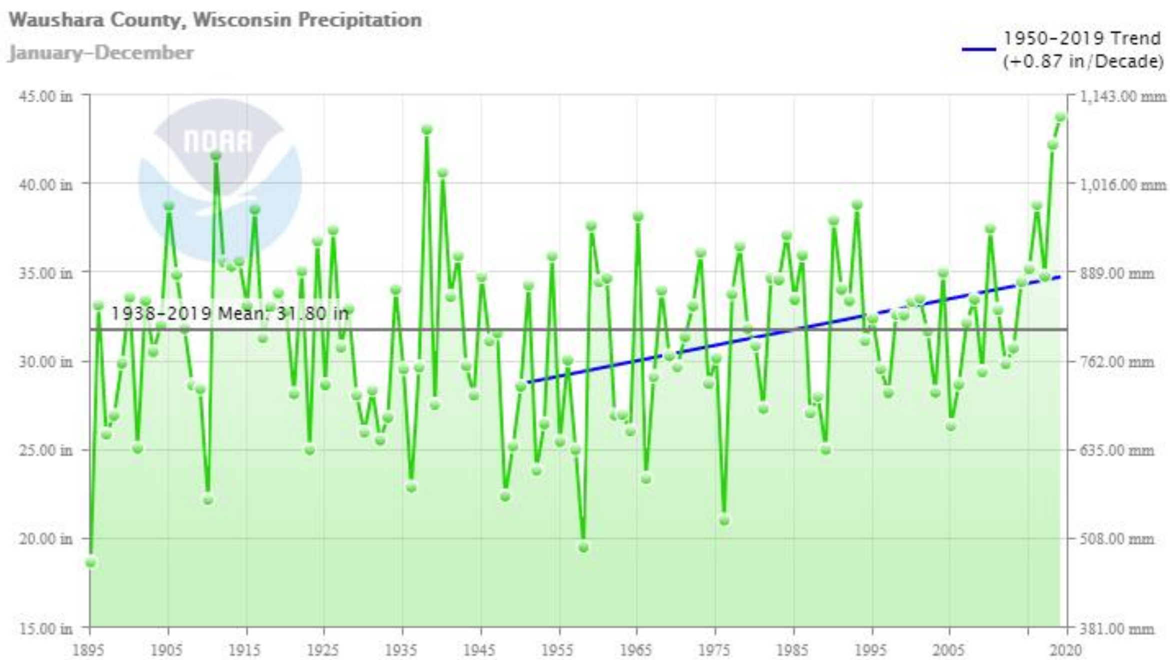

Figure 66. Annual precipitation in Waushara County, WI from 1895-2019. Black line denotes mean annual precipitation from 1938-2019. Blue line denotes increasing decadal trend 1950-2019. Source: U.S. Climate Divisional Database, NOAA, 2020.

To investigate how the uncertainty in recharge estimates might affect lake levels simulated by MODFLOW, the USGS conducted a Monte Carlo analysis on critical parameters associated with the Soil Water Balance (SWB) model, which estimates recharge and pumping values used by MODFLOW. These parameters describe properties of the system such as how deep plant roots extend into the ground and the percentage of water absorbed from the ground that a plant species will release through transpiration. The USGS ran the three 38-year MODFLOW scenarios using 350 different combinations of values for these parameters (model runs), varied around a single "base" parameter set that represented best estimates of each parameter (Fienen et al., 2021). We then calculated the difference in median lake level between the no-irrigated-agriculture and current-irrigated-agriculture scenarios for each run and selected the two runs at approximately the 10^{th} and 90^{th} percentile for differences in median lake level. We call these two runs the "small-drawdown" and "large-drawdown" runs. These runs are not equivalent to upper and lower confidence intervals, but they serve essentially the same purpose in our analysis: to quantify uncertainty in the SWB parameterization. We evaluate impacts to the lake level regime under the base, small-drawdown, and large-drawdown runs. For brevity, we display the hydrologic metrics of only the base run in the tables and figures. If a threshold is impacted even under the small drawdown run, we have high confidence that this aspect of lake hydrology is impacted under current pumping conditions. If a threshold is only impacted under the large drawdown run, there is a smaller but non-zero chance that this metric is impacted. Thus, we conclude that an indicator is significantly impacted under the current-irrigated-agriculture scenario if two or three model runs cross the significance threshold. If one of three model runs crosses the threshold, we give caution that current-irrigated-agriculture may impact the indicator.

We only ran the single base run for the potential-irrigated-agriculture scenario. Thus, our conclusions about whether indicators are significantly impacted or not impacted under potential-irrigated-agriculture conditions are based on whether each indicator crosses its significance threshold in the base run. For indicators that are significantly impacted in the potential- but not the current-irrigated-agriculture scenario, our final evaluation is caution. This is because the models show that the current build out of irrigated agriculture is not significantly impacted, but further build out could cause impacts.

Time Period of Analysis

Our analysis of significant impacts to the study lakes is based upon changes in hydrologic metrics calculated from the lake level time series produced by MODFLOW under different irrigation scenarios. Hydrologic metrics can be sensitive to both the length and specific time frame of a time series, especially when time series are non-stationary (Kennard et al., 2010). We evaluated the length of the MODFLOW lake level time series needed to produce robust metrics, as well as the stationarity of climate data that feed into each scenario.

To determine whether a 33-year lake level time series produces hydrologic metrics that are suitably robust for our intended use, we conducted a sensitivity analysis. We used long-term lake level data sets from two other seepage lakes in Wisconsin. Devils Lake in Baraboo, Sauk County, Wisconsin is a moderately clear seepage lake with a maximum depth of 47 feet, located 40 miles southwest of Pleasant Lake. Devils Lake has experienced similar climatic conditions to the study lakes, although it has different geology and land use. We used a 68-year monthly lake level record beginning in 1936 and ending before the installation of a control structure in 2002. Anvil Lake is a moderately clear seepage lake in Washington, Vilas County, with a maximum depth of 32 feet. We used a 46-year lake level record from Anvil Lake from 1936 to 1981 because large gaps in the lake level record occur after 1981.

We modeled this sensitivity study based on Kennard et al.'s (2010) analysis of uncertainty in streamflow hydrologic metrics. We randomly selected 1 year of continuous monthly lake levels, 2 years, 3 years (etc.) up to 60 years, or 46 years for Anvil Lake, performing this random selection 100 times for each time series length. We then calculated all hydrologic metrics for each simulation. For each time series length, we use the 100 simulations to calculate the bias (percent bias, PBIAS; Eq. 12), precision (coefficient of variation, CV; Eq. 13), and accuracy (root mean square error (RMSE); Eq. 14) in each hydrologic metric as compared with the "true" values. The true values (that is, values describing the entire history of the lake) are of course unknowable and non-stationary, but we approximate them as the metrics calculated using the complete time series (46 or 62 years).

$$PBIAS = 100 * \left(\frac{y_i - \hat{y}}{\hat{y}}\right) \quad \text{(Eq. 12)}$$

$$CV = 100 * \left(\frac{s}{\bar{y}}\right) \quad \text{(Eq. 13)}$$

$$RMSE = \sqrt{(1/n) * \sum_{i=1}^{n} (y_i - \hat{y})^2} \quad \text{(Eq. 14)}$$

In the above, $\hat{y}$ is the observed value from the complete record, y_i is one simulated value with a shorter time period, $\bar{y}$ is the mean value from all 100 simulations with a shorter time period, and s is the standard deviation of all 100 simulated values for that shorter time period.

In keeping with Kennard et al. (2010), we considered metrics biased if PBIAS was greater than 30% and imprecise if CV was greater than 30%. Acceptable accuracy was determined on a per-metric basis, as each metric has different units and thus a different acceptable range. These measurements of error were evaluated most closely for a 33-year time series, which is the length of the 1986-2018 period.

From this sensitivity analysis, we conclude that 33 years of lake level data adequately describe the hydrologic metrics and therefore, the MODFLOW scenarios are of sufficient length to evaluate differences in hydrology between them (Table 38, Supplemental Information I). Magnitude metrics all had acceptable levels of bias and variance, but accuracy was not always within 0.5 feet. The number of occurrences of high and low levels (frequency metric) and median duration of high and low levels (duration metric) were the least-reliable metrics for a 33-year time series, but the reliability of these metrics varied substantially among the exceedance levels evaluated. Rate of change metrics were generally reliable. Despite our decision to choose a span of years which excluded the longest gaps in the Anvil Lake record, the sensitivity analysis may have been influenced by more numerous, smaller gaps in the record. As the number of sampled years increases, so does the probability of having at least one gap in the sampled record.

For each hydrologic metric, we consider the estimated bias, variance, and accuracy of a 33-year time series when comparing the change in hydrologic metrics among MODFLOW scenarios. We made *a priori* estimates of acceptable accuracy for each metric, but in the context of evaluating changes in these metrics between MODFLOW scenarios, the most important consideration is how the estimated accuracy, variance, and bias compare to the difference between MODFLOW scenarios. For instance, if accuracy of the median lake level was estimated to be 1.5 feet in the sensitivity analysis and the difference between the no-irrigated-agriculture and current-irrigated-agriculture scenarios was 5 feet, we would conclude that model uncertainty does not inhibit evaluation of irrigated agriculture.

Table 38. Suitability of 33-year time series compared to longer time series for calculating hydrologic metrics.

Metric		33-year time series[1]	> 33-year time series	Conclusion
Magnitude	Median levels	*Bias:* < 5% *Variance*: < 5% [2]*Accuracy*: < 0.75 ft	Bias and variance remain very low. Accuracy continues to gradually improve but is generally better on Anvil Lake.	Bias and variance are low, and accuracy is within 0.75 ft. Overall median (as opposed to monthly) achieves all three *a priori* thresholds.
	Exceedance probabilities	*Bias*: < 5% *Variance*: < 5% [2]*Accuracy*: < 0.8 ft	Bias and variance remain very low. Accuracy continues to gradually improve.	Bias and variance are low, and accuracy is within 0.8 ft.
	Exceedance probability ranges	*Bias*: < 20% *Variance*: < 25% [2]*Accuracy*: < 1.2 ft	All measures of error or improve only slightly. Annual ranges and 10-90% ranges most uncertain.	Bias and variance are low. Accuracy is ~1.2 ft for annual and monthly 10-90% ranges for Devils Lake, but <1 ft for Anvil Lake. Accuracy plateaus until almost the entire time series is included (62 years for Devils Lake and 46 years for Anvil Lake)
	CV of maximum lake depth	*Bias*: < 20% *Variance*: < 24% *Accuracy*: < 1%	All measures of error plateau or slightly improve.	The 33-year time series sufficiently captures the CV of maximum lake depth for Devils Lake and Anvil Lake.
Frequency	Count of high and low lake levels	[2]*Bias*: < 50% [2]*Variance*: < 34% [2]*Accuracy*: < 2.5 times	Most measures of error plateau or slightly improve, but some accuracies on Devils Lake never achieve thresholds. Variance is erratic for 90% exc. prob.	Performance of the 33-year time series varies among exceedance levels. RMSE remains high even as number of years approach the entire time series.
	Departure from median levels	*Bias*: < 30% *Variance*: < 15% *Accuracy*: < 5%	Bias, variance, and accuracy plateau or slightly improve at both lakes.	33-year time series represents character of the full times series well.
Duration	Median duration	[2]*Bias*: > 100% [2]*Variance*: < 40% [2]*Accuracy*: < 3 mo.	Mixed behavior, especially at Anvil Lake.	33- year time series may not reflect the character of the full time series. More uncertainty with extreme levels.
	CV of duration	[2]*Bias*: < 50% *Variance*: < 30% *Accuracy*: < 100%	Most measures of error plateau or slightly improve, but bias and accuracy remain high for some exceedance levels. Bias of high levels increases at > 20 yrs for Devils Lake.	Some exceedance probabilities may be biased with 33-year time series. RMSE also varies among exceedance levels. A 33-year time series represents the full times series well for some exceedance levels.
Rate of Change	Median rise/fall rate	*Bias*: < 20% *Variance*: < 13% [2]*Accuracy*: < 0.2 ft	All measures of error plateau or slightly improve.	Bias and variance are low, and accuracy is within 0.15 ft for all but the median 12-month fall rate at Devils Lake, which is at 0.2 ft accuracy. 33-year time series represents full times series well.
	CV of rise/fall rate	*Bias*: < 13% *Variance*: < 8% [2]*Accuracy*: < 20%	All measures of error plateau or slightly improve.	Bias and variance are low. Devils Lake and Anvil Lake accuracy converges at very different rates. 33-year time series represents full time series well.

[1]Maximum error between Devils Lake and Anvil Lake. [2]Metric did not reach *a priori* target at 33 years

Pleasant Lake

In the no-irrigated-agriculture scenario, Pleasant Lake levels usually fluctuate within a 2.9-ft range (Table 39, Figure 67, Figure 68), which is small relative to the maximum depth of Pleasant Lake (Table 40). Lake levels fall below the median for at least one month seven times over the 33-year scenario, indicating that levels transition from high to low once every 5 years, on average (Table 41). However, actual duration above or below the median level is highly variable and can be as short as a few months or as long as 14 years with a median duration of six and five months, respectively (Table 41, Figure 69). The timing of high vs. low levels does not show a strong seasonal pattern (Table 42), so events like spring snowmelt or summer evapotranspiration are not reliable predictors of lake levels. In addition, Pleasant Lake levels change by 0.4 ft/year on average (Table 43, Figure 70) which is much smaller than the full range in lake levels and further indicates that fluctuations between high and low lake levels do not occur on annual or shorter time scales but rather on longer, multi-year time scales.

Table 39. Modeled lake elevation, area, volume, mean depth, and max depth (standard deviation) associated with given exceedance probabilities at Pleasant Lake.

Metric	Irrigated Agriculture Scenario	Elevation (ft)	Area (acres)	Volume (acre-ft)	Mean Depth (ft)	Max Depth (ft)
Infrequent High	No	979.6 (0.4)	130.6 (1.5)	2012 (56)	15.4 (0.3)	24.4 (0.4)
	Current	979.1 (0.4)	129.3 (1.4)	1951 (56)	15.1 (0.3)	23.9 (0.4)
	Potential	979.1	129.2	1949	15.1	23.9
Frequent High	No	978.4 (0.5)	127.2 (1.7)	1861 (70)	14.6 (0.3)	23.2 (0.5)
	Current	978.0 (0.5)	125.9 (1.4)	1804 (58)	14.3 (0.3)	22.8 (0.5)
	Potential	977.7	125.2	1771	14.1	22.5
Median	No	977.6 (0.5)	124.9 (1.5)	1761 (62)	14.1 (0.3)	22.4 (0.5)
	Current	977.2 (0.4)	123.4 (1.5)	1713 (54)	13.9 (0.3)	22.1 (0.4)
	Potential	977.0	122.2	1678	13.7	21.8
Frequent Low	No	977.0 (0.5)	122.3 (2.0)	1681 (66)	13.7 (0.3)	21.8 (0.5)
	Current	976.6 (0.5)	120.8 (2.0)	1637 (58)	13.6 (0.3)	21.4 (0.5)
	Potential	976.5	120.2	1622	13.5	21.3
Infrequent Low	No	976.7 (0.5)	120.9 (2.2)	1641 (65)	13.6 (0.3)	21.5 (0.5)
	Current	976.3 (0.5)	118.7 (2.3)	1594 (57)	13.4 (0.2)	21.1 (0.5)
	Potential	976.2	118.1	1581	13.4	21.0

One way we can see that Pleasant Lake level variability is controlled by long-term drivers is via the duration of lake levels below the median level (Table 41, Figure 69). By definition, lake levels drop below the median level for half of the 33-year period, or a total of 16.5 years. However, these low periods do not occur regularly throughout the time series as they would if seasonal or annual drivers were the strongest control on lake levels. Instead, there is a single 14-year period (from year 11 to year 25) when lake levels are continuously below the median level (Figure 67, Figure 69). This period is not consistently dry but rather includes four of the 10 highest precipitation years in the entire 33-year simulation (Figure 71), thus year-to-year variability in weather does not directly correspond to Pleasant Lake levels. During this period, there appears to be a good relationship between changing lake levels and groundwater flow dynamics, which reflect local to regional groundwater levels and gradients. At Pleasant Lake, groundwater outflow is always larger than groundwater inflow. The early part of this 14-year low period,

Table 40. Modeled median lake level and coefficient of variation in maximum depth (standard deviation) across all months and across each season at Pleasant Lake.

Metric	Irrigated Agriculture Scenario	Median Lake Level (ft)	CV of Max Depth (%)
Overall	No	977.6 (0.5)	4.5 (0.2)
	Current	977.2 (0.4)	4.5 (0.2)
	Potential	977.0	4.6
Winter	No	977.6 (0.5)	4.3 (0.2)
	Current	977.3 (0.4)	4.3 (0.2)
	Potential	977.0	4.3
Spring	No	977.6 (0.5)	4.5 (0.2)
	Current	977.3 (0.4)	4.6 (0.2)
	Potential	977.0	4.6
Summer	No	977.6 (0.5)	4.4 (0.1)
	Current	977.2 (0.4)	4.4 (0.2)
	Potential	977.0	4.5
Fall	No	977.6 (0.5)	5.0 (0.1)
	Current	977.2 (0.4)	4.9 (0.1)
	Potential	976.9	5.1

when lake levels are still slowly falling, contains four of the top 10 largest net groundwater flow years (highest loss from the lake to the groundwater system), while the latter part, when lake levels begin to rise again, contains the top three smallest net groundwater flow years (smallest loss from the lake to the groundwater system) (Figure 71, Figure 72). Pleasant Lake levels are therefore an integrated response to both weather and nearby groundwater levels over multi-year to decadal time scales.

The infrequent high, frequent high, median, frequent low, and infrequent low water levels shift 0.4 to 0.5 feet lower from the no-irrigated-agriculture scenario to the current-irrigated-agriculture scenario (Table 39). This reduction in lake levels is remarkably uniform across time (Figure 67) across seasons (Table 40), and across lake level magnitudes (Figure 68). We find the frequency, duration, rate of change, and timing of water levels as well as the lake water budget are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario (Figure 67 to Figure 72, Table 39 to Table 45, Supplemental Information II: Lake Water Budgets). The relatively constant downward shift in lake levels results in longer durations above or below the no-irrigated-agriculture frequent high, median, and frequent low (Table 41), but not compared to the current-irrigated-agriculture levels. This indicates that irrigated agriculture does not alter the variability of lake levels at Pleasant Lake, it simply shifts levels lower.

In the potential-irrigated-agriculture scenario, lake levels drop by an additional 0.0-0.3 ft (Table 39), with the largest decline occurring at the median lake level. As in the current-irrigated-agriculture scenario, the frequency, duration, rate of change, and timing of water levels as well as the lake water budget are approximately the same as in the no-irrigated-agriculture scenario (Figure 67 to Figure 72, Table 39 to Table 45); the main effect of additional groundwater withdrawals is to shift lake levels lower.

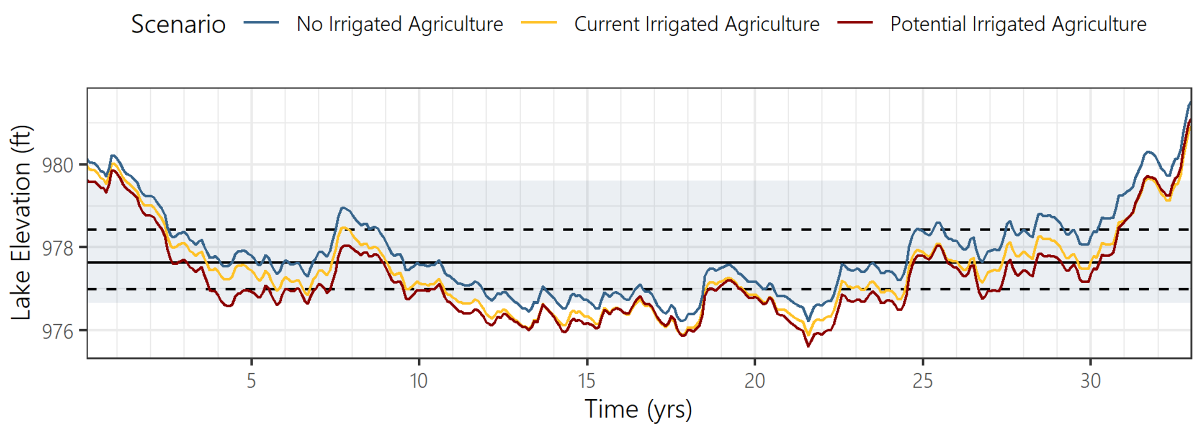

Figure 67. Modeled lake levels for irrigation scenarios at Pleasant Lake. Lake level elevation at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios. The shaded rectangle extends from the infrequent low to the infrequent high level for the no-irrigated-agriculture scenario, with dashed lines denoting the frequent low and frequent high level for the no-irrigated-agriculture scenario and the solid horizontal line representing the median level for the no-irrigated-agriculture scenario.

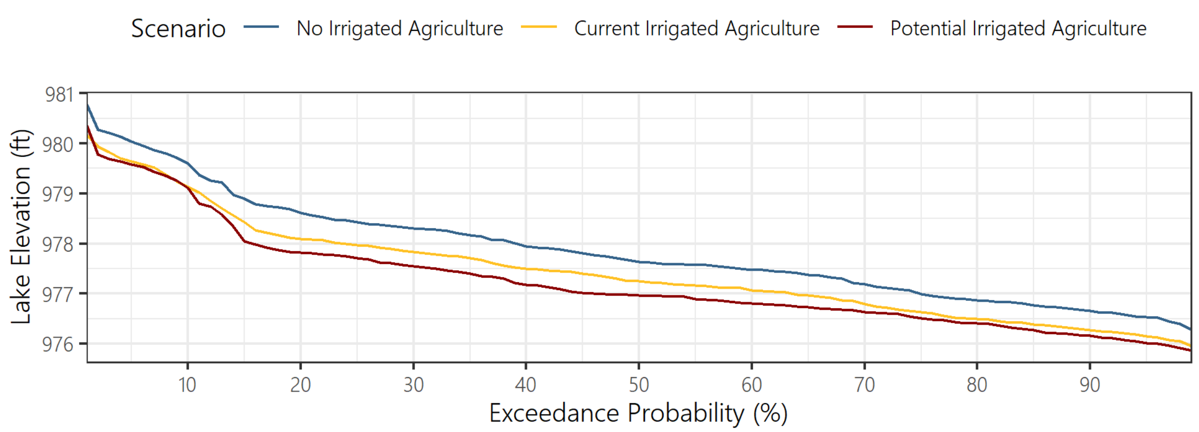

Figure 68. Lake level exceedance probability curves for irrigation scenarios at Pleasant Lake. Lake level exceedance probability curves at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios.

Table 41. Modeled frequencies and durations of lake levels in excess of given exceedance probabilities (standard deviation) at Pleasant Lake. The change in frequency and duration under the current- and potential-irrigated-agriculture scenarios compares lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Metric	Irrigated Agriculture Scenario	Times Exceeded for 1+ months	Times Exceeded for 2+ yrs	Median Duration (months)	CV of Duration (%)
Infrequent High	No	2 (0)	0 (0)	20 (5)	11 (28)
	Current	4 (1)	0 (0)	6 (4)	33 (26)
	Potential	4	0	4	59
Frequent High	No	7 (1)	2 (0)	11 (3)	93 (13)
	Current	3 (2)	2 (0)	27 (8)	74 (36)
	Potential	2	2	28	3
Above Median	No	8 (1)	3 (0)	6 (5)	145 (22)
	Current	6 (2)	3 (1)	24 (7)	61 (23)
	Potential	7	2	12	85
Below Median	No	7 (1)	1 (1)	5 (2)	216 (37)
	Current	5 (2)	2 (0)	10 (10)	157 (24)
	Potential	6	2	18	148
Frequent Low	No	5 (0)	1 (0)	22 (2)	59 (8)
	Current	6 (2)	2 (1)	6 (9)	154 (41)
	Potential	10	2	6	151
Infrequent Low	No	5 (1)	0 (0)	5 (1)	71 (8)
	Current	4 (2)	1 (1)	22 (7)	86 (38)
	Potential	8	2	4	147

Table 42. Modeled frequencies at Pleasant Lake at which median seasonal levels are higher than median levels in the season prior or growing season (April-Oct) prior (spring only) (standard deviation).

Metric	Irrigated Agriculture Scenario	% Years > Prior Season	% Years > Prior Growing Season
Winter	No	38.7 (1.4)	
	Current	41.9 (1.8)	
	Potential	41.9	
Spring	No	50.0 (2.3)	37.5 (2.1)
	Current	50.0 (1.8)	37.5 (2.0)
	Potential	46.9	40.6
Summer	No	43.8 (2.5)	
	Current	46.9 (3.4)	
	Potential	56.2	
Fall	No	43.8 (1.5)	
	Current	43.8 (0.8)	
	Potential	43.8	

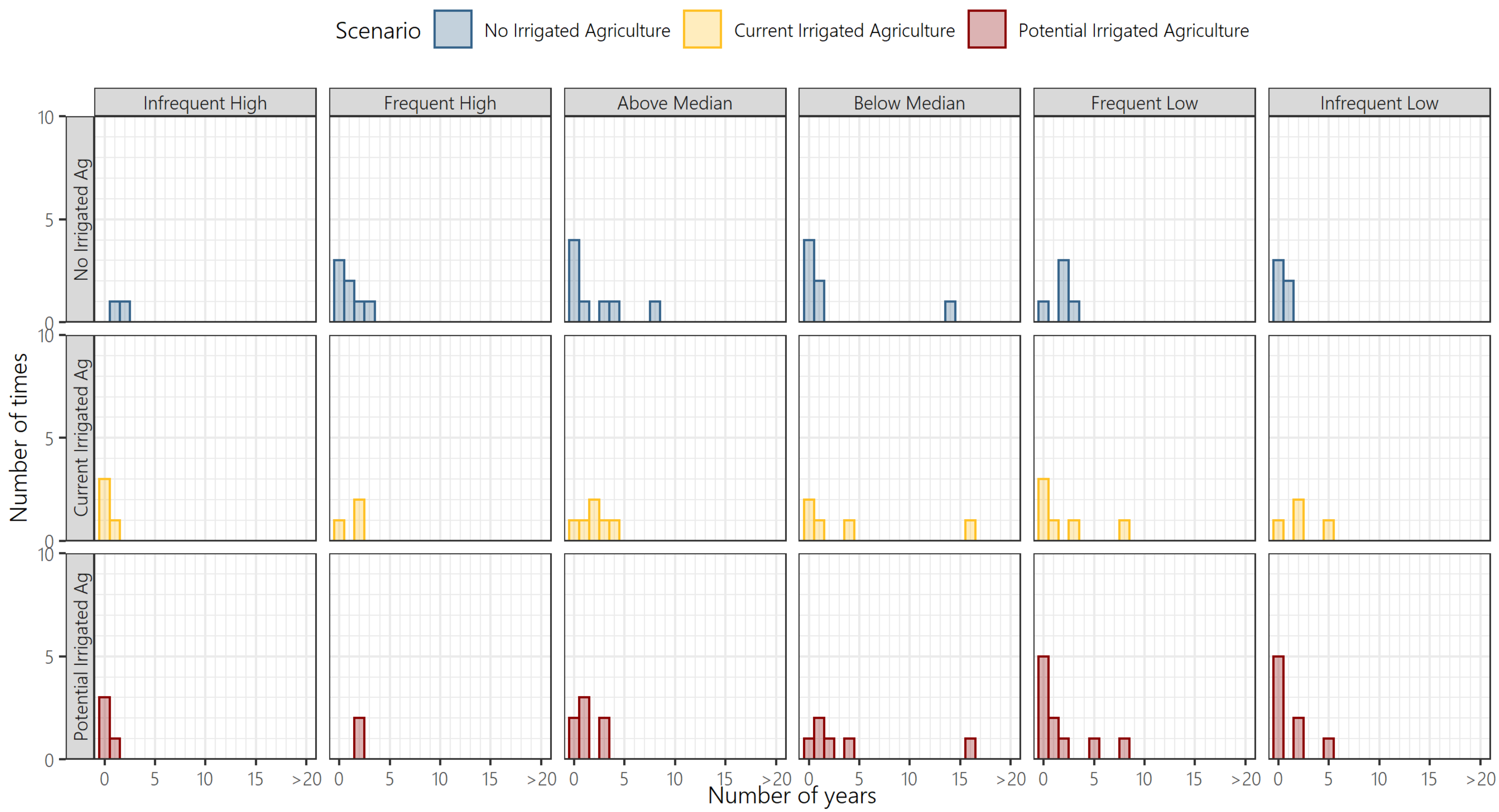

Figure 69. Durations in excess of lake level exceedance probabilities at Pleasant Lake. Histogram showing the number of times lake levels are below the infrequent low, frequent low, and median or above the infrequent high, frequent high, and median for 0-1, 1-2, etc. years. Duration under the current- and potential-irrigated-agriculture scenarios compare lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Table 43. Modeled rate of change (rise and fall) in Pleasant Lake levels as well as coefficient of variation in rate of change, and number of times rates exceeded 1.5 ft/time period over 1 month, 3 months, and 12 months (standard deviation).

Metric	Irrigated Agriculture Scenario	Median Rise Rate (ft/time)	CV of Rise Rate (%)	Times Rise Rate > 1.5 ft/time	Median Fall Rate (ft/time)	CV of Fall Rate (%)	Times Fall Rate > 1.5 ft/time
1 Month	No	0.1 (0.0)	88 (1)	0 (0)	-0.1 (0.0)	-72 (1)	0 (0)
	Current	0.1 (0.0)	87 (1)	0 (0)	-0.1 (0.0)	-73 (1)	0 (0)
	Potential	0.1	87	0	-0.1	-80	0
3 Month	No	0.2 (0.0)	90 (2)	0 (0)	-0.2 (0.0)	-67 (2)	0 (0)
	Current	0.2 (0.0)	90 (2)	0 (0)	-0.2 (0.0)	-67 (1)	0 (0)
	Potential	0.2	91	0	-0.2	-74	0
12 Month	No	0.4 (0.0)	80 (1)	4 (1)	-0.4 (0.0)	-69 (1)	0 (0)
	Current	0.4 (0.0)	84 (2)	3 (1)	-0.4 (0.0)	-65 (2)	0 (0)
	Potential	0.4	80	5	-0.4	-73	0

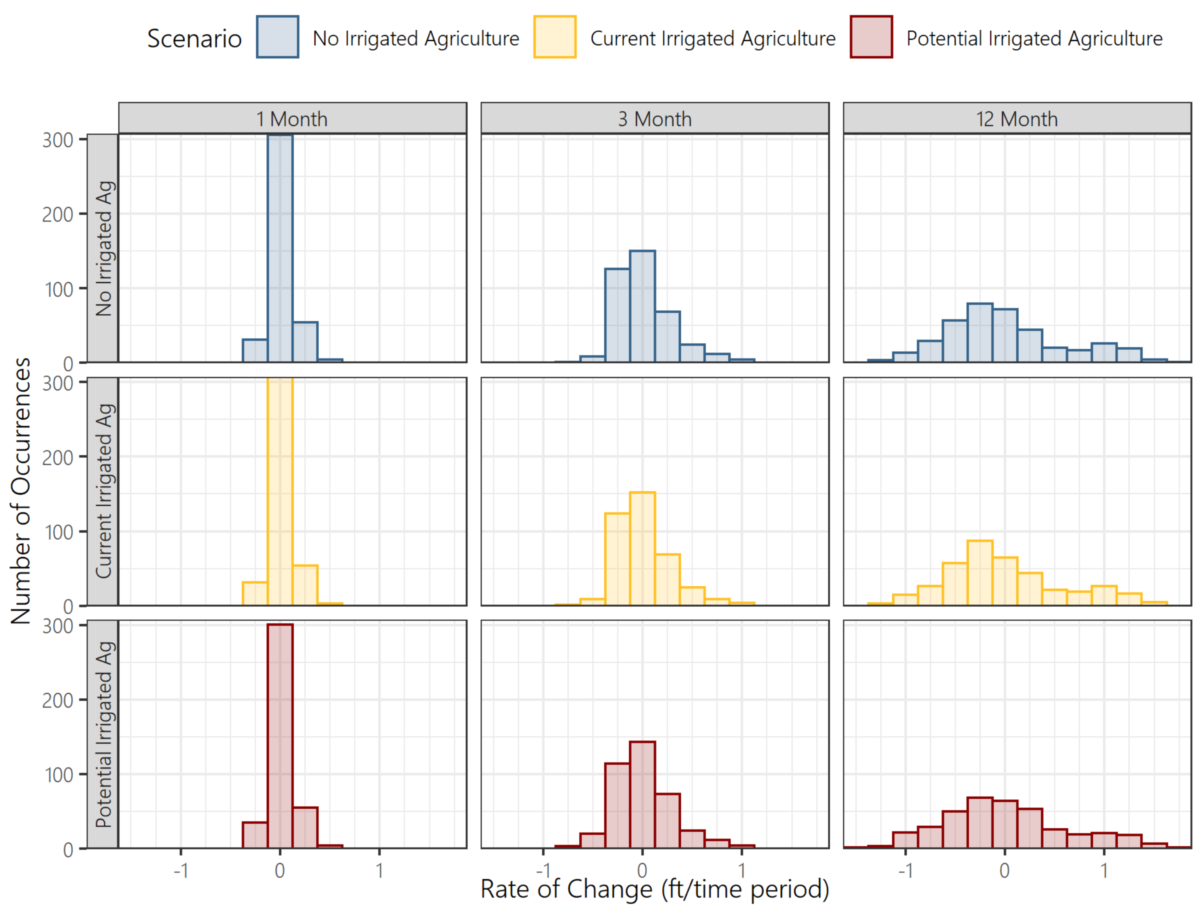

Figure 70. Rate of change in lake levels at Pleasant Lake. Histograms show the distribution in the rate of change in lake levels (ft/time period) across one month, 3 months, and 12 months.

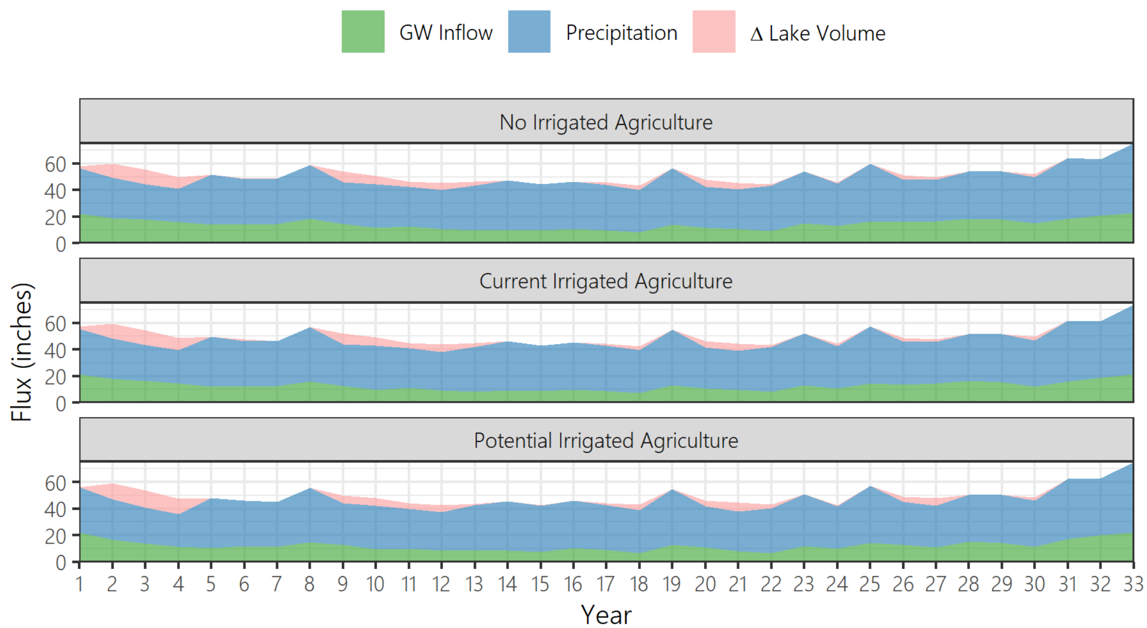

Figure 71. Modeled inflow in inches, Pleasant Lake. Annual precipitation, groundwater inflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

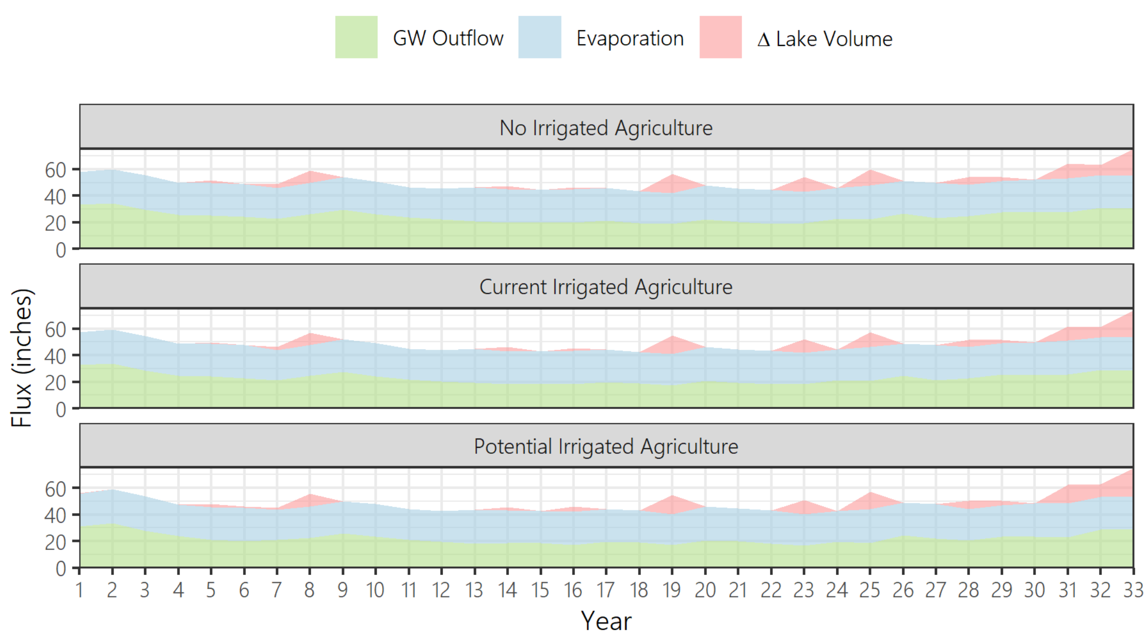

Figure 72. Modeled outflow in inches, Pleasant Lake. Annual evaporation, groundwater outflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

Table 44. Modeled water balance volumes as a percent of inflow and outflow for each model scenario at Pleasant Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (%)	No	48.4	69.2	78.1
	Current	49.2	71.3	80.5
	Potential	49.7	71.5	81.0
Groundwater Inflow (%)	No	18.8	28.0	38.5
	Current	16.9	24.7	37.2
	Potential	15.0	23.7	39.0
Evaporation (%)	No	32.7	48.0	56.7
	Current	33.3	49.6	58.0
	Potential	32.9	50.9	57.9
Groundwater Outflow (%)	No	33.3	47.1	57.8
	Current	31.5	44.9	57.5
	Potential	31.1	44.9	56.8
Δ Lake Volume (%) (pos = inflow, neg = outflow)	No	-19.5	-2.2	27.2
	Current	-20.5	-3.4	28.1
	Potential	-24.2	-1.7	29.0

Table 45. Modeled water balance volumes (ac-ft) and lake water residence time (yr) for each model scenario at Pleasant Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (ac-ft/yr)	No	262	350	587
	Current	260	343	583
	Potential	256	341	584
Groundwater Inflow (ac-ft/yr)	No	81	153	253
	Current	70	129	234
	Potential	63	117	245
Evaporation (ac-ft/yr)	No	237	255	279
	Current	233	251	278
	Potential	231	247	277
Groundwater Outflow (ac-ft/yr)	No	192	247	373
	Current	176	220	365
	Potential	167	214	363
Δ Lake Volume (ac-ft/yr)	No	-229	10	116
	Current	-229	15	120
	Potential	-240	7	137
Residence Time (yr)	No	2.5	3.6	4.2
	Current	2.5	3.7	4.3
	Potential	2.5	3.8	4.6

Long Lake

In the no-irrigated-agriculture scenario, Long Lake levels usually fluctuate within a 5.9-ft range (Table 46, Figure 73, Figure 74). This range is very large relative to the maximum depth of Long Lake (Table 47), which varies from 2.9 ft to 8.8 ft over this range in lake levels (Table 46). Lake levels fall below the median for at least one month seven times over the time period examined, indicating that lake levels transition from high to low every 5 years on average. However, actual durations above and below the median are variable and range from just a few months to 14 years with a median duration of 15 and five months, respectively (Table 48, Figure 76). The timing of high vs. low levels at Long Lake does not show a strong seasonal pattern (Table 49), and the annual change in lake levels (on average 0.6 to 0.7 ft/year; Table 50, Figure 75) is much smaller than the full range in lake levels. Thus, fluctuations between high and low lake levels do not occur on annual or shorter time scales but on longer, multi-year time scales.

Table 46. Modeled lake elevation, area, volume, mean depth, and max depth (standard deviation) associated with given exceedance probabilities at Long Lake.

Metric	Irrigated Agriculture Scenario	Elevation (ft)	Area (acres)	Volume (acre-ft)	Mean Depth (ft)	Max Depth (ft)
Infrequent High	No	1100.8 (0.7)	55.0 (1.4)	324 (35)	5.9 (0.5)	8.8 (0.7)
	Current	1098.7 (0.9)	49.1 (2.6)	211 (47)	4.3 (0.7)	6.6 (0.9)
	Potential	1098.5	48.5	202	4.2	6.4
Frequent High	No	1098.5 (0.8)	48.7 (2.4)	204 (43)	4.2 (0.6)	6.5 (0.8)
	Current	1095.6 (1.0)	38.0 (4.3)	76 (42)	2.0 (0.8)	3.5 (1.0)
	Potential	1095.3	36.5	65	1.8	3.2
Median	No	1097.6 (0.8)	45.7 (2.5)	160 (38)	3.5 (0.6)	5.5 (0.8)
	Current	1094.3 (1.0)	29.3 (7.1)	32 (36)	1.1 (0.7)	2.2 (1.0)
	Potential	1093.8	24.8	19	0.8	1.8
Frequent Low	No	1095.9 (0.8)	39.1 (3.5)	86 (36)	2.2 (0.6)	3.8 (0.8)
	Current	1093.2 (1.0)	15.2 (9.1)	6 (25)	0.4 (0.6)	1.2 (1.0)
	Potential	1093.1	12.2	4.0	0.4	1.0
Infrequent Low	No	1094.9 (0.8)	34.2 (4.7)	52 (31)	1.5 (0.6)	2.9 (0.8)
	Current	1092.8 (1.0)	6.6 (9.8)	1 (19)	0.2 (0.5)	0.7 (1.0)

We see the same dynamics at Long Lake from year 11 to year 25 as at Pleasant Lake: a continuous low period with several high precipitation years, large losses to groundwater flow early in the time period, and gains from groundwater flow late in the time period (Figure 73, Figures 76 – 78). This further illustrates that Long Lake levels are an integrated response to both weather and nearby groundwater levels over multi-year to decadal time scales.

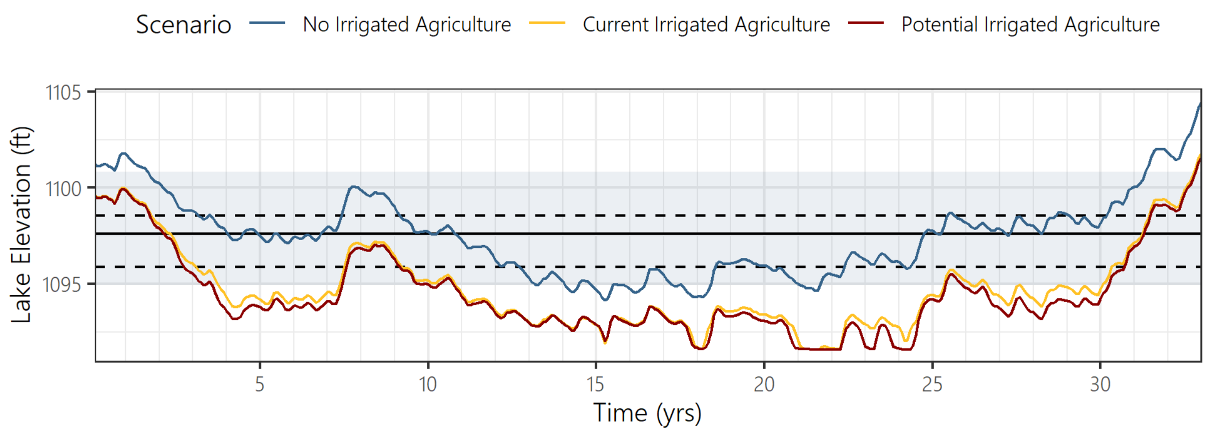

Figure 73. Modeled lake levels for irrigation scenarios at Long Lake. Lake level elevation at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios. The shaded rectangle extends from the infrequent low to the infrequent high level for the no-irrigated-agriculture scenario, with dashed lines denoting the frequent low and frequent high level for the no-irrigated-agriculture scenario and the solid horizontal line representing the median level for the no-irrigated-agriculture scenario.

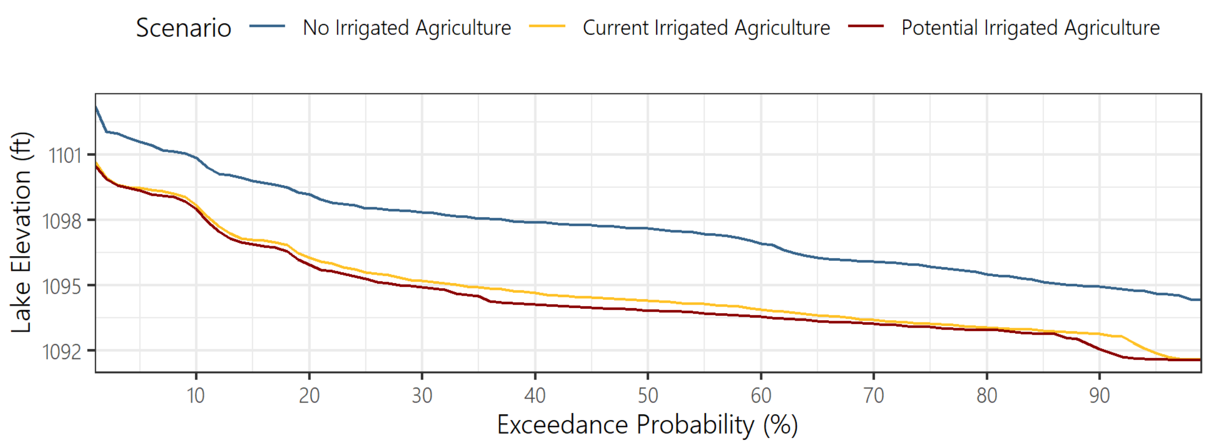

Figure 74. Lake level exceedance probability curves for irrigation scenarios at Long Lake. Lake level exceedance probability curves at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios.

Water levels shift 2.2 to 3.3 ft lower in the current-irrigated-agriculture scenario compared to the no-irrigated-agriculture scenario. This reduction in lake levels is remarkably uniform across time (Figure 73), across seasons (Table 47), and mostly across lake level magnitudes, though the median drops one foot more than the infrequent high and the infrequent low (Figure 74, Table 46). The frequency, duration, rate of change, and timing of water levels are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario (Figure 73 to Figure 76, Table 46 to Table 50), though very fast fall rates may be slightly more common under irrigated agriculture at Long

Lake. The relatively constant downward shift in lake levels results in longer durations above or below the no-irrigated-agriculture frequent high, median, and frequent low (Table 48), but not compared to the current-irrigated-agriculture levels. The duration below the no-irrigated-agriculture median lengthens from 5 to 347 months in the current-irrigated-agriculture scenario (Table 48), dropping below the median in year 3 and staying low until year 31 (Figure 73). Water balance fluxes are minimally affected relative to one another but they flow through a much smaller lake volume in the current-irrigated-agriculture scenario, which causes the median lake water residence time to fall from 0.9 years to just 0.3 years (Figure 77, Figure 78, Table 51, Table 52). Overall, irrigated agriculture does not alter the variability of lake levels at Long Lake, it primarily shifts levels lower. Because Long Lake is so shallow, this drawdown almost doubles percent variability in lake depth (Table 47) and triples the rate at which water is flushed through the lake.

Table 47. Modeled median lake level and coefficient of variation in maximum depth (standard deviation) across all months and across each season at Long Lake.

Metric	Irrigated Agriculture Scenario	Median Lake Level (ft)	CV of Max Depth (%)
Overall	No	1097.6 (0.8)	37.9 (5.0)
	Current	1094.3 (1.0)	78.6 (23.8)
	Potential	1093.9	90.4
Winter	No	1097.5 (0.7)	38.2 (5.4)
	Current	1094.1 (1.0)	85.7 (29.1)
	Potential	1093.6	100.1
Spring	No	1097.5 (0.7)	39.1 (5.4)
	Current	1094.1 (1.0)	82.5 (25.3)
	Potential	1093.9	95.8
Summer	No	1097.8 (0.7)	36.4 (4.7)
	Current	1094.5 (1.0)	71.0 (20.0)
	Potential	1094.1	78.6
Fall	No	1097.7 (0.8)	39.1 (4.9)
	Current	1094.4 (1.0)	79.1 (23.3)
	Potential	1093.9	92.3

In the potential-irrigated-agriculture scenario, lake levels drop by an additional 0.1-0.7 ft (Table 46). The largest decline occurs at the infrequent low lake level, which drops to the minimum elevation of the lake (1092.1 ft). This indicates that Long Lake is completely dry at least 10% of the time in the potential-irrigated-agriculture scenario. Because Long Lake is shallower in this scenario than in the current-irrigated-agriculture scenario, the percent variability in lake depth increases as well (Table 47). As in the current-irrigated-agriculture scenario, the frequency, duration, rate of change, and timing of water levels as well as the lake water budget are approximately the same as in the no-irrigated-agriculture scenario (Figures 73 - 76; Tables 46 – 50; Supplemental Information II: Lake Water Budgets); the main effect of additional groundwater withdrawals is to shift lake levels lower.

Table 48. Modeled frequencies and durations of lake levels in excess of given exceedance probabilities (standard deviation) at Long Lake. The change in frequency and duration under the current- and potential-irrigated-agriculture scenarios compares lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Metric	Irrigated Agriculture Scenario	Times Exceeded for 1+ months	Times Exceeded for 2+ yrs	Median Duration (months)	CV of Duration (%)
Infrequent High	No	2 (1)	0 (0)	20 (4)	4 (31)
	Current	1 (1)	0 (0)	3 (4)	NA (34)
	Potential	1	0	3	NA
Frequent High	No	6 (1)	2 (0)	12 (6)	99 (14)
	Current	2 (1)	0 (1)	20 (7)	7 (30)
	Potential	2	0	20	4
Above Median	No	8 (2)	4 (0)	15 (13)	101 (14)
	Current	2 (1)	1 (1)	24 (6)	14 (29)
	Potential	2	1	23	12
Below Median	No	7 (2)	1 (0)	5 (6)	217 (31)
	Current	1 (1)	1 (1)	347 (118)	NA (26)
	Potential	1	1	350	NA
Frequent Low	No	3 (1)	2 (0)	27 (7)	104 (15)
	Current	2 (2)	2 (1)	153 (79)	92 (43)
	Potential	2	2	158	90
Infrequent Low	No	7 (1)	0 (0)	6 (1)	58 (10)
	Current	5 (2)	3 (1)	29 (50)	135 (54)
	Potential	5	3	47	127

Table 49. Modeled frequencies at Long Lake at which median seasonal levels are higher than median levels in the season prior or growing season (April-Oct) prior (spring only) (standard deviation).

Metric	Irrigated Agriculture Scenario	% Years > Prior Season	% Years > Prior Growing Season
Winter	No	45.2 (1.5)	
	Current	41.9 (3.6)	
	Potential	45.2	
Spring	No	50.0 (1.8)	28.1 (2.3)
	Current	46.9 (2.7)	28.1 (2.6)
	Potential	43.8	28.1
Summer	No	43.8 (2.1)	
	Current	43.8 (3.1)	
	Potential	46.9	
Fall	No	40.6 (1.3)	
	Current	37.5 (2.2)	
	Potential	34.4	

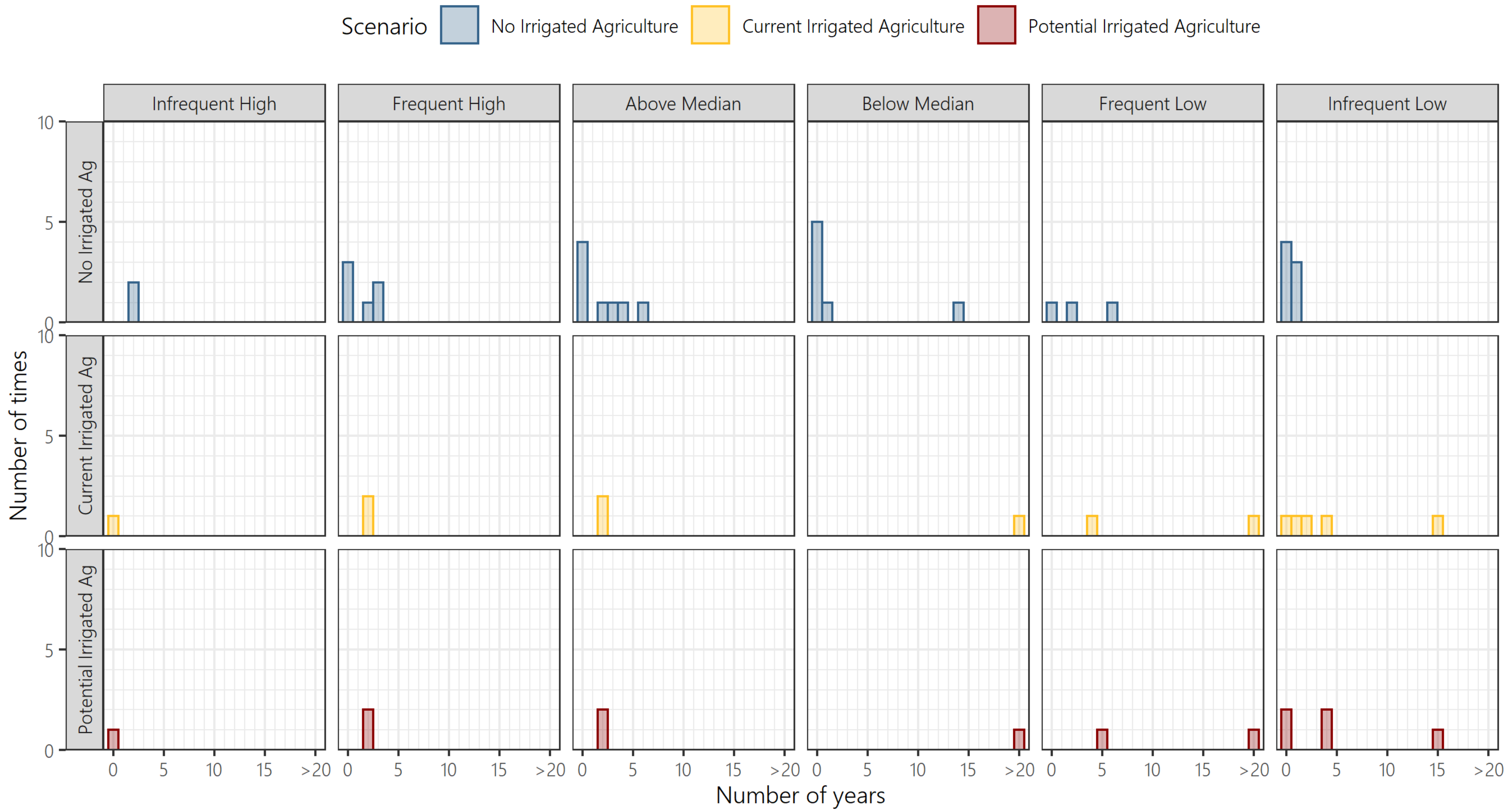

Figure 75. Durations in excess of lake level exceedance probabilities at Long Lake. Histogram showing the number of times lake levels are below the infrequent low, frequent low, and median or above the infrequent high, frequent high, and median for 0-1, 1-2, etc. years. Duration under the current- and potential-irrigated-agriculture scenarios compare lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Table 50. Modeled rate of change (rise and fall) in Long Lake levels as well as coefficient of variation in rate of change, and number of times rates exceeded 1.5 ft/time period over 1 month, 3 months, and 12 months (standard deviation).

Metric	Irrigated Agriculture Scenario	Median Rise Rate (ft/time)	CV of Rise Rate (%)	Times Rise Rate > 1.5 ft/time	Median Fall Rate (ft/time)	CV of Fall Rate (%)	Times Fall Rate > 1.5 ft/time
1 Month	No	0.1 (0.0)	85 (1)	0 (0)	-0.1 (0.0)	-58 (1)	0 (0)
	Current	0.2 (0.0)	87 (5)	0 (0)	-0.1 (0.0)	-76 (10)	0 (0)
	Potential	0.1	91	0	-0.1	-80	0
3 Month	No	0.3 (0.0)	84 (1)	1 (1)	-0.3 (0.0)	-60 (1)	0 (0)
	Current	0.3 (0.0)	88 (4)	3 (1)	-0.3 (0.0)	-67 (8)	0 (0)
	Potential	0.4	89	7	-0.3	-74	0
12 Month	No	0.7 (0.0)	77 (2)	52 (1)	-0.6 (0.0)	-73 (2)	16 (3)
	Current	0.8 (0.1)	82 (3)	51 (3)	-0.6 (0.1)	-82 (5)	44 (4)
	Potential	0.8	87	54	-0.6	-85	41

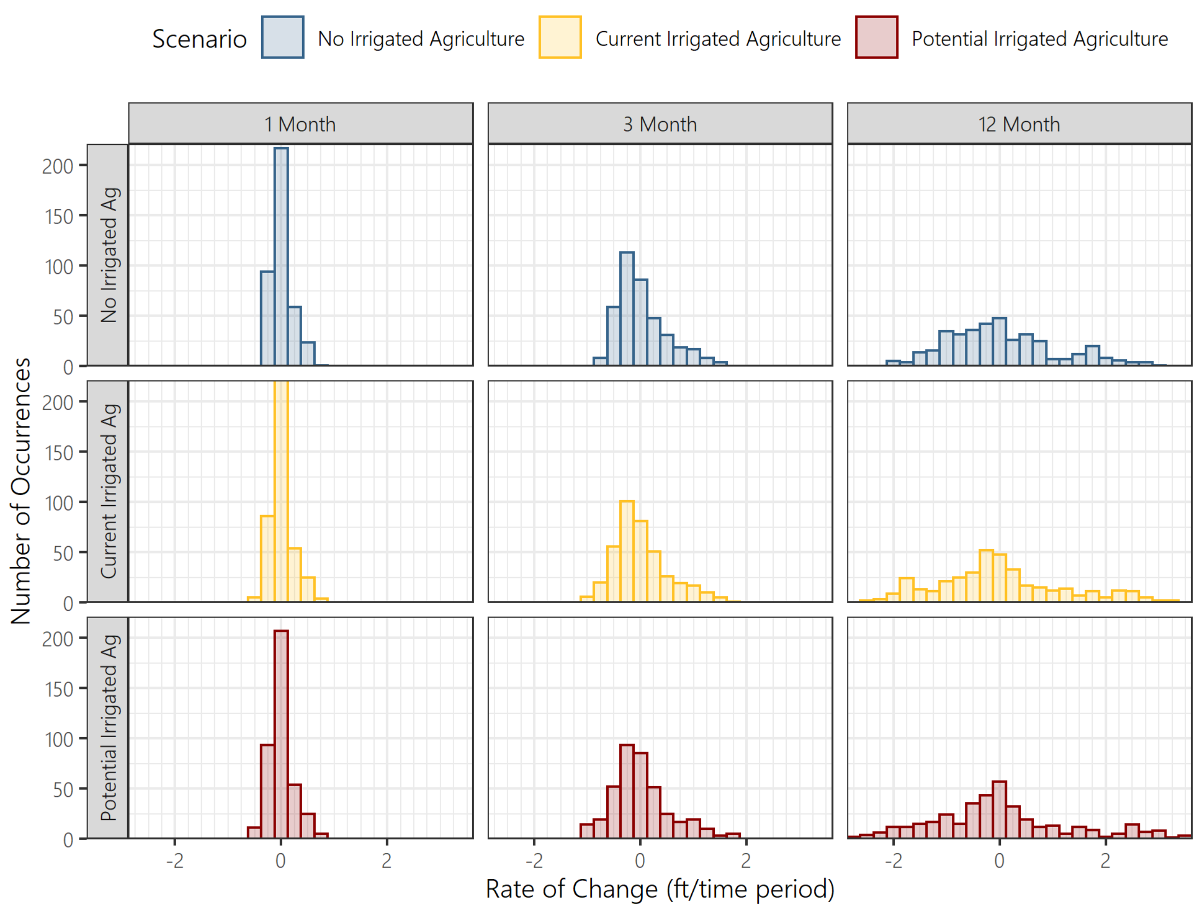

Figure 76. Rate of change in lake levels at Long Lake. Histograms show the distribution in the rate of change in lake levels (ft/time period) across one month, 3 months, and 12 months.

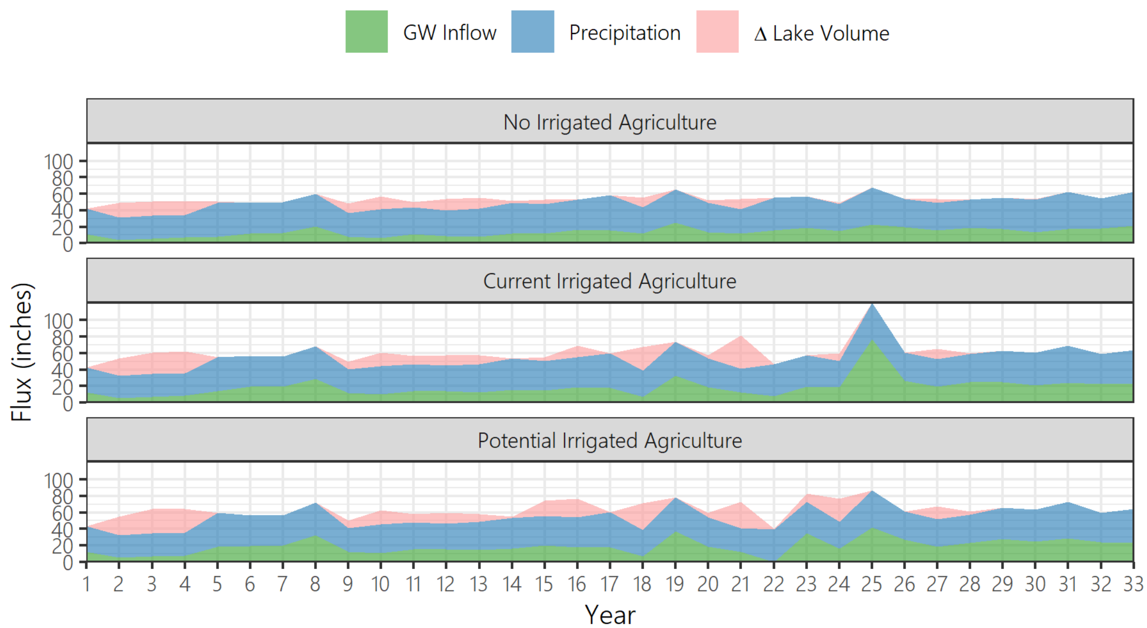

Figure 77. Modeled inflow in inches, Long Lake. Annual precipitation, groundwater inflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

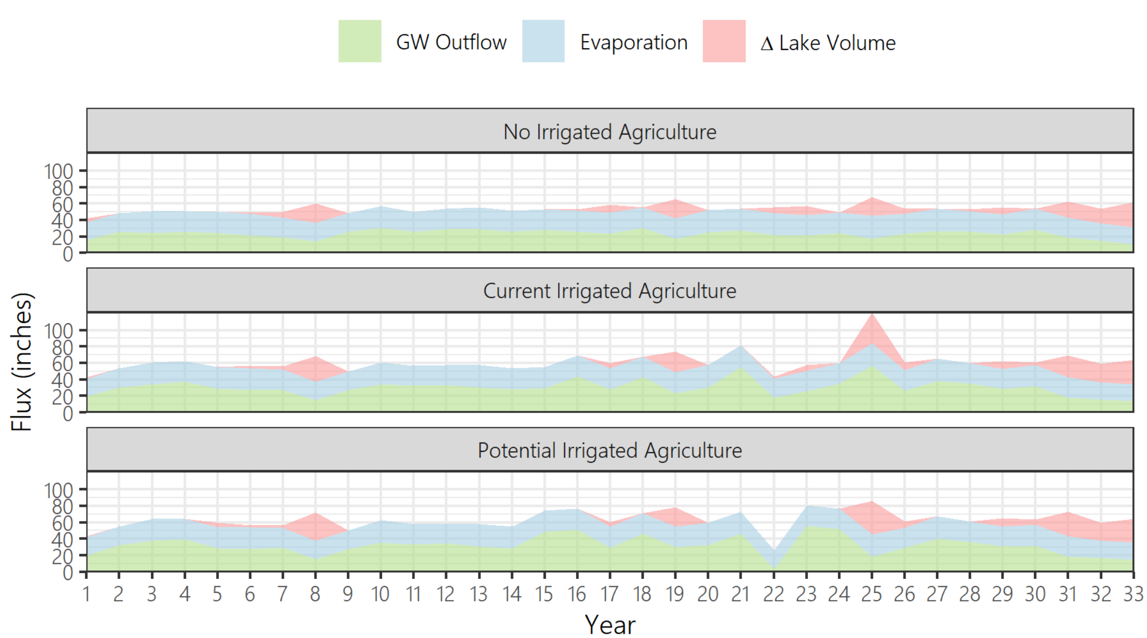

Figure 78. Modeled outflow in inches, Long Lake. Annual evaporation, groundwater outflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

Table 51. Modeled water balance volumes as a percent of inflow and outflow for each model scenario at Long Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (%)	No	53.4	66.3	82.1
	Current	45.0	62.0	75.4
	Potential	42.3	60.0	94.6
Groundwater Inflow (%)	No	8.3	26.3	37.7
	Current	9.8	31.1	42.4
	Potential	0.0	30.4	44.4
Evaporation (%)	No	33.3	47.3	54.4
	Current	32.5	43.8	52.8
	Potential	32.1	44.2	64.6
Groundwater Outflow (%)	No	17.0	48.0	55.0
	Current	20.8	45.8	58.1
	Potential	19.3	45.8	59.5
∆ Lake Volume (%) (pos = inflow, neg = outflow)	No	-35.9	-2.0	49.7
	Current	-43.6	5.4	46.2
	Potential	-47.3	6.6	47.7

Table 52. Modeled water balance volumes (ac-ft) and lake water residence time (yr) for each model scenario at Long Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (ac-ft/yr)	No	73	125	207
	Current	0	73	207
	Potential	0	59	206
Groundwater Inflow (ac-ft/yr)	No	19	42	110
	Current	0	25	117
	Potential	0	26	118
Evaporation (ac-ft/yr)	No	58	93	108
	Current	0	53	106
	Potential	0	42	105
Groundwater Outflow (ac-ft/yr)	No	45	77	122
	Current	0	53	140
	Potential	0	45	147
∆ Lake Volume (ac-ft/yr)	No	-157	4	83
	Current	-150	-2	96
	Potential	-147	-1	104
Residence Time (yr)	No	0.4	0.9	2.2
	Current	0.0	0.3	1.5
	Potential	0.0	0.2	1.5

Plainfield Lake

In the no-irrigated-agriculture scenario, Plainfield Lake levels usually fluctuate within a 5.4-ft range (Table 53, Figure 79, Figure 80). Plainfield Lake has very similar lake level magnitudes and a similar range in lake levels as nearby Long Lake, but because the bottom of Plainfield Lake is at a lower elevation than Long Lake, the same lake level elevations result in slightly deeper lake depths and less variation in lake depth (Table 54). Lake levels fall below the median for at least one month 5 times over the time period examined, indicating that lake levels transition from high to low every 7 years on average. However, actual durations above and below the median are variable and range from just a few months to 14 years with a median duration of 22 and 7 months, respectively (Table 55, Figure 79). The timing of high vs. low levels at Plainfield Lake does not show a clear seasonal pattern (Table 56), and the annual change in lake levels (on average 0.7 ft/year; Table 57, Figure 82) is much smaller than the full range in lake levels. Thus, fluctuations between high and low lake levels do not occur on annual or shorter time scales but on longer, multi-year time scales.

Table 53. Modeled lake elevation, area, volume, mean depth, and max depth (standard deviation) associated with given exceedance probabilities at Plainfield Lake.

Metric	Irrigated Agriculture Scenario	Elevation (ft)	Area (acres)	Volume (acre-ft)	Mean Depth (ft)	Max Depth (ft)
Infrequent High	No	1100.5 (0.5)	46.5 (1.0)	306 (25)	6.6 (0.4)	11.0 (0.5)
	Current	1099.0 (0.7)	42.6 (2.3)	238 (30)	5.6 (0.4)	9.5 (0.7)
	Potential	1098.9	41.8	232	5.5	9.4
Frequent High	No	1098.5 (0.7)	39.1 (2.7)	216 (29)	5.5 (0.3)	9.0 (0.7)
	Current	1096.3 (0.8)	33.9 (1.9)	139 (27)	4.1 (0.5)	6.9 (0.8)
	Potential	1096.1	33.4	129	3.9	6.6
Median	No	1097.3 (0.6)	35.9 (1.9)	173 (23)	4.8 (0.4)	7.8 (0.6)
	Current	1095.0 (0.8)	31.4 (1.5)	96 (25)	3.1 (0.6)	5.5 (0.8)
	Potential	1094.6	30.4	83	2.7	5.1
Frequent Low	No	1095.9 (0.6)	33.1 (1.4)	125 (22)	3.8 (0.5)	6.4 (0.6)
	Current	1093.8 (0.8)	28.4 (2.1)	60 (24)	2.1 (0.6)	4.4 (0.8)
	Potential	1093.6	27.9	55	2.0	4.1
Infrequent Low	No	1095.1 (0.6)	31.5 (1.4)	98 (21)	3.1 (0.5)	5.6 (0.6)
	Current	1093.2 (0.8)	26.5 (2.8)	44 (23)	1.7 (0.6)	3.7 (0.8)
	Potential	1092.9	25.1	36	1.4	3.5

We see the same dynamics at Plainfield Lake from year 11 to year 25 as at Pleasant and Long lakes: a continuous low period with several high precipitation years, large losses to groundwater flow early in the time period, and gains from groundwater flow late in the time period (Figure 79, Figure 81, Figure 83, Figure 84). This further illustrates that Plainfield Lake levels are an integrated response to both weather and nearby groundwater levels over multi-year to decadal time scales.

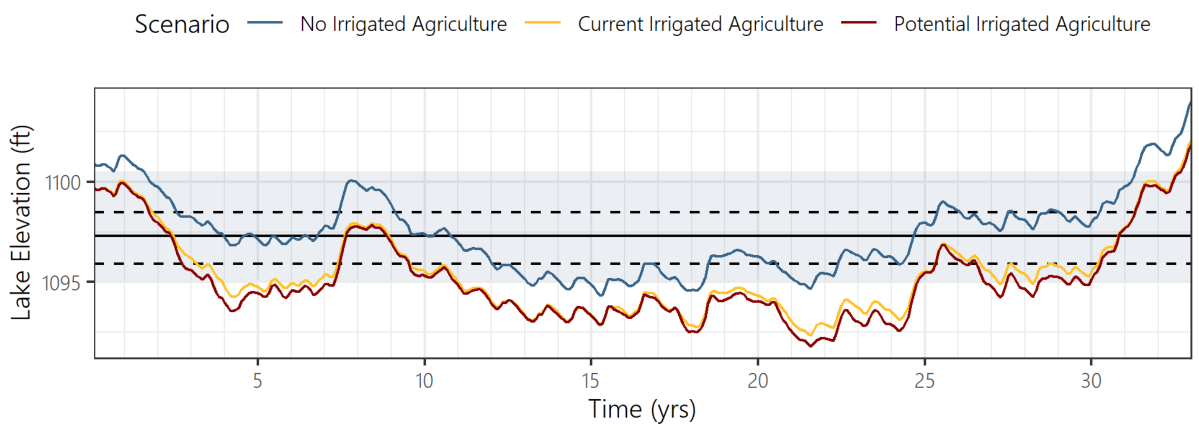

Figure 79. Modeled lake levels for irrigation scenarios at Plainfield Lake. Lake level elevation at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios. The shaded rectangle extends from the infrequent low to the infrequent high level for the no-irrigated-agriculture scenario, with dashed lines denoting the frequent low and frequent high level for the no-irrigated-agriculture scenario and the solid horizontal line representing the median level for the no-irrigated-agriculture scenario.

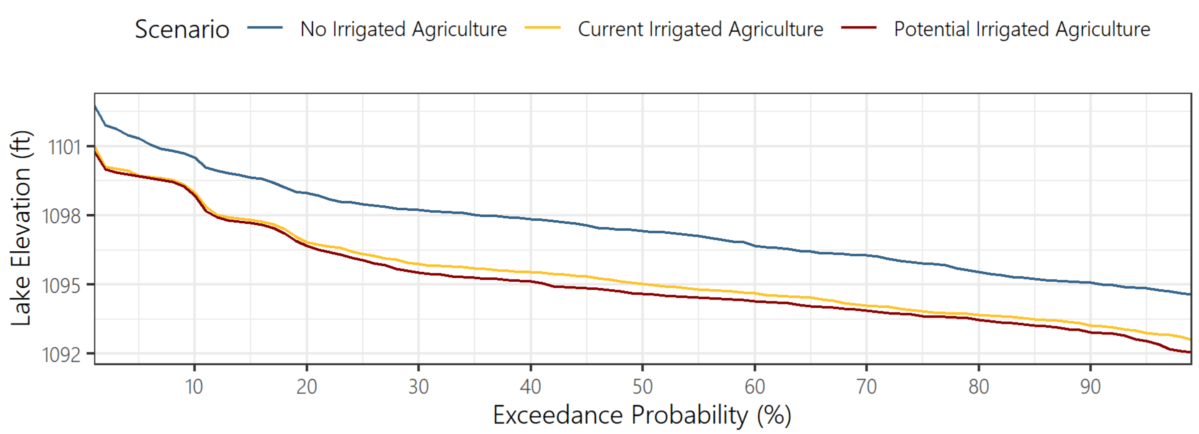

Figure 80. Lake level exceedance probability curves for irrigation scenarios at Plainfield Lake. Lake level exceedance probability curves at each study lake under the no-irrigated-agriculture (blue), current-irrigated-agriculture (yellow), and potential-irrigated-agriculture (red) modeled scenarios.

Water levels shift 1.5 to 2.3 ft lower from the no-irrigated-agriculture scenario to the current-irrigated-agriculture scenario. This reduction in lake levels is remarkably uniform across time (Figure 79), across seasons (Table 54), and mostly across lake level magnitudes, though the median drops the most (Table 53, Figure 80). Since the drawdown at Plainfield Lake is less than at Long Lake (around 2 ft vs. 3ft) and Plainfield Lake is deeper than Long Lake, this drawdown does not increase variability in lake depth as dramatically as at Long Lake (around 9% vs. 41% increase, Table 54). The frequency, duration, rate of change, and timing of water levels at Plainfield Lake are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario (Figure 79 to Figure 82, Table 53 to Table 57), though very fast fall rates may be slightly more common under the current-irrigated-agriculture scenario at Plainfield Lake. The relatively constant downward shift in lake levels results in longer durations above or below the no-irrigated-agriculture frequent high, median, and frequent low (Table 55), but not compared to the current-irrigated-agriculture levels. The duration below the no-irrigated-agriculture median lengthens from 7 to 262 months in the current-irrigated-agriculture scenario (Table 55), dropping below the median in year 9 and staying low until year 31 (Figure 79). Water balance fluxes are minimally affected relative to one another, but the smaller lake volumes under current irrigated agriculture cause the median lake water residence time to fall from 1.4 years to 0.9 years (Figure 83 and Figure 84, Table 58 and Table 59). Overall, irrigated agriculture does not alter the variability of lake levels at Plainfield Lake; it primarily shifts levels lower.

Table 54. Modeled median lake level and coefficient of variation in maximum depth (standard deviation) across all months and across each season at Plainfield Lake.

Metric	Irrigated Agriculture Scenario	Median Lake Level (ft)	CV of Max Depth (%)
Overall	No	1097.3 (0.6)	24.3 (1.8)
	Current	1095.1 (0.7)	33.6 (4.1)
	Potential	1094.6	36.6
Winter	No	1097.1 (0.6)	24.1 (1.8)
	Current	1094.9 (0.8)	33.6 (4.3)
	Potential	1094.5	36.9
Spring	No	1097.3 (0.6)	24.8 (1.9)
	Current	1095.0 (0.8)	35.1 (4.6)
	Potential	1094.5	38.1
Summer	No	1097.3 (0.6)	23.7 (1.7)
	Current	1095.1 (0.7)	32.3 (3.8)
	Potential	1094.7	34.6
Fall	No	1097.4 (0.6)	25.4 (1.7)
	Current	1095.2 (0.7)	34.5 (4.0)
	Potential	1094.6	38.0

In the potential-irrigated-agriculture scenario, lake levels drop by an additional 0.2-0.4 ft (Table 53), with the largest decline occurring at the median lake level. As in the current-irrigated-agriculture scenario, the frequency, duration, rate of change, and timing of water levels as well as the lake water budget are approximately the same as in the no-irrigated-agriculture scenario (Figure 79 to Figure 82, Table 53 to Table 57, Supplemental Information II: Lake Water Budgets); the main effect of additional groundwater withdrawals is to shift lake levels lower.

Table 55. Modeled frequencies and durations of lake levels in excess of given exceedance probabilities (standard deviation) at Plainfield Lake. The change in frequency and duration under the current- and potential-irrigated-agriculture scenarios compares lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Metric	Irrigated Agriculture Scenario	Times Exceeded for 1+ months	Times Exceeded for 2+ yrs	Median Duration (months)	CV of Duration (%)
Infrequent High	No	3 (1)	0 (0)	11 (5)	55 (27)
	Current	1 (1)	0 (0)	6 (3)	NA (33)
	Potential	1	0	4	NA
Frequent High	No	6 (0)	2 (0)	14 (2)	82 (5)
	Current	2 (1)	0 (1)	22 (5)	3 (31)
	Potential	2	0	20	3
Above Median	No	6 (1)	3 (0)	22 (13)	117 (12)
	Current	3 (1)	2 (1)	27 (5)	29 (24)
	Potential	3	2	27	31
Below Median	No	5 (1)	1 (0)	7 (5)	179 (17)
	Current	2 (1)	2 (1)	162 (84)	87 (24)
	Potential	2	2	163	87
Frequent Low	No	4 (1)	1 (0)	21 (8)	92 (25)
	Current	6 (2)	2 (1)	15 (35)	153 (41)
	Potential	4	3	51	110
Infrequent Low	No	6 (1)	0 (0)	6 (0)	25 (12)
	Current	6 (2)	1 (1)	7 (18)	192 (52)
	Potential	6	2	9	165

Table 56. Modeled frequencies at Plainfield Lake at which median seasonal levels are higher than median levels in the season prior or growing season (April-Oct) prior (spring only) (standard deviation).

Metric	Irrigated Agriculture Scenario	% Years > Prior Season	% Years > Prior Growing Season
Winter	No	45.2 (2.1)	
	Current	45.2 (2.3)	
	Potential	48.4	
Spring	No	46.9 (1.5)	31.2 (2.9)
	Current	50.0 (1.5)	28.1 (2.7)
	Potential	46.9	31.2
Summer	No	43.8 (2.6)	
	Current	40.6 (3.2)	
	Potential	46.9	
Fall	No	43.8 (2.3)	
	Current	40.6 (2.3)	
	Potential	37.5	

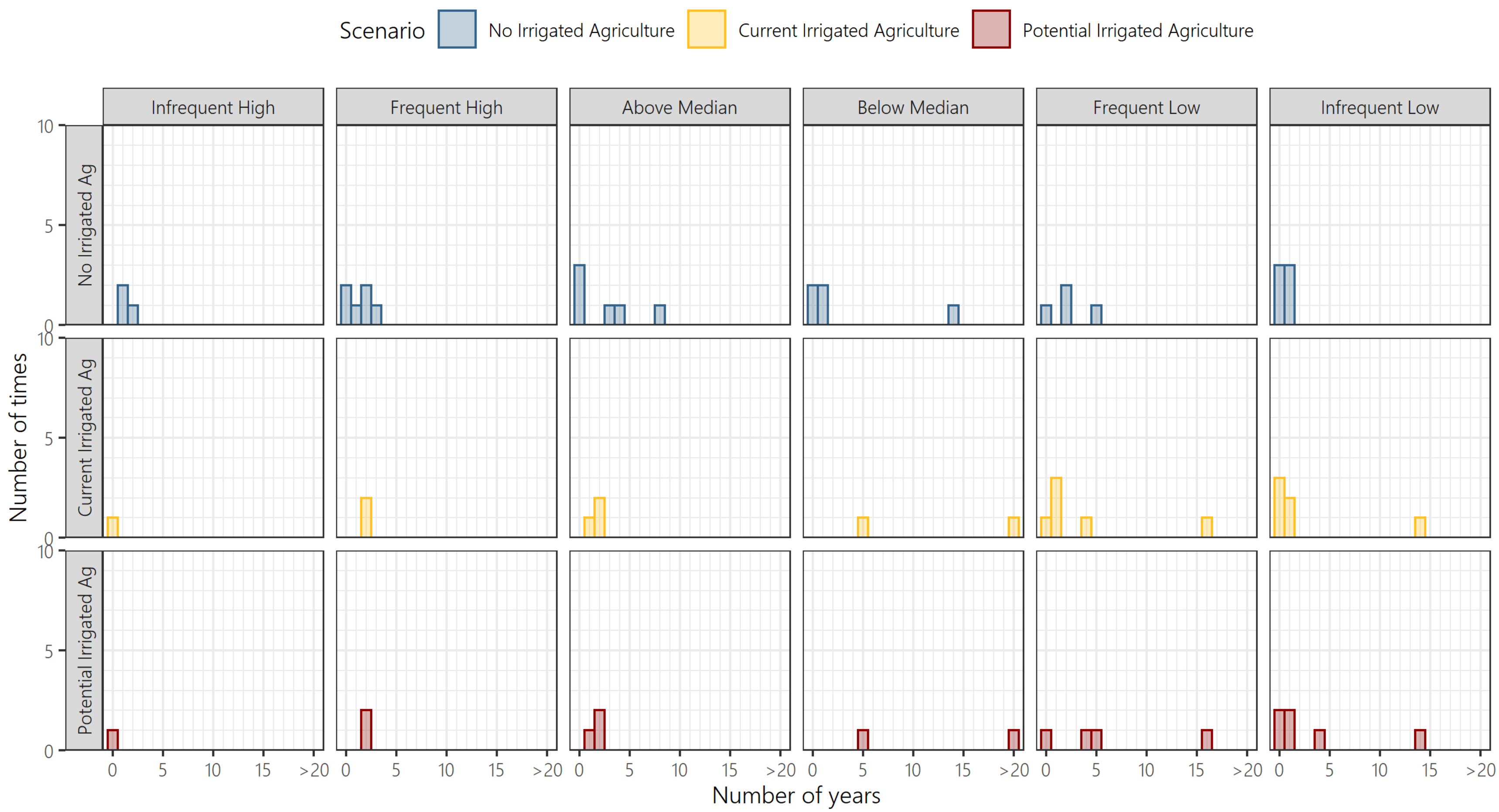

Figure 81. Durations in excess of lake level exceedance probabilities at Plainfield Lake. Histogram showing the number of times lake levels are below the infrequent low, frequent low, and median or above the infrequent high, frequent high, and median for 0-1, 1-2, etc. years. Duration under the current- and potential-irrigated-agriculture scenarios compare lake levels to the exceedance probability elevations in the no-irrigated-agriculture scenario.

Table 57. Modeled rate of change (rise and fall) in Plainfield Lake levels as well as coefficient of variation in rate of change, and number of times rates exceeded 1.5 ft/time period over 1 month, 3 months, and 12 months (standard deviation).

Metric	Irrigated Agriculture Scenario	Median Rise Rate (ft/time)	CV of Rise Rate (%)	Times Rise Rate > 1.5 ft/time	Median Fall Rate (ft/time)	CV of Fall Rate (%)	Times Fall Rate > 1.5 ft/time
1 Month	No	0.1 (0.0)	85 (1)	0 (0)	-0.1 (0.0)	-60 (1)	0 (0)
	Current	0.1 (0.0)	83 (1)	0 (0)	-0.1 (0.0)	-57 (2)	0 (0)
	Potential	0.1	83	0	-0.1	-68	0
3 Month	No	0.3 (0.0)	85 (2)	1 (1)	-0.3 (0.0)	-61 (1)	0 (0)
	Current	0.3 (0.0)	84 (1)	2 (1)	-0.3 (0.0)	-56 (2)	0 (0)
	Potential	0.4	80	4	-0.3	-67	0
12 Month	No	0.7 (0.0)	82 (2)	50 (1)	-0.7 (0.0)	-75 (2)	21 (1)
	Current	0.7 (0.0)	88 (2)	52 (1)	-0.7 (0.0)	-77 (1)	34 (3)
	Potential	0.7	89	53	-0.7	-81	46

Figure 82. Rate of change in lake levels at Plainfield Lake. Histograms show the distribution in the rate of change in lake levels (ft/time period) across one month, 3 months, and 12 months.

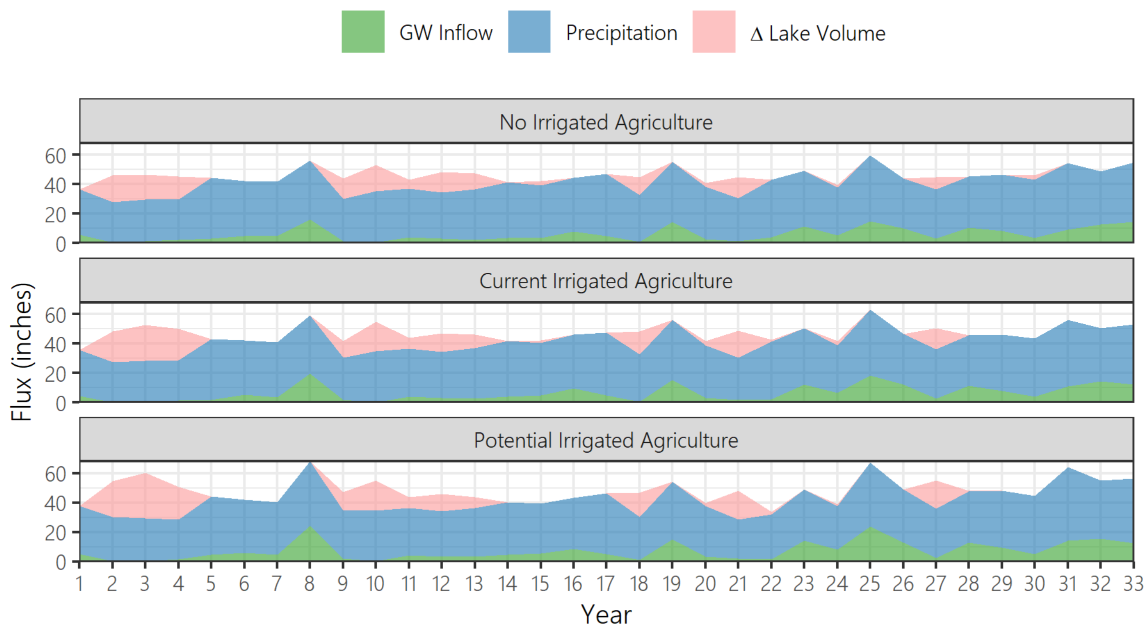

Figure 83. Modeled inflow in inches, Plainfield Lake. Annual precipitation, groundwater inflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

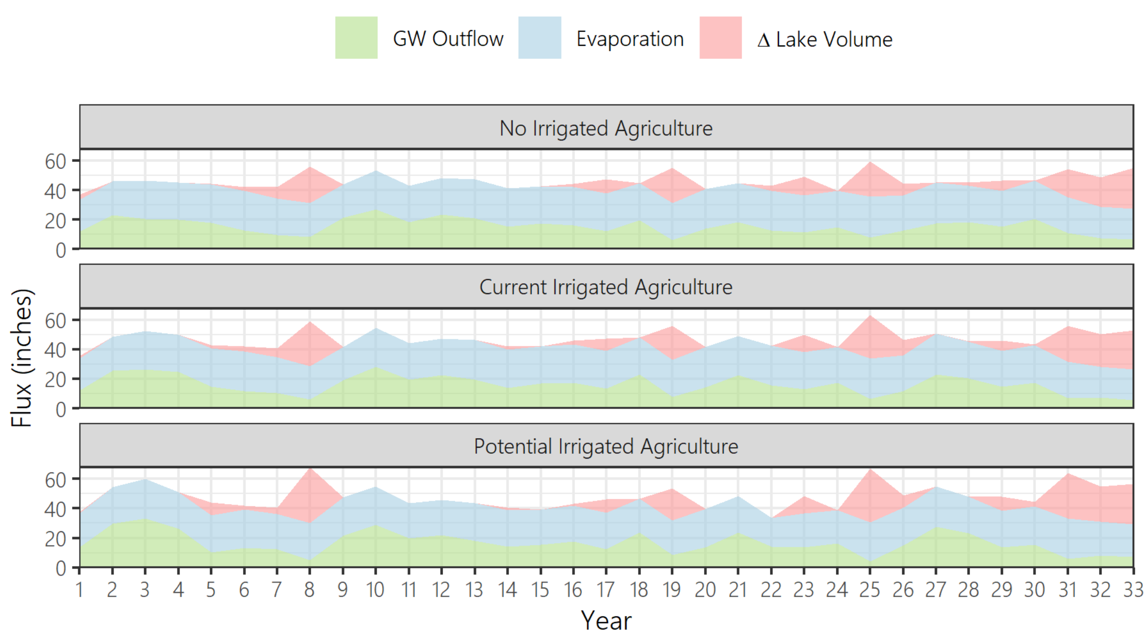

Figure 84. Modeled outflow in inches, Plainfield Lake. Annual evaporation, groundwater outflow, and change in lake volume in inches per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume

Table 58. Modeled water balance volumes as a percent of inflow and outflow for each model scenario at Plainfield Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (%)	No	58.7	76.7	93.2
	Current	52.3	75.9	95.8
	Potential	47.3	74.1	90.0
Groundwater Inflow (%)	No	1.0	9.8	28.4
	Current	0.1	9.6	31.7
	Potential	0.5	11.2	35.2
Evaporation (%)	No	37.7	55.9	66.3
	Current	39.2	55.0	65.5
	Potential	37.5	52.7	65.9
Groundwater Outflow (%)	No	11.4	37.1	50.7
	Current	9.2	36.6	52.5
	Potential	5.8	36.7	54.8
Δ Lake Volume (%) (pos = inflow, neg = outflow)	No	-39.6	0.6	50.8
	Current	-47.1	0.6	50.8
	Potential	-52.1	2.3	55.4

Table 59. Modeled water balance volumes (ac-ft) and lake water residence time (yr) for each model scenario at Plainfield Lake.

Flux	Irrigated Agriculture Scenario	Minimum	Median	Maximum
Precipitation (ac-ft/yr)	No	79	106	170
	Current	65	93	169
	Potential	49	90	169
Groundwater Inflow (ac-ft/yr)	No	2	13	61
	Current	0	10	59
	Potential	1	12	67
Evaporation (ac-ft/yr)	No	65	78	89
	Current	45	67	88
	Potential	32	64	87
Groundwater Outflow (ac-ft/yr)	No	17	45	90
	Current	14	37	97
	Potential	9	36	101
Δ Lake Volume (ac-ft/yr)	No	-117	-1	71
	Current	-111	-1	80
	Potential	-106	-2	90
Residence Time (yr)	No	0.8	1.4	2.8
	Current	0.4	0.9	2.3
	Potential	0.3	0.8	2.3

Comparison Between Modeled and Observed Lake Levels

MODFLOW is useful for exploring how different land use and irrigation scenarios could affect lake levels. Because many of the ecosystem impacts we are evaluating are stage-dependent, MODFLOW lake level predictions are ideally within the range expected given observed lake levels. We empirically tested model accuracy using the calibration period (2012 – 2018) and qualitatively evaluated how well MODFLOW predictions overlapped with observations in the no-irrigated-agriculture and current-irrigated-agriculture scenarios (1986 – 2018).

The comparison between the calibration period (2012 – 2018) of MODFLOW lake level estimates and observed lake levels indicated that MODFLOW predicted lake levels well. This comparison used all observed lake level data from USGS, DNR, and Waushara County from 2012 – 2018. The RMSE was 0.50 feet on Pleasant Lake, 0.17 feet on Long Lake and 0.48 feet on Plainfield Lake. These results allow us to consider how model uncertainty influences our ability to evaluate significant impacts of irrigation on the three lakes by comparing the margin of error in lake level estimates to the differences observed between scenarios and the ecosystem significance thresholds.

The MODFLOW irrigated agriculture scenarios use the same set of model parameters as those used in the calibration period. However, all three scenarios represent land use that differs from what was actually in place during the climate period assessed (1981 – 2018). Observed lake levels represent a combination of climate, land cover, and irrigation effects. The MODFLOW scenarios represent observed climate variability, but do not capture the change of irrigation well installation over this time period. The MODFLOW scenarios also do not attempt to recreate any other changes to the Central Sands that occurred during the period, including deforestation or reforestation, changes in non-irrigated agricultural land use, changes in municipal, industrial, or other non-agricultural high capacity wells, changes in farming practices, or any other variable other than removing irrigated agriculture. Thus, we can expect lake level observations to loosely overlap with some combination of the exceedance probabilities from both the no-irrigated-agriculture and current-irrigated-agriculture scenarios. Because of this, predicted lake levels and exceedance probabilities in the no-irrigated-agriculture and current-irrigated-agriculture scenarios should be similar to, but not match precisely with observed levels during the 1981-2018 period.

In the no-irrigated-agriculture and current-irrigated-agriculture scenarios, predictions of lake levels qualitatively match observed lake levels on Long Lake and Plainfield Lake, but are likely underestimating Pleasant Lake levels by approximately two feet (Figure 14; Pruitt, 2021). Long Lake’s observed levels are mostly within the no-irrigated-agriculture 10-90% exceedance probability range, though some of the lowest observations dip down into the current-irrigated-agriculture range. The same is true for Plainfield Lake. The early aerial photo observations on Pleasant Lake overlap the no-irrigated-agriculture scenario range better than do the Waushara County historical data, which are several feet higher. The Waushara County data during the low lake levels in the mid-2000’s overlap the MODFLOW scenarios. The extremely high lake levels from the past few years go beyond the 10% exceedance probability on all three lakes, which is expected given that the lakes were at their highest levels on record during that period. Thus, we conclude that MODFLOW’s no-irrigated-agriculture and current-irrigated-agriculture scenarios match observed lake level data sufficiently well. Some caution should be used when interpreting stage-specific impacts on Pleasant Lake. Fortunately, Pleasant Lake is much deeper, so stage-specific impacts are less widespread across indicators on Pleasant Lake than on Long and Plainfield Lakes.

Water Chemistry

Literature Review

There are two main ways that water level fluctuations resulting from changes in groundwater flow can impact lake water quality. First, changes in groundwater contributions to lake water and chemical budgets can alter lake chemistry and buffering capacity. Second, changes in water levels that affect the lake mixing regime can alter internal nutrient processes and impact oxygen availability for fish. While some amount of water level variation is expected in seepage lakes, it is possible that large changes to groundwater flows could drive these lakes into new chemical and physical states which are outside the desirable range for native aquatic organisms.

Impacts to Lake Solute Budgets

Groundwater is often neglected in studies of lake water budgets and chemistry budgets (Rosenberry et al., 2015; Lewandowski et al., 2015), but it is commonly the main source of dissolved chemicals (solutes) in lakes (Figure 10; Kenoyer and Anderson, 1989; Vanek, 1991; Lewandowski et al., 2015; Nisbeth et al., 2019). Because solute concentrations in groundwater are typically much higher than concentrations in precipitation, even lakes with a relatively small amount of groundwater inflow can receive most of their solutes from groundwater (Kenoyer and Anderson, 1989; Lewandowski et al., 2015). This means that persistent declines in groundwater inflow can reduce the concentration of solutes in seepage lakes (Webster et al., 1996). However, if declines in groundwater inflow coincide with sufficiently large declines in lake levels, it is possible that evapoconcentration of solutes in a smaller lake volume may instead increase the concentration of solutes in the lake (Webster et al., 1996). Higher salinity is in fact a common outcome of lower lake levels during drought, but these increases are not always significant, and this response is not universal (Mosley, 2015). The dominant lake water chemistry response to lower lake levels depends on lake water residence time, which can change with lake levels, as well as the relative magnitude of groundwater inflow vs. precipitation and groundwater outflow vs. evaporation, which can change under different groundwater flow or climatic conditions.

Given these complex relationships among lake volume, groundwater flow, and climate, it is difficult to predict which response will dominate within a given lake over long time periods without either a) monitoring water chemistry over that time period, or b) modeling the lake solute budget across a range of climate and groundwater flow conditions. However, a dramatic change in either direction (higher or lower salinity) could significantly impact lake water quality, since moderate amounts of solutes are necessary for maintaining normal biological and chemical processes, but too much can be toxic (see p. 41). In calcium bicarbonate systems like the study lakes, magnesium is generally well correlated with alkalinity, calcium, and conductivity (see p. 41) and thus can serve as a proxy for changes in these more biologically active parameters.

Impacts to Lake Mixing Regimes

While nutrient dynamics can be impacted by the same factors as lake solute budgets, both internal nutrient loading and dissolved oxygen (DO) availability are also strongly controlled by lake mixing regimes. As discussed earlier (see p. 41), water quality and water clarity decline when in-lake concentrations of phosphorus increase, a phenomenon that can occur due to increases in external loading or internal loading. Low DO conditions in the hypolimnion release phosphorus bound to the sediment, and though phosphorus becomes labile, it mostly remains in the hypolimnion where it is unable to fuel algae blooms near the surface. Lakes that mix throughout the summer can bring phosphorus to the surface where algae have enough light to grow. Even fully mixed lakes tend to stratify long enough for anoxia to develop and release more phosphorus from the sediment at multiple times in the season. Thus, consistently stratified lakes can often maintain better water quality and water clarity in surface waters than well-mixed lakes.

Stratification is strongly controlled by water level: the deeper a lake is, the more likely it is to stratify (Lathrop and Lillie, 1980; Heiskary and Wilson, 2005; Welch and Cooke, 2005). The importance of water levels to stratification combined with the importance of stratification to internal nutrient processes means that water levels exert a strong control on water quality and water clarity. When a stratified lake becomes shallower, it becomes less resistant to mixing. This can reduce the length of summer stratification and/or increase the number of summer deep mixing events, both of which lead to declines in water quality (Mosley, 2015; Robertson et al., 2018). Changing water levels have also been shown to be an important predictor of Secchi depth (i.e., water clarity) at Wisconsin lakes; higher water levels increase water clarity in highly eutrophic lakes, though they have variable response on water clarity in mesotrophic lakes and can decrease water clarity in oligotrophic lakes (Lisi and Hein, 2019). Although the mechanisms are unknown, most eutrophic lakes in the study were also polymictic, indicating that flushing and possibly less mixing improved water clarity in high water years. Silver Lake, one of the oligotrophic lakes, experienced higher external nutrient loading during high water years, which decreased water clarity (Robertson et al., 2009). Internal nutrient processes can be difficult to model explicitly without detailed information on sediment pools of phosphorus and lake temperature profiles over time, but a lake that transitions from being stratified to partially or well-mixed due to water level declines is also likely to experience a decline in water quality.

Methods

Impacts to Lake Solute Budgets

Many lake solute and nutrient budgets are affected due to biological uptake or chemical precipitation. With less than two years of water chemistry monitoring, we had very little information on uptake rates in the study lakes and no information on how these rates might vary at lower lake levels. Given these uncertainties, we focused our evaluation on a solute that is typically semi-conservative with very little loss to biological uptake or precipitation: magnesium (Otsuki and Wetzel, 1974; Webster et al., 1996). As a major cation, magnesium concentration is well correlated with concentrations of other major ions, alkalinity, and salinity (Wetzel, 2001). In the study lakes, groundwater is the primary source of all of these solutes (see p. 41). While magnesium itself is not thought to have a toxic upper limit or minimum lower limit, dramatic changes in magnesium would correspond with dramatic changes in other water chemistry parameters to which aquatic life is sensitive (e.g., salinity, calcium, alkalinity, and nutrients).

To estimate lake magnesium concentrations for each modeled scenario, we used the following mass balance equation for a conservative solute in a seepage lake and solved for $C_{lake,2}$ on a daily time step:

$$C_{lake,2} = \frac{(C_{lake,1} * V_{lake,1}) + (C_P * P) + (C_{GWin} * GW_{in}) - (C_{lake,1} * GW_{out})}{V_{lake,2}} \quad \text{(Eq. 15)}$$

where C_x is the concentration of magnesium (g/m^3), P is the volume of precipitation (m^3/d), GW_{in} is the volume of groundwater inflow (m^3/d), GW_{out} is the volume of groundwater outflow (m^3/d), $V_{lake,1}$ is the initial lake volume (m^3), and $V_{lake,2}$ is the lake volume at the end of the time step (m^3). All volumes (lake volume, precipitation, groundwater inflow, groundwater outflow) were provided by the groundwater flow model outputs, with monthly lake volumes linearly interpolated to daily values. Precipitation magnesium concentrations were obtained from the closest National Atmospheric Deposition Program station at Devils Lake (site id: WI31, lat: 43.4352, long: -89.6801), and we used the median value for the entire record (January 14, 2014 to October 28, 2019) in this equation (0.038 mg/L). We set the initial lake magnesium concentration equal to the median value measured during the study period at each lake (Table 10).

Groundwater inflow magnesium concentrations showed little temporal variation during the study period, but notable spatial variation (Figure 25, Figure 27, Figure 29). Since groundwater inflow rates can also vary spatially, this created uncertainty in whether the median measured upgradient magnesium concentration represented the median magnesium concentration actually entering the lake. To better constrain groundwater inflow magnesium concentrations, we solved for groundwater inflow concentrations during the calibration period of the groundwater flow model (representing historical 2012-2018 conditions) by rearranging the mass balance equation as follows:

$$C_{GWin} = \frac{(C_{lake,2} * V_{lake,2}) - (C_{lake,1} * V_{lake,1}) - (C_P * P) + (C_{lake} * GW_{out})}{GW_{in}} \qquad \text{(Eq. 16)}$$

All volumes (lake volume, precipitation, groundwater inflow, groundwater outflow) were provided by the MODFLOW calibration for water year 2018 (October 2017 through September 2018). Precipitation magnesium concentration was set to the median value for the entire NADP record (0.038 mg/L). Since we observed very little change in lake magnesium concentrations across water year 2019, we used the median lake concentration in September and October 2018 as $C_{lake,1}$ and the median lake concentration in September and October 2019 as $C_{lake,2}$. Solving for C_{GWin} yielded values that were within the range of measured upgradient groundwater magnesium concentrations at Plainfield Lake, slightly higher than measured at Pleasant Lake, and slightly lower than measured values at Long Lake (Table 10, Table 60). We then used these groundwater inflow concentrations to solve for lake magnesium concentration in each modeled scenario (Eq. 15).

Table 60. Observed precipitation and lake magnesium concentrations (mg/L) used to solve for groundwater inflow concentrations used for modeled scenarios.

Lake	Precipitation	Initial Lake	GWin
Pleasant	0.038	18.40	39.38
Long	0.038	5.87	12.17
Plainfield	0.038	16.40	45.83

We defined a significant change in lake magnesium concentrations in two ways. First, we evaluated the median and typical range (80% confidence interval) of lake magnesium concentration for each scenario. If the median lake magnesium concentration in either of the two irrigation scenarios was lower or higher than the typical range of magnesium concentration in the no-irrigated-agriculture scenario (i.e., outside of the 80% range of no-irrigated-agriculture lake magnesium concentrations), we concluded the median lake concentration was significantly impacted. Second, we evaluated the maximum lake magnesium concentration for each scenario. If the maximum lake magnesium concentration in an irrigation scenario was more than two times higher than the maximum magnesium concentration in the no-irrigated-agriculture scenario, we concluded the maximum lake concentration was significantly impacted.

Impacts to Lake Mixing Regimes

Lake stratification is well-correlated with descriptors of lake morphometry such as lake area and maximum or mean lake depth (Table 61). Commonly used empirical relationships for classifying a lake as stratified or non-stratified include the Lathrop-Lillie ratio (Lathrop and Lillie, 1980), Minnesota lake geometry ratio (Heiskary and Wilson, 2005; Hondzo and Stefan, 1996), and the Osgood index (Welch and Cooke, 2005). We focused on stratification at Pleasant Lake since it is the only study lake that currently stratifies.

Table 61. Empirical lake stratification classifications.

Name	Ratio	Stratified Lakes	Non-Stratified Lakes
Lathrop-Lillie ratio	$R = \frac{Max\ Depth\ (m) - 0.1}{\log_{10}(Area\ (ha))}$	R > 3.8	R < 3.8
MN lake geometry ratio	$R = \frac{(Area\ (m^2))^{0.25}}{Max\ Depth\ (m)}$	R > 4	R < 4 Intermittently stratified: 2.5 < R < 4.5
Osgood index	$R = \frac{Mean\ Depth\ (m)}{\sqrt{Area\ (km^2)}}$	R > 6-7	R < 6

Based on empirical relationships between lake morphometry and lake stratification developed with data sets across many lakes, Pleasant Lake would no longer stratify at an elevation of 976.6 ft (Lathrop-Lillie ratio), 976.9 ft (Minnesota lake geometry ratio), or 977.4 ft (Osgood index, Figure 86). While the Osgood index tipping point is over 0.5 ft higher than the other values, the Osgood index is very near the threshold value of 6 for a wide range of elevations (~973 ft - 977.4 ft) that encompass the other estimated tipping points. We used the Lathrop-Lillie ratio as our single best estimate of this stratification tipping point since it was developed based on Wisconsin lakes and is used in other guidance for water quality assessment in Wisconsin (DNR, 2019c).

For each modeled scenario, we evaluated whether Pleasant Lake would stratify at the infrequent high, frequent high, median, frequent low, and infrequent low lake levels. If the lake would stratify in the no-irrigated-agriculture scenario but would not stratify under the current-irrigated-agriculture or potential-irrigated-agriculture scenarios, we concluded that the lake was significantly impacted. Thus, this significance determination is based on the expected change in stratification dynamics given generalized relationships with lake morphometry; it is not based on observed temperature profile data from Pleasant Lake at a range of lake elevations because not enough historical data is available.

Pleasant Lake

Pleasant Lake magnesium concentrations range from 18.4 mg/L to 24.6 mg/L with a median of 22.5 mg/L in the no-irrigated-agriculture scenario. This is similar to, but slightly higher than the mean observed lake magnesium concentration of 18.4 mg/L in 2018-2019. In the current-irrigated-agriculture scenario, the median lake magnesium concentration decreases slightly to 21.3 mg/L, which remains within the typical range (80% confidence interval) of lake concentrations under the no-irrigated-agriculture scenario (20.2 mg/L to 24.8 mg/L, Table 62). The maximum lake magnesium concentration also decreases slightly to 23.9 mg/L, so salinization is not a concern. Lake magnesium concentrations continue to decrease slightly in the potential-irrigated-agriculture scenario (Table 62). These observations as well as the timeseries of lake magnesium concentrations (Figure 85) indicate that the primary effect of lower water levels and lower groundwater inflow at Pleasant Lake is a slight reduction in the supply of solutes to the lake, which results in a slightly lower lake concentration. At Pleasant Lake, dilution has the potential to reduce the amount of calcium and thus the amount of marl, a calcified precipitate which is important for water clarity in Pleasant Lake (see p. 41). However, these calculations of lake magnesium concentrations, which are typically well-correlated with calcium concentrations, indicate that this dilution effect is minor and likely does not constitute a significant impact in either the current-irrigated-agriculture or potential-irrigated-agriculture scenario.

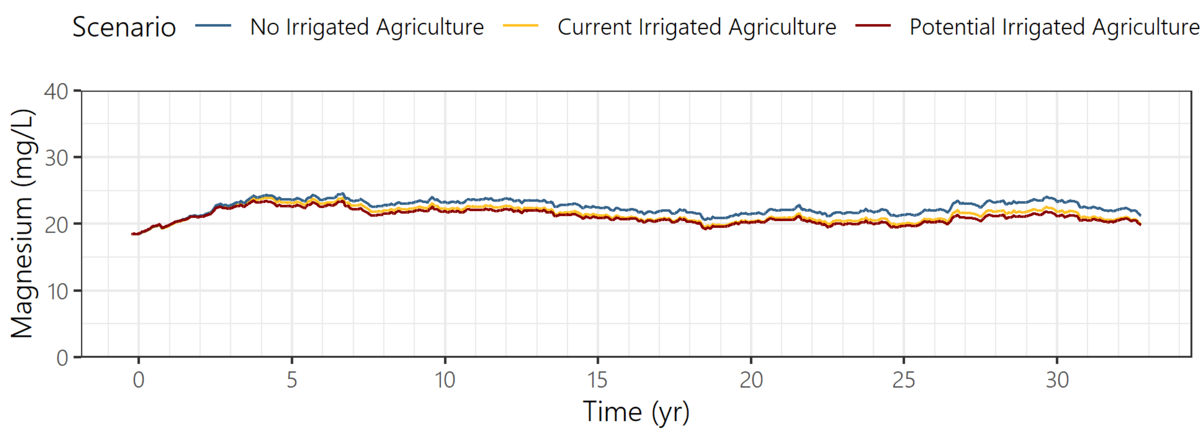

Figure 85. Lake magnesium concentrations under modeled scenarios at Pleasant Lake. Calculated daily lake magnesium concentrations based on groundwater flow model outputs for each modeled scenario as well as assumed precipitation, groundwater inflow, and initial lake magnesium concentrations.

We use an empirical relationship derived from many Wisconsin lakes to examine the role of lake level on stratification, and this relationship expects a higher likelihood of mixing as lake levels decline (Figure 86). In all modeled scenarios, Pleasant Lake is near or below the stratification tipping point at very low levels. This indicates that summer mixing events may occur when lake levels are at the low end of their range, regardless of irrigation. In the no-irrigated-agriculture scenario, Pleasant Lake levels range from over 3 ft higher than the stratification tipping point (at the infrequent high) to just above the stratification tipping point (at the infrequent low) (Table 62). In the current-irrigated-agriculture scenario, one model run drops below the stratification tipping point at the infrequent low, but it does not drop below the significance threshold which accounts for uncertainty in model estimates of recharge. In the potential-irrigated-agriculture scenario, both the frequent low and infrequent low drop below the stratification tipping point, but not below the significance thresholds. We find there is not sufficient evidence to conclude that stratification at Pleasant Lake is significantly impacted by groundwater withdrawals because the differences between modeled lake levels and the stratification tipping point are not greater than the uncertainty in modeled lake levels. However, we suggest that caution is warranted due to how close Pleasant Lake is to the stratification tipping point at low lake levels.

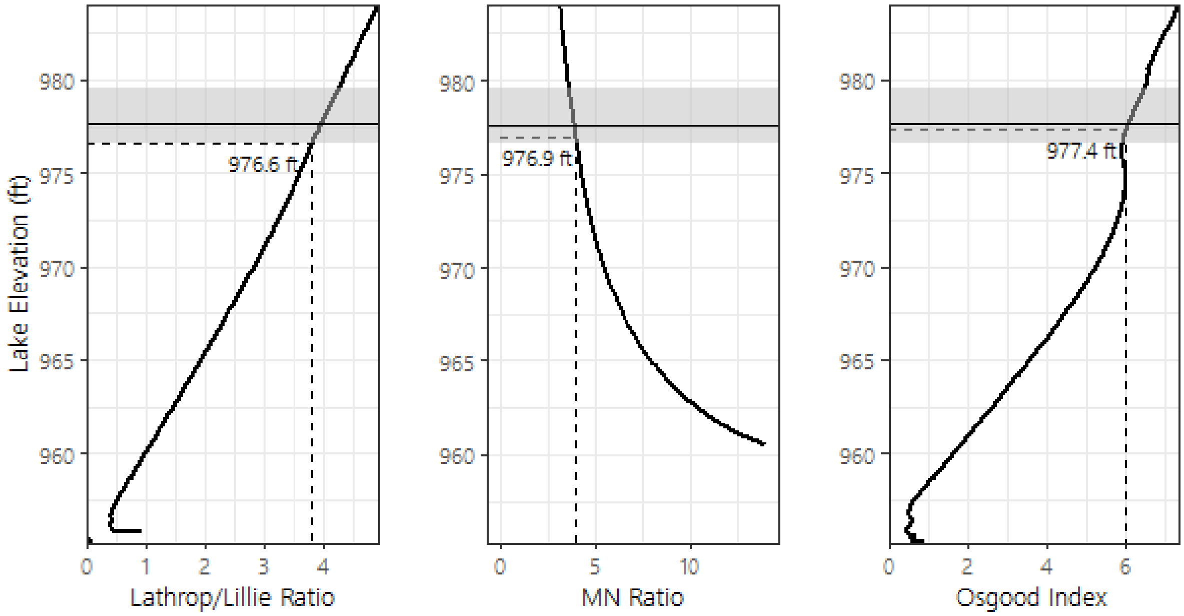

Figure 86. Pleasant Lake stratification. Calculated empirical ratios relating lake maximum or mean depth and lake area based on lake elevation at Pleasant Lake. Grey bars represent the no-irrigated-agriculture range between infrequent high and infrequent low levels, with the black horizontal line denoting the median level.

We evaluate how groundwater withdrawals could affect lake stratification in relative terms, but not in absolute terms. This is because the observed lake level elevations on Pleasant Lake slightly differ from MODFLOW predictions and because actual stratification dynamics are more complex. There may be some mixing events at elevations higher than 976.6 ft asl and stratified events at elevations below this threshold. We compared temperature profiles with lake elevations on 18 occasions when both observations occurred in the same month (June to August 2001 to 2019). Pleasant Lake was stratified on 14 of those occasions, and the lake level elevations in those months ranged from 978.3 to 982.7 ft asl. This is consistent with the 976.6 ft asl threshold derived from the Lathrop-Lillie equation. We have never observed a lake level below 976.6 ft asl, so we cannot confirm that Pleasant Lake mixes below this elevation with in-lake data. However, Pleasant Lake does mix in summer on occasion, especially in August. The four mixed profiles that coincide with lake level data showed that mixing can occur at elevations of 979.1 to 980.8 ft asl, all of which are above the Lathrop-Lillie threshold but toward the lower end of the range of observed lake levels (Figure 14). Still, the lake stratified at some point during every summer with profile data except in 2009, when the only two profiles (taken in July and August) showed that Pleasant Lake was mixed. This field data confirms that the morphometry of Pleasant Lake places it near the tipping point of dimictic vs. polymictic lakes and therefore, lake level fluctuations can influence stratification dynamics. It also reminds us that stratification thresholds provide useful guidelines but are not absolute. Thus, our conclusion that current-irrigated-agriculture and potential-irrigated-agriculture scenarios warrant caution on Pleasant Lake is robust, but continuous in-lake data at a range of lake elevations are needed to observe how lake levels affect the absolute frequency of summer mixing events.

Table 62. Significant impacts of groundwater withdrawals on Pleasant Lake's water chemistry. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential irrigated-ag scenario?	Ecological Impact
Magnitude				
Infrequent High (979.6 ft asl)	B: -3.4 ft S: -3.5 ft L: -4.5 ft	No B: -0.5 ft S: -0.1 ft L: -0.5 ft	No B: -0.5 ft	Lake stays stratified
Frequent High (978.4 ft asl)	B: -2.4 ft S: -2.5 ft L: -3.7 ft	No B: -0.5 ft S: -0.1 ft L: -0.7 ft	No B: -0.7 ft	Lake stays stratified
Median (977.6 ft asl)	B: -1.5 ft S: -1.7 ft L: -2.7 ft	No B: -0.4 ft S: -0.1 ft L: -0.6 ft	No B: -0.7 ft	Lake stays stratified
Frequent Low (977.0 ft asl)	B: -0.9 ft S: -1.1 ft L: -2.2 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	No B: -0.5 ft	Lake destratifies, but uncertainty in lake level estimates and recharge mean that all three scenarios straddle the elevation at which the lake destratifies.
Infrequent Low (976.7 ft asl)	B: -0.6 ft S: -0.7 ft L: -1.8 ft	No B: -0.4 ft S: -0.0 ft L: -0.6 ft	No B: -0.5 ft	Lake destratifies, but uncertainty in lake level estimates and recharge mean that all three scenarios straddle the elevation at which the lake destratifies.
Fluxes				
Median Mg concentration (22.5 mg/L)	B: 20.2 - 24.8 mg/L S: 20.4 – 25.1 mg/L L: 22.5 – 27.0 mg/L	No B: 21.3 mg/L S: 22.7 mg/L L: 23.9 mg/L	No B: 21.0 mg/L	Typical solute concentrations do not shift beyond normal range
Maximum Mg concentration (24.6 mg/L)	B: >49.2 mg/L S: >49.9 mg/L L: >53.5 mg/L	No B: 23.9 mg/L S: 24.7 mg/L L: 25.4 mg/L	No B: 23.5 mg/L	Salinity does not dramatically increase; maximum Mg remains less than 2x prior maximum.

Long Lake

Long Lake magnesium concentrations range from 5.7 mg/L to 10.4 mg/L with a median of 6.7 mg/L in the no-irrigated-agriculture scenario. This matches well with the mean observed lake magnesium concentration of 5.9 mg/L in 2018-2019. In the irrigated-agriculture scenarios, the median lake magnesium concentration increases slightly to 7.8 mg/L (current-irrigated-agriculture) or 8.1 mg/L (potential-irrigated-agriculture), which remains within the typical range (80% confidence interval) of lake concentrations under the no-irrigated-agriculture scenario (Table 63) and is not a concern. However, the maximum lake magnesium concentration rises to over 100 mg/L in both the current- and potential-irrigated-agriculture scenarios, a dramatic increase in salinity that does constitute a significant impact. The time series of lake magnesium concentration indicates that while this extreme salinity occurs in only the driest years, spikes in lake magnesium concentration are generally more common in the current- and potential-irrigated-agriculture scenarios than in the no-irrigated-agriculture scenario (Figure 87). This indicates that at Long Lake, the primary effect of lower water levels and lower groundwater inflow is a more rapid contraction of lake volume and strong evapoconcentration effect. Closer examination of the relationship between lake magnesium concentrations and lake level indicates that the evapoconcentration effect occurs in the current- and potential-irrigated-agriculture scenarios when the lake drops below 1093.4 ft, at which point lake magnesium concentrations begin to exceed the groundwater inflow concentration (12.1 mg/L) (Figure 88).

Table 63. Significant impacts of groundwater withdrawals on Long Lake's water chemistry. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential-irrigated-ag scenario?	Ecological Impact
Median Mg concentration (6.7 mg/L)	B: 6.0 – 8.2 mg/L S: 6.0 – 8.1 mg/L L: 6.1 – 7.8 mg/L	No B: 7.8 mg/L S: 7.2 mg/L L: 7.6 mg/L	No B: 8.1 mg/L	Median solute concentration does not shift beyond normal range
Maximum Mg concentration (10.4 mg/L)	B: >20.7 mg/L S: >20.0 mg/L L: >17.3 mg/L	**Yes** **B: >> 100 mg/L** S: 13.5 mg/L **L: 19.1 mg/L**	**Yes** **B: >> 100 mg/L**	Salinity increases dramatically; maximum Mg increases by a factor of 2 (L) or greater (B).

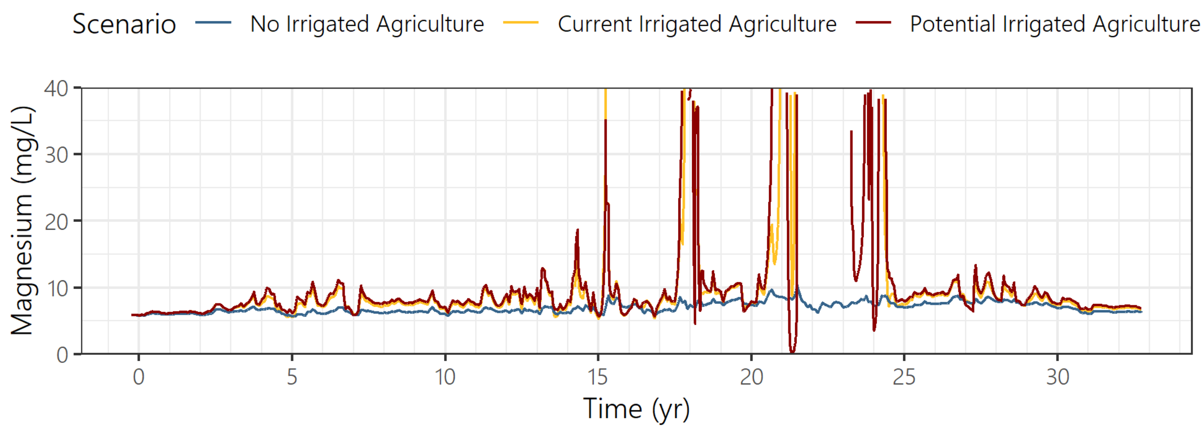

Figure 87. Lake magnesium concentrations under modeled scenarios at Long Lake. Calculated daily lake magnesium concentrations based on groundwater flow model outputs for each modeled scenario as well as assumed precipitation, groundwater inflow, and initial lake magnesium concentrations. Note that the y-axis is limited to 40 mg/L, but calculated lake magnesium concentrations (current- and potential-irrigated-agriculture) spike to >>100 mg/L.

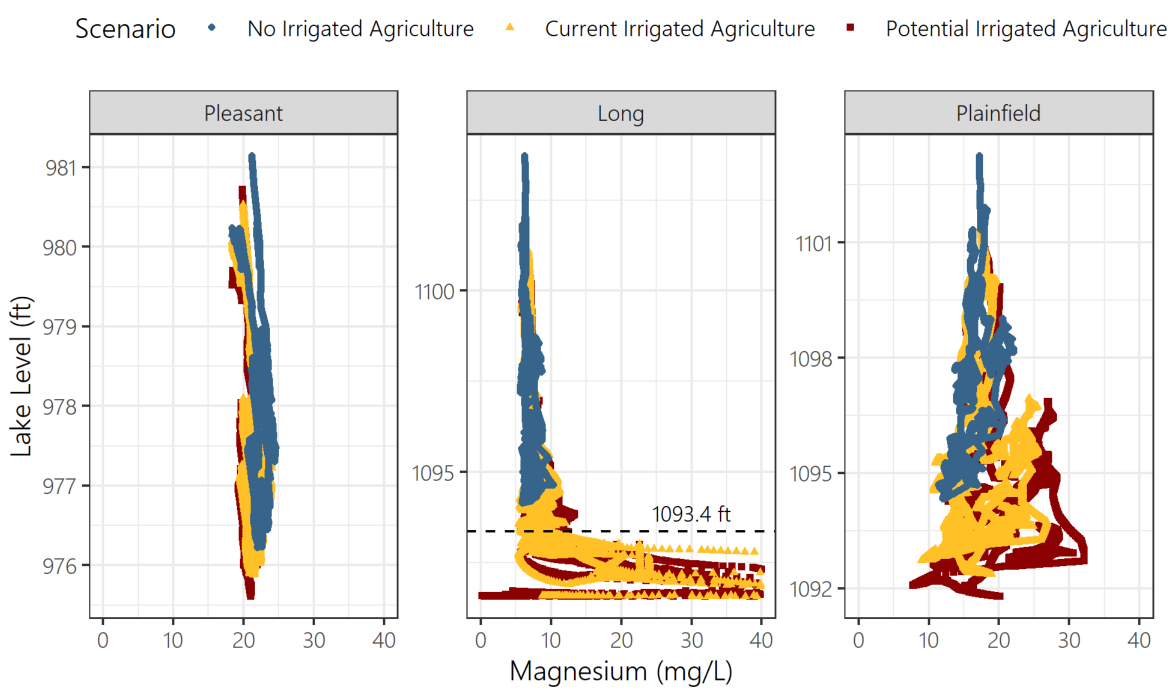

Figure 88. Lake levels vs. lake magnesium concentrations. The relationship between lake level and calculated lake Mg concentrations indicates that at Long Lake, lake magnesium concentrations begin to exceed groundwater inflow concentrations (i.e., there is an evapoconcentration effect) at elevations below 1093.4 ft. Lake concentrations never exceed groundwater inflow concentrations at Pleasant or Plainfield. Note that the x-axis is limited to 40 mg/L, but calculated lake magnesium concentrations for Long Lake (current- and potential-irrigated-agriculture) spike to >>100 mg/L.

Plainfield Lake

Plainfield Lake magnesium concentrations range from 11.4 mg/L to 22.1 mg/L with a median of 16.2 mg/L in the no-irrigated-agriculture scenario. This matches well with the mean observed lake magnesium concentration of 16.5 mg/L in 2018-2019. In the irrigated-agriculture scenarios, the median lake magnesium concentration increases slightly to 16.6 mg/L (current-irrigated-agriculture) and 18.0 mg/L (potential-irrigated-agriculture), which remains within the typical range (80% confidence interval) of lake concentrations under the no-irrigated-agriculture scenario (Table 64) and is not a concern. The maximum lake magnesium concentration also rises to 26.8 mg/L (current-irrigated-agriculture) or 32.2 mg/L (potential-irrigated-agriculture), but this increase is not large enough to constitute a significant impact. The time series of lake magnesium concentration indicates that lower water levels and lower groundwater inflow at Plainfield Lake leads to mixed effects on lake water chemistry (Figure 89). In the early years of the modeled scenario, lake magnesium concentrations in the current-irrigated-agriculture scenario are slightly lower than in the no-irrigated-agriculture scenario, indicating that lake water chemistry is driven by a loss in supply of solute to the lake. However in later years, an evapoconcentration effect is more common, with lake concentrations in the current-irrigated-agriculture scenario often slightly higher than in the no-irrigated-agriculture scenario. In the potential-irrigated-agriculture scenario, the periods of dilution are more subtle and the periods of concentration are more substantial, indicating that continued groundwater withdrawals exacerbate the evapoconcentration effects, not the dilution effects. While intriguing, these changes in lake water chemistry dynamics are minor and do not constitute a significant impact in either scenario.

Table 64. Significant impacts of groundwater withdrawals on Plainfield Lake's water chemistry. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential-irrigated-ag scenario?	Ecological Impact
Median Mg concentration (16.2 mg/L)	B: 13.1 – 20.6 mg/L S: 12.7 – 20.2 mg/L L: 15.8 – 22.4 mg/L	No B: 16.6 mg/L S: 16.2 mg/L L: 16.7 mg/L	No B: 18.0 mg/L	Typical solute concentrations do not shift beyond normal range
Maximum Mg concentration (22.1 mg/L)	B: >44.2 mg/L S: >42.9 mg/L L: >46.7 mg/L	No B: 26.8 mg/L S: 23.0 mg/L L: 25.4 mg/L	No B: 32.2 mg/L	Salinity does not dramatically increase; maximum Mg remains less than 2x prior maximum.

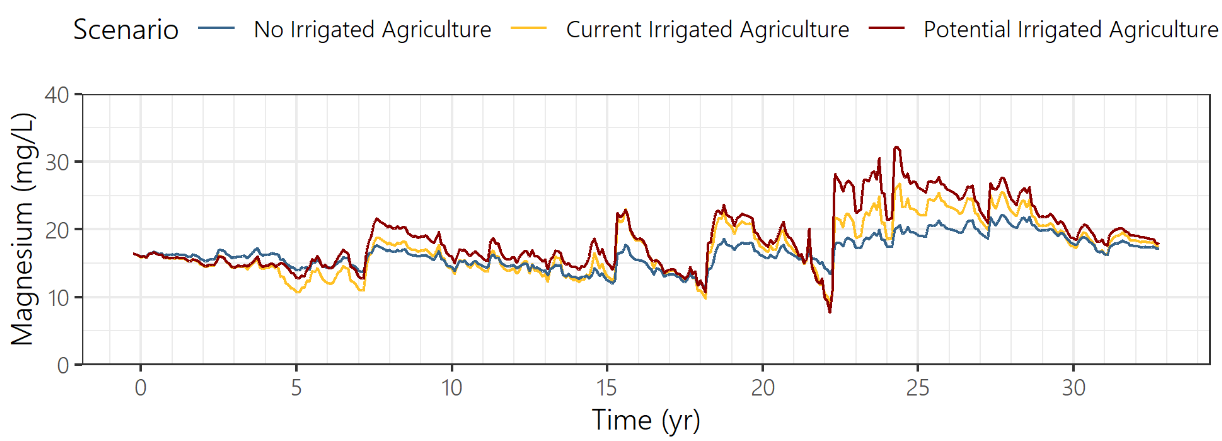

Figure 89. Lake magnesium concentrations under modeled scenarios at Plainfield Lake. Calculated daily lake magnesium concentrations based on groundwater flow model outputs for each modeled scenario as well as assumed precipitation, groundwater inflow, and initial lake magnesium concentrations.

Aquatic and Wetland Plant Communities

Literature Review

Water level fluctuations are a natural component of lake hydrologic regimes and are critical for maintaining the high-quality plant communities that have adapted to this environment. Plant communities shift lakeward as water levels recede and shift landward as water levels rise (Mortsch, 1998; Quinlan and Mulamoottil, 1987; Wilcox et al., 2008). The act of flooding and drying maintains wetlands at more productive, intermediate stages of development (Mortsch, 1998). In the Great Lakes, the diversity of beach plant communities increases with increasing fluctuations; stable water levels are detrimental to these plant communities (Keddy and Reznicek, 1986). Similar trends have been observed on inland lakes in Australia, where species richness of low-statured macrophyte communities near shore increases with increasing intra-annual water level fluctuations (Riis and Haws, 2002).

High water levels are important for killing back trees, shrubs, grasses, and invasive plants like cattails (Keddy and Reznicek, 1986; Mortsch, 1998). The response to flooding will depend on plant tolerance to inundation and anoxia (Seabloom et al., 2001). Pines encroaching from the dry uplands will be killed by seasonal inundations, but other woody species like cottonwoods can survive inundation for a full growing season before significant mortality is evident (Whitlow and Harris, 1979). During high water periods, the soils become anoxic and fine sediments may be removed by water circulation. Emergent species will propagate vegetatively and eventually die in deep water whereas floating and submergent species will expand.

Low water periods, on the other hand, allow inland beach and emergent seeds to germinate, and if they remain low, survive long enough to reproduce and add to the seed bank. Submerged vegetation and possibly emergents will die at high elevations that are no longer inundated, often leaving behind mudflats (Hudon et al., 2004). The mudflats or exposed sandy areas will be colonized by annuals and bulrushes or inland beach species, all of which need exposed shoreline to germinate from seed (Markham 1982). Existing emergent plants also survive low water periods by increasing below-ground biomass, presumably gaining access to a deepened water table (Hudon et al., 2004). Macroscopic algae often become more abundant, thriving at shallow water depths where there is high light intensity, warm water temperatures, and high nutrient concentrations released from the sediments and decomposing vascular plants (Hudon et al., 2004). During low water periods, the soils are less anoxic and allow colonization by wetland and upland species more tolerant to drier conditions (Keddy and Reznicek, 1986). If low water levels remain, sedges, wetland grasses, invasive species (e.g. *Phalaris arundinacea*, *Phragmites australis* ssp. *australis* and *Typha X glauca*), and eventually shrubs and trees will dominate and replace emergent and inland beach species (Mortsch, 1998; Hudon et al., 2004). As sedges and cattails become dense, peat accumulates (Mortsch, 1998). Although wetlands often enhance water quality, water quality can also be more degraded at low water levels (Mortsch, 1998). Lower water volumes and longer residence times can result in greater turbidity, higher concentrations of pollutants, and lower dissolved oxygen (Mortsch, 1998).

Plant community distributions will shift with changing water levels, but a variety of factors related to the landscape, hydrology, and plant characteristics affect how those changes occur. Plants should be able to migrate with fluctuating water levels if the slope is shallow, there are not natural or anthropogenic barriers, and if suitable substrate exists along the entire continuum (Seabloom et al., 2001; Hudon et al., 2004). For example, the inland beach community requires a sandy substrate, which is often maintained via physical processing at the splash zone. As water levels recede beyond that zone, the substrate is often composed of a thick layer of muck. This muck would need to be exposed to the air and decompose before inland beach species could colonize the area.

Five aspects of the hydrologic regime influence how plants respond to fluctuating water levels: timing, magnitude, duration, frequency, and the rate of change (Poff et al., 1997). In terms of timing, plants require stable water levels during the germination phase; otherwise seedlings may die. Annuals can respond to seasonal fluctuations, whereas perennials must be able to tolerate the range of water levels that occur within a year (Keddy and Reznicek, 1986; Mortsch, 1998). The distribution of perennials will change at interannual time scales of water level fluctuations (Keddy and Reznicek, 1986; Mortsch, 1998). A combined example of magnitude and duration is that emergent plants will likely die when the water depth increases beyond 1-meter depth for an extended period of time (Hudon, 1997). A rapid increase by 0.5 meter results in immediate vegetation destruction, and a 0.3-m decline in water level can result in dense emergent plant growth (Mortsch, 1998). Another study along the St. Lawrence River wetlands observed barren mudflats with dense filamentous algae after the water level dropped by ~1 m within 1 year (Hudon, 2004). In general, perennial wetland plants can survive up to 1 year of dry or flooded conditions, but submergents die if exposed to dry conditions (Hudon, 1997; Hudon, 2004). Even most water-tolerant trees like willows and cottonwoods die after 2 years of flooded conditions (Whitlow and Harris, 1979). A water level rise of 0.3 m above the mean for 3-5 years will reduce or eliminate emergents (Mortsch, 1998). A model of plant community response to water level changes found that plant communities would stabilize within 1-2 years after flooding but take more than 2 years to stabilize after a drought due to colonization limitations (Seabloom et al., 2001). In fact, it took wetland communities (emergents in particular) 3-5 years to re-establish after low water level conditions in the Great Lakes (Quinlan and Mulamootil, 1987; Mortsch, 1998).

The Recruitment Box Model, which integrates the five hydrologic metrics used here, has successfully been used to recommend river flow plans to restore riparian plant communities along regulated rivers (Rood et al., 2005). The concept identifies the elevations along the riverbank at which seeds (e.g., willows and cottonwoods) could germinate; seedlings will desiccate if established too high and will be scoured out if established too low (Mahoney and Rood, 1998). The model then accounts for the root growth rate of a seedling and required soil moisture content to determine water level recession rates that will support the growing seedlings, overlaying the river's hydrograph with the seasonal timing of plant establishment and growth.

The characteristics of plant species will also determine how plant communities respond to water level fluctuations. Rhizomatous plants will spread more slowly than those that reproduce by seed, but plants that spread by seed need the appropriate environmental conditions to germinate and this varies across species (Seabloom et al., 2001). For example, emergent plant species germinated in mudflats within 2-5 years of low water levels and reached their full extent after 5 years of stable water levels (Hudon, 2004; Quinlan and Mulamootil, 1987). The longevity of the seed bank and dispersal distances also play a factor in plant responses to water level changes. Seeds are densely distributed in the littoral zones of lakes, but density decreases with increasing water depth (Manny, 1984). Thus, the magnitude of water level change in relation to the spatial distribution of seed densities will also be important for determining plant community response to lower water levels. If water level decline results in a rapid and large lakeward recession, new areas of lakebed with low seed densities of emergent and wetland plants may be exposed. This will delay the response and could shift the wetland community toward invasive species or other early colonizers with long seed dispersal distances. However, if this change occurs slowly enough (multiyear recession), the seed bank distribution could theoretically shift lakeward in time with declining water levels.

Natural History of a Federally Threatened Plant

Plainfield Lakes hosts the world's largest population of a federally threatened, Wisconsin endemic plant species, so ensuring that the lake level regime continues to support this species is critical. It is an herbaceous perennial in the legume family that is often found growing most densely in a band near the water's edge where few other plants grow. It is short-lived, averaging 1-4 years though it may be able to live up to 14 years (U.S. Fish and Wildlife Service, 2013). It occupies sparsely vegetated inland beaches along sandy lakeshores of shallow seepage lakes. Periodic fluctuations in water levels are required to inundate portions of the lakeshore and eliminate competition from surrounding woody and herbaceous species. Although adult plants are killed by floods, these periods are critical in maintaining habitat for future generations.

Like many other plants that occupy this or similarly dynamic habitats, the seed bank plays a critical role in the species' persistence. Because high lake levels will kill adult plants, the seed bank is necessary to recolonize suitable habitat once waters recede. Seed dispersal is minimal, making it unlikely seed will be transported into the site from elsewhere. Seed production varies but may be as high as hundreds of seeds per individual (Tippery, 2014). The average number of seeds per meter (and 5 cm deep) ranges from 341 to 1798 (Feldman, 2010). Little research has been done on this plant's seed viability, but prolonged flooding at Plainfield Lake from 1940-1947 suggests seeds can remain viable for at least 8 years. Studies on congeners found that seeds remain viable in the soil for at least 5-10 years (Ralphs and Cronin, 1987; Winslow, 2002; Luna, 2008). When lake levels recede, great flushes of germination often occur as this plant is one of the first species to take advantage of the newly exposed habitat. Plants can produce seed in their second year (Tippery, 2014), building up the seed bank once again.

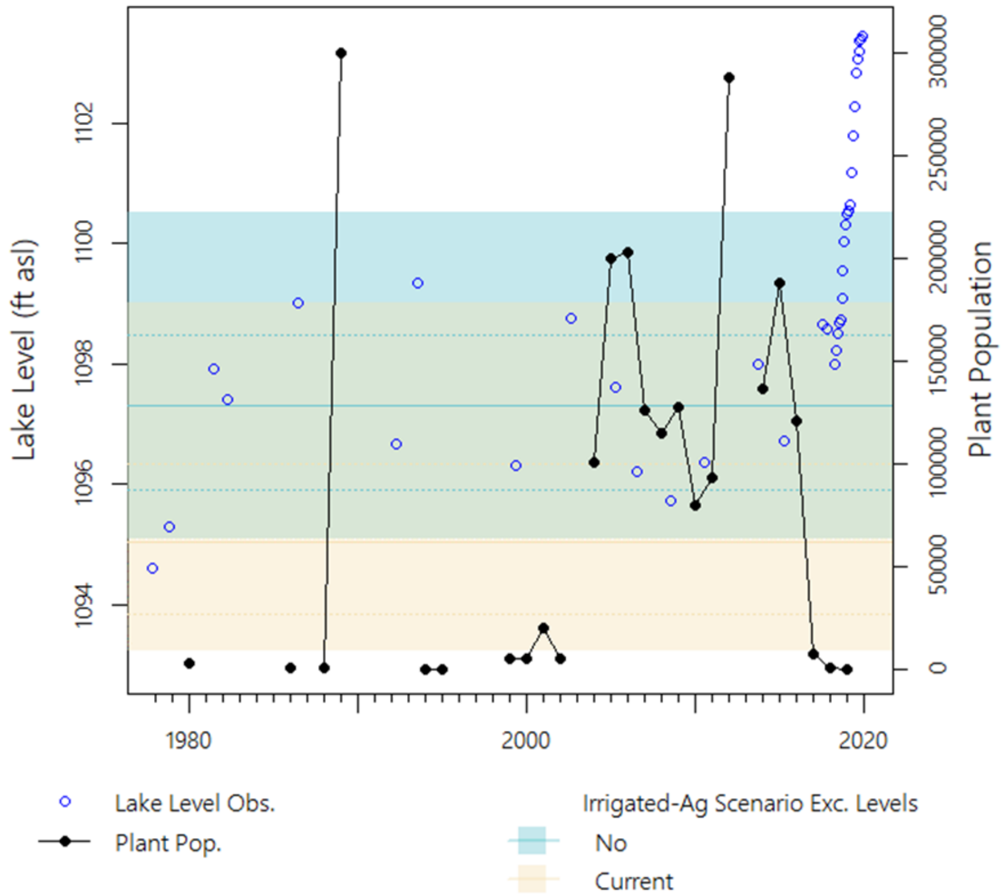

Figure 90. Federally threatened plant population, Plainfield Lake. Population size of a federally threatened plant on the shore of Plainfield Lake through time in relation to observed lake levels and MODFLOW-derived exceedance probabilities in the no-irrigated-agriculture and current-irrigated-agriculture scenarios. Shaded areas depict 10-90% exceedance probabilities, dashed lines depict 25-75% exceedance probabilities, and the solid horizontal lines depict the median (50%) lake level exceedance probabilities.

Seed germination more commonly occurs as lake levels decrease and expose bare habitat, but seed germination flushes can also occur as lake levels increase. Their thick seed coat requires some soaking as well as scarification to germinate; this combined with variable conditions around each seed results in staggered germination patterns that occasionally occur as water levels come up; seeds that were deposited further up the lakeshore at a time of higher lake levels become exposed to groundwater from rising lake levels and germinate. For this reason, fluctuating lake levels spur germination both as lake levels decrease and increase. For example, an abundant population occurred in 2005 and 2006 after lake levels began falling in 2002 (Figure 90).

Conserving this species requires maintaining a multiyear hydroperiod where floods do not submerge suitable habitat for longer than seeds remain viable, and droughts are not prolonged enough to kill seedlings and/or allow surrounding competition to encroach. Based on population numbers and studies on similar natural communities it is likely that the federally threatened plant requires a few years of low water per decade. Since this plant is not an annual and cannot mature from seedling to fruiting adult in a single year, prolonged periods of low water are needed to allow enough time for seeds to germinate, mature to adult plants, flower, set seed, and rejuvenate the seed bank. However, the plants will succumb to desiccation and/or encroachment from surrounding vegetation if lake levels remain low, and the population eventually declines. Pines encroaching from the dry uplands will be killed by seasonal inundations, but other woody species like cottonwoods can survive inundation for a full growing season before significant mortality is evident (Whitlow and Harris, 1979). We observed this pattern at Plainfield Lake in 2019-2020 (Figure 91). This hydroperiod is similar to coastal plain marshes, which need 1-3 years of low water followed by more frequent and/or prolonged years of high water to persist (Keddy and Reznicek, 1982; Schneider, 1994).

Figure 91. Flooding of upland vegetation, Plainfield Lake. High water levels caused young pine trees to die, but flood tolerant shrubs and trees like willows and cottonwoods are still green. Photo taken on August 7, 2019 from the public access site on Plainfield Lake.

Methods

To develop quantitative plant thresholds for lake level magnitudes, we evaluated how changes in lake level affect the study lake plant communities based on plant water depth requirements. We combined our own observations with common values reported in the literature to define plant water depth distributions (Epstein, 2017). Upland plants must be outside the saturated zone of the water table. Inland beach plants generally straddle the lake level and extend landward up to beach areas that are dry at the surface (Epstein, 2017). Emergent plants exhibit strong zonation along a depth gradient; they are often found out to 3 feet deep, but can occur to 6.5 feet (Epstein, 2017). Emergents were not prevalent in Pleasant and Long Lakes and were limited to shallower depths, so we defined the deep end of their range at 3 feet for those two lakes (Figure 92). We used a deeper range at Plainfield Lake since *Schoenoplectus acutus,* a species associated with deeper water levels than many other emergents*,* was abundant and grew out to 7 feet deep in 2018 (Figure 92). The water level rise of 2019 at Plainfield Lake shifted the central distribution of *S. acutus* even deeper to 10 feet, but at these depths, *S. acutus* began to die back. Floating-leaved plants often occur near the deep limit of emergents and extend lakeward (Epstein, 2017). We defined the floating-leaved depth distribution using the depths observed in 2018 on Long and Plainfield Lakes (Figure 93) and the statewide depth distribution of the most common species we found on these lakes (Figure 94). Finally, the full suite of submergent plants could grow at the deepest points of Long and Plainfield Lakes, but we observed two submergent plant communities on Pleasant Lake. Pondweeds occupied the nearshore areas (≤ 15 feet deep) and macroalgae the deep (Figure 95). Because lake levels fluctuate dramatically on two of the three lakes and many plants can survive one season of less than ideal conditions, we used wider depth ranges than one might typically consider for these plant communities. In addition, there can be strong plant species zonation within each of the plant community types, and the wider depth range reflects the full range of species that could be represented.

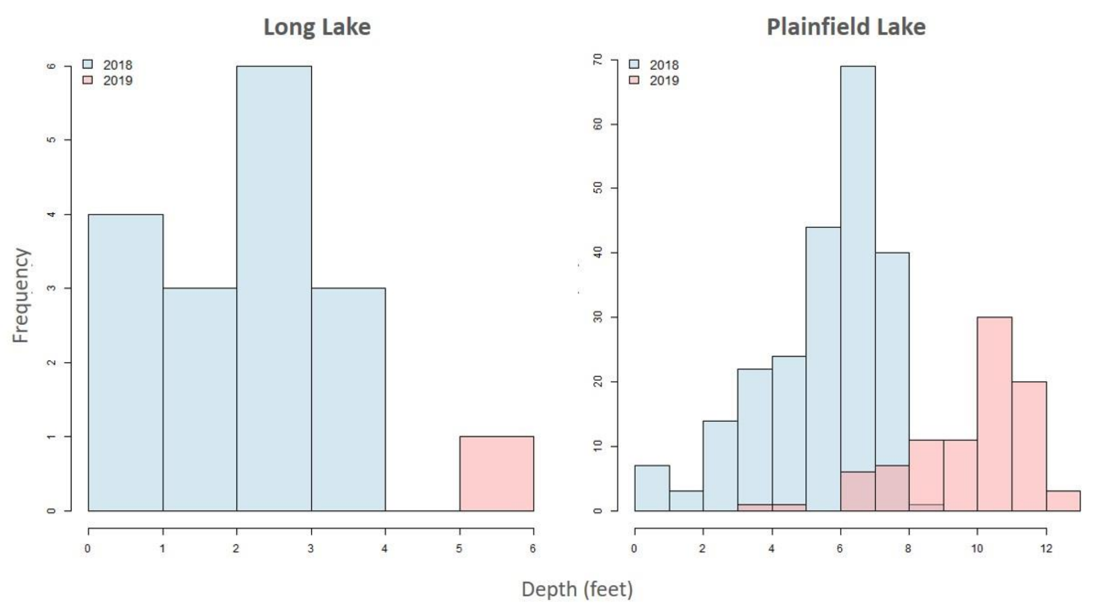

Figure 92. Emergent plant depth distribution, Long and Plainfield lakes. Depth distribution of emergent plants on Long Lake (primarily Juncus effusus) and Plainfield Lake (primarily Schoenoplectus acutus) derived from plant point intercept surveys in 2018 and 2019.

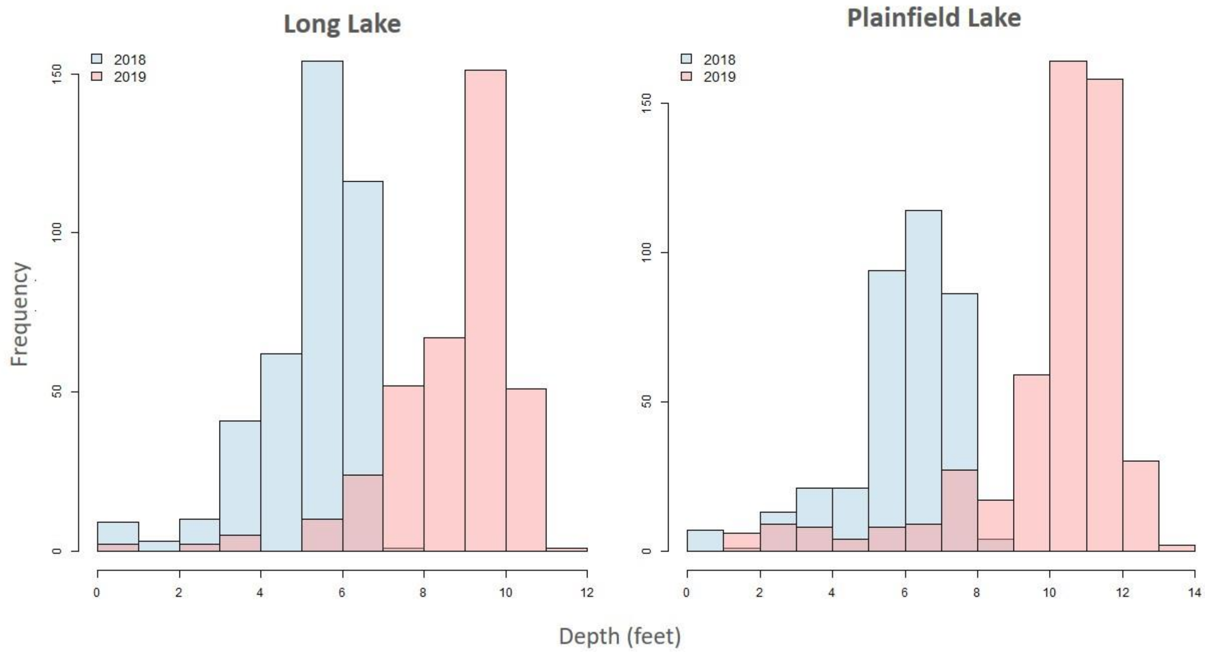

Figure 93. Floating plant depth distribution, Long and Plainfield lakes. Depth distribution of floating plants on Long Lake and Plainfield Lake derived from plant point intercept surveys in 2018 and 2019.

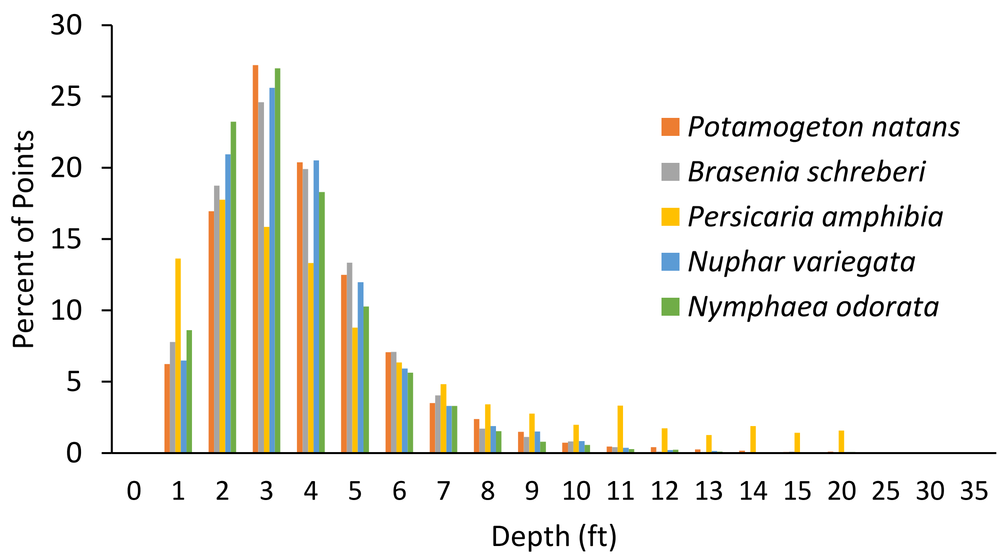

Figure 94. Floating plant depth distribution, all Wisconsin lakes. Depth distribution of floating leaf plant species common to Pleasant, Long, and Plainfield Lakes derived from plant point intercept surveys statewide.

We then combined the depth ranges of each plant community type (Table 65) with the bathymetry of the lake to determine how much the areal coverage of each plant community would change with vertical changes in lake level. We defined each lake footprint to include the entire surface area at lake levels near the highest levels observed in 2020 (982.9, 1104.5, and 1105.5 ft asl on Pleasant, Long, and Plainfield Lakes, respectively). This means that at median lake levels, upland plants could compose a substantial area of the total footprint we evaluated. It gives ample room both above and below the median to observe how plant communities could shift with changing lake levels. At each lake elevation, from the highest elevation observed to the deepest point, we calculated the percent of the lake footprint that could be covered by each plant community given its depth requirements. We evaluated lake level change at 0.1-ft increments and defined a significant change in magnitude as one that causes areal coverage of any plant community to change by more than 10% of the lake footprint.

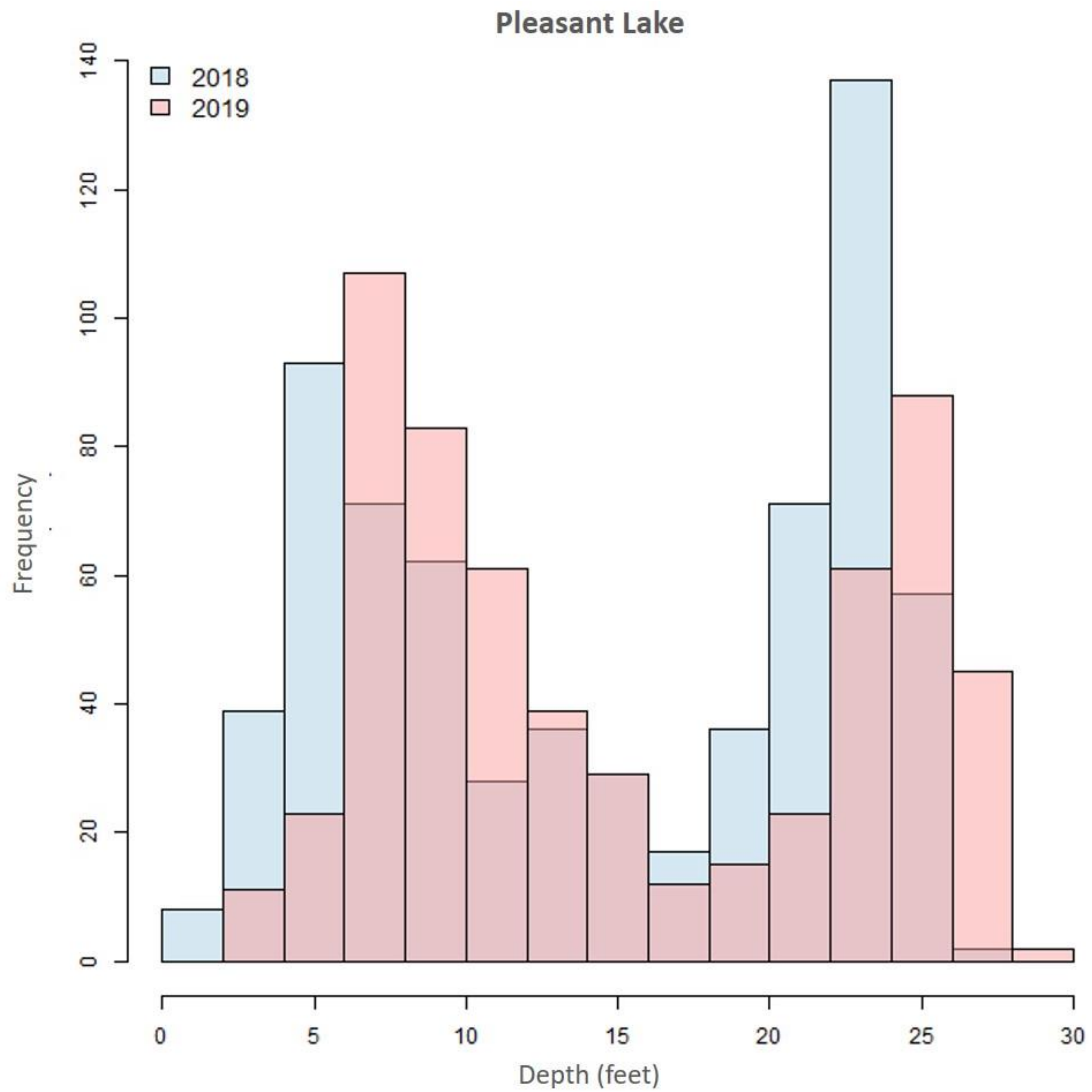

Figure 95. Submergent plant depth distribution, Pleasant Lake. Depth distribution of submergent plants on Pleasant Lake in 2018 and 2019. The distribution to the left (<15 feet) is dominated by the submergent pondweed community and that on the right (>15 feet) is composed of the macroalgae *Chara globularis* and *Nitella flexilis*.

Table 65. Depth ranges of each plant community by lake. Positive values indicate that the plants can grow up to x feet above the water table. Negative values mean the plants can grow to y feet below the water table or y feet lake depth. For example, inland beach occurs on land up to 1.6 feet above ground water and out to 1.6 feet deep in the lake.

Lake	Plant community	Shallow Limit (ft)	Deep Limit (ft)
All	Upland	Highest point	+1
All	Inland Beach	+1.6	-1.6
Pleasant & Long	Shallow Emergent	+1	-3
Plainfield	Deep Emergent	+1	-7
All	Floating-leaved	-3	-8
Long & Plainfield	Submergent	-1.6	Deepest point
Pleasant	Submergent Pondweeds	-1.6	-15
Pleasant	Submergent Macroalgae	-16	Deepest point

Due to the short time frame of this study, we did not observe changes in plant community coverage across the full range of lake levels. Still, the reduction in floating and emergent plants we observed on Long Lake and Plainfield Lake from 2018 to 2019 with rising water levels supports our expectations based on depth requirements. To evaluate how plant communities would change in the MODFLOW scenarios, we assumed the maximum coverage possible of each plant community given its depth requirements. In reality, some plant community types are rare or non-existent presently (e.g., Pleasant Lake has very limited Emergent Marsh). This may be due to factors other than lake levels, but they are not evaluated here.

Although we did not develop quantitative plant thresholds for frequency and duration, we examined how irrigation affected these aspects of hydrology and qualitatively evaluated significance. We specifically looked for lake levels to remain above or below the lake median for at least two years. Prolonged high lake levels prevent trees and other upland plants from establishing on the lakebed and prolonged low lake levels allow inland beach and emergent plants to germinate, and for some species, reproduce. The effect of irrigation on the frequency of prolonged high and low lake levels would likely be more robust for quantitative evaluation if available climate data allowed us to model a longer time series; prolonged highs and lows only occurred 1-4 times over the 33-year climate period evaluated without irrigation.

We conclude that both the rate of change and timing are not impacted in the current-irrigated-agriculture scenario on all three study lakes (Table 42, Table 49, Table 56, Figure 69, Figure 75, Figure 82) and thus, do not in turn impact plant communities.

Evaluating a Federally Threatened Plant on Plainfield Lake

The DNR's Bureau of Natural Heritage Conservation has been monitoring the federally threatened plant population at Plainfield Lake since the mid 1980's and has been collaborating with UW-Stevens Point and UW-Whitewater on detailed demographic studies since 2006. Although our observed lake level record does not entirely coincide with the plant population observations, the combined records allow us to specify the hydrology necessary for the species to persist. Plants were absent or rare in 1986, 1994, 2002, and 2017-2019 when lake levels were 1098.6 to 1103.4 ft asl (Figure 90). During these high-water years, the beach was flooded with water and the plants were submerged. Conversely, plants were abundant in 2005, 2012, 2014, and 2015 when lake levels were 1096.4 to 1098.0 ft asl. There were also moderately abundant plants in 2006, 2008, and 2014 with lake levels of 1095.2 – 1098.0 ft asl. This suggests that lake elevations near the median lake level (1097.3 ft asl) and ranging almost from the frequent low to frequent high (1095.9 to 1098.5 ft asl) are ideal for the threatened plants (using lake exceedance probabilities derived from the no-irrigated-agriculture MODFLOW scenario).

Maintaining lake levels in the range observed in the past is most conservative for preserving the federally threatened plant. Because of the uncertainty in the ability of this plant to shift its distribution landward or lakeward beyond its historical extent, our significance threshold for this plant required the median lake level to remain within the range of our estimated uncertainty in the no-irrigated-agriculture scenario: ± 0.6 ft.

Pleasant Lake

The plant communities on Pleasant Lake change very little from the infrequent low (90% exceedance probability) to infrequent high (10% exceedance probability) in the no-irrigated-agriculture scenario (Figure 96, Figure 97). At the median lake level, Submergent Macroalgae cover most of the lake footprint, which includes the entire area ≤ 983.2 ft asl, followed by Submergent Pondweeds (32%). Floating-leaved marsh (13%), Emergent Marsh (14%), Inland Beach (9%), and Upland (10%) cover a smaller proportion of the lake footprint and are limited to the lake margins (Table 66). The acreage of these plant communities is fairly constant from the infrequent high to low, depicted by the vertical or gently sloping lines within the blue shaded bands in Figure 97; the difference in areal coverage of each plant community varies by only 4-7% from the infrequent high to infrequent low. The standard deviation in plant areal coverage associated with 349 model runs without irrigation is ≤ 1.3% across plant community types and exceedance probabilities (Table 66). Nearshore differences in the plant communities occur from the infrequent low to high, particularly along the gradually sloped north shore and southwest bay (Figure 96). The peninsula along the north shore is composed primarily of upland plants, followed by inland beach and emergent plants extending lakeward. At the infrequent high, much of the peninsula is under shallow water and floating-leaved plants extend much closer to shore.

Aquatic and wetland plants are not significantly impacted in the current-irrigated-agriculture scenario in terms of any magnitude metrics (Table 67). The areal coverage of each plant community does not change by more than 10% at any exceedance level. To cause a >10% change in areal coverage, lake levels would need to decline by 2.5 feet from the infrequent low to 4 feet from the infrequent high (Table 66). Current-irrigated-agriculture only causes declines of 0 – 0.7 feet (Table 67), which translate to at most, a 2% change in areal coverage of a particular plant community type. This conclusion is further underscored by how similar the distribution of plant community types is in the no-irrigated-agriculture and current-irrigated-agriculture scenarios. There is more variability in plant community distribution from the infrequent low to infrequent high than there is between the no-irrigated-agriculture and current-irrigated-agriculture scenarios (Figure 96). Further, the range from the infrequent low to high (2.9 ft) does not significantly change in the current-irrigated-agriculture scenario (Table 67).

Table 66. Areal percent cover of plant communities in Pleasant Lake at five exceedance probability lake elevations in the no-irrigated-agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. Estimates are from the base run (one standard deviation derived from 349 model runs for each scenario).

Metric	Irrigated Agriculture Scenario	Upland (% of lake)	Inland Beach (% of lake)	Emergents (% of lake)	Floating-leaved (% of lake)	Submergent Macroalgae (% of lake)	Submergent Pondweeds (% of lake)
Infrequent High	No	4.8 (1.1)	7.8 (0.3)	10.4 (0.4)	17.8 (0.4)	55.5 (0.7)	33.9 (0.2)
	Current	6.6 (1.2)	8.0 (0.2)	10.6 (0.4)	16.9 (0.6)	54.7 (0.8)	33.7 (0.2)
	Potential	6.6	8.0	10.6	16.9	54.7	33.7
Frequent High	No	8.0 (1.3)	7.6 (0.3)	12.4 (1.0)	15.0 (1.1)	53.3 (1.1)	33.1 (0.4)
	Current	9.0 (1.0)	8.3 (0.5)	13.5 (0.9)	13.8 (1.1)	52.2 (1.0)	32.5 (0.5)
	Potential	9.6	8.9	13.9	13.3	51.7	32
Median	No	9.8 (1.1)	9.0 (0.7)	14.0 (0.9)	13.1 (1.1)	51.5 (1.0)	31.9 (0.7)
	Current	10.5 (0.9)	10.1 (0.9)	14.7 (0.8)	12.2 (1.0)	50.5 (1.0)	30.8 (0.8)
	Potential	11	10.8	15.1	11.7	49.8	30.4
Frequent Low	No	11.0 (1.1)	10.8 (1.1)	15.0 (0.9)	11.8 (1.1)	49.9 (1.3)	30.4 (1.0)
	Current	11.8 (1.1)	11.7 (1.1)	15.5 (0.6)	11.2 (0.9)	49.0 (1.2)	29.7 (0.9)
	Potential	12.2	11.9	15.6	11.0	48.7	29.5
Infrequent Low	No	11.7 (1.2)	11.6 (1.1)	15.5 (0.7)	11.2 (1.0)	49.0 (1.3)	29.8 (0.9)
	Current	12.8 (1.2)	12.4 (1.0)	15.6 (0.5)	10.7 (0.8)	48.0 (1.2)	29.0 (0.8)
	Potential	13.1	12.7	15.6	10.6	47.7	29.2

Under the potential-irrigated-agriculture scenario, lake levels fall up to an additional 0.3 ft. This results in up to a two percent change in the areal coverage of each plant community compared to the no-irrigated-agriculture scenario, which is not a significant reduction in lake levels (Table 67). The range from the infrequent low to high does not significantly change in the potential-irrigated-agriculture scenario (Table 67).

Step changes to the plant communities would occur at more extreme lake level declines (Figure 97). As lake levels drop from 974 to 971 ft asl, the submergent pondweed marsh rapidly expands from 45 to 88 acres, covering almost the entire lake (Figure 98). At 970.2 ft asl, the submergent macroalgae marsh would be non-existent. *Chara globularis* and *Nitella flexilis* would likely still occur, but in tandem with other species and at lower densities more similar to that found at shallower depths. The Floating-leaved Marsh also undergoes rapid expansion as lake levels decline from 968 to 964 ft asl, more than tripling its extent (from 19 to 64.6 acres). At this extreme, Floating-leaved Marsh could extend across the entire lake and upland plants would expand by an additional 56 acres in the lake footprint. Emergent plants exhibit a similar pattern at even more extreme lake level declines, increasing from 16.5 acres to 59.8 acres as lake levels decline from 963 to 959 ft asl. Given the bath-tub shape of Pleasant Lake, changes to plant community coverage are small and gradual at first, but then undergo dramatic changes at more extreme lake level decline. With larger declines, the entire lakebed would become shallow enough for first the pondweed component of Submergent Marsh, then Floating-leaved Marsh, and finally, Emergent Marsh. These wholesale shifts in the plant community would fundamentally change the lake ecosystem.

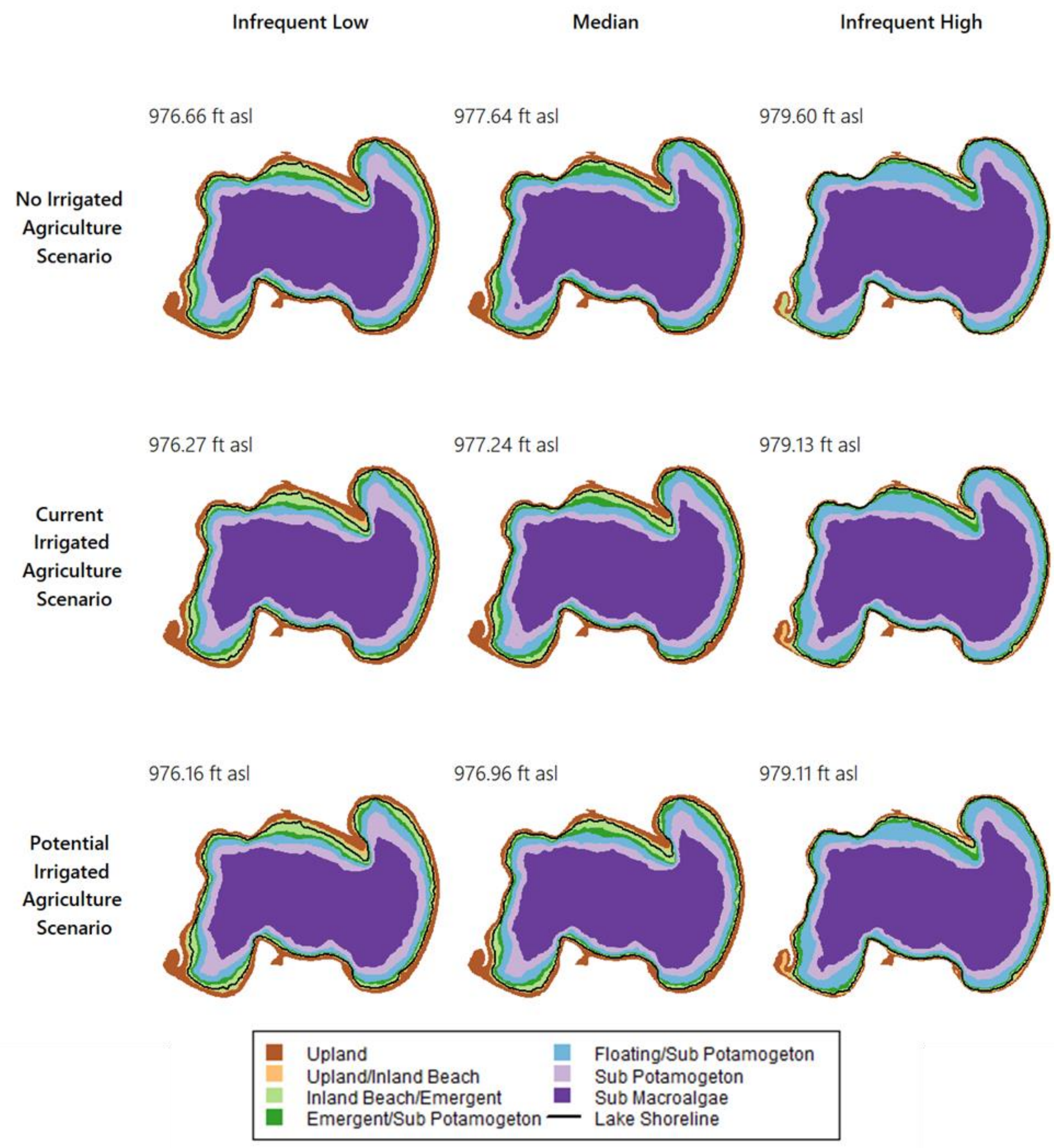

Figure 96. Plant community spatial distribution, Pleasant Lake. Spatial distribution of plant communities on Pleasant Lake at the infrequent low, median and infrequent high under the no-irrigated agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. All maps use lake water elevations derived from the base model run.

Table 67. Significant impacts of groundwater withdrawals on Pleasant Lake's plant communities. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Ecological response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Ecological response to potential-irrigated-ag
Magnitude					
Infrequent High (979.6 ft asl)	B: -4.0 ft S: -4.0 ft L: -4.2 ft	No B: -0.5 ft S: -0.1 ft L: -0.5 ft	Upland increases by 2%; all other plant communities change by < 1%.	No B: -0.5 ft	Upland increases by 2%; all other plant communities change by < 1%.
Frequent High (978.4 ft asl)	B: -3.6 ft S: -3.6 ft L: -4.0 ft	No B: -0.5 ft S: -0.1 ft L: -0.7 ft	All plants change by 1% or less.	No B: -0.7 ft	All plants change by 2% or less.
Median (977.6 ft asl)	B: -3.1 ft S: -3.2 ft L: -3.8 ft	No B: -0.4 ft S: -0.1 ft L: -0.6 ft	All plants change by 1% or less.	No B: -0.7 ft	All plants change by 2% or less.
Frequent Low (977.0 ft asl)	B: -2.7 ft S: -2.8 ft L: -3.5 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	All plants change by 1% or less.	No B: -0.5 ft	All plants change by 1% or less.
Infrequent Low (976.7 ft asl)	B: -2.6 ft S: -2.6 ft L: -3.3ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	All plants change by 1% or less.	No B: -0.5 ft	All plants change by 1% or less.
Infrequent Low to Infrequent High (2.9 ft)	B: ±0.12 ft S: ±0.12 ft L: ±0.12 ft	No B: -0.09 ft S: -0.05 ft L: +0.11 ft	The range between infrequent high and infrequent low does not change significantly.	No B: +0.01 ft	The range between infrequent high and infrequent low does not change significantly.

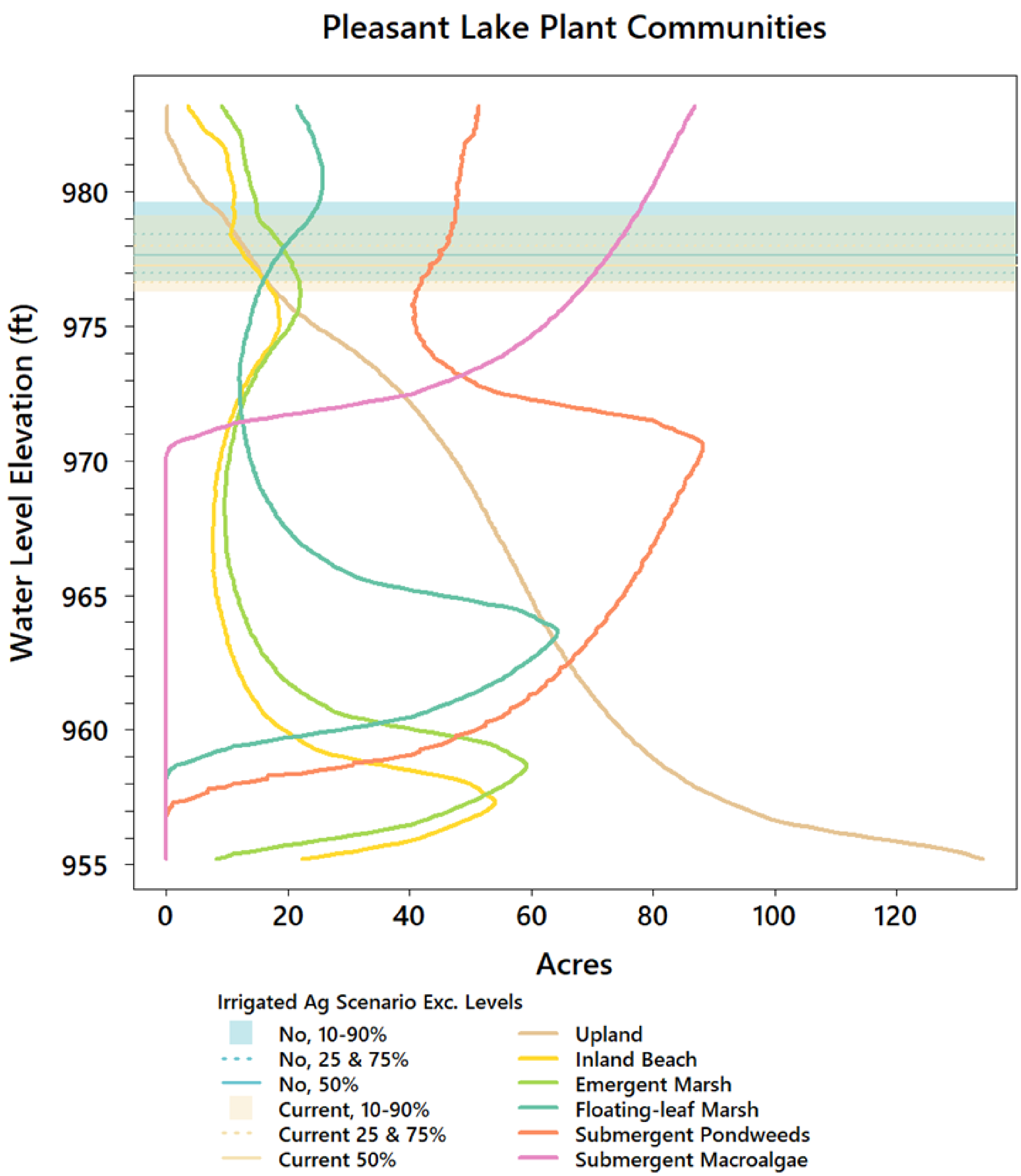

Figure 97. Plant community areal coverage, Pleasant Lake. Change in areal coverage of each plant community across a full range of lake level elevations on Pleasant Lake based on the depth tolerances of each plant community.

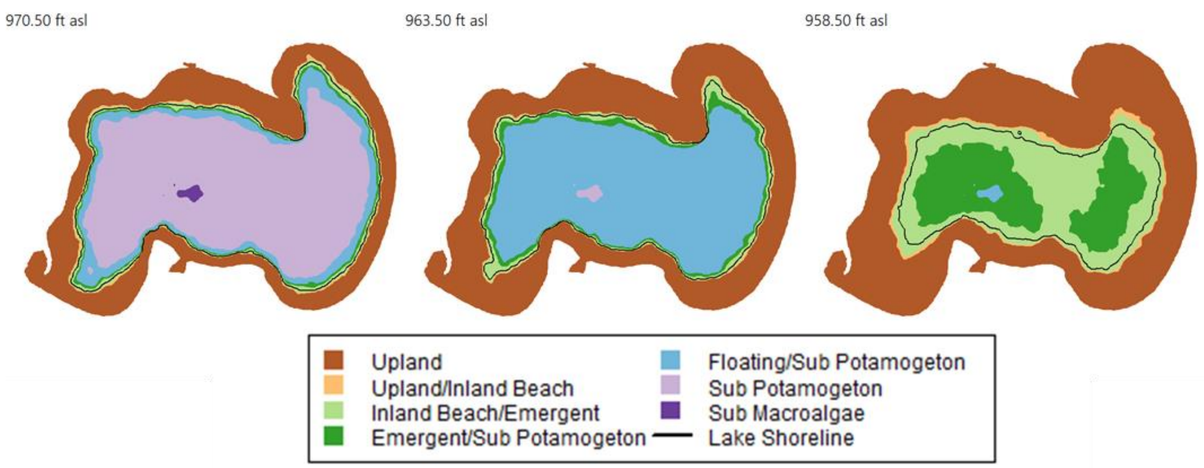

Figure 98. Plant community spatial distribution under extreme declines, Pleasant Lake. Spatial distribution of plant communities on Pleasant Lake at the elevations where submergent *Potamogeton*, Floating-leaved Marsh, and Emergent Marsh each reach their maximal extent. These occur at extreme lake level declines.

The frequency and duration at which lake levels remain above or below the median lake level (977.6 ft asl) does not appear to be impacted in the current-irrigated-agriculture scenario, but the variability around these estimates is high due to the relatively short, 33-year time period and small number of events. Lowering the entire lake level time series effectively reduces the number of times that the lake level crosses the no-irrigated-agriculture median, and therefore, also increases the duration of each event. For example, the frequency at which lake levels remain below the median lake level decreases from seven times in the no-irrigated-agriculture scenario to five times in the current-irrigated-agriculture scenario, and the median duration of these events increases from five to 10 months (Table 41, Figure 67, Figure 69). Although the uncertainty in these estimates precludes a robust significance determination, this combination of frequency and duration should be considered in the future as it better characterizes the dynamic nature of lake level fluctuations and how they can act as a disturbing or stabilizing driver for plant communities.

Long Lake

Plant communities shift dramatically in the no-irrigated-agriculture scenario as Long Lake's water levels go from the infrequent low to the infrequent high, a total range of 5.9 feet (Table 68, Figure 99, Figure 100). Because Long Lake is so shallow and gently sloped, large changes in the plant communities occur with small vertical changes in lake level. Long Lake fluctuates from being a deep Emergent Marsh at the infrequent low to a lake with small, open-water patches at the infrequent high (Figure 100). In general, Submergent and Floating-leaved Marsh decline with decreasing lake levels, whereas Upland, Inland Beach, and Emergent Marsh expand. The lake level with maximum coverage of Emergent Marsh is 1095.5 ft asl, so Emergent Marsh coverage begins to contract as lake levels fall to the infrequent low, at 1094.9 ft asl. At the infrequent low, most of the lake footprint (including the entire area ≤ 1104.6 ft asl) is composed of Emergent Marsh (63%), Inland Beach (42%), and Upland (38%) with a contiguous stand of Submergent Marsh (28%) left in the middle of the lake (Figure 100). At the median lake level, Submergent Marsh (63%) and Floating-leaved Marsh (50%) dominate with Emergent Marsh (28%), Inland Beach (18%) and Upland (23%) along the lake margin. At the infrequent high, Submergent Marsh (80%) and Floating-leaved Marsh (64%) still dominate, but here, there are patches too deep for Floating-leaved Marsh (Figure 100). Emergent Marsh (18%), Inland Beach (13%), and Upland (10%) form concentric rings along the lake margin with less overall area than at the median.

Table 68. Areal percent cover of plant communities in Long Lake at five exceedance probability lake elevations in the no-irrigated-agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. Estimates are from the base run (one standard deviation derived from 349 model runs for each scenario).

Metric	Irrigated Agriculture Scenario	Upland (% of lake)	Inland Beach (% of lake)	Emergents (% of lake)	Floating-leaved (% of lake)	Submergents (% of lake)
Infrequent High	No	9.6 (2.2)	12.9 (0.7)	17.7 (1.0)	64.0 (10.8)	80.4 (2.7)
	Current	18.1 (3.8)	16.0 (1.5)	22.5 (3.2)	60.7 (6.7)	68.9 (5.0)
	Potential	18.9	16.4	23.1	59.2	68.4
Frequent High	No	18.6 (3.4)	16.3 (1.3)	22.9 (2.6)	59.6 (5.6)	68.7 (4.4)
	Current	33.9 (5.7)	29.9 (8.5)	62.6 (13.5)	6.2 (18.7)	41.4 (13.1)
	Potential	35.8	33.2	64.7	0.7	37.0
Median	No	23.0 (3.6)	18.0 (1.8)	28.3 (5.3)	50.4 (8.0)	62.7 (5.0)
	Current	43.1 (7.7)	56.1 (13.2)	57.8 (9.0)	0.0 (13.2)	8.5 (19.0)
	Potential	48.0	58.8	53.2	0.0	0.3
Frequent Low	No	32.4 (4.7)	27.1 (7.1)	58.1 (12.3)	13.1 (16.6)	45.8 (10.8)
	Current	56.0 (8.8)	53.1 (8.9)	45.4 (7.9)	0.0 (5.8)	0.0 (14.0)
	Potential	58.3	51.3	43.2	0.0	0.0
Infrequent Low	No	38.2 (5.4)	42.1 (11.1)	62.5 (8.4)	0.0 (12.6)	28.0 (15.1)
	Current	63.5 (10.4)	47.5 (7.3)	38.1 (9.4)	0.0 (3.9)	0.0 (10.3)
	Potential	83.7	36.5	18.9	0.0	0.0

Aquatic and wetland plants are significantly impacted in the current-irrigated-agriculture scenario for all magnitude metrics (Table 69). The base, large drawdown, and small drawdown runs all show that irrigated agriculture significantly alters the plant communities from the infrequent low to the frequent high. Depending on the model run and exceedance probability evaluated, irrigated agriculture causes a 0.7 to 4-ft decrease in lake levels, and significance thresholds range from -0.2 feet at the infrequent low to -2 feet at the infrequent high (base run). As lake levels decline, Submergent and Floating-leaved Marsh decline and Upland, Inland Beach, and Emergent Marsh increase (Figure 99). The current-irrigated-agriculture scenario draws the frequent low and infrequent low down so much that Emergent Marsh loses area from the lake margin instead of gaining area toward the lake center (Figure 99, Figure 100).

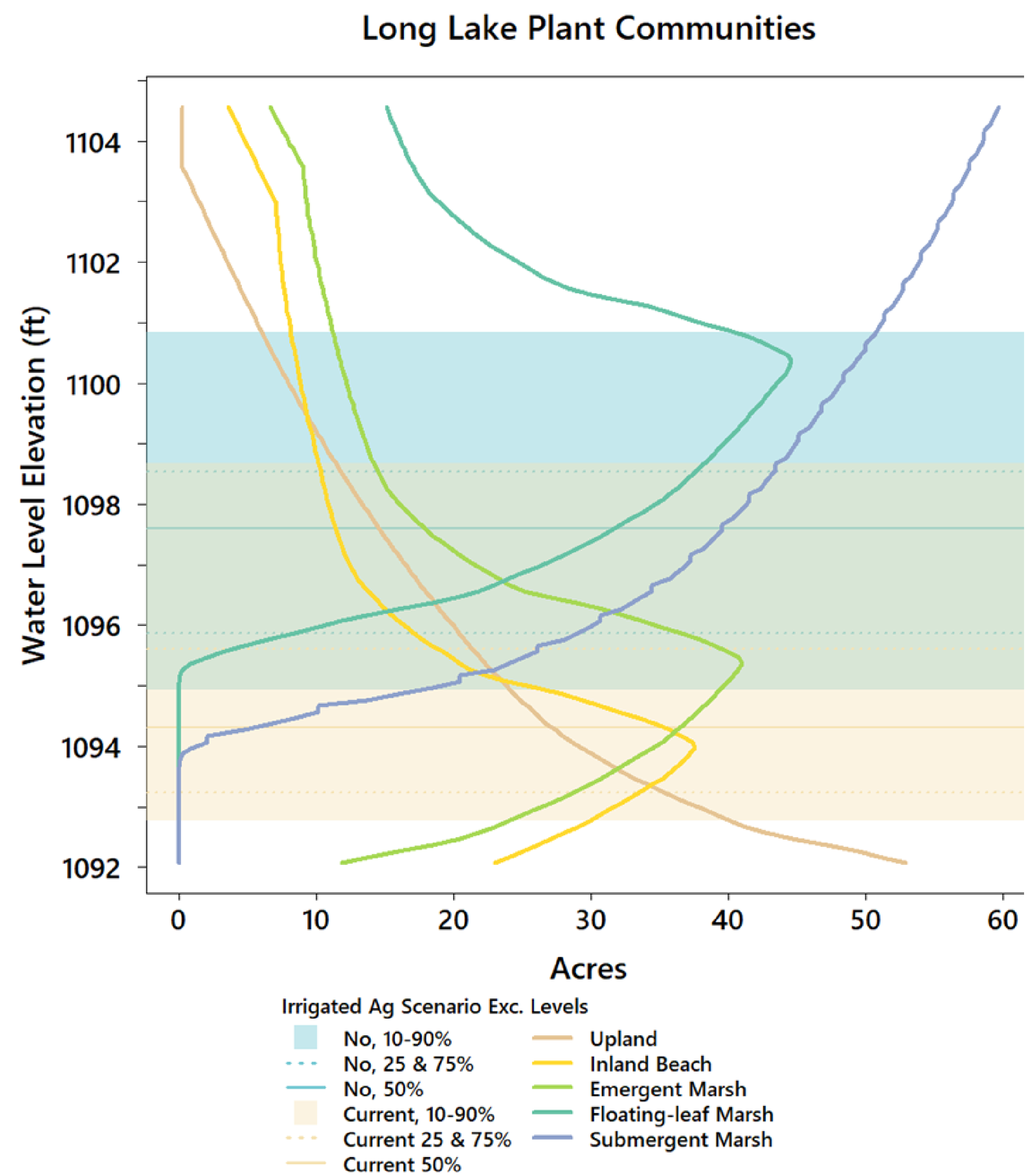

Figure 99. Plant community areal coverage, Long Lake. Change in areal coverage of each plant community across a full range of lake level elevations on Long Lake based on the depth tolerances of each plant community.

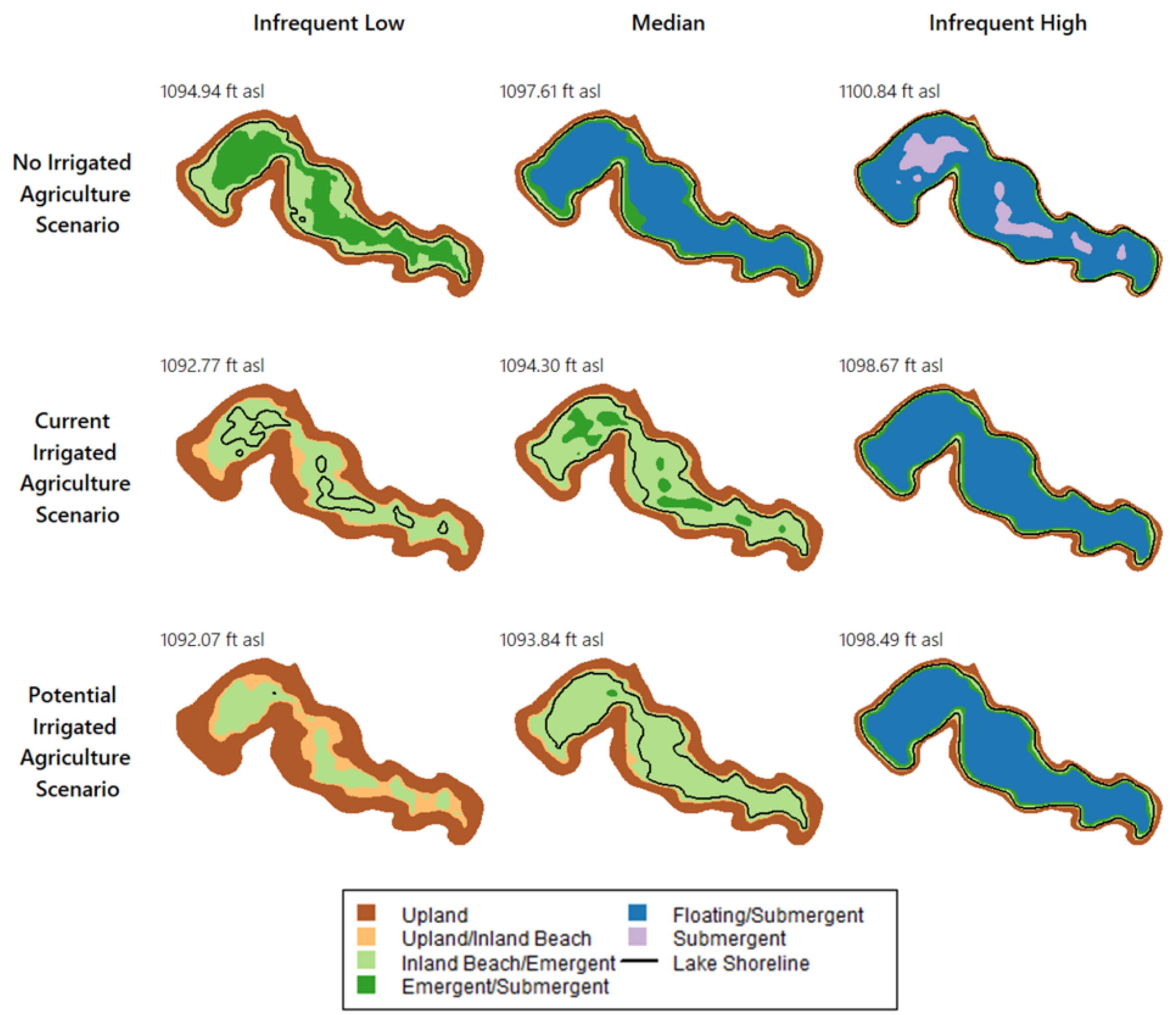

Figure 100. Plant community spatial distribution, Long Lake. Spatial distribution of plant communities on Long Lake at the infrequent low, median and infrequent high under the no-irrigated-agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. All maps use lake water elevations derived from the base model run.

In sum, the current-irrigated-agriculture scenario draws down the lake such that at the infrequent low and median, Long Lake becomes a shallow marsh dominated by Inland Beach and Emergent Marsh (Figure 100). At the median lake level, only small patches at the center of the lake are deep enough for Submergent Marsh. The infrequent high is least affected by irrigation, still dominated by Submergent and Floating-leaved Marsh, but there are no longer patches of open water too deep for Floating-leaved Marsh. The range from the infrequent low to infrequent high did not change significantly for the base and small-drawdown runs but increased by 0.5 feet in the large-drawdown run (Table 69).

Table 69. Significant impacts of groundwater withdrawals on Long Lake's plant communities. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Ecological response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Ecological response to potential-irrigated-ag
Magnitude					
Infrequent High (1100.8 ft asl)	B: -2.0 ft S: -0.5 ft L: -1.0 ft	**Yes** **B: -2.2 ft** **S: -0.7 ft** **L: -2.8 ft**	Submergents decrease by 12%.	**Yes** **B: -2.3 ft**	Submergents decrease by 12%.
Frequent High (1098.5 ft asl)	B: -1.0 ft S: -1.1 ft L: -2.0 ft	**Yes** **B: -2.9 ft** **S: -1.4 ft** **L: -3.8 ft**	All plants change by > 14%; floating-leaved decrease by 53%.	**Yes** **B: -3.2 ft**	All plants change by > 17%; floating-leaved decrease by 59%.
Median (1097.6 ft asl)	B: -0.7 ft S: -0.8 ft L: -1.5 ft	**Yes** **B: -3.3 ft** **S: -1.8 ft** **L: -4 ft**	All plants change by > 20%; floating -leaved and submergents decrease by > 50%.	**Yes** **B: -3.8 ft**	All plants change by > 24%; floating-leaved decrease by 50% and submergents decrease by 62%.
Frequent Low (1095.9 ft asl)	B: -0.4 ft S: -0.4 ft L: -0.8 ft	**Yes** **B: -2.6 ft** **S: -1.2 ft** **L: -3.8 ft**	All plants change by > 12%; submergents decrease by 46%.	**Yes** **B: -2.8 ft**	All plants change by > 13%; submergents decrease by 46%.
Infrequent Low (1094.9 ft asl)	B: -0.2 ft S: -0.3 ft L: -0.5 ft	**Yes** **B: -2.2 ft** **S: -0.8 ft** **L: -3.3 ft**	Submergents decrease by 28%; emergents decrease by 24%; upland increases by 25%.	**Yes** **B: -2.9 ft**	Submergents decrease by 28%; emergents decrease by 44%; upland increases by 46%.
Infrequent Low to Infrequent High (5.9 ft)	B: ±0.2 ft S: ±0.2 ft L: ±0.2 ft	**Caution** B: -0.001 ft S: +0.08 ft **L: +0.5 ft**		**Yes** **B: +0.5 ft**	

Aquatic and wetland plants are significantly impacted in the potential-irrigated-agriculture scenario as well (Table 69). The areal changes in plant cover are similar to the current-irrigated-agriculture scenario at the infrequent high, frequent high, and frequent low. At these magnitudes, lake levels decrease by an additional 0.1 to 0.3 feet from the current to potential-irrigated-agriculture scenario. More dramatic changes to the plant communities occur under the potential-irrigated-agriculture scenario at the median and infrequent low. Submergent Marsh decreases by an additional 12% with the drop in lake level at the median, leaving behind a single, small patch that is still deep enough for Submergent Marsh (Figure 100). At the infrequent low, Emergent Marsh decreases by an additional 22% and Upland increases by an additional 21%. At this point, most of the lake basin consists of Upland, with patches deep enough for Inland Beach and Emergent Marsh in the center (Figure 100).

The frequency and duration at which lake levels remain above or below the median lake level (1097.6 ft asl) is likely impacted in the current-irrigated-agriculture scenario. Even though the low number of events makes this metric less robust, the difference between the no-irrigated-agriculture and current-irrigated-agriculture values is large (Table 48, Figure 75). For example, the frequency at which lake levels remain below the median lake level for over one month decreases from seven times in the no-irrigated-agriculture scenario to one time in the current and potential-irrigated-agriculture scenarios. The median duration of these events increases from five to 347 (current) or 350 (potential) months (Table 48, Figure 75). The lower frequency and longer duration of prolonged low and high lake levels follow from the significant reduction in the magnitude of lake levels (Table 68). In the current and potential-irrigated-agriculture scenarios, the lake level falls below 1097.6 ft asl early in the record and only rises above at the end of the record (Figure 73). The ring of now dead trees around the perimeter of the eastern portion of the lake is an example of the type of upland vegetation encroachment that these model scenarios indicate intensifies with irrigation: longer durations of low lake levels allow trees to become very well-established between less frequent periods of prolonged high levels (Figure 101).

Figure 101. Flooding of upland vegetation, Long Lake. Trees that established on the lakebed of Long Lake during prolonged low water levels (below the median from 2004 – 2016). The trees died during the most recent prolonged high lake levels.

Plainfield Lake

Plainfield Lake's plant communities shift dramatically as water levels go from the infrequent low to the infrequent high in the no-irrigated-agriculture scenario, a total range of 5.4 feet (Figure 102, Figure 103). At the infrequent low, most of the lake footprint (defined as the entire area ≤ 1105.6 ft asl) is composed of Emergent Marsh (61%) followed by and mixed with Submergent Marsh (50%). Floating-leaved Marsh (37%) and Upland (39%) are the next most prevalent (Table 70). Inland Beach coverage is limited compared to the other plant communities, forming a ring around the lake that straddles the infrequent low lake level (14%). At the median lake level, more than half of the lake footprint is covered by Emergent Marsh (70%), Submergent Marsh (60%), and Floating-leaved Marsh (55%), and the deepest point becomes too deep for Emergent Marsh. At the infrequent high, Submergent Marsh (77%) dominates. Much of the lake is too deep for Emergent and Floating-leaved Marsh, though both are still prevalent around the perimeter of the lake (39% Emergent, 26% Floating-leaved). Inland Beach prevalence changes little (15%), and Upland is limited to the periphery of the lake (12%).

Table 70. Areal percent cover of plant communities in Plainfield Lake at five exceedance probability lake elevations in the no-irrigated-agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. Estimates are from the base run (one standard deviation derived from 349 model runs for each scenario).

Metric	Irrigated Agriculture Scenario	Upland (% of lake)	Inland Beach (% of lake)	Emergents (% of lake)	Floating-leaved (% of lake)	Submergents (% of lake)
Infrequent High	No	11.7 (1.8)	14.8 (2.0)	38.8 (1.3)	26.1 (3.0)	77.1 (3.5)
	Current	17.0 (2.8)	19.8 (1.8)	49.4 (6.8)	51.3 (10.6)	66.1 (4.2)
	Potential	17.6	20.0	51.8	54.6	65.3
Frequent High	No	19.9 (3.4)	19.7 (1.2)	60.1 (8.5)	57.6 (8.5)	64.2 (3.4)
	Current	34.6 (4.6)	12.5 (2.7)	65.8 (3.8)	49.3 (4.3)	56.1 (2.9)
	Potential	35.5	12.3	64.8	47.0	55.3
Median	No	30.1 (4.4)	17.7 (1.9)	69.6 (5.4)	54.7 (3.3)	59.6 (2.4)
	Current	39.4 (3.1)	13.9 (2.0)	61.0 (2.8)	35.8 (9.3)	49.9 (4.3)
	Potential	41.0	15.9	59.3	26.2	46.4
Frequent Low	No	36.0 (3.1)	12.4 (1.6)	64.4 (2.5)	45.8 (4.8)	54.7 (2.7)
	Current	43.6 (3.1)	21.6 (6.7)	56.7 (3.1)	8.0 (14.3)	37.8 (9.1)
	Potential	44.4	23.7	56.0	3.2	35.8
Infrequent Low	No	39.2 (2.6)	13.8 (1.7)	61.2 (2.4)	36.6 (8.2)	50.3 (3.7)
	Current	46.3 (3.5)	32.0 (9.6)	54.2 (3.4)	0.9 (12.5)	26.0 (12.1)
	Potential	47.9	38.3	52.6	0.4	19.9

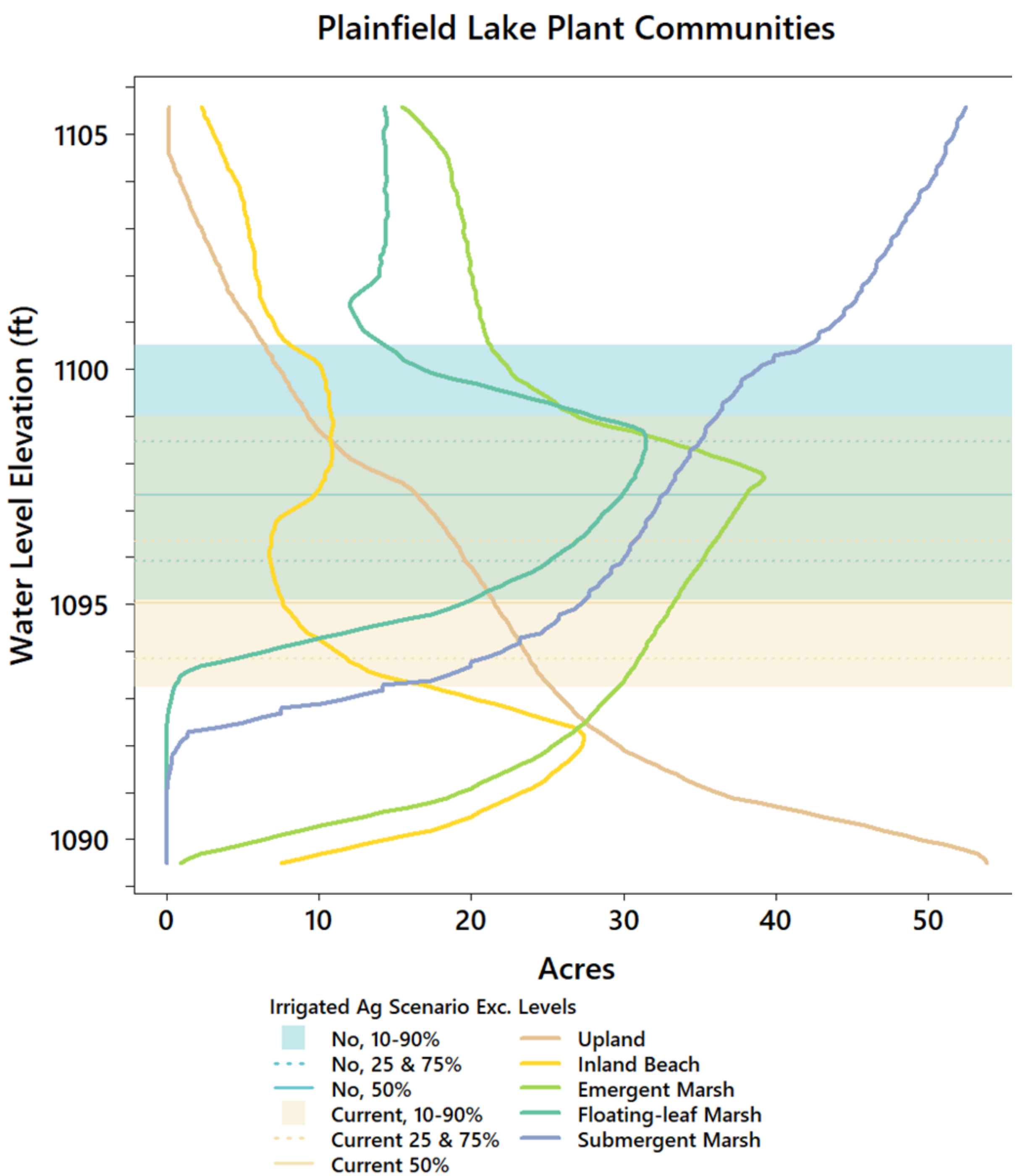

Figure 102. Plant community areal coverage, Plainfield Lake. Change in areal coverage of each plant community across a full range of lake level elevations on Plainfield Lake based on the depth tolerances of each plant community

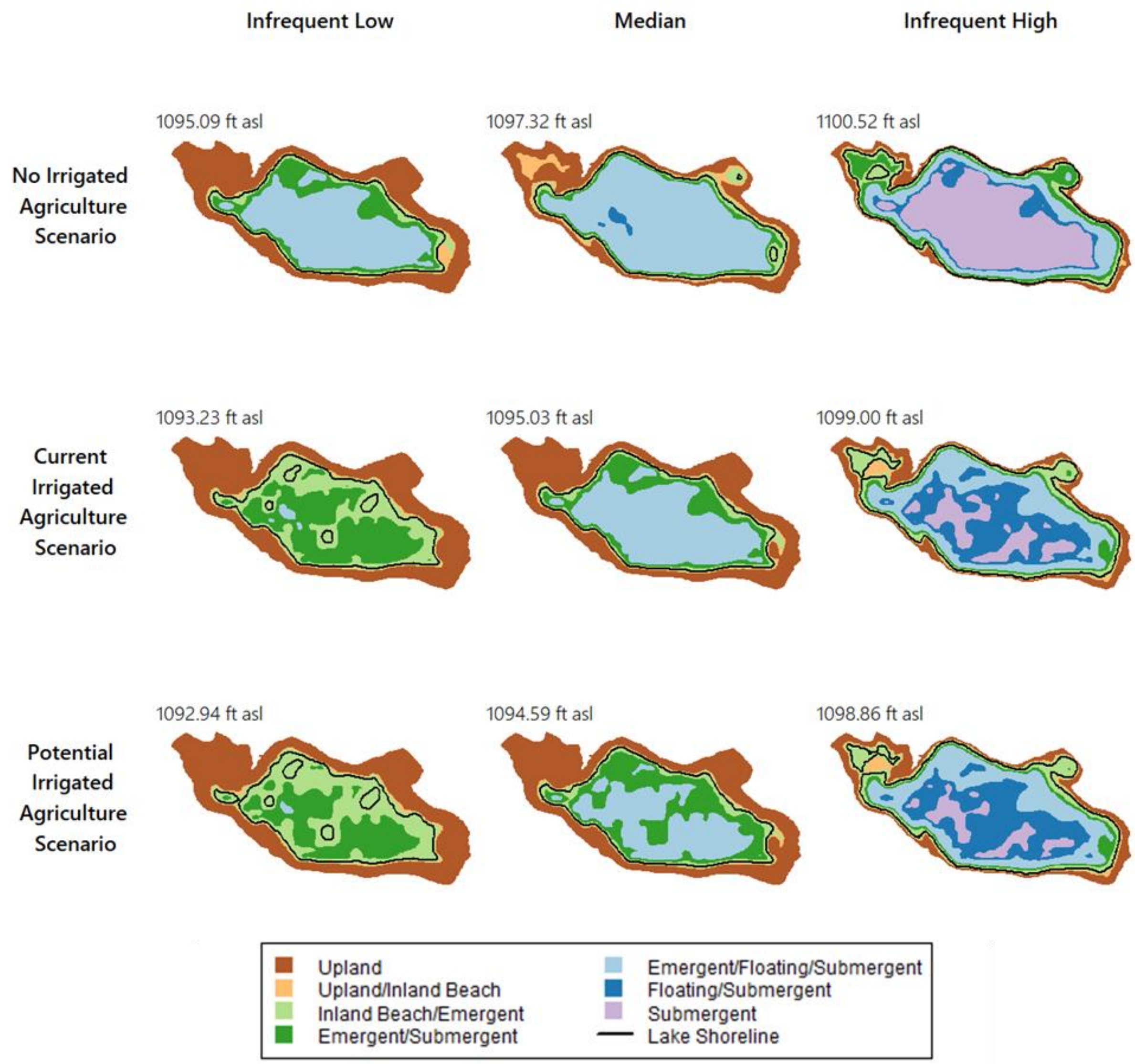

Figure 103. Plant community spatial distribution, Plainfield Lake. Spatial distribution of plant communities on Plainfield Lake at the infrequent low, median and infrequent high under the no-irrigated-agriculture, current-irrigated-agriculture, and potential-irrigated-agriculture scenarios. All maps use lake water elevations derived from the base model run.

Aquatic and wetland plants are significantly impacted in the current-irrigated-agriculture scenario for all magnitude metrics (Table 71). The base and large-drawdown runs show that irrigated agriculture significantly alters the plant communities from the infrequent low to the infrequent high. The small drawdown run also shows significant impacts at the frequent high, median and infrequent low. Depending on the model run and exceedance probability evaluated, current levels of irrigated agriculture cause a 0.4 to 2.9-foot decrease in lake levels, and significance thresholds range from -0.5 to -0.9 feet (base run). Submergent Marsh decreases and Upland increases as lake levels decline (Figure 102). Inland Beach, Floating-leaved, and Emergent Marsh initially gain area as lake levels decline from the infrequent high and plants move lakeward; they then lose area as lake levels decline further and

Table 71. Significant impacts of groundwater withdrawals on Plainfield Lake's plant communities. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Ecological response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Ecological response to potential-irrigated-ag
Magnitude					
Infrequent High (1100.5 ft asl)	B: -0.8 ft S: -0.9 ft L: -1.7 ft	**Yes** **B: -1.5 ft** S: -0.4 ft **L: -2.0 ft**	Emergents gain 11%, floating-leaved gain 25%, and submergents lose 11%.	**Yes** **B: -1.7 ft**	Emergents gain 13%, floating-leaved gain 29%, and submergents lose 12%.
Frequent High (1098.5 ft asl)	B: -0.6 ft S: -0.5 ft L: -0.6 ft	**Yes** **B: -2.1 ft** **S: -1.0 ft** **L: -2.9 ft**	Upland gains 15%.	**Yes** **B: -2.4 ft**	Upland gains 16%, floating-leaved lose 11%.
Median (1097.3 ft asl)	B: -0.6 ft S: -0.6 ft L: -0.6 ft	**Yes** **B: -2.3 ft** **S: -1.1 ft** **L: -2.8 ft**	Exceeds threshold to protect federally threatened plant. Floating-leaved lose 19%.	**Yes** **B: -2.7 ft**	Exceeds threshold to protect federally threatened plant. Floating-leaved lose 29%, submergents lose 13%, emergents lose 10%, and upland gains 11%.
Frequent Low (1095.9 ft asl)	B: -0.9 ft S: -0.9 ft L: -1.7 ft	**Yes** **B: -2.1 ft** S: -0.9 ft **L: -2.7 ft**	Floating-leaved lose 38%, submergent loses 17%.	**Yes** **B: -2.3 ft**	Floating-leaved lose 43%, submergents lose 19%, and inland beach gains 11%.
Infrequent Low (1095.1 ft asl)	B: -0.5 ft S: -0.6 ft L: -1.2 ft	**Yes** **B: -1.9 ft** **S: -0.6 ft** **L: -2.5 ft**	Inland beach gains 18%, floating-leaved lose 36%.	**Yes** **B: -2.1 ft**	Inland beach gains 24%, floating-leaved lose 36%, and submergents lose 30%.
Infrequent Low to Infrequent High (5.4 ft)	B: ±0.2 ft S: ±0.2 ft L: ±0.2 ft	**Yes** **B: +0.3 ft** **S: +0.2 ft** **L: +0.4 ft**	The range between the infrequent low and infrequent high increases by 0.3 ft.	**Yes** **B: +0.5 ft**	The range between the infrequent low and infrequent high increases by 0.5 ft.

habitat is lost from the lake margin. The maximal areal extent for Inland Beach is at 1092 ft asl, that of Emergent Marsh is 1097.7, and that of Floating-leaved Marsh is 1098.7 ft asl. The current-irrigated-agriculture scenario draws the infrequent low down such that Plainfield Lake becomes an Emergent Marsh with extensive Upland around the perimeter and only a small patch deep enough for Floating-leaved Marsh. At the current-irrigated-agriculture scenario median lake level, Emergent Marsh and Upland extend further lakeward, leaving less area deep enough for Floating-leaved Marsh. At the current-irrigated-agriculture infrequent high, Plainfield Lake only has small patches of open water too deep for Floating-leaved Marsh. The range from the infrequent low to infrequent high grew significantly larger (by 0.2 to 0.4 feet) in all three runs (Table 71).

Aquatic and wetland plants are significantly impacted in the potential-irrigated-agriculture scenario as well (Table 71). The areal changes in plant cover are similar to the current-irrigated-agriculture scenario at the infrequent high, which drops by an additional 0.2 feet from the current to potential-irrigated-agriculture scenario. More dramatic changes to the plant communities occur under the potential-irrigated-agriculture scenario at all other magnitudes. For example, the additional 0.4-foot drop in the median lake level from the current to potential-irrigated-agriculture scenario results in an additional 10% loss in Floating-leaved Marsh. Submergent Marsh loses 13%, Emergent Marsh loses 10%, and Upland gains 11%. In general, Plainfield Lake fills in with more Upland, Inland Beach, and Emergent Marsh at the infrequent low and median (Figure 103). The range from the infrequent low to infrequent high grew significantly larger, from 5.4 feet in the no-irrigated-agriculture scenario to 5.9 feet in the potential-irrigated-agriculture scenario (base run).

Upland plants would expand lakeward and replace aquatic and wetland plants if lake levels dropped even more. At 1092.5 ft asl, Floating-leaved Marsh disappears altogether, with Emergent Marsh covering the entire lake area and only 2.6 acres still deep enough for Submergent Marsh (Figure 102). Submergent Marsh disappears at 1091.2 ft asl. From this elevation and lower, Upland would rapidly expand its distribution, filling in all but the deepest spot at 1089.5 ft asl.

The frequency and duration at which lake levels remain above or below the median lake level (1097.3 ft asl) is likely impacted in the current-irrigated-agriculture scenario, but the low number of events makes this metric less robust (Table 55, Figure 81). For example, the frequency at which lake levels remain below the median lake level decreases from five times in the no-irrigated-agriculture scenario to two times in the current and potential-irrigated-agriculture scenarios. The median duration of these events increases from seven to 162 (current) or 163 (potential) months (Table 55, Figure 81). The lower frequency and longer duration of prolonged low and high lake levels with irrigation follow from the significant reduction in the magnitude of lake levels (Figure 79). Similar to Long Lake, the dead trees that inhabit the perimeter of Plainfield Lake are an example of the upland vegetation encroachment that modeled scenarios indicate becomes more intense under irrigated agriculture (Figure 91).

Significant Impacts to a Federally Threatened Plant

All three model runs show that the current-irrigated-agriculture scenario significantly impacts the federally threatened plant, with drops of 1.1 to 2.8 ft below the median (Table 71). We also require the exceedance probability range from the infrequent low to infrequent high to remain within that of our estimated error. The current-irrigated-agriculture scenario significantly increase the range by 0.2 to 0.4 feet according to all three runs, and the potential-irrigated-agriculture scenario significantly increases the range by 0.5 feet (Table 71). More extreme fluctuations could benefit the plant by creating more suitable habitat, killing encroaching upland vegetation in a landward direction and mineralizing muck sediments lakeward, as long as these extreme levels are not overly prolonged. However, changes to the hydrologic regime could be detrimental to the plant, and both irrigated-agriculture scenarios indicate more extreme water level fluctuations.

We conclude that the current and potential-irrigated-agriculture scenarios significantly impact this federally threatened plant because two of two indicators are not met. Both irrigated-agriculture scenarios reduce the median lake level and make lake level fluctuations more extreme. This could be detrimental to population persistence as the limit of suitable habitat at low lake levels is unknown, and a decline in lake levels could require the federally threatened plant to shift its distribution lakeward. All areas of exposed lakebed may not support this plant because 1) it is not uniformly distributed around the lake and 2) areas of the lakebed that have been inundated for long periods likely have organic soil (e.g., muck), which is not suitable for colonization.

Fish Communities

Literature Review

As long-lived aquatic animals, fish integrate the effects of water level fluctuations across many years and through different ecosystem pathways. To survive and reproduce, fish require water with appropriate levels of dissolved oxygen and other chemicals, food resources such as invertebrates and small fish, and habitat to support spawning and rearing. The water level regime can influence each of these requirements directly or indirectly. A change in water level immediately changes the total amount of physical habitat available to fishes as water levels inundate or strand areas of hard substrate, coarse woody habitat, and aquatic plants. Over months and years, patterns of water level fluctuations can affect the amount and distribution of these resources, in turn altering food web dynamics and competitive interactions. Habitat and dietary preferences vary by species and shift as fish grow from fry to juveniles to adults (Inskip, 1982; Stuber et al., 1982). Thus, a rise or decline in water level will not have uniformly positive or negative impacts on the fish community (e.g. Sutela and Vehanen, 2008), but will act uniquely on each life stage and species of fish.

Volume and Area

Water levels determine the total volume and benthic area of a given lake, which influence the maximum biomass of fish that a water body can support. Most fish communities rely on both pelagic and benthic sources of food (Vander Zanden and Vadeboncoeur, 2002), so loss of either total lake volume (reducing pelagic primary production by phytoplankton) or benthic area (reducing primary production by rooted plants and epiphytic algae in the littoral zone) will reduce the carrying capacity of a given water body. Worldwide, lakes produce on average 73 pounds of fish per acre per year, however fish production can vary greatly between lakes. Fish production estimates in north temperate lakes range from 2 to 350 pounds per acre per year (Randall et al., 1995). Lakes that support greater rates of fish production tend to be larger, more eutrophic, warmer, and have high densities of small-bodied fishes (Leach et al., 1987; Randall et al., 1995). These estimates of areal or volumetric fish production rates can be used to investigate how much a reduction in lake area or volume would reduce overall fish production and ultimately impact fisheries. Lake bathymetry determines the degree to which changes in lake level alter total habitat.

Nearshore Habitat and Aquatic Plants

Studies of water levels' impacts on fish often focus on the dramatic changes to the littoral zone as water levels decline (e.g. Paller, 1997; Leira and Cantonati, 2008). Near-shore areas have high biovolumes of aquatic plants, coarse woody habitat (CWH), and areas of hard substrate, critical resources for many fishes. In the short term, the degree to which these resources are lost or gained with water level fluctuations depends on their distribution across the lake basin in relation to lake bathymetry. In the long term, water level fluctuations change habitat itself by altering plant distributions and sediment deposition patterns (Hofmann et al., 2008).

In the near-shore area, CWH largely consists of downed trees. As lake levels decline, the loss of these structurally complex refugia can increase the predation pressure upon prey fishes such as yellow perch, reducing their abundance and ultimately limiting the growth rate of their predators such as largemouth bass (Gaeta et al., 2014; Schindler et al., 2000). In many lakes, hard substrates such as sand, gravel and cobble are found near the shallows; fine particles tend to be transported farther from shore before settling (Hofmann et al., 2008). Several species present in our study lakes prefer to deposit eggs on hard substrate or newly flooded vegetation (Table 72), and the loss of these resources has been implicated in declines in fish populations as water levels receded (Paller, 1997; Kallemeyn, 1987).

The fate of fish and aquatic plants are so closely tied that the aquatic plant assemblage can be a better predictor of the fish community than water chemistry (Cvetkovic et al., 2010). Aquatic plants shelter smaller fish from predators, reduce wave action, increase temperature gradients, release dissolved oxygen into the water column, and support the macroinvertebrates that make up a large part of many species' diets (Table 72; Carpenter and Lodge, 1986; Stansfield et al., 1997). Large-scale loss of near-shore aquatic plants disrupts the food web that includes the fishes feeding and sheltering in beds of aquatic plants, including juveniles of species that later become largely piscivores such as largemouth bass (Havens et al., 2005; Johnson et al., 2007).

Spawning and Rearing Habitat

Certain fishes are susceptible to water level fluctuations during spawning and the early development of fry. Requirements for suitable spawning habitat vary across species, but include a range of acceptable substrates, temperatures, water velocities, and chemical requirements. Requirements for spawning habitat are often different from the general habitat requirements for adults of the same species, so lack of available spawning habitat can restrict a species' ability to recover after a normal fluctuation in population.

Centrarchid species such as bluegill, pumpkinseed, black crappie, and largemouth bass practice nest-building and some degree of parental care (Olson et al., 2006; Lawson et al., 2001). These fishes will build nests in water up to 10 feet deep as water temperatures warm in the late spring and may prefer sand or gravel but can successfully spawn on a variety of substrates (Becker, 1983; Reed and Pereira, 2009).

Table 72. Habitat preferences, diet, and dissolved oxygen tolerances of common fishes in the study lakes (Becker, 1983; Valley et al., 2010; Morgan and Godin, 1985; Inskip, 1982; Krieger et al., 1983; Stuber et al., 1982a; Stuber et al., 1982b)

Species	Spawning	Juvenile Habitat and Diet	Adult Habitat and Diet	DO Tolerance
Bluegill (*Lepomis macrochirus*)	Nest guarders. Prefer fine sand to gravel but will spawn in almost any substrate. Spawn in shallows up to 5 ft deep May to June when water >= 65°F.	Hide in vegetation to avoid predators. Will shift to feeding on zooplankton in the pelagic zone depending on predation risk. Diet similar to adults.	Use CWH or macrophytes to deter predation. Tolerate warm waters up to 80° F. Prefer productive lakes with lots of littoral habitat. Opportunistic feeders with a flexible diet. Primarily zooplankton and insects but will take wide variety of prey	> 5 mg/L, can tolerate lower levels for short durations
Largemouth bass (*Micropterus salmoides*)	Nest guarders, preferring gravel, but able to spawn on a great variety of substrates including mud. Spawn as water temps reach 54 - 59°F. Will build nests up to 6 ft deep.	Young of year use vegetation to shelter like bluegill. Early transition to piscivory important for first year of survival. Feed on small crustaceans and insects.	Lakes with extensive shallow areas but some areas deeper for overwintering. Very tolerant of warm waters (up to 85°F). Diet consists of crayfish and fish.	Growth reduced below 8 mg/L, distress beginning below 5 mg/L and death below 1 mg/L
Black Crappie (*Pomoxis nigromaculatus*)	Nest builder, males clear small depressions of debris, usually around vegetation or soft mud. Occurring March to July around 64 - 68 °F. Fry forage in beds of vegetation.	Need abundant cover. Feed on aquatic insects and crustaceans.	Low turbidity, abundant vegetation. Tend to linger in dense vegetation during daytime. Generally use littoral areas when not feeding. Adults forage in open water on microcrustaceans, insects and small fish.	Assumed to be similar to other freshwater fish, preferring above 5 mg/L.
Northern Pike (*Esox lucius*)	Deposit eggs on submerged vegetation in calm, shallow water as water temperatures reach 46 - 54°F. Good year-classes during years with high water in spring.	Juveniles become piscivorous at around 2 inches length but continue to feed on insects opportunistically. May have less tolerance for low DO than adults.	Ambush predators; require vegetation or CWH for cover and surprise. Smaller pike tend to use shallower littoral habitat. Broad range of temperature tolerance, up to 75°F .	Can tolerate several days of DO < 1.5 mg/L, probably need at least 3.0 mg/L
Yellow Perch (*Perca flavescens*)	Spawn in shallows (3 - 11 ft) April to June or at 45 - 56 °F. Release eggs near inundated vegetation or rock, sand, gravel if veg is not available. Rising water levels during this time favorable.	Similar habitat requirements to adults. Fry dependent on zooplankton, then moving to chironomids, amphipods and ostracods.	Littoral habitats with moderate amounts of vegetation. Tend to be found less often with increasing turbidity. Adults are generalists feeding on fish, insects and crayfish.	5 mg/L needed for most of the time, can tolerate some time below that amount, < 1.5 mg/L lethal.
Banded Killifish (*Fundulus diaphanous*)	Spawn June through August in temperatures above 70°F. May seek gravel substrate or vegetation.		Associated with macrophytes and *Chara* in particular. Not found in eutrophic lakes. Adults form schools in shallow water and feed on benthic macroinvertebrates and cladocerans.	

Iowa Darter (*Etheostoma exile*)	Spawn late April to early June in shallows, eggs develop for about 2-3 weeks. Spawn on fibrous roots, algae, or sand and gravel	Juveniles feed on amphipods, copepods, and rotifers.	Use plant cover and rubble. Generalist diet. Feed on small crustaceans, arthropods, insect larvae, fish eggs. Prefers clear water.	Very tolerant of low oxygen, reported to survive winter hypoxia ~0.2 mg/L
Bluntnose Minnow (*Pimephales notatus*)	Nests in small holes or over sand and gravel. Seeks to place adhesive eggs on underside of an object. Spawns May – August in Wisconsin. May spawn multiple times in a year.	NA	Bottom feeder: diet consists of midge larvae, insects, algae, and detritus.	NA
Mimic Shiner (*Notropis volucellus*)	Spawns May – July in Wisconsin.	NA	Feed on midge larvae, crustaceans, insects	NA

Northern pike, arguably Pleasant Lake's most important game fish, are vulnerable to lake level changes during the spawning season. Pike spawn soon after ice-out, seeking recently inundated vegetation in shallow water (sometimes only a few inches deep) when water temperatures first reach between 46 and 54°F (Inskip, 1982). Pike fry at similar latitudes spend several weeks to three months in shallow water near their hatching site (Oele et al., 2018; Hunt and Carbine, 1951). Though the greatest spawning success occurs upon dense mats of flooded upland plants, pike use many of the plants common in the shallow littoral zone of Pleasant Lake, including *Chara* spp., *Najas* spp., and *Potamogeton* spp. (McCarraher and Thomas, 1972; Kallemeyn, 1987).

Yellow perch have less specific spawning habitat requirements. Perch can spawn in deeper water then pike and can use hard substrate if debris or flooded vegetation is not available, but similarly benefit from steady or rising spring water levels and newly inundated vegetation (Weber and Les, 1982; Krieger et al., 1983; Robillard and Marsden, 2001). Perch also deposit eggs on *Chara* spp., woody debris, and more rarely cobble or gravel (Weber and Les, 1982).

Water Quality

The lake level regime also changes the character of aquatic habitat through effects on temperature, dissolved oxygen, and water chemistry. Fish species and life stages have differing tolerances for temperature, dissolved oxygen, pH, and salinity, and have optimal conditions for growth and reproduction. The lake elevation, or the total volume of water, affects how quickly temperatures will rise in the summer and fall in the winter, while the surface area and total depth of the lake will determine whether the lake stratifies. Stratification produces gradients of temperature, oxygen, and other chemicals with depth, with consequences for nutrient cycling and lake chemistry. Unsuitable chemical conditions, especially low dissolved oxygen and high temperature, reduce the total amount of suitable fish habitat in a lake and can ultimately cause mortality. The availability of dissolved oxygen is a primary concern for the fish communities of shallow lakes such as Long and Plainfield Lakes. Most freshwater fishes, including the most prevalent species in these two lakes, prefer dissolved oxygen concentrations above 5 mg/L. While many species of fishes have some ability to tolerate low dissolved oxygen, prolonged exposure to low but non-lethal levels can still have physiological consequences (Wu et al., 2003).

The lake level regime can influence both the amount of oxygen available in the water and rate at which it is used, especially in shallow lakes. Dissolved oxygen is delivered to lakes directly from the atmosphere, from inflowing waters, or by the photosynthetic activity of submerged vegetation and phytoplankton. Respiration by living organisms and the decay of organic material remove dissolved oxygen from the water column. Hypoxia occurs when these processes remove oxygen faster than it can be replenished. In shallow lakes with abundant aquatic plants, decomposition mostly occurs near the sediment along the lakebed (Meding and Jackson, 2001). Compared to a deep lake with the same biomass of aquatic plants, a shallow lake holds less dissolved oxygen overall, and has a greater area of active decomposition relative to total volume. If lake levels drop, a shallow lake becomes more vulnerable to hypoxia as volume is lost but the rate of decomposition across the bottom remains constant. Hypoxia can occur in late summer as aquatic plants begin to die back and water temperatures increase (warm water can hold less oxygen than cool water). In winter, ice prevents atmospheric oxygen from reaching the lake, and snow cover blocks sunlight that would otherwise allow plants and phytoplankton to produce oxygen via photosynthesis. Without any inputs of oxygen, respiration slowly depletes the oxygen in the water over the winter. Lake levels at the time of ice-on “lock in” the total amount of oxygen available until ice-off occurs in the spring.

Methods

We quantified the different types of available habitat at the full range of lake elevations, enabling us to calculate changes in habitat with reductions in lake levels. We used bathymetric data and the Storage Capacity tool in ArcMap 10.6 to estimate lake area and volume at 0.1-ft elevation intervals. A spline function fit the relationships between elevation and area and elevation and volume (R Core Team, 2019). We defined thresholds for loss of area and volume as greater than a 10% loss from conditions in the no-irrigated-agriculture scenario.

We did not directly measure fish production in these three lakes, so we estimated fish production using the formula derived by Downing et al. (1990, eq. 17), which predicts fish production (FP in pounds per acre per year) using average epilimnetic total phosphorus (TP).

$$\log_{10} FP = 0.332 + 0.531 \log_{10} TP \qquad \text{(Eq. 17)}$$

Downing et al. used a data set of 23 lakes in the northern hemisphere that are comparable to our study lakes in terms of mean depth and total phosphorus concentrations. The authors specifically sought out studies which measured the production of each important fish species in a lake. Other studies (e.g. Leach et al., 1987; Randall et al., 1995) have pointed to the importance of total phosphorus in predicting fish production or yield.

Because of the importance of northern pike as a game fish in Pleasant Lake, and the special status of the banded killifish, we developed a metric to account for their spawning requirements. In 2019, Pleasant Lake reached the lower limit of pike spawning temperatures (46.4 °F) on April 21st, signaling the initiation of spawning. Thus, water level changes during pike spawning and fry development in April, May, June, and July have important consequences for pike year class strength in Pleasant Lake. Rising water levels during spring, or at least maintaining sufficient water levels during early development of fry to prevent desiccation and stranding, is a crucial first step for a successful year class of pike (Oele et al., 2018). Banded Killifish initiate spawning in shallows when water temperatures reach 70 °F and continue into August (Becker, 1983), so we extended this requirement for stable or rising water levels into August. For each year, our metric calculates whether 1) spring levels are higher than the previous year’s growing season mean (presence of submerged upland vegetation), and 2) whether levels drop by less than two inches a month from March through August (slowly enough for fry to emigrate from shallow areas without being stranded). Pike in particular seek to deposit their eggs on terrestrial vegetation submerged in shallow water, but other species such as perch and bass also thrive in high-water years (Bonvechio and Allen, 2005; Becker, 1983). Thus, this metric serves to protect multiple species. We define a significant impact as a decrease in the percent of good spawning years, meeting the two conditions above, beyond 1 SD of that in the no-irrigated-agriculture scenario.

We also used georeferenced substrate hardness data from the sonar survey on Pleasant Lake to calculate mean hardness at 0.1-ft elevation intervals. We compared the hardness score to our field measurements of substrate composition and defined hard substrate as having a score greater than 0.4. We defined an impact to this characteristic as a change in water levels that would bring the average hardness at appropriate spawning depths (0.5 – 5 ft) below 0.4. Although hard substrate is regenerated as lake levels fall and more lakebed is exposed to waves and oxic conditions (den Heyer and Kalff, 1998), we were not able to reliably estimate the speed of this process, so we conservatively evaluated this threshold as though no hard substrate would be regenerated as lake levels declined in our modeled scenarios.

Pleasant Lake

In the no-irrigated-agriculture scenario, fish communities living in Pleasant Lake experience small changes in the total available habitat as the lake level ranges from the infrequent low to infrequent high (Table 73, Figure 104). Volume changes more rapidly than area with elevation. Even so, volumes at the infrequent low and high are only 93% and 114% of the median, respectively. We estimate that average yearly fish production in the no-irrigated-agriculture scenario ranges from 848 to 917 pounds (Table 73).

Table 73. Surface area and volume of Pleasant Lake at different lake level elevations under MODFLOW no-irrigated-agriculture scenario.

Lake level (ft)	Change from median (ft)	Surface area (ac)	Change in area from median (ac)	Percent of median area	Volume (Ac-ft)	Change in volume from median (Ac-ft)	Percent of median volume	Est. Fish prod. (lbs/yr)	Est. change in fish prod. (lbs/yr)
982.64	5	139.92	15.08	112%	2424.79	663.71	138%	982.24	105.92
981.64	4	138.00	13.16	111%	2285.81	524.72	130%	968.76	92.44
980.64	3	134.96	10.13	108%	2149.22	388.13	122%	947.42	71.10
979.64	2	130.67	5.84	105%	2016.66	255.57	115%	917.30	40.99
978.64	1	127.66	2.83	102%	1887.42	126.33	107%	896.17	19.86
977.64	0	124.83	0.00	100%	1761.09	0.00	100%	876.31	0.00
976.64	-1	120.74	-4.09	97%	1638.16	-122.93	93%	847.59	-28.72
975.64	-2	114.68	-10.16	92%	1520.23	-240.86	86%	805.05	-71.26
974.64	-3	108.46	-16.37	87%	1408.77	-352.32	80%	761.39	-114.93
973.64	-4	103.46	-21.37	83%	1302.90	-458.19	74%	726.29	-150.03
972.64	-5	99.42	-25.41	80%	1201.53	-559.56	68%	697.93	-178.39
971.64	-6	95.94	-28.89	77%	1103.80	-657.29	63%	673.50	-202.82
970.64	-7	92.82	-32.01	74%	1009.40	-751.69	57%	651.60	-224.72
969.64	-8	90.24	-34.59	72%	917.81	-843.28	52%	633.48	-242.83
968.64	-9	87.91	-36.92	70%	828.71	-932.38	47%	617.13	-259.19
surface area and volume at lake levels exceeded 10, 25, 50, 75, and 90% of the time									
979.60	1.97	130.57	5.74	105%	2012.38	251.29	114%	916.60	40.28
978.43	0.79	127.09	2.26	102%	1861.12	100.03	106%	892.17	15.86
977.64	0.00	124.83	0.00	100%	1761.09	0.00	100%	876.31	0.00
976.99	-0.64	122.28	-2.55	98%	1681.48	-79.61	95%	858.41	-17.91
976.66	-0.98	120.83	-4.00	97%	1640.67	-120.42	93%	848.23	-28.09

The total amount of high-quality fish habitat provided by aquatic plants in the no-irrigated-agriculture scenario does not change substantially as lake levels range from the infrequent low to the infrequent high (Figure 97). The acres covered by Floating-leaved Marsh and Submergent Pondweeds decline and the acreage of Emergent Marsh increases as lake levels fall from the infrequent high to the infrequent low, but not enough to affect the fish species that prefer to shelter among aquatic plants, which includes the majority of species present on the study lakes (Table 72). Large amounts of Submergent Macroalgae, a habitat associated with banded killifish (Valley et al. 2010), is also available at all lake level elevations in the no-irrigated-agriculture scenario. We are not able to predict the abundance of littoral CWH available under modeling scenarios. In general, recruitment of CWH to the littoral zone should be encouraged on Pleasant Lake into the future, but changes in the lake level regime will not exacerbate the current shortage of this type of habitat.

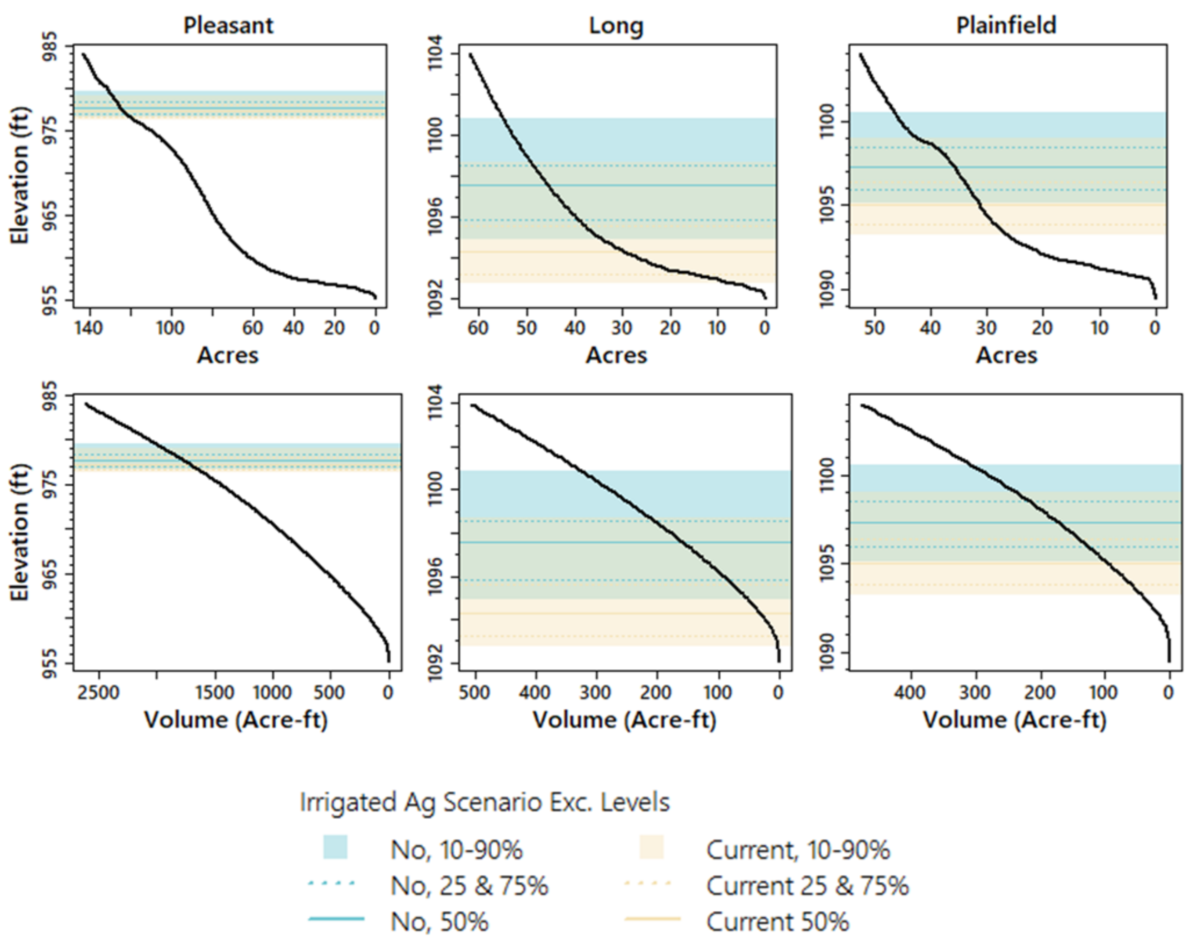

Figure 104. Changes in lake area and volume with lake levels.

Under the no-irrigated-agriculture scenario lake level regime, fishes in Pleasant Lake also have access to important spawning and rearing habitat. Species that prefer to spawn on sand or gravel, such as bluegill, bass, and pumpkinseed have access to shallow areas of hard substrate even at the infrequent low level (Figure 105). Species that prefer to deposit eggs on submerged vegetation would also successfully spawn under this lake level regime. In nearly one-third of years (31.3%), spring lake levels exceeded the previous year's growing season mean and did not drop more than two inches a month through August. We also note that most species have preferences for a particular spawning habitat but will still find some success if this habitat is not available. A reduction in the area of ideal spawning habitat will not cause a proportional reduction in spawning success. Little information is available on the spawning behavior of banded killifish and the other smaller fishes in Pleasant Lake: Iowa darter, bluntnose minnow, and mimic shiner (Table 72). However, in the no-irrigated-agriculture scenario, many types of habitat remain accessible, including shallow open areas of sand, gravel or cobble, dense stands of

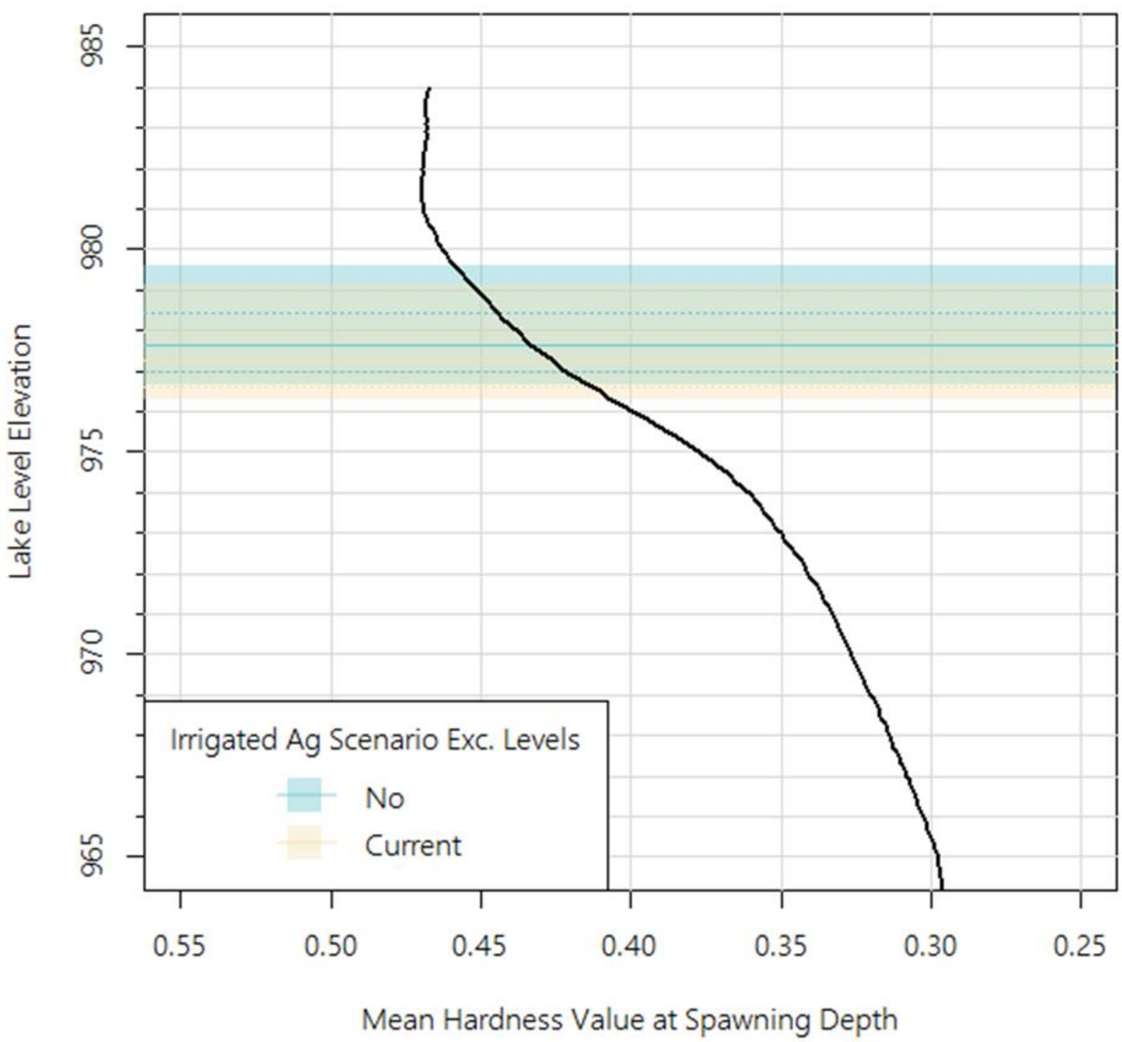

Figure 105. Pleasant Lake mean substrate hardness. Mean hardness of substrate available at appropriate centrarchid spawning depths (0.5 to 5 ft) by lake elevation.

submerged macrophytes, sparser areas of floating-leaved plants, and low-growing mats of *Chara* spp. and *Nitella* spp.

Pleasant Lake's fish community is not impacted by current amounts of groundwater withdrawal (Table 74). The greatest change from the no-irrigated-agriculture scenario to the current-irrigated-agriculture scenario is a uniform 0.4 to 0.5-ft reduction in lake levels across all exceedance probabilities (Table 74, Figure 68). This corresponds with only slight losses of lake surface area and volume, and thus total potential aquatic habitat. At each exceedance level, areas and volumes in the current-irrigated-agriculture scenario are at least 96% of the areas and volumes without irrigation. Changes in area and volume that occur naturally as lake levels vary are much greater than the differences in area and volume between scenarios. Pleasant Lake also remains unimpacted by changes in area and volume with the large-drawdown run.

The quality of hard substrate available for spawning and rearing by centrarchid species declines slightly in the current-irrigated-agriculture scenario, but not enough to threaten the fish community (Figure 106). Average substrate hardness at appropriate spawning depths is above 0.4 at the infrequent low level and increases as lake levels rise (Figure 105). Thus, this substrate metric which represents the present distribution of substrate hardness is not significantly impacted according to the current-irrigated-agriculture scenario. Loss of hard substrate is not likely to be a top concern in the long-term either because physical processes regenerate hard substrate. If lake levels drop enough that the mean hardness at spawning depths is less than 0.4, new areas of lakebed would become exposed to waves and oxic conditions, which transport fine particles to deeper areas and increase the mineralization rate of organic matter (den Heyer and Kalff, 1998).

The current-irrigated-agriculture scenario also predicts that the occurrence of favorable spring and summer water levels will remain unchanged, with 31.3% of years producing favorable conditions. During other years, pike, perch, and other species will attempt to spawn and likely find some success in sub-optimal spawning habitat.

Under the potential-irrigated-agriculture scenario, lake levels on Pleasant Lake decline only a few inches further, not enough to cause a significant impact to the fish community. Of the five exceedance levels we examined (infrequent low, frequent low, median, frequent high, and infrequent high), the median level declined the most from the current-irrigated agriculture scenario to the potential-irrigated agriculture scenario. This decline was about 0.3 feet, or less than four inches, and corresponds to a loss of less than 3% of lake area and less than 5% of lake volume relative to the no-irrigated-agriculture scenario. Fluctuations in area and volume within individual scenarios (changes from the infrequent low to the infrequent high) remain fairly consistent and are always larger than changes in area and volume between scenarios. Even with this modeled potential expansion of irrigation in the study area, Pleasant Lake's fish community is unlikely to suffer from loss of habitat. Modeled declines in Pleasant Lake's level under the potential-irrigated-agriculture scenario also do not significantly alter the availability of hard substrate for spawning. Even at the infrequent low, average substrate hardness remains above the threshold of 0.4.

Providing lake levels do not drop below the significance thresholds for total volume and area (10% loss, up to 1.4 to 1.6 feet lower), the littoral plant communities of Pleasant Lake will experience little change in their distribution (Figure 97). We consider the distribution of Submergent Pondweeds (1.6 to 15 feet depth) a good proxy for areas of prime fish habitat for structure and prey, and the acreage of

Submergent Pondweeds remains stable under the current-irrigated-agriculture and potential-irrigated-agriculture scenarios. Only when lake levels drop about 20 feet below the range of modeled levels in either scenario does the area of Submergent Pondweeds become a concern for the fish community (Figure 96).

Table 74. Significant impacts of groundwater withdrawals on Pleasant Lake's fish communities. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric/ Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential-irrigated-ag scenario?	Ecological Impact
Magnitude				
Infrequent High (979.6 ft asl)	B: -1.6 ft S: -1.6 ft L: -1.6 ft	No B: -0.5 ft S: -0.1 ft L: -0.5 ft	No B: -0.5 ft	Lake volume decreases by 3% or less; lake area decreases by 2% or less; mean substrate hardness does not change (all scenarios).
Frequent High (978.4 ft asl)	B: -1.5 ft S: -1.5 ft L: -1.6 ft	No B: -0.5 ft S: -0.1 ft L: -0.7 ft	No B: -0.7 ft	Lake volume decreases by 5% or less; lake area decreases by 2% or less; mean substrate hardness does not change (all scenarios).
Median (977.6 ft asl)	B: -1.4 ft S: -1.5 ft L: -1.5 ft	No B: -0.4 ft S: -0.1 ft L: -0.6 ft	No B: -0.7 ft	Lake volume decreases by 5% or less; lake area decreases by 2% or less; mean substrate hardness does not change (all scenarios).
Frequent Low (977.0 ft asl)	B: -1.0 ft S: -1.1 ft L: -1.5 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	No B: -0.5 ft	Lake volume decreases by 4% or less; lake area decreases by 2% or less; mean substrate hardness does not change (all scenarios).
Infrequent Low (976.7 ft asl)	B: -0.6 ft S: -0.8 ft L: -1.5 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	No B: -0.5 ft	Lake volume decreases by 4% or less; lake area decreases by 2% or less; mean substrate hardness does not change (all scenarios).
Timing				
Percent of years with high spring water and steady levels through summer (31%)	B: 29% S: 29% L: 35%	No B: 31% S: 31% L: 38%	No B: 38%	Frequency of good conditions remains the same or increases.

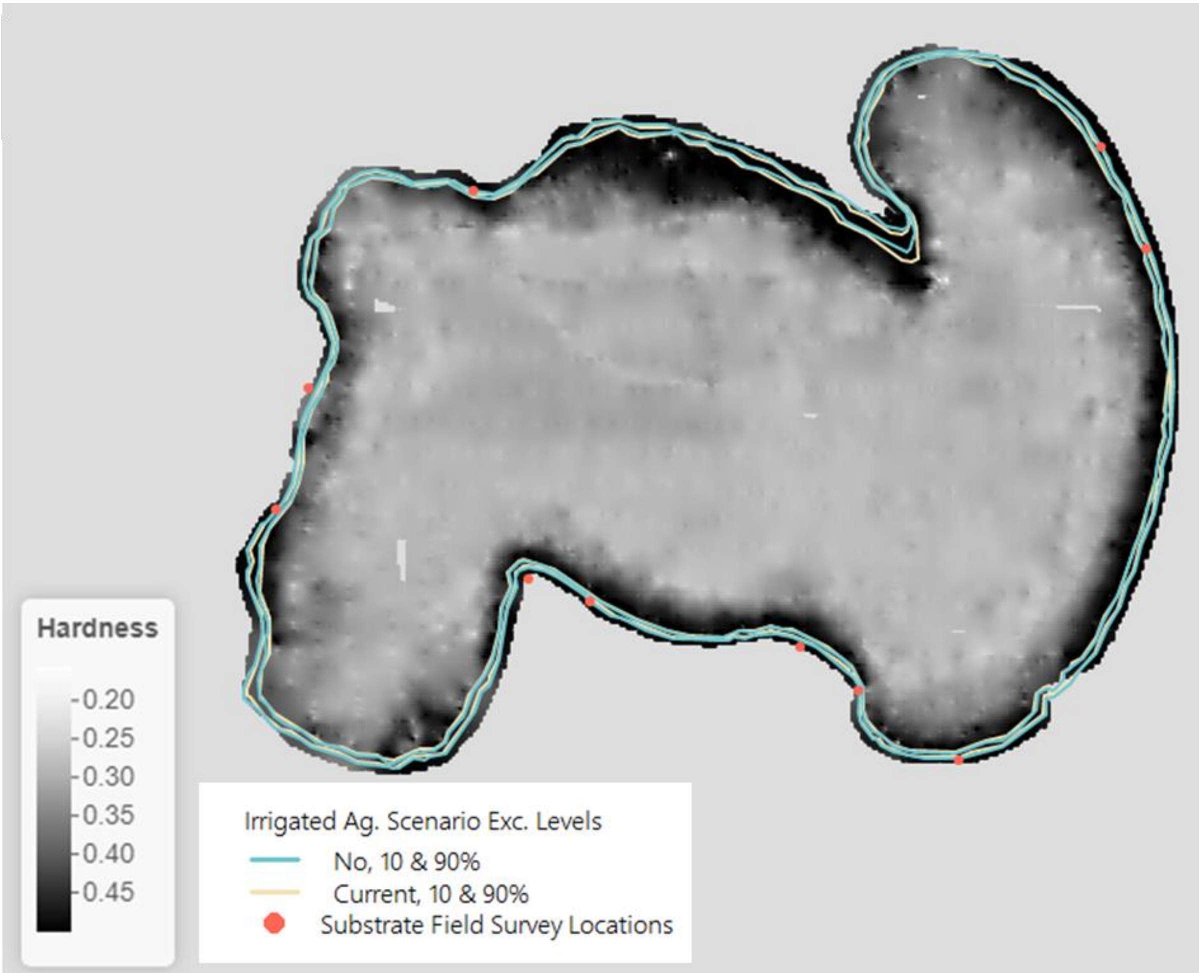

Figure 106. Pleasant Lake substrate hardness. Hardness across Pleasant Lake measured by boat-mounted sonar on August 13, 2018. Red dots are approximate locations where field crews visually located and more closely assessed hard substrate composition. Contour lines depict the elevations of the infrequent low and infrequent high lake levels in the no-irrigated-agriculture and current-irrigated-agriculture scenarios.

Long Lake

The no-irrigated-agriculture scenario shows that natural climatic variation causes large changes in Long Lake's lake area and volume because of its shallowness and gradual slope (Table 75, Figure 104). Lake area is 75% of the median at the infrequent low and 120% of the median at the infrequent high. Changes in volume are even more dramatic: volume is 32% to 202% of the median from the infrequent low to the infrequent high (Table 75). Even in the no-irrigated-agriculture scenario, the mean depth can be shallow enough to cause fish kills (Table 46). Estimated fish production changes in proportion to area, ranging from 333 lbs/yr at the infrequent low to 535 lbs/yr at the infrequent high (Table 75). As a result of these dramatic but expected changes in area and volume, fishes in Long Lake will be subjected to more competition for space and food as lake levels undergo normal declines, likely leading to reduced growth (Bartz and Bunde, 2020a). Survivors of low-water periods may grow rapidly as water levels rebound.

Table 75. Surface area and volume of Long Lake at different lake level elevations under the MODFLOW no-irrigated-agriculture scenario.

Lake level (ft)	Change from median level (ft)	Surface area (ac)	Change in area from median (ac)	Percent of median area	Volume (Ac-ft)	Change in volume from median (Mgal)	Percent of median volume	Est. Fish prod. (lbs)	Est. change in fish prod. (lbs)
1100.11	2.5	53.14	7.47	116%	284.11	123.91	177%	517.05	72.74
1099.61	2.0	51.78	6.11	113%	257.86	97.67	161%	503.82	59.51
1099.11	1.5	50.37	4.71	110%	232.32	72.12	145%	490.10	45.79
1098.61	1.0	48.87	3.21	107%	207.50	47.30	130%	475.51	31.19
1098.11	0.5	47.30	1.63	104%	183.44	23.25	115%	460.23	15.92
1097.61	0.0	45.66	0.00	100%	160.19	0.00	100%	444.27	0.00
1097.11	-0.5	43.93	-1.73	96%	137.79	-22.40	86%	427.44	-16.87
1096.61	-1.0	42.09	-3.57	92%	116.27	-43.92	73%	409.54	-34.78
1096.11	-1.5	40.12	-5.55	88%	95.71	-64.49	60%	390.37	-53.94
1095.61	-2.0	37.96	-7.71	83%	76.17	-84.03	48%	369.35	-74.96
1095.11	-2.5	35.39	-10.28	77%	57.81	-102.38	36%	344.34	-99.97
1094.61	-3.0	31.76	-13.90	70%	40.99	-119.20	26%	309.02	-135.29
1094.11	-3.5	27.49	-18.18	60%	26.11	-134.08	16%	267.48	-176.83
1093.61	-4.0	22.29	-23.38	49%	13.64	-146.55	9%	216.88	-227.43
1093.11	-4.5	12.52	-33.14	27%	4.70	-155.49	3%	121.82	-322.49
1092.61	-5.0	3.90	-41.77	9%	0.62	-159.57	0%	37.95	-406.36
surface area and volume at lake levels exceeded 10, 25, 50, 75, and 90% of the time									
1100.84	3.23	54.98	9.32	120%	323.69	163.50	202%	534.96	90.64
1098.54	0.93	48.68	3.02	107%	204.28	44.09	128%	473.66	29.34
1097.61	0.00	45.66	0.00	100%	160.19	0.00	100%	444.27	0.00
1095.86	-1.75	39.08	-6.59	86%	85.96	-74.24	54%	380.25	-64.06
1094.94	-2.67	34.22	-11.45	75%	51.84	-108.36	32%	332.96	-111.35

Long Lake's fish community is impacted by the reduction in levels that occur under the current-irrigated-agriculture scenario due to loss of volume and area (Table 76). At each exceedance level, the 2 to 3-foot decline in lake levels observed in the current-irrigated-agriculture scenario reduces volume and area by more than 10%. The volumetric losses are especially severe at lower elevations, with losses of 35% at the frequent high to 97% at the infrequent low (base run). Area and volume significantly decline in the current-irrigated-agriculture scenario even according to the small-drawdown run , with volumetric losses of 12% to 47%. To prevent an impact to the volume of Long Lake, levels would have to decline by less than 0.6 feet from the infrequent high and less than 0.2 feet from the infrequent low (Table 76). The most recent fish kill on Long Lake occurred in 2006, when DNR staff observed levels between 1093.75 and 1094.0 ft asl. That range of lake levels is below the infrequent low under the no-irrigated-agriculture scenario and between the frequent low and median level under the current-irrigated-agriculture scenario, meaning that the likelihood of lake levels associated with the 2006 fish kill increases from <10% to 25-50% with irrigated agriculture.

Table 76. Significant impacts of groundwater withdrawals on Long Lake's fish communities. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric/ Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Ecological response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Ecological response to potential-irrigated-ag
Magnitude					
Infrequent High (1100.8 ft asl)	B: -0.6 ft S: -0.6 ft L: -0.7 ft	**Yes** **B: -2.2 ft** **S: -0.8 ft** **L: -2.8 ft**	Lake volume decreases by 35% (B), 12% (S), 36% (L). Lake area decreases by 11% (B), 3% (S), 11% (L).	**Yes** **B: -2.3 ft**	Lake volume decreases by 38%. Lake area decreases by 12%.
Frequent High (1098.5 ft asl)	B: -0.4 ft S: -0.5 ft L: -0.6 ft	**Yes** **B: -2.9 ft** **S: -1.4 ft** **L: -3.8 ft**	Lake volume decreases by 63% (B), 30% (S), 59% (L). Lake area decreases by 22% (B), 9% (S), 21% (L).	**Yes** **B: -3.2 ft**	Lake volume decreases by 68%. Lake area decreases by 25%.
Median (1097.6 ft asl)	B: -0.4 ft S: -0.4 ft L: -0.5 ft	**Yes** **B: -3.3 ft** **S: -1.7 ft** **L: -4.0 ft**	Lake volume decreases by 80% (B), 42% (S), 70% (L). Lake area decreases by 36% (B), 13% (S), 27% (L).	**Yes** **B: -3.8 ft**	Lake volume decreases by 88%. Lake area decreases by 46%.
Frequent Low (1095.9 ft asl)	B: -0.2 ft S: -0.2 ft L: -0.4 ft	**Yes** **B: -2.6 ft** **S: -1.2 ft** **L: -3.8 ft**	Lake volume decreases by 92% (B), 48% (S), 83% (L). Lake area decreases by 61% (B), 16% (S), 38% (L).	**Yes** **B: -2.8 ft**	Lake volume decreases by 95%. Lake area decreases by 69%.
Infrequent Low (1094.9 ft asl)	B: -0.2 ft S: -0.2 ft L: -0.3 ft	**Yes** **B: -2.2 ft** **S: -0.8 ft** **L: -3.3 ft**	Lake volume decreases by 97% (B), 47% (S), 89% (L). Lake area decreases by 81% (B), 18% (S), 47% (L).	**Yes** **B: -2.9 ft**	Lake volume and lake area decrease by 100% (lake is dry).

The modeled expansion of irrigated agriculture, or potential-irrigated-agriculture scenario, decreases lake levels on Long Lake by a further 2 to 8 inches. Relative to the no-irrigated-agriculture scenario, 38% of lake volume is lost from the infrequent high, and 95% is lost from the frequent low. At the infrequent low level, Long Lake is essentially dry. The lake would also spend more time at or below our estimate of the lake level during the most recent documented fish kill (Bartz and Bunde, 2020a), making it more difficult for populations to recover enough to provide recreational fishing opportunities during high-water years.

Substrate across the bed of Long Lake is homogenous so changes in lake level will not influence this component of habitat. Species that require hard substrate for spawning are unlikely to successfully reproduce on Long Lake under any modeled scenario. Fish surveys have demonstrated that largemouth bass and bluegill are able to successfully reproduce and grow on Long Lake, though the size of those populations will depend on the level of the lake and whether areas away from the aerators maintain sufficient dissolved oxygen levels during winter. Other centrarchids with similar spawning habitat requirements, or other species with the ability to spawn on soft substrate would likely be able to reproduce in the future. Adequate spawning and rearing habitat will continue to exist as lake levels decline until other factors, such as total available habitat and the threat of hypoxia, begin to influence the health of the fish community.

Although Long Lake is shallow enough for aquatic plants to grow across the entire lake at even the highest lake levels, the density of aquatic plants, particularly floating-leaved plants, will likely decrease at high water levels. Lake levels were above the infrequent high in 2018 and 2019, and we observed a large decrease in the coverage of floating-leaved aquatic plants. This may create more open water and edge habitat, which could improve predation success and reduce the density of bluegills. Thus, high-water periods are important for reducing aquatic plant abundance and preventing infilling of upland and wetland plants. Conversely, prolonged low water in Long Lake will allow encroachment by emergent, wetland, and upland plants (Figure 100), further reducing the amount of habitat available to fish. At the point where emergent plants could grow across a large proportion of Long Lake’s basin, the lake would more closely resemble an ephemeral pond or wetland. This additional plant growth could prevent fish from accessing areas of high oxygen near the aerators.

Our field measurements of dissolved oxygen on Long Lake suggest that decomposition processes consume enough oxygen in late summer or late winter for local hypoxia to develop in areas more than a few hundred feet from the aerators. All of our field measurements were taken during 2018 and 2019, when lake levels were at their highest since 2001, according to limited historical observations. Instances of low oxygen would likely be more prevalent at lower lake levels, but we do not have enough information to develop a quantitative metric for evaluating loss of oxygenated habitat. Even isolated areas of non-lethal hypoxia place additional stress on Long Lake’s fish community, because total available habitat is already so limited. While the aerators will prevent some fish kills by offering areas of consistently high oxygen, populations squeezed into these areas by low oxygen elsewhere in the lake will experience more predation and competition for resources. Despite the aerators, a fish kill occurred during a period of low levels in 2006 (Figure 14). At the time of the kill, the maximum depth of Long Lake was less than two feet. Conserving lake volume will help maintain oxygenated water in Long Lake, and the ecosystem indicator for volume sets a reasonable expectation.

Plainfield Lake

DNR does not manage a fishery on Plainfield Lake, so we did not include fish as a benchmark in our evaluation. Historical fisheries reports indicated that low lake levels were associated with fish kills in the winter of 1959-1960 and again in 1961-1962. Additionally, in contrast to Long Lake, Plainfield Lake does not have a boat ramp, and there is no lake association on Plainfield Lake to support management options such as aerators or stocking. Plainfield Lake will continue to host transient fish communities during high-water years that provide limited recreational fishing opportunities.

The lake and surrounding area have great ecological value as fishless hemi-marsh (half open water and half emergent plants) habitat for plants, invertebrates, birds, and amphibians (Schilling et al., 2008). The absence of fish in similar small or ephemeral ponds and wetlands is associated with higher abundance and species richness of aquatic invertebrates (Hanson et al., 2012; Epstein, 2017) and amphibians (Knutson et al., 2004). Our assessment of lake level impacts on the plant community identifies thresholds that will be protective of the plant communities currently on Plainfield Lake, and by

Table 77. Surface area and volume of Plainfield Lake at different lake level elevations under MODFLOW no-irrigated-agriculture scenario.

Lake level (ft)	Change from median level (ft)	Surface area (ac)	Change in area from median (ac)	Percent of median area	Volume (Ac-ft)	Change in volume from median (Mgal)	Percent of median volume	Est. Fish prod. (lbs)	Est. change in fish prod. (lbs)
1099.82	2.5	45.11	9.23	126%	273.72	32.79	158%	391.10	80.04
1099.32	2.0	43.62	7.74	122%	251.50	25.55	145%	378.19	67.12
1098.82	1.5	41.52	5.64	116%	230.13	18.59	133%	359.98	48.92
1098.32	1.0	38.45	2.57	107%	210.21	12.10	121%	333.36	22.30
1097.82	0.5	37.08	1.21	103%	191.33	5.95	111%	321.48	10.42
1097.32	0.0	35.88	0.00	100%	173.08	0.00	100%	311.08	0.02
1096.82	-0.5	34.95	-0.93	97%	155.38	-5.77	90%	303.02	-8.05
1096.32	-1.0	33.82	-2.06	94%	138.19	-11.37	80%	293.22	-17.84
1095.82	-1.5	32.90	-2.98	92%	121.50	-16.81	70%	285.24	-25.82
1095.32	-2.0	31.88	-4.00	89%	105.31	-22.08	61%	276.40	-34.66
1094.82	-2.5	30.92	-4.95	86%	89.61	-27.20	52%	268.08	-42.99
1094.32	-3.0	29.88	-6.00	83%	74.39	-32.16	43%	259.06	-52.00
1093.82	-3.5	28.38	-7.50	79%	59.83	-36.90	35%	246.05	-65.01
1093.32	-4.0	26.85	-9.02	75%	45.98	-41.41	27%	232.79	-78.27
1092.82	-4.5	24.66	-11.22	69%	33.12	-45.61	19%	213.80	-97.26
1092.32	-5.0	21.39	-14.49	60%	21.58	-49.37	12%	185.45	-125.61
surface area and volume at lake levels exceeded 10, 25, 50, 75, and 90% of the time									
1100.52	3.20	46.52	10.64	130%	305.77	43.24	177%	403.33	92.27
1098.47	1.16	39.07	3.19	109%	216.24	14.06	125%	338.74	27.67
1097.32	0.00	35.88	0.00	100%	173.08	0.00	100%	311.08	0.00
1095.91	-1.41	33.05	-2.82	92%	124.63	-15.79	72%	286.54	-24.52
1095.09	-2.23	31.44	-4.44	88%	97.93	-24.49	57%	272.58	-38.48

extension the organisms that rely on those plants. The plant community indicators we developed are closely tied to lake area and volume and give an indication of available habitat for both fish and wildlife. The areal loss of habitat deep enough to support Submergent and Floating-Leaved Marsh also indicates a reduction in suitable habitat for fish and thus, the frequency at which Plainfield Lake can support fish. Waterfowl benefit from a hemi-marsh condition, but open water would fill in with vegetation under the current-irrigated-agriculture scenario.

Human Use

Background

Our survey of property owners along Pleasant Lake and Long Lake indicated that many are concerned about impacts of low lake levels on their use and enjoyment of the lake and on lake ecology (Figure 56, Figure 57, Figure 62, Figure 63). The previous sections address most of the property owners' concerns related to potential impacts to water quality, aquatic plant and fish communities. Although we were unable to quantitatively address all human use aspects identified in the survey, we considered ways to evaluate motorized and non-motorized boating, safety, dock use, and aesthetics.

People motorboat, jet ski, and waterski on Pleasant Lake, albeit a small percentage of survey respondents (Figure 55). Wisconsin does not allow speed boating on lakes less than 50 acres in area. Accounting for the 100-ft slow no wake buffer around the lake and assuming a round lake, this equates to a minimum lake area of 62.5 acres for speed boating. However, crowding may occur at higher lake levels, limiting motorboating before it becomes completely infeasible. For this reason, other studies quantify speed boat carrying capacity on lakes to develop safe boating policies (e.g., Lake Ripley Management District, 2003). This approach quantifies the area of the lake that is deep enough for high-speed boating and uses surveys to count the number of different types of boats at various times of day on weekdays and weekends. The final carrying capacity then specifies the required area per boat type, with larger areas needed for faster boats and for mixed use. If boat use is higher than the carrying capacity, safety becomes a concern and policies are often developed to manage boat use. Although a carrying capacity analysis does not exist for Pleasant Lake, slow no wake hours indicate that there is a need to manage boating. Assuming a literature value of 20 acres per boat (Kusler, 1972; Jaakson et al., 1989), Pleasant Lake can support around six speed boats operating at a time.

Survey respondents from both Pleasant Lake and Long Lake indicated that they are likely to move or modify their docks due to lake level changes. Though this may often be necessary on seepage lakes with large water level fluctuations driven by climatic variability, this phenomenon could be magnified by groundwater pumping. Florida's administrative code for managing lake levels (Chapter 40D-8) surveys the elevation of the lakebed and requires at least a two-foot water depth at the end of docks (Figure 107).

Ninety-five percent of survey respondents agreed or strongly agreed that low lake levels reduced the aesthetic appeal of Long Lake. In an attempt to address this impact, we calculated how often Long Lake meets the definition of a lake under the three irrigated-agriculture scenarios.

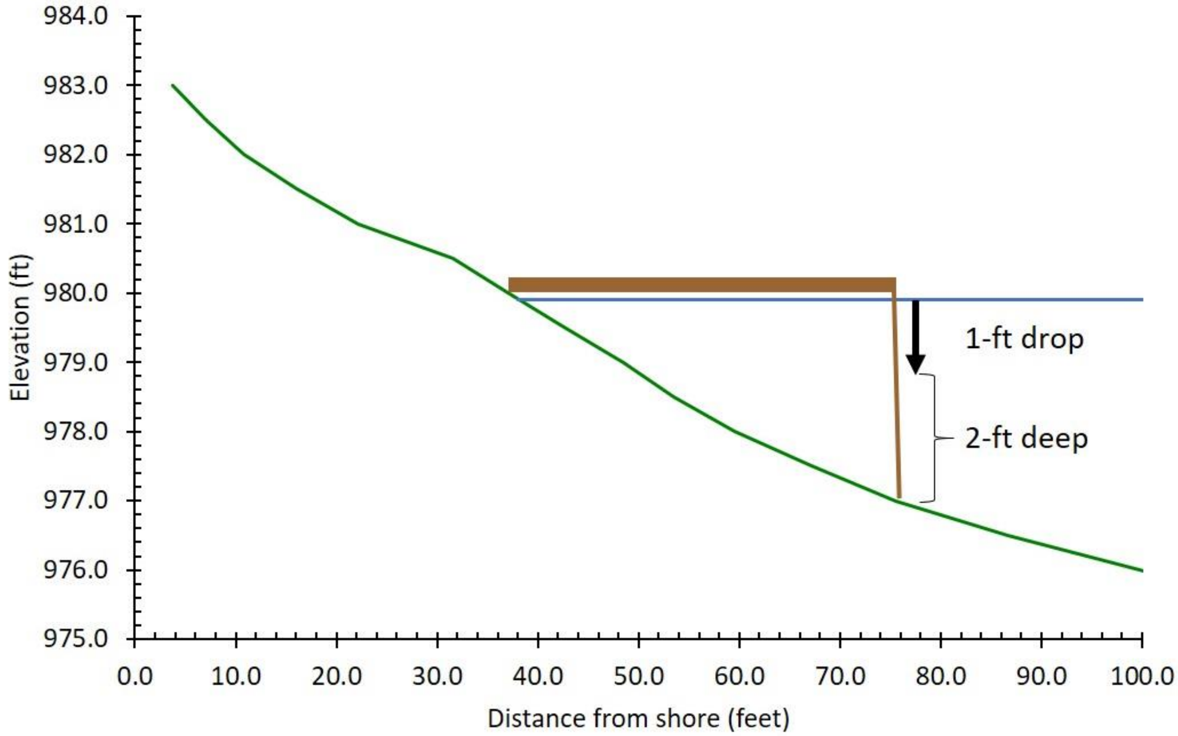

Figure 107. Dock usage approach, Pleasant Lake. Illustration of the technique used to evaluate the effect of lake levels on dock usage. Average lake profile on Pleasant Lake (green line) overlaid by a dock of average length (brown). This process was repeated at all water levels modeled over the 38-year time period to determine the water depth at the end of the dock. There should be at least 2 ft of water in June for dock installation and at least 2 feet remaining if water levels drop from June 1 to August 31.

Methods

To evaluate impacts of groundwater withdrawals on human uses of the study lakes, we first evaluated the effect of irrigated agriculture on boating activities. On Pleasant Lake, we evaluated the impact of lower lake levels on speed boating, water skiing, and jet skiing. We determined the elevation at which Pleasant Lake would become too small to allow speed boating (i.e., less than 62.5 acres). We also evaluated the impact of lower lake levels at less extreme declines assuming a 10% loss in area could negatively impact the speed boating experience and reduce safety due to crowding.

Long Lake and Plainfield Lake are too shallow for high-speed boating, but lake level declines can limit non-motorized boating. An elevation of 1096.8 ft asl on Long Lake and 1096.3 ft asl on Plainfield Lake ensures a lake depth > 3 ft across the entire basin, which is deep enough to inhibit or limit shallow emergent plant growth and support paddle sports. We calculated the percent of time the lake level exceeds the lake-specific elevation under all three irrigated-agriculture scenarios. A decrease beyond one standard deviation from the no-irrigated-agriculture scenario is significant. High water levels are important for creating open water habitat on Long Lake, which also affects boating. We evaluated the frequency that Long Lake is > 1100.84 ft asl, which creates mid-lake patches too deep for floating-leaved plants (Figure 100). We determined significance by evaluating change beyond one standard deviation of the no-irrigated-agriculture runs.

We also evaluated two components of dock usage: 1) whether the lake is deep enough to install a dock in spring, and 2) whether the lake level remains deep enough through the summer so that it does not need to be moved lakeward. We created an average lake profile for each lake by dividing the lake volume by lake area at 0.1-ft increments of lake elevations. The resulting number is the horizontal distance travelled from the lake shore toward the center of the lake between the two elevations. We then overlaid the average dock length as reported by survey respondents (39 feet on Pleasant and 23 feet on Long) to determine the depth of water at the end of the average dock (Figure 107). We require at least 2-ft depth on Pleasant Lake, where motorboats are prevalent, and at least 1-ft depth on Long Lake, where non-motorized boats are more common. We then calculated the percent of years that the spring lake elevation was high enough to attain the proper depth at the end of the average dock. A decrease beyond one standard deviation in the no-irrigated-agriculture scenario is significant. The second metric defined the maximum drop in lake levels that could occur from June 1 to August 31 while still maintaining at least 2 ft of water at the end of the dock in Pleasant Lake and at least 1 ft of water at the end of the dock on Long Lake. Again, we calculated the percent of years that docks could remain in place; a decrease beyond one standard deviation in the no-irrigated-agriculture scenario is significant. We also combined these two metrics to a general “good dock year” metric and defined significance using the same approach.

Finally, we evaluated how irrigation affects the frequency at which Long Lake and Plainfield Lake are defined as lakes versus wetlands. For the National Lakes Assessment, the Environmental Protection Agency (EPA) defines a lake as > 2.47 acres in total area with a maximum depth of 3.28 feet and at least 0.25 acres of open water. EPA surveys smaller waterbodies with less open water as part of the National Wetland Condition Assessment. For our modeling purposes, we defined Long and Plainfield Lake as “lakes” if there is at least 0.25 acres greater than 3.28 feet deep. Though deeper depths may be necessary to create open water, this definition is still helpful for defining when Long and Plainfield Lakes are more like a wetland versus a lake. We then calculated the percent of time that this criterion is met in the no-irrigated-agriculture scenario and defined a significant decrease as greater than one standard deviation from the no-irrigated-agriculture runs (Long Lake) or, if standard deviation was zero, > 1% decrease from the no-irrigated-agriculture runs (Plainfield Lake).

Pleasant Lake

The current-irrigated-agriculture scenario does not show impacts to boating on Pleasant Lake. Irrigation-induced lake level declines are not large enough to make Pleasant Lake too small for speed boating (Table 78). At 959.9 ft asl, the lake area would fall below 62.5 acres, which is a 17.7-ft drop from the median lake level. This is well beyond the 0 to 0.7-ft drops predicted by MODFLOW under irrigated agriculture. However, crowding might be experienced at smaller lake level declines. A 10% loss in lake area would occur at 1.9 to 3.5 ft below the infrequent low to infrequent high. For example, a loss of 12.4 acres would constitute a significant drop from the median. None of the model runs found a significant effect of current irrigated agriculture on areal loss (Table 78).

Table 78. Significant impacts of groundwater withdrawals on human uses of Pleasant Lake. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric/ Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Human use response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Human use response to potential-irrigated-ag
Magnitude					
Infrequent High (979.6 ft asl)	B: -3.5 ft S: -3.6 ft L: -3.8 ft	No B: -0.5 ft S: -0.1 ft L: -0.5 ft	Lake area decreases by 1% (B), <1% (S), 2% (L).	No B: -0.5 ft	Lake area decreases by 1%.
Frequent High (978.4 ft asl)	B: -2.8 ft S: -2.9 ft L: -3.6 ft	No B: -0.5 ft S: -0.1 ft L: -0.7 ft	Lake area decreases by 1% (B), <1% (S), 2% (L).	No B: -0.7 ft	Lake area decreases by 2%.
Median (977.6 ft asl)	B: -2.3 ft S: -2.5 ft L: -3.1 ft	No B: -0.4 ft S: -0.1 ft L: -0.6 ft	Lake area decreases by 1% (B), <1% (S), 1% (L).	No B: -0.7 ft	Lake area decreases by 2%.
Frequent Low (977.0 ft asl)	B: -2.1 ft S: -2.1 ft L: -2.7 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	Lake area decreases by 1% (B), 0% (S), 1% (L).	No B: -0.5 ft	Lake area decreases by 2%.
Infrequent Low (976.7 ft asl)	B: -2.0 ft S: -2.5 ft L: -2.0 ft	No B: -0.4 ft S: 0.0 ft L: -0.6 ft	Lake area decreases by 2% (B), <1% (S), 2% (L).	No B: -0.5 ft	Lake area decreases by 2%.

Table 78 (cont.). Significant impacts of groundwater withdrawals on human uses of Pleasant Lake. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Hydrologic Metric/ Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Human use response to current-irrigated-ag	Impact under potential-irrigated-ag scenario?	Human use response to potential-irrigated-ag
Frequency					
Speed boating allowed (100% of time)	B: -0% S: -0% L: -0%	No B: 0% S: 0% L: 0%	Lake area remains >120 acres.	No B: 0%	Lake area remains >118 acres.
Good dock season (42%)	B: -18.8% S: -18.8% L: -18.8%	**Caution** B: -12.1% S: 0.0% **L: -21.2%**	Percent of years that are deep enough in spring and sustained through summer declines (L).	**Yes** **B: -21.2%**	Percent of years that are deep enough in spring and sustained through summer declines.
Good spring dock installation (61%)	B: -16.3% S: -16.3% L: -16.3%	**Caution** **B: -18.2%** S: -3.0% L: -15.2%	Lake levels are at least 2 ft deep at the end of the average dock in June less often (B).	**Yes** **B: -24.2%**	Lake levels are at least 2 ft deep at the end of the average dock in June less often.
Dock remains in place full season (70%)	B: -9.5% S: -9.5% L: -9.5%	No B: +1.4% S: +3.3% L: -8.2%	Minimal change in frequency at which water depth at the end of the average dock remains at least 2 ft from June to August.	**Yes** **B: -11.7%**	Frequency at which water depth at the end of the average dock remains at least 2 ft from June to August decreases.

The current-irrigated-agriculture scenario does not show significant impacts to dock usage, but a few metrics warrant caution. As a whole, the percent of years that provide for a good dock season did not significantly decrease in the current-irrigated-agriculture scenario (Table 78). This means that the lake was deep enough at the end of the average dock in June and remained deep enough throughout the summer. It should be noted here that even without irrigation, good dock years only occurred in 42% of years. This may indicate that the assumption of an average dock length along an average lake profile does not adequately capture the hydrologic conditions that ensure good dock usage. We recommend caution because: 1) the good dock season metric decreased by 21% in the large-drawdown run, and 2) the base run of the current-irrigated-agriculture scenario showed a 18% decrease in years with deep enough water for spring installation (Table 78). The other “good dock” and “spring installation” runs were not significantly impacted, nor were any of the runs for the “full season” indicator, warranting caution rather than a significant impact.

The potential-irrigated-agriculture scenario draws lake levels 0 to 0.3 feet lower than the current-irrigated-agriculture scenario. This additional decline in lake levels does not significantly affect any of the boating indicators as the additional areal loss is very small. However, it is a sufficient decrease to significantly impact all three dock usage indicators. A good spring installation decreases in frequency by 24%, the frequency at which docks remain in place for the summer season decreases by 12%, and the combined good dock season indicator decreases by 21% (Table 78).

Long Lake

The current-irrigated-agriculture scenario turns Long Lake from a waterbody that exhibits a lake state most of the time to one that exhibits a wetland state most of the time. The base run shows Long Lake is a lake (more than 0.25 acres greater than 3.28 feet deep) 81% of the time in the no-irrigated-agriculture scenario but is only a lake 27% of the time in the current-irrigated-agriculture scenario. The small-drawdown and large-drawdown runs also showed that current irrigation significantly reduces the frequency that Long Lake exhibits a lake state.

Table 79. Significant impacts of groundwater withdrawals on human uses of Long Lake. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated-agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential-irrigated-ag scenario?	Human use response to current and potential-irrigated-ag
Frequency				
Exhibits lake state (81%)	B: -10.2% S: -10.2% L: -10.2%	**Yes** **B: -53.8%** **S: -21.5%** **L: -43.4%**	**Yes** **B: -57.3%**	Frequency that Long Lake has > 0.25 acres that are > 3.28 ft deep significantly decreases.
Deep enough for paddle sports (62%)	B: -11.6% S: -11.6% L: -11.6%	**Yes** **B: -44.4%** **S: -20.2%** **L: -65.2%**	**Yes** **B: -46.0%**	Frequency that lake elevations are above 1096.8 ft asl during summer significantly decreases. This lake elevation provides 3-foot depth across the lake basin.
Deep enough for open water (10%)	B: -6.7% S: -6.7% L: -6.7%	**Yes** **B: -9.1%** S: -4.0% **L: -21.0%**	**Yes** **B: -9.1%**	Frequency that lake elevations are above 1100.84 ft asl significantly declines. Lake levels this high should create open-water patches too deep for floating-leaved plants.
Good dock season (61%)	B: -14.4% S: -14.4% L: -14.4%	**Yes** **B: -48.5%** **S: -27.3%** **L: -66.7%**	**Yes** **B: -48.5%**	Percent of years that provide good dock conditions (deep enough in spring and sustained levels throughout summer) significantly decreased.
Good spring dock installation (76%)	B: -11.2% S: -11.2% L: -11.2%	**Yes** **B: -54.5%** **S: -18.2%** **L: -51.5%**	**Yes** **B: -57.6%**	Lake levels are at least 1-ft deep at the end of the average dock in June significantly less often, impacting dock installation.
Dock remains in place full season (80%)	B: -7.8% S: -7.8% L: -7.8%	**Yes** **B: -22.9%** **S: -22.1%** **L: -40.4%**	**Yes** **B: -13.3%**	When docks can be installed, frequency at which water depth at the end of the average dock remains at least 1 ft from June to August significantly decreases.

Figure 108. Stranded docks at Long Lake. Stranded docks on Long Lake in June 2006. Photo courtesy of Tim Asplund.

Given the shift toward a wetland state, we found that the current-irrigated-agriculture scenario also significantly impacts non-motorized boating activities. To maintain sufficient open water for non-motorized boating on Long Lake, the water depth should be greater than 3 ft across a contiguous basin (elevation greater than 1096.8 ft asl). This is important for preventing the infilling of shallow emergent and riparian wetland plants, which could reduce the navigability of Long Lake. The current-irrigated-agriculture scenario reduces the frequency at which this occurs according to all three runs; the base run shows that irrigated agriculture decreases the frequency of paddle sport suitability from 62% to 18% (Table 79). Floating-leaved plants can form dense mats across Long Lake and make navigability difficult. Although abundant floating-leaved plants are ecologically beneficial, they will begin to die back when water levels are high, especially at depths greater than 8 ft. Patches greater than 8 ft deep occur at an elevation of 1100.84 ft asl (Table 79). Lake levels this high are rare, occurring 10% of the time (base run), but are important for creating open water habitat. The current-irrigated-agriculture scenario significantly reduced the frequency of open water habitat such that it occurs 1% or less of the time (base and large drawdown runs). The small drawdown run did not show a significant reduction (Table 79).

Dock usage on Long Lake is significantly impacted under the current-irrigated-agriculture scenario. All three model runs were significant for all three dock metrics (Table 79). As a whole, the percent of years that provide for a good dock season significantly decreased with irrigated agriculture from 61% to 13% (base run). The base run showed that moving from the no-irrigated-agriculture scenario to the current-irrigated-agriculture scenario decreased the percent of years with deep enough water for spring installation from 76% to 22%. The percent of years that lake levels remain deep enough for the dock throughout the summer decreased from 80% to 57% (base run). The inutility of a dock on Long Lake during a low water period in June 2006 is apparent (Figure 108).

All human use indicators are significantly impacted under the potential-irrigated-agriculture scenario as well (Table 79). However, the severity of impact changes little from the current- to potential-irrigated-agriculture scenario. For example, the frequency at which Long Lake is deep enough for paddle sports decreases by 44.4% under the current-irrigated-agriculture scenario and by 46% under the potential-irrigated-agriculture scenario. In general, the frequency of each indicator decreased by 0 – 3.5% more in the potential-irrigated-agriculture scenario.

Plainfield Lake

The frequency at which Plainfield Lake is deep enough for paddle sports is significantly reduced according to all three model runs in the current and potential-irrigated-agriculture scenarios (Table 80). According to the base run, the frequency declined from 71% to 27% (current) or 24% (potential). The current-irrigated-agriculture scenario does not indicate a change in the lake state of Plainfield Lake, but the large-drawdown run warrants caution. The base run shows Plainfield Lake is a lake (more than 0.25 acres greater than 3.28 feet deep) 100% of the time under the no-irrigated-agriculture scenario and does not change at all under current-irrigated-agriculture according to the base run and small-drawdown run (Table 80). The large-drawdown run of the current-irrigated-agriculture scenario significantly reduces the frequency of Plainfield's lake status by 4.3%. The potential-irrigated-agriculture scenario further reduces the frequency of Plainfield's lake status by 8.1%.

Table 80. Significant impacts of groundwater withdrawals on human uses of Plainfield Lake. For the current-irrigated-agriculture scenario, we provide the thresholds for the base run (B), the small-drawdown run (S), and the large-drawdown run (L), describe the significant ecological responses for the base run, and determine which indicators are significantly impacted (bold) using all three runs. Current-irrigated agriculture significance is: Yes (2 or 3 runs significant), Caution (1 run significant), No (no runs significant). For the potential-irrigated-agriculture scenario, we have and report results for the base run only. Indicators that are significantly impacted (bold) exceed the corresponding threshold for the base run.

Ecosystem Indicator (no-irrigated-ag scenario)	Significant Impact Thresholds	Impact under current-irrigated-ag scenario?	Impact under potential-irrigated-ag scenario?	Human use response to current and potential-irrigated-ag
Frequency				
Exhibits lake state (100%)	B: -1% S: -1% L: -1%	**Caution** B: 0.0% S: 0.0% **L: -4.3%**	**Yes** **B: -8.1%**	Frequency that Plainfield Lake has > 0.25 acres that are > 3.28 ft deep (lake elevations above 1092.9 ft asl) significantly decreases (current L and potential).
Deep enough for paddle sports (62%)	B: -10.3% S: -10.3% L: -10.3%	**Yes** **B: -43.4%** **S: -20.2%** **L: -50.0%**	**Yes** **B: -47.0%**	Frequency that lake elevations are above 1096.3 ft asl during summer significantly decreases. This lake elevation provides 3-foot depth across the lake basin.

Area Contributing to Impacts

Background

Given that Long and Plainfield lakes are significantly impacted under the current-irrigated-agriculture scenario, a logical follow up question is: what area contributes to this significant reduction in lake levels? The area which contributes to lake drawdown is different than the lake capture zone, or the area upgradient of the lake which contributes to groundwater inflow. Lake drawdown occurs in part due to lower water tables upgradient of the lake which decrease groundwater inflow, but an increase in groundwater outflow due to a lower water table downgradient of the lakes can also contribute to lake drawdown. The most important factors controlling whether a well influences a lake are distance and pumping rate. Thus, the area contributing to the reduction in lake levels contains wells both upgradient and downgradient of the lakes.

Methods

To delineate the minimum area contributing to the reduction in lake levels at Long and Plainfield Lakes, the DNR and USGS devised an additional suite of modeling scenarios (Fienen et al., 2021). In these scenarios, we systematically removed wells that were included in the current-irrigated-agriculture scenario and changed the associated land use to what was assigned in the no-irrigated-agriculture scenario (base run parameterization). We removed wells one at a time beginning with the well closest to the centroid of Long Lake and removing additional wells as they would be encountered by moving radially away from the lake. After each additional well was removed we re-ran the entire 38-year climate scenario, repeating this until all 321 wells in the Plainfield Lakes inset model were removed and the entire inset model was identical to the land uses assigned in the no-irrigated-agriculture scenario. Thus, the scenario in which the N^{th} well was removed at a distance *X* miles from Long Lake can be interpreted as representing a scenario in which the *N* closest wells were removed, or in which there was an *X* mile radius of no-irrigated-agriculture around Long and Plainfield lakes. All told, this approach yielded 321 38-year timeseries of lake levels which we evaluated for impacts to the ecosystem indicators for Long and Plainfield Lakes. We ran these modeling simulations to help us understand the extent of the area contributing to drawdown at Long and Plainfield lakes; these simulations are not meant to represent a recommended management approach. Rather, this suite of modeling simulations allowed us to define the minimum area contributing to significant impacts to Long and Plainfield Lakes.

Long Lake

These modeling scenarios indicate that if all 190 wells within a 4.8 mile radius of Long Lake were removed and land use was converted to what was assigned in the no-irrigated-agriculture scenario, all significance thresholds would be met at Long Lake in terms of all 19 ecosystem indicators (Figure 109). This area extends slightly beyond the boundaries of the inset model, so there are 34 wells that exist within a 4.8-mile radius of Long Lake whose impacts are not explicitly included in these simulations. This small number of wells does not affect our general finding that around 200 wells within 5 miles of Long Lake contribute to the significant reduction in lake levels.

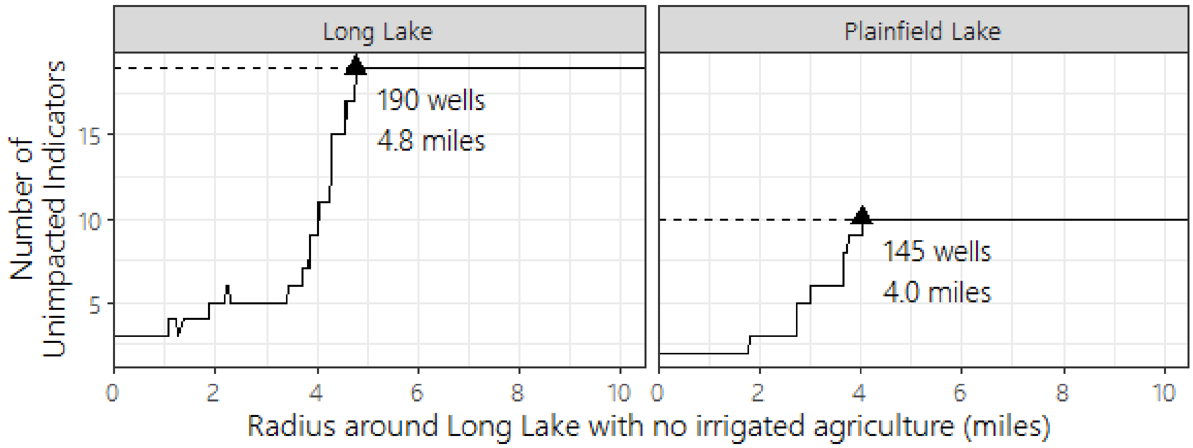

Figure 109. Number of unimpacted indicators vs. radius of no-irrigated-agriculture. The number of unimpacted ecosystem indicators with increasing radius of no-irrigated-agriculture (miles). Long Lake reaches zero impacted indicators with a 4.8 mile radius of no-irrigated-agriculture around Long Lake (190 high capacity irrigation wells replaced by other land uses in the MODFLOW inset model) and Plainfield Lake reaches zero impacted indicators with a 4.0 mile radius of no-irrigated-agriculture around Long Lake (145 high capacity irrigation wells replaced by other land uses).

Modeling scenarios also illustrate the effects of eliminating irrigated agriculture from smaller areas (Figure 110). For example, a 2.6-mile radius of no-irrigated-agriculture (51 wells removed) increases the amount of time Long Lake exhibits a lake state from 26% of the time in the current-irrigated-agriculture scenario to 51% of the time. This is lower than the significance threshold (71%) or the no-irrigated-agriculture value (81%) but would likely constitute a substantial improvement from the perspective of a lake user. Similarly, a 2.5-mile radius of no-irrigated-agriculture (40 wells removed) doubles the lake volume at the median lake level from 31.6 acre-ft in the current-irrigated-agriculture scenario to 63.4 acre-ft. While a four- to five-fold increase is necessary to entirely remedy the impact (with the significance threshold at 144.2 acre-ft and the no-irrigated-agriculture volume at 160.2 acre-ft), this would still be a substantial improvement in terms of available fish habitat.

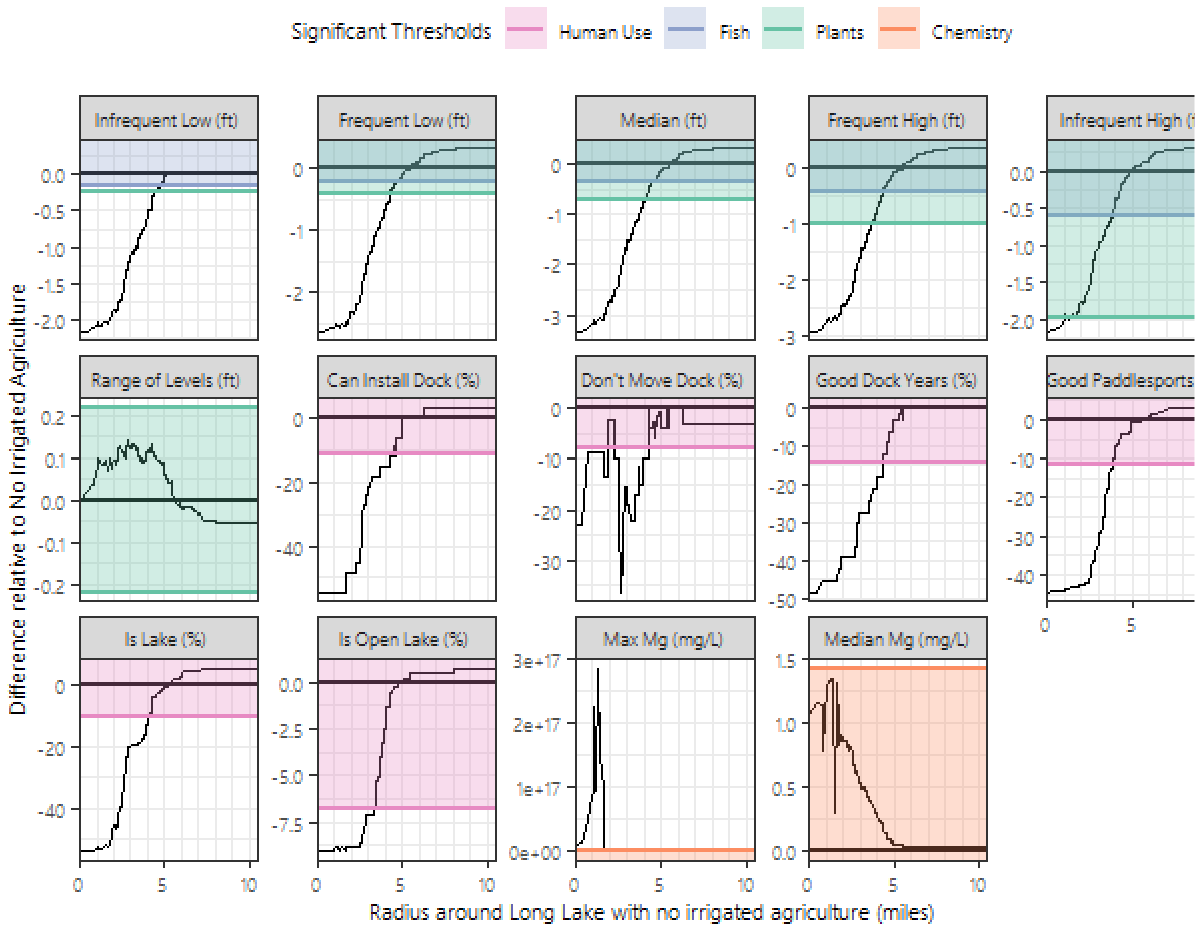

Figure 110. Severity of impact vs. radius of no-irrigated-agriculture, Long Lake. The difference in key metrics related to 19 ecosystem indicators at Long Lake relative to no-irrigated-agriculture values as a function of increasing radius of no-irrigated-agriculture. Significance thresholds for the most sensitive ecosystem indicator within each category are denoted with colored lines. The shaded areas denote the differences from no-irrigated-agriculture where the ecosystem indicators are not significantly impacted (e.g. "Is Lake" is not significantly impacted if the difference is > -10%).

Plainfield Lake

These modeling scenarios indicate that if all 145 wells within a 4.0 mile radius of Long Lake were removed and land use was converted to what was assigned in the no-irrigated-agriculture scenario, all significance thresholds would be met at Plainfield Lake in terms of all 9 ecosystem indicators (Figure 109). Thus, protecting Long Lake from significant impacts is likely to protect Plainfield Lake as well.

Substantially increased lake levels at Plainfield Lake are also possible with smaller areas and fewer wells involved (Figure 111). For example, a 2.5-mile radius of no-irrigated-agriculture (38 wells removed) reduces the amount of drawdown in the median lake level from 2.3 ft in the current-irrigated-agriculture scenario to 1.5 ft. This is still a larger drawdown than the significance threshold to conserve a federally threatened plant (-0.6 ft) but would be an improvement. It also would be enough of an increase to reach the significance threshold for floating-leaved plants (-1.5 ft).

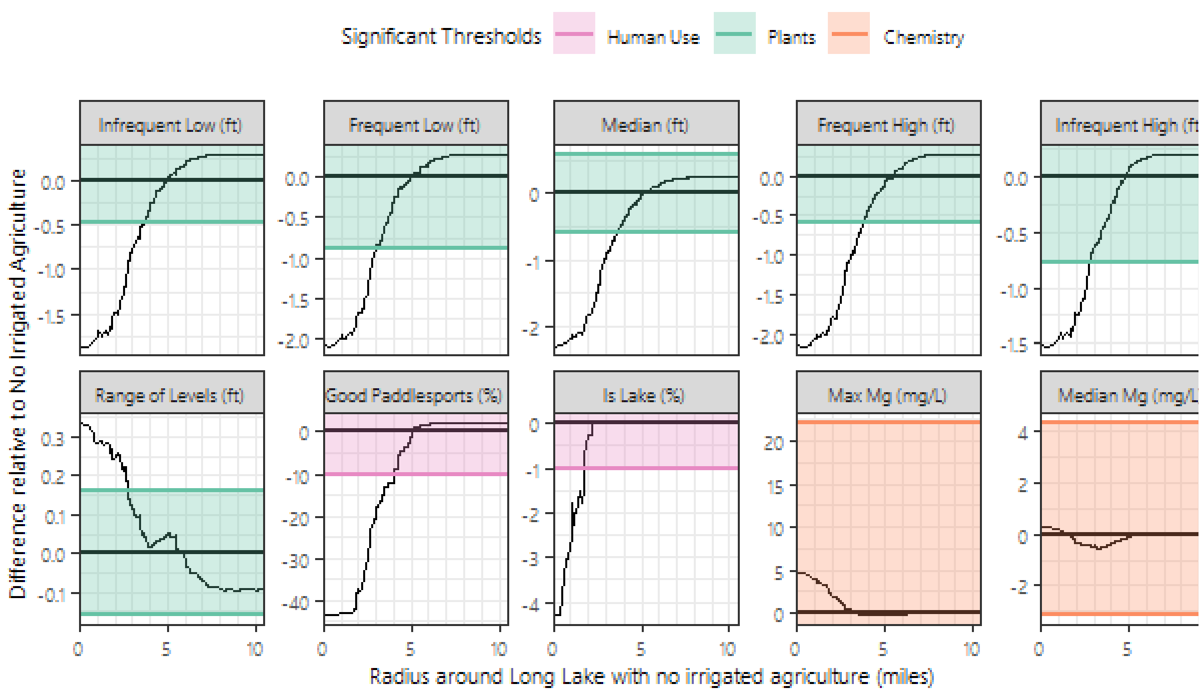

Figure 111. Severity of impact vs. radius of no-irrigated-agriculture, Plainfield Lake. The difference in key metrics related to 9 ecosystem indicators at Plainfield Lake relative to no-irrigated-agriculture values as a function of increasing radius of no-irrigated-agriculture. Significance thresholds for the most sensitive ecosystem indicator within each category are denoted with colored lines. The shaded areas denote the differences from no-irrigated-agriculture where the ecosystem indicators are not significantly impacted (e.g. "Is Lake" is not significantly impacted if the difference is > -1%).

Summary of Lake Level Impacts

The current-irrigated-agriculture scenario indicates significant impacts to Long Lake and Plainfield Lake, but not to Pleasant Lake. One reason for the difference between lakes is that both Long Lake and Plainfield Lake are located at the groundwater divide. These two lakes naturally experience large water level fluctuations due to climatic variation, and their median water levels drop by 3.3 (Long) and 2.3 (Plainfield) feet due to modeled current irrigated agriculture. Pleasant Lake water levels fluctuate, but to a lesser extent. It is located closer to streams where groundwater levels are held relatively constant and therefore, irrigated agriculture has a smaller effect on water levels, drawing the median lake level down by 0.4 feet. Pleasant Lake is also a deep, dimictic lake with a bathtub-shape whereas Long and Plainfield Lakes are shallow, polymictic lakes with gradual topography. This means that lake level changes result in small horizontal shifts of the lake shoreline on Pleasant Lake, but very large horizontal shifts on the other two lakes. Long Lake and, to a lesser extent Plainfield Lake, is so shallow that simulated lake level declines under the current-irrigated-agriculture scenario can actually dry the lake up. Thus, both the landscape position and morphometry of Pleasant Lake make it more resilient to the impacts of irrigated agriculture than Long Lake and Plainfield Lake.

The potential-irrigated-agriculture scenario results in further lake level declines, with the median dropping an additional 0.2 feet on Pleasant Lake, 0.5 feet on Long Lake, and 0.4 feet on Plainfield Lake.

Most significance determinations remain the same with two exceptions: 1) human use on Pleasant Lake becomes significantly impacted due to all three dock usage indicators, and 2) the second of two human use indicators on Plainfield Lake (how often it exhibits a lake state) also becomes significantly impacted. The other indicators do not change status between the current- and potential-irrigated-agriculture scenarios, remaining as either significantly impacted, caution, or not impacted. On Long Lake and Plainfield Lake, the potential-irrigated-agriculture scenario draws lake levels down enough to result in even more extreme areal changes in plant coverage and losses in lake area and volume. The infrequent low lake level on Long Lake becomes completely dry. Below, we summarize the lake-specific impacts, or lack thereof, of the current- and potential-irrigated-agriculture scenarios.

Pleasant Lake

The modeled current-irrigated-agriculture scenario does not result in significant impacts to Pleasant Lake (Figure 112); it decreases lake levels by 0.4 to 0.5 feet and, because Pleasant Lake is 22.1 feet deep at the median, it does not change the coefficient of variation in maximum lake depth. Current irrigated agriculture also maintains the same range of 2.9 feet from the infrequent low to the infrequent high lake level. We find the frequency, duration, rate of change, and timing of water levels as well as the lake water budget are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario. Irrigated agriculture does not alter the variability of lake levels at Pleasant Lake, it simply shifts levels lower.

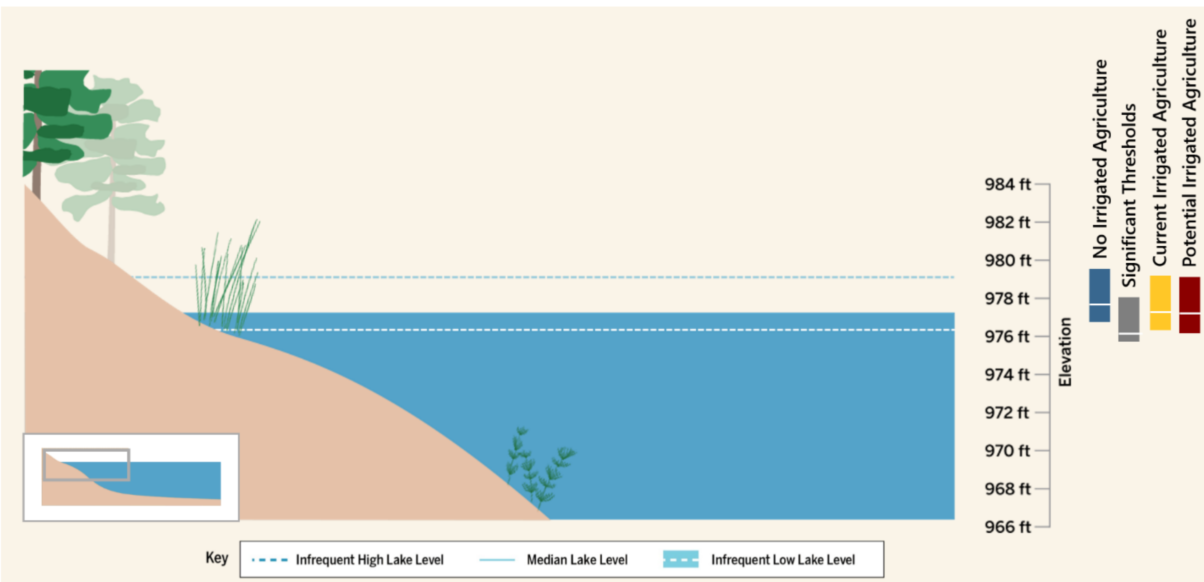

Figure 112. Pleasant Lake hydrologic change. Pleasant Lake profile with the current-irrigated-agriculture scenario infrequent high, median, and infrequent low levels depicted. Bars on the right are to scale with the elevation scale bar and denote the range between the infrequent high and infrequent low and the median level (white line) corresponding to the no-irrigated-agriculture scenario (blue), significant ecosystem thresholds (grey), current-irrigated-agriculture scenario (yellow), and potential-irrigated-agriculture scenario (red).

Although Pleasant Lake's hydrology is slightly lowered in the current-irrigated-agriculture scenario, the magnitude of change is small enough that ecosystem and human use indicators are not significantly impacted (Figure 113). All three representative model runs (the base parameterization and the runs representing small drawdown and large drawdown) indicated that the current-irrigated-agriculture scenario does not impact ecosystem indicators at Pleasant Lake with two exceptions (Table 81, Table 82). One of the three runs found a significant impact to the "good dock season" and the "good spring dock installation" indicators (Table 78, Table 82). This warrants caution, but not a significant impact.

Another indicator that warrants caution is stratification, primarily because Pleasant Lake is near the tipping point between a dimictic and polymictic lake and there is limited historical data documenting how lake levels influence stratification at this particular lake. Although Pleasant Lake is almost shallow enough at times to become unstratified during summer, modeled current-irrigated-agriculture does not significantly impact stratification according to any of the three runs. At the infrequent low, lake levels fall from above to below 976.6 ft asl, the threshold at which the Lathrop-Lillie model predicts Pleasant Lake will become unstratified. However, the 0.4-foot drop in the current-irrigated-agriculture scenario is within the uncertainty in lake level elevations caused by uncertainty in recharge estimates. Because our significance thresholds account for this uncertainty, we conclude that there is insufficient evidence that irrigated agriculture impacts Pleasant Lake stratification. This is further exacerbated by the knowledge that the Lathrop-Lillie ratio approximates stratification well, but is not absolute. Still, uncertainty in modeled lake levels and the significance threshold does not preclude a possible impact. Stratification fundamentally changes physical processes in the lake and could increase internal phosphorus loading and cause algal blooms. Thus, we recommend frequent temperature profile and lake level monitoring in summer to improve understanding of Pleasant Lake's stratification dynamics, especially at lower lake levels.

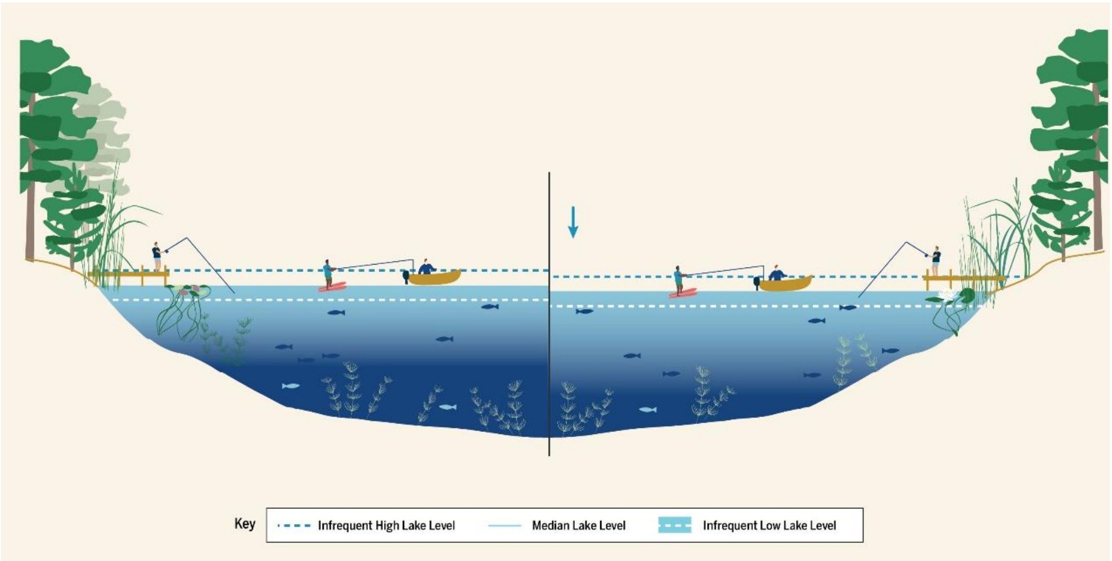

Figure 113. Pleasant Lake ecosystem impacts. Conceptual schematic of the Pleasant Lake ecosystem in the no-irrigated-agriculture scenario (left) and the current-irrigated-agriculture scenario (right). The lake ecosystem is not significantly impacted in the current-irrigated-agriculture scenario.

All other indicators are clearly unimpacted in the current-irrigated-agriculture scenario, even after accounting for uncertainty. Current-irrigated-agriculture slightly dilutes the magnesium concentration in Pleasant Lake, but the change in magnesium concentration is very small and within the variability of the no-irrigated-agriculture scenario. Lower lake levels did not significantly change the percent areal cover of different plant community types, nor did it significantly reduce the volume or area of habitat for fish. In fact, the range from the infrequent low to infrequent high in the no-irrigated-agriculture scenario (mostly driven by precipitation) is greater than the difference between the no-irrigated-agriculture and current-irrigated-agriculture scenarios for plant and fish habitat indicators. For example, plant areal coverage varies by 4%-7% from the infrequent low to high, but the largest change induced by modeled irrigation is 2%. Although there was a slight decrease in average substrate hardness at appropriate depths for fish spawning, sufficient hard substrate remains under the current-irrigated-agriculture scenario. Our field work noted a deficit of coarse woody habitat in the near-shore areas of Pleasant Lake. This and the model results suggest that, for the foreseeable future, sensible shoreline development and the conservation of near-shore aquatic plants will remain the best ways to protect and improve Pleasant Lake's fish community. Both of these issues can be addressed through standard lake management practices. Both boating and the dock use indicator determining whether a dock would need to be moved lakeward mid-season are unimpacted by the current-irrigated-agriculture scenario.

Pleasant Lake is not immune to impacts of lower lake levels. The most sensitive indicator at median and higher levels is the loss of volumetric habitat for fish. More than 10% lake volume is lost when lake levels drop 1.4 to 1.6 feet from no-irrigated-agriculture lake levels (e.g., a drop from 977.6 to 976.2 ft asl of the median lake level, Table 73, Table 74). Lake stratification is the most sensitive indicator at lower levels, with the lake becoming clearly mixed when modeled lake levels drop below 976.1 ft asl (Table 62). With a greater than 10% loss in area, speedboating becomes limited at 2.0 to 3.5 ft below the no-irrigated-agriculture lake levels (Table 78). Finally, upland plants gain more than 10% area at 2.6 to 4.0 ft below no-irrigated-agriculture lake levels (Table 67).

The potential-irrigated-agriculture scenario did not cause lake levels to fall enough to reach any of the thresholds described above. All indicators related to magnesium concentrations, plants, fish, and boating remained unimpacted. Stratification also remained unimpacted, but again, we recommend caution for this indicator. Like in the current-irrigated-agriculture scenario, the elevation of the frequent low and infrequent low fell below the stratification threshold of 976.6 ft asl but remained within model uncertainty. All three dock usage indicators became significantly impacted.

Thus, we conclude that Pleasant Lake is unimpacted by irrigated agriculture but a few items warrant caution: 1) dock usage may be impacted under the current-irrigated-agriculture scenario and is significantly impacted in the potential-irrigated-agriculture scenario, and 2) Pleasant Lake may be at risk of becoming unstratified due to irrigated agriculture, especially when lake levels are already naturally low.

Table 81. Most limiting thresholds (base run) and significance determination (all 3 runs) for each category of magnitude metric evaluated by lake. The magnitude threshold is significant if irrigated agriculture lowers the lake level below the listed lake level elevation (ft asl). The range metric is significant if it changes beyond the expected values listed (Long and Plainfield Lakes' ranges increased). Colors indicate the level of impact: blue = not impacted, yellow = caution, orange = impacted. The two chemistry indicators classified as caution account for error in lake level estimates and uncertainty in the elevation at which Pleasant Lake destratifies. The range increase on Long Lake is significantly impacted (increased) by one of three runs under the current-irrigated-agriculture scenario and under the potential-irrigated-agriculture scenario, warranting caution.

	Pleasant				**Long**		**Plainfield**
Metric	*Chemistry*	*Plants*	*Fish*	*Human Use*	*Plants*	*Fish*	*Plants*
Infrequent High	976.2	975.6	**978.0**	976.1	1098.9	**1100.2**	**1099.7**
Frequent High	976.1	974.9	**976.9**	975.6	1097.5	**1098.1**	**1097.9**
Median	976.1	974.5	**976.2**	975.3	1096.9	**1097.3**	**1097.9**
Frequent Low	**976.1**	974.3	976.0	974.9	1095.5	**1095.6**	**1095.0**
Infrequent Low	**976.1**	974.1	976.0	974.7	1094.7	**1094.8**	**1094.6**
Range		2.8-3.1			5.7-6.1		5.3-5.6

Table 82. Thresholds (base run) and significance determination for each category of frequency, rate of change, and timing metric evaluated by lake. The impact is significant if the listed expression is met under irrigated agriculture (e.g., if the median magnesium concentration is < 20.2 mg/L). Colors indicate the level of impact: blue = not impacted, yellow = caution, red = impacted. The good dock install & season and good dock install indicators on Pleasant Lake warrant caution because one of three model runs are significant under current irrigated agriculture. The potential-irrigated-agriculture scenario finds a significant impact on a good dock season on Pleasant Lake, and the lake definition indicator warrants caution on Plainfield Lake for both reasons (one of three model runs is significant under current irrigated agriculture and potential irrigated agriculture is significant).

Metric	**Pleasant**	**Long**	**Plainfield**
Chemistry			
Median Mg (mg/L)	< 20.2	> 8.2	> 20.6
Maximum Mg (mg/L)	> 49.2	> 20.7	> 44.2
Fish			
Spawning (%)	35.4	-	-
Human Use			
Boating (%)	< 99.0	< 50.5	< 60.4
Open Water (%)	-	< 3.1	-
Good Dock Install & Season (%)	< 23.6	< 46.2	-
Good Dock Install (%)	< 44.4	< 64.5	-
Good Dock Season (%)	< 60.5	< 72.2	-
Meets Lake Definition (%)	-	< 70.6	< 99.0

Lakefront residents should expect to adjust their dock with fluctuating lake levels, particularly on seepage lakes that exhibit more dramatic fluctuations. The no-irrigated-agriculture scenario suggests that only 39% of years provide sufficient depth for motorboats at the end of the average dock both during spring installation and throughout that summer season. In addition, one of three model runs found a significant impact under the current-irrigated-agriculture scenario on each of dock installation in spring and dock use for the summer individually (Table 82). Thus, a more thorough and dock-specific analysis may be necessary to understand how hydrology affects dock usage. When developing a dock usage indicator, it is important to recognize that even without irrigation, lake levels are predicted to vary interannually by 2.9 feet 80% of the time.

Long Lake

The modeled current-irrigated-agriculture scenario results in significant impacts to all aspects of Long Lake. Lake levels decrease by 2.2-3.3 feet across all exceedance probabilities and over time. Because Long Lake is so shallow, the current-irrigated-agriculture scenario reduces the maximum lake depth at the median lake level from 5.5 feet to 2.2 feet (Figure 114). This results in a large increase in the coefficient of variation in maximum lake depth, from 38% to 79%. Water balance fluxes are minimally affected relative to one another, but they flow through a much smaller lake volume in the current-irrigated-agriculture scenario, which causes the median lake water residence time to fall from 0.9 years to just 0.3 years. The large range in lake levels of 5.9 feet from the infrequent low to the infrequent high remains nearly the same under the current-irrigated-agriculture scenario. The frequency, duration, rate of change, and timing of water levels are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario. However, the uniform downward shift in lake levels under current-irrigated-agriculture means that the frequency and duration change in reference to the no-irrigated-agriculture lake levels, with a very long period of lake levels below the no-irrigated-agriculture median. In addition, lake level declines of more than 1.5 feet/year occur nearly three times as often under the current-irrigated-agriculture scenario.

Water chemistry, plants, fish, and human use are significantly impacted by the hydrologic change in the current-irrigated-agriculture scenario (Figure 115). Seventeen of 19 indicators evaluated are significantly impacted by current irrigated agriculture according to at least two of the three representative model runs (Table 81, Table 82). The range from the infrequent low to infrequent high is the only indicator that is significantly impacted by a single model run, and the median magnesium concentration is the only indicator that is not significantly impacted by any of the three model runs. The median magnesium concentration slightly increases in the current-irrigated-agriculture scenario but stays within the variance of concentrations in the no-irrigated-agriculture scenario. However, the maximum magnesium concentration dramatically increases to >100 mg/L under the current-irrigated-agriculture scenario, likely due to evapoconcentration at lake levels below 1093.4 ft asl. Although this does not occur very often, concentrations >100 mg/L are well above the 0-50 mg/L magnesium concentrations typically found in Wisconsin lakes (Lillie and Mason, 1980).

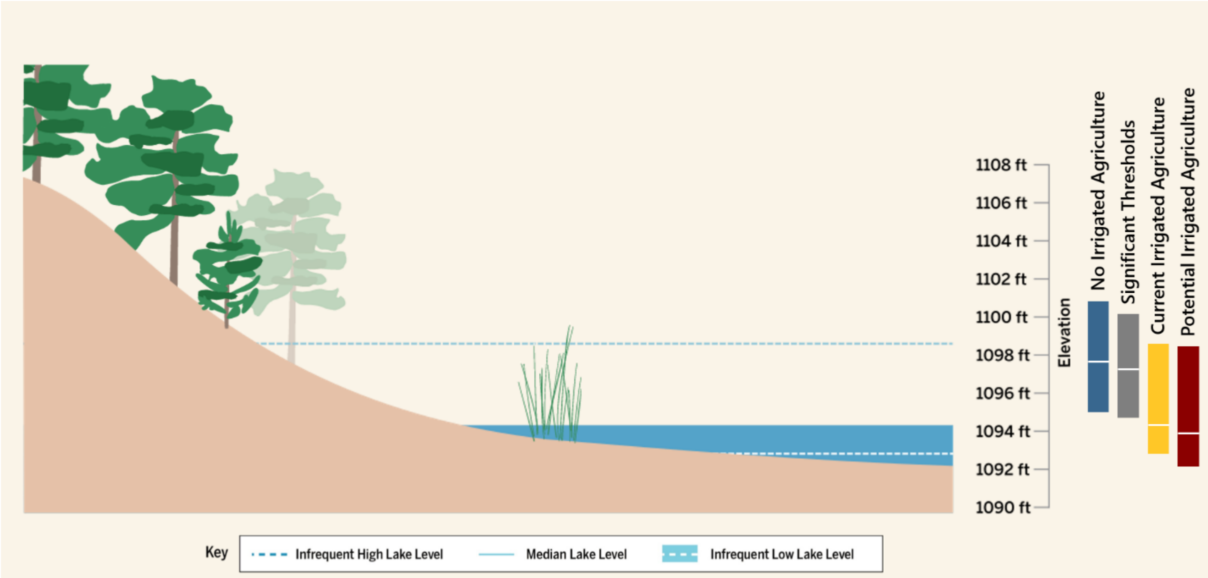

Figure 114. Long Lake hydrologic change. Long Lake profile with the current-irrigated-agriculture scenario infrequent high, median, and infrequent low levels depicted. Bars on the right are to scale with the elevation scale bar and denote the range between the infrequent high and infrequent low and the median level (white line) corresponding to the no-irrigated-agriculture scenario (blue), significant ecosystem thresholds (grey), current-irrigated-agriculture scenario (yellow), and potential-irrigated-agriculture scenario (red).

The current-irrigated-agriculture scenario also significantly impacts plant and fish communities and human use of Long Lake. In general, Submergent and Floating-leaved Marsh lose habitat area as Upland and Inland Beach gain habitat area. Emergent Marsh initially gains and then loses area with lake level decline. Lake level declines in the infrequent low, infrequent low, and median levels result in the complete loss of Floating-leaved Marsh, and Submergent Marsh is fully lost under the current-irrigated-agriculture scenario at the frequent low. These shifts in the plant community from Submergent to Emergent and finally Upland dominance show that Long Lake transitions from being deep enough and large enough to be classified as a lake 81% of the time in the no-irrigated-agriculture scenario to only 27% of the time in the current-irrigated-agriculture scenario. The large volumetric and areal loss of aquatic habitat from modeled irrigation also impacts the fish community. The lake has aerators to prevent fish kills due to low oxygen, but even aerators cannot combat the large losses of water in this shallow basin. Finally, the current-irrigated-agriculture scenario significantly impacts non-motorized boating both in terms of retaining enough water to float and enough water to prevent infilling of emergent and floating-leaved plants. It also renders docks irrelevant most of the time.

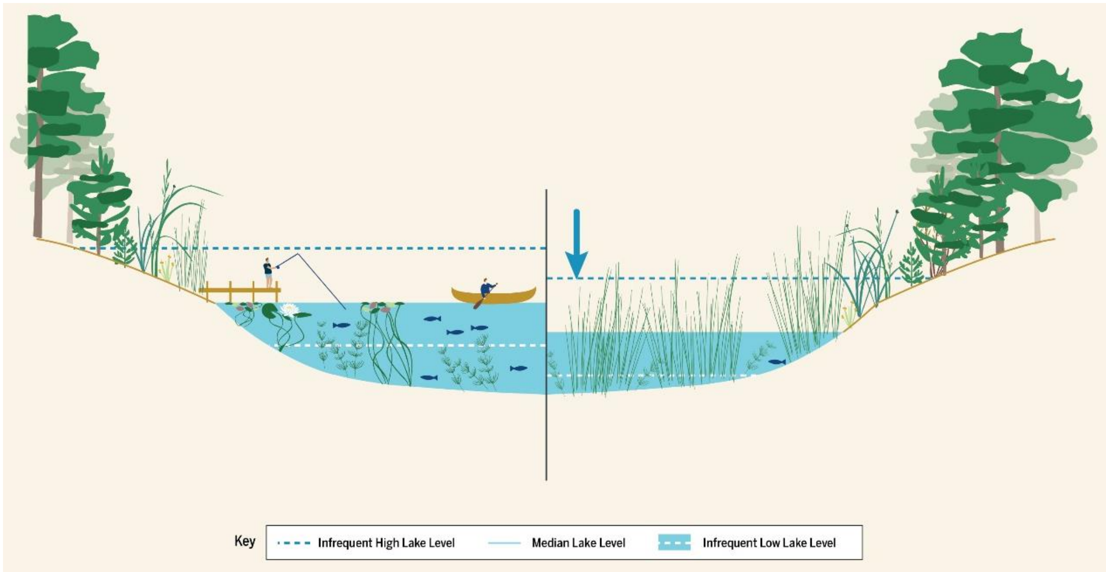

Figure 115. Long Lake ecosystem impacts. Conceptual schematic of the Long Lake ecosystem in the no-irrigated-agriculture scenario (left) and the current-irrigated-agriculture scenario (right). The lake ecosystem is significantly impacted in the current-irrigated-agriculture scenario.

Under the potential-irrigated-agriculture scenario, lake levels fall an additional 0.1-0.7 feet compared to the current-irrigated-agriculture scenario with the most dramatic declines from the median and infrequent low. All indicators are significantly impacted except for the median magnesium concentration. The range from the infrequent low to high increases by 0.5 feet, changing this indicator from caution under current-irrigated-agriculture to significantly impacted. Most indicators respond to potential-irrigated-agriculture to a similar degree as they do to current-irrigated-agriculture, but some responses are more severe. The additional 0.5-foot drop from the median increases lake areal loss (from 36% in current to 45% in potential-irrigated-agriculture), and the additional 0.7-foot drop from the infrequent low results in no wetted area at all. Losses in Submergent and Emergent Marsh and gains in Upland become more dramatic.

Plainfield Lake

The current-irrigated-agriculture scenario results in significant impacts to the plant communities and human use on Plainfield Lake through its effects on altered hydrology (Figure 116). Lake levels decrease by approximately 1.5 to 2.3 feet across all exceedance probabilities, decreasing the maximum depth at the median lake level from 7.8 to 5.5 feet. Given that Plainfield Lake is deeper and experiences a lesser decline in lake level than Long Lake, the coefficient of variation of maximum depth only modestly increases with the addition of modeled irrigation (from 24% to 34%). The median lake water residence time falls from 1.4 to 0.9 years in the current-irrigated-agriculture scenario, but the relative contribution of precipitation and groundwater to the water budget does not change. The range from the infrequent low to infrequent high significantly increases from 5.4 to 5.7 feet. The frequency, duration, rate of change, and timing of water levels at Plainfield Lake are all approximately the same under the current-irrigated-agriculture scenario as they are in the no-irrigated-agriculture scenario. However, the uniform downward shift in lake levels under current-irrigated-agriculture means that the frequency and duration change in reference to the no-irrigated-agriculture lake levels, with two long periods of lake levels below the median. In addition, lake level declines of more than 1.5 feet/year occur 1.6 times as often under the current-irrigated-agriculture scenario. Like on the other lakes, current-irrigated-agriculture shifts Plainfield Lake's levels lower.

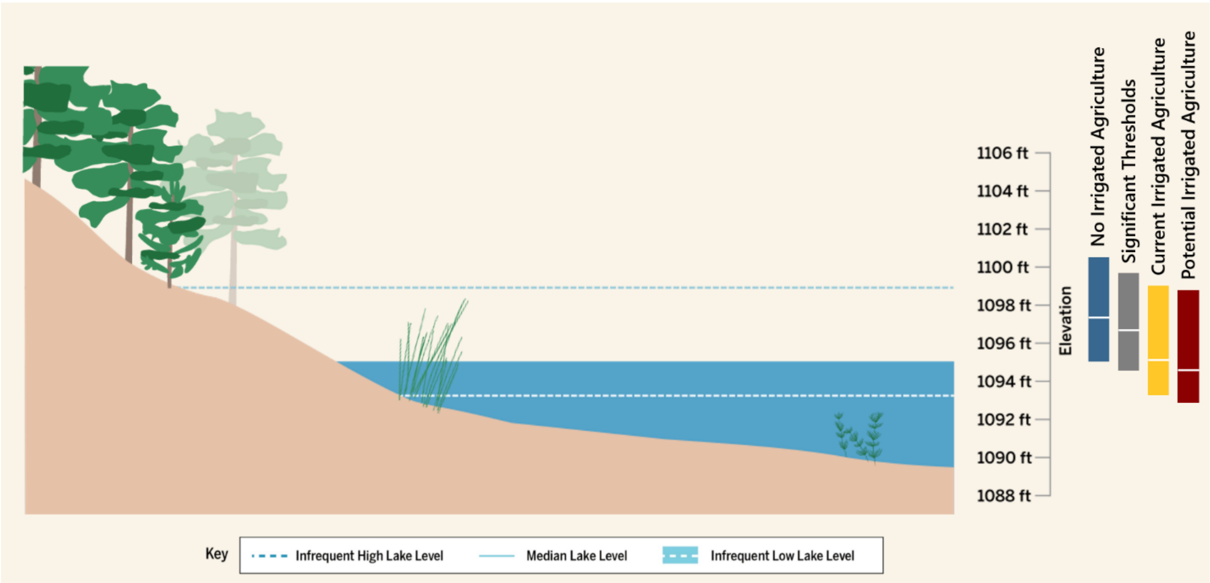

Figure 116. Plainfield Lake hydrologic change. Plainfield Lake profile with the current-irrigated-agriculture scenario infrequent high, median, and infrequent low levels depicted. Bars on the right are to scale with the elevation scale bar and denote the range between the infrequent high and infrequent low and the median level (white line) corresponding to the no-irrigated-agriculture scenario (blue), significant ecosystem thresholds (grey), current-irrigated-agriculture scenario (yellow), and potential-irrigated-agriculture scenario (red).

The current-irrigated-agriculture scenario results in significant impacts to the plant community and human use on Plainfield Lake, but not water chemistry (Figure 117). Of nine evaluated indicators, all six plant magnitude metrics are significantly impacted by current irrigated agriculture according to at least two of three model runs, the two chemistry metrics are not significantly impacted by any of the three runs, and one of two human use metrics is significantly impacted while the other warrants caution (Table 81, Table 82). The current-irrigated-agriculture scenario generally shifts Plainfield Lake toward the drier side of the plant continuum with gains in Upland, Inland Beach, and Emergent Marsh and widespread losses of Floating-leaved and Submergent Marsh. We did not directly evaluate fish because Plainfield Lake has fish kills on occasion and is not managed for a fishery. However, the plant indicators are closely tied to lake area and volume and give an indication of available habitat for both fish and wildlife. The areal loss of habitat deep enough to support Submergent and Floating-Leaved Marsh also indicates a reduction in suitable habitat for fish and thus, the frequency at which Plainfield Lake can support fish. Waterfowl benefit from a hemi-marsh condition, but open water would fill in with vegetation under the current-irrigated-agriculture scenario.

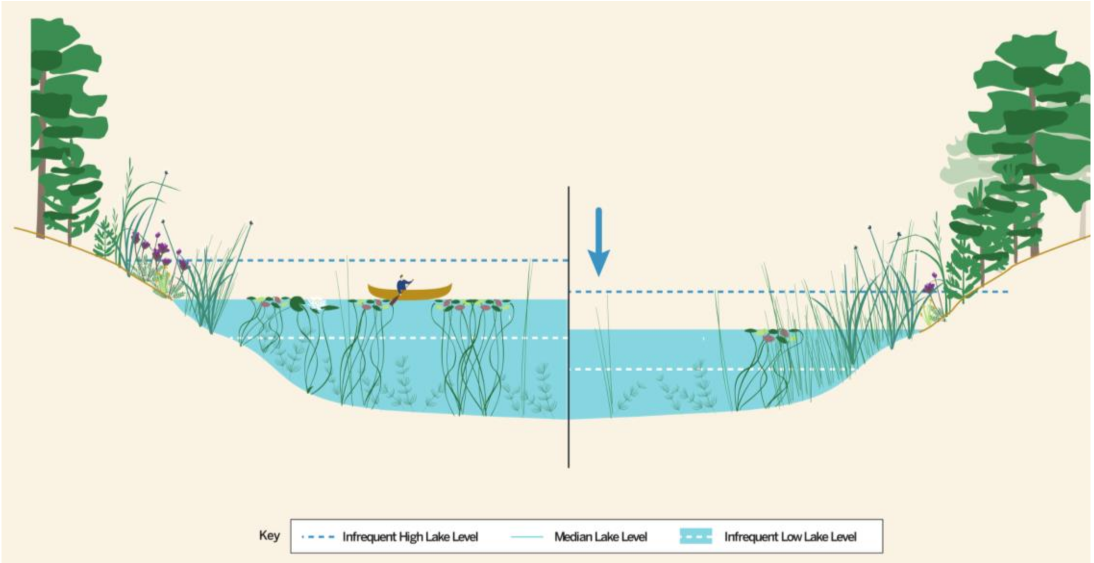

Figure 117. Plainfield Lake ecosystem impacts. Conceptual schematic of the Plainfield Lake ecosystem in the no-irrigated-agriculture scenario (left) and the current-irrigated-agriculture scenario (right). The plant community is significantly impacted in the current-irrigated-agriculture scenario.

The long-term conservation of a federally threatened plant is the resource most vulnerable to lowered lake levels on Plainfield Lake. This inland beach plant thrives on exposed sand when lake levels are low but requires flooded periods to kill back competitors like shrubs and trees. Thus, maintaining a similar median and range of lake level fluctuations as has occurred in the past is critical. Current irrigated agriculture reduces the median lake level and makes lake level fluctuations more extreme. This could be detrimental to population persistence as the limit of suitable habitat at low lake levels is unknown, and a decline in lake levels could require the federally threatened plant to shift its distribution lakeward.

Under the current-irrigated-agriculture scenario, both the median and maximum magnesium concentrations remained within the range of the no-irrigated-agriculture scenario. Over time, Plainfield Lake exhibits a few short periods of dilution and longer more pronounced evapoconcentration effects of modeled irrigation, but overall maintains the same solute balance.

Plainfield Lake is in a State Natural Area with only two private residences along the lake shore and a public boat launch area. Human uses are significantly impacted in the current-irrigated-agriculture scenario because the frequency that Plainfield Lake is deep enough for non-motorized boating drops from 62% to 19% of the time. Caution is warranted for the other human use indicator that we evaluated; the large drawdown run showed that current-irrigated-agriculture reduces the frequency that Plainfield Lake exhibits a lake state from 100% to 96% of the time.

Under the potential-irrigated-agriculture scenario, lake levels fall an additional 0.1-0.4 feet compared to the current-irrigated-agriculture scenario with the most dramatic decline from the median. Most indicators respond in a similar way: both chemistry indicators remain unimpacted, and all plant indicators remain significantly impacted. Changes to plant areal coverage become more severe with the additional declines in lake level from the infrequent low to frequent high. In general, Upland, Inland Beach, and Emergent Marsh fill in lakeward as Submergent and Floating-leaved Marsh decline. The frequency at which Plainfield Lake exhibits a lake state declines by 8%, shifting this indicator from caution under current-irrigated-agriculture to significantly impacted under potential-irrigated-agriculture. The frequency that Plainfield Lake is suitable for paddle sports remains significantly impacted.

Study Limitations

Our conclusions regarding the impacts of groundwater withdrawals on Pleasant Lake, Long Lake, and Plainfield Lake are robust and based on multiple criteria, but it is important to recognize the limitations of any study. We summarize the key limitations of the study and show how the study methodology and conclusions are sound and defensible despite data limitations.

First, we lack comprehensive long-term data sets on the three study lakes that include paired observations of lake levels and lake ecosystem indicators. Partial records of each provide evidence that supports our conclusions, but full records would allow us to explicitly understand how water chemistry, plant distributions, or fish communities change at low and high lake levels. Furthermore, our 2018 and 2019 field seasons only observed the lakes during high water years, and some processes can behave differently at low lake levels. Although our lake characterization study collected large amounts of data on key parameters, our time and resources were finite and there are biological components of the ecosystems that we did not monitor or explicitly consider, including invertebrates, amphibians, reptiles, mammals, and birds. Finally, historical data that quantify water withdrawals, crop rotations, land use, and water levels are not available at the resolution and time frame necessary to explicitly quantify how much historical groundwater withdrawals have affected lake levels over recent decades. Because the climate-driven lake level cycle occurs at the scale of decades, use of a groundwater flow model was crucial to better understand the relative effects of climate and groundwater withdrawals on lake hydrology.

Despite the limitations above, MODFLOW accurately captures the long-term dynamics of all three lakes, characterizing Pleasant Lake as having much more stable water levels than Long and Plainfield Lakes, which exhibit large water level fluctuations over time. At Long and Plainfield, the historic lake level observations and ecological clues indicate that these shallow lakes experience relatively large natural water level fluctuations. Ecological indicators of historic water level fluctuations include: 1) a history of fish kills at Long and Plainfield lakes prior to widespread irrigation, and 2) a population of a federally threatened plant species that depends on large water level fluctuations. MODFLOW finds more muted effects of weather and groundwater withdrawals on Pleasant Lake's levels, and this is logical. Because Pleasant Lake is larger and deeper than the other lakes, lake level declines result in smaller percent changes to maximum lake depth, area, and volume. In addition, groundwater levels at Pleasant Lake are constrained by the elevation of nearby streams that act as discharge points and are less variable. These lake dynamics are reflected in the modeled lake levels used for our analyses.

We compared modeled to observed lake levels to assess the strength of our conclusions. The MODFLOW calibration allows us to calculate the error in MODFLOW estimates of observed lake levels, and these were 0.17 to 0.5 feet on the three lakes. The error in estimated lake levels was smaller than the drop in lake levels that constitutes a significant impact for the most sensitive indicator on each lake. One partial exception is that Pleasant Lake can only drop 0.4 feet from the frequent low and 0.1 feet from the infrequent low before destratifying according to the base run only, which is smaller than the lake level RMSE of 0.5 feet. (The significance thresholds at these two magnitudes are greater than 0.5

feet because they also account for uncertainty in recharge in the no-irrigated-agriculture scenario). In addition, the error in estimated lake levels was similar to the lake level drop in the current-irrigated-agriculture scenario. Thus, Pleasant Lake's likelihood to stratify at the infrequent low and frequent low are the only indicators that are difficult to evaluate given error in the MODFLOW estimates of lake levels and uncertainty in the recharge model. This is not of concern for any other metrics on any other lakes.

The differences between the predicted magnitude of drawdowns and magnitudes of impacts were large compared to the error in MODFLOW lake level estimates for all of the other indicators on the three lakes. On Long and Plainfield Lakes, the modeled drops in lake levels are greater than the error in MODFLOW estimates in the current- and potential-irrigated-agriculture scenarios. For example, MODFLOW showed that the current-irrigated-agriculture scenario would draw Long Lake down by around two to three feet, but the significance thresholds for many ecosystem indicators were less than one foot or even one-half foot. Conversely, MODFLOW showed that the current-irrigated-agriculture scenario would draw Pleasant Lake down by around one-half foot, but most ecosystem indicators would require a drop of at least one foot (and up to four feet) to significantly impact the lake. Modeled drops under the potential-irrigated-agriculture scenario are also greater than the error in MODFLOW estimates on Pleasant Lake.

The Monte Carlo approach allows us to examine uncertainty in the Soil Water Balance model parameterization and to examine the range of current-irrigated-agriculture scenario results for a suite of reasonable SWB model input values. We can then build our evaluation on the base parameterization as well as runs that resulted in large vs. small drawdowns from irrigated agriculture; this increases confidence that real-world conditions fall within the range of results we evaluated. Our final conclusions on impact significance are consistent across the range of outcomes we evaluated. We make significance determinations based on the outcome of at least two of the three model runs for each ecosystem indicator. If only one of three runs shows a significant impact, we conclude the indicator warrants caution. This occurred for two indicators on Pleasant Lake and one indicator on Plainfield Lake.

Most ecosystem indicators come to the same significance conclusion for a single lake. Pleasant Lake is not significantly impacted according to 23 of 28 ecosystem indicators (with the remaining five indicating caution). Long Lake is significantly impacted for 17 of 19 ecosystem indicators with one indicator warranting caution. Plainfield Lake is significantly impacted by six of six plant indicators and none of the two chemistry indicators; one human use indicator is impacted while the other warrants caution.

Finally, the ecosystem indicators we evaluated represent a wide variety of aspects of each of the three lakes. We presume that the fauna not explicitly evaluated should be protected in part by ensuring good water quality and good habitat.

Recommendations for Future Work

Future monitoring and analysis will not only be essential for successfully managing water levels in the three lakes but will also allow us to confirm our assumptions regarding ecosystem dynamics at low lake levels. Although lake levels are currently very high, when precipitation inevitably decreases, they will fall again. We suggest that, in addition to continuing lake level monitoring, these lakes should be monitored regularly for water quality and biological indicators. Annual wetland plant and aquatic plant point intercept surveys on Long Lake and Plainfield Lake would better tie observed distributions to lake level dynamics and elucidate lag times in plant response. Paired fisheries surveys on Long Lake would also improve understanding of lake level effects on growth rates, recruitment, and fish kills. Monitoring solutes during low water levels would confirm the evapoconcentration effect we expect to see on Long Lake. On Pleasant Lake, more frequent temperature profile monitoring in mid- to late-summer would better quantify the risk of destratification when lake levels are low. Finally, more work should be done to understand and respond to the concerns of lake residents not sampled by the survey. A tailored monitoring plan focused on the significantly impacted indicators and any emerging indicators of concern should be developed for each lake.

While we stress the importance of paired hydrologic and ecosystem monitoring, we do not expect these metrics to serve as real-time signals of when to start or stop groundwater withdrawals within a single growing season. The strong, interannual lake level cycle is important for these lake ecosystems, and the measure of successful management will be at the scale of decades. Thus, we recommend continued reliance on models to anticipate the likely effectiveness of alternate groundwater management plans. We developed an ecosystem indicator evaluation package in R that inputs MODFLOW lake levels and outputs the ecosystem indicator and significance determination. Thus, this package could be used to not only determine if significant impacts are likely to be remedied by a particular management plan, but also how much a given indicator would likely improve. Pairing these modeling efforts with lake and groundwater monitoring would aid in developing and evaluating the long-term success of groundwater management as lake levels cycle between their highs and lows.

With some further development, the process used in this study to evaluate the impacts of reduced water levels on lakes can be applied to other lakes. By using the tools and lessons learned in this study, methods for future lake evaluations could be streamlined and far less expensive. A simple, first-cut approach could use bathymetric maps to determine volumetric losses and areal losses with decreasing lake levels from the five magnitude metrics. As in this study, a 10% loss in volume or area could be used as the significance threshold. Fish, plant, and human use surveys could then be conducted to tailor specific ecosystem indicators to a given lake based on lake-specific resources and possibly establish lake-specific significance thresholds. Detailed chemistry mass balance studies are likely unnecessary, but possible changes in lake mixing dynamics are important on lakes near the threshold between dimictic and polymictic. The same ecosystem indicator package in R used in this study could also be used or adapted to evaluate impacts of lower water levels on other lakes.

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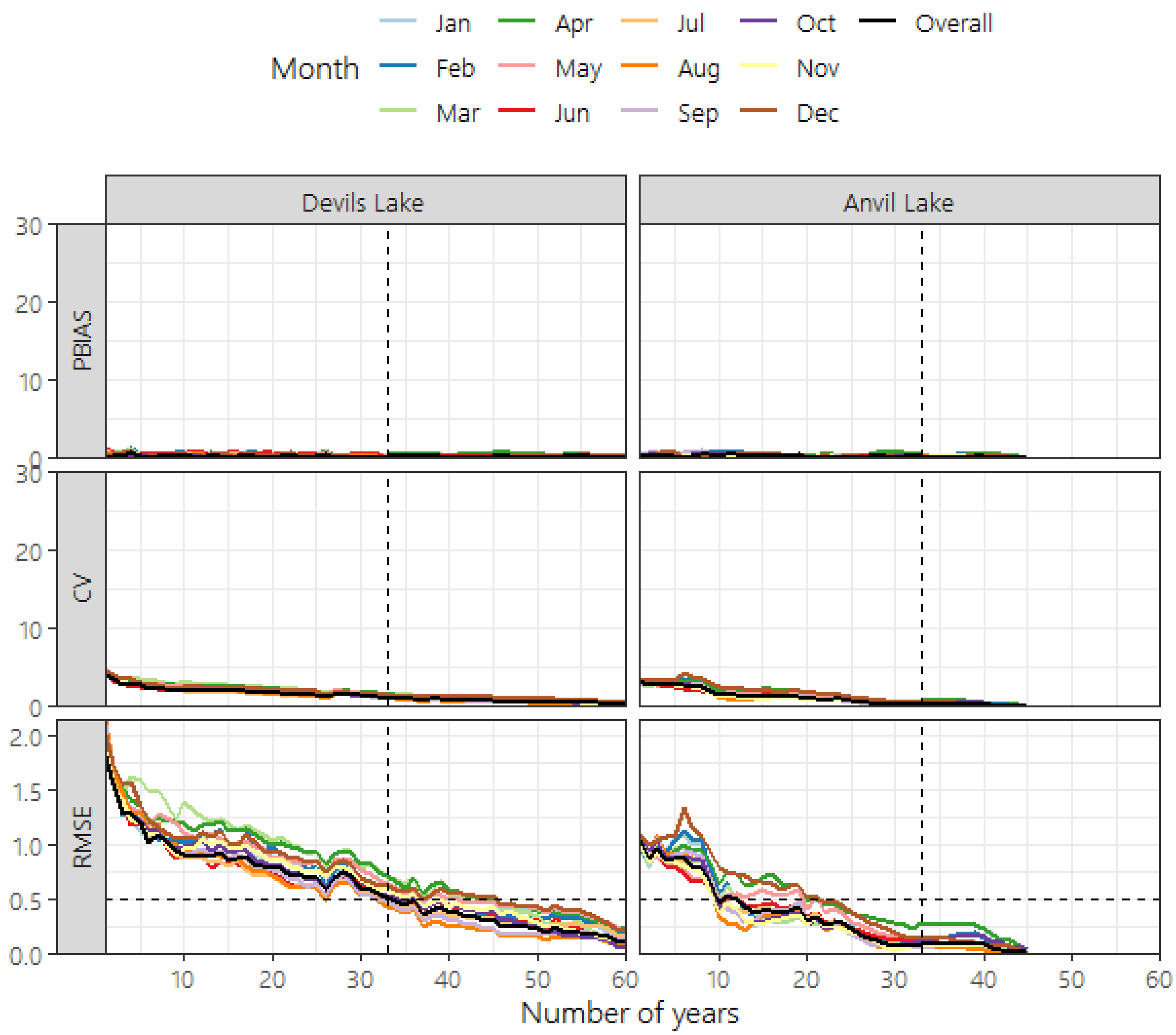
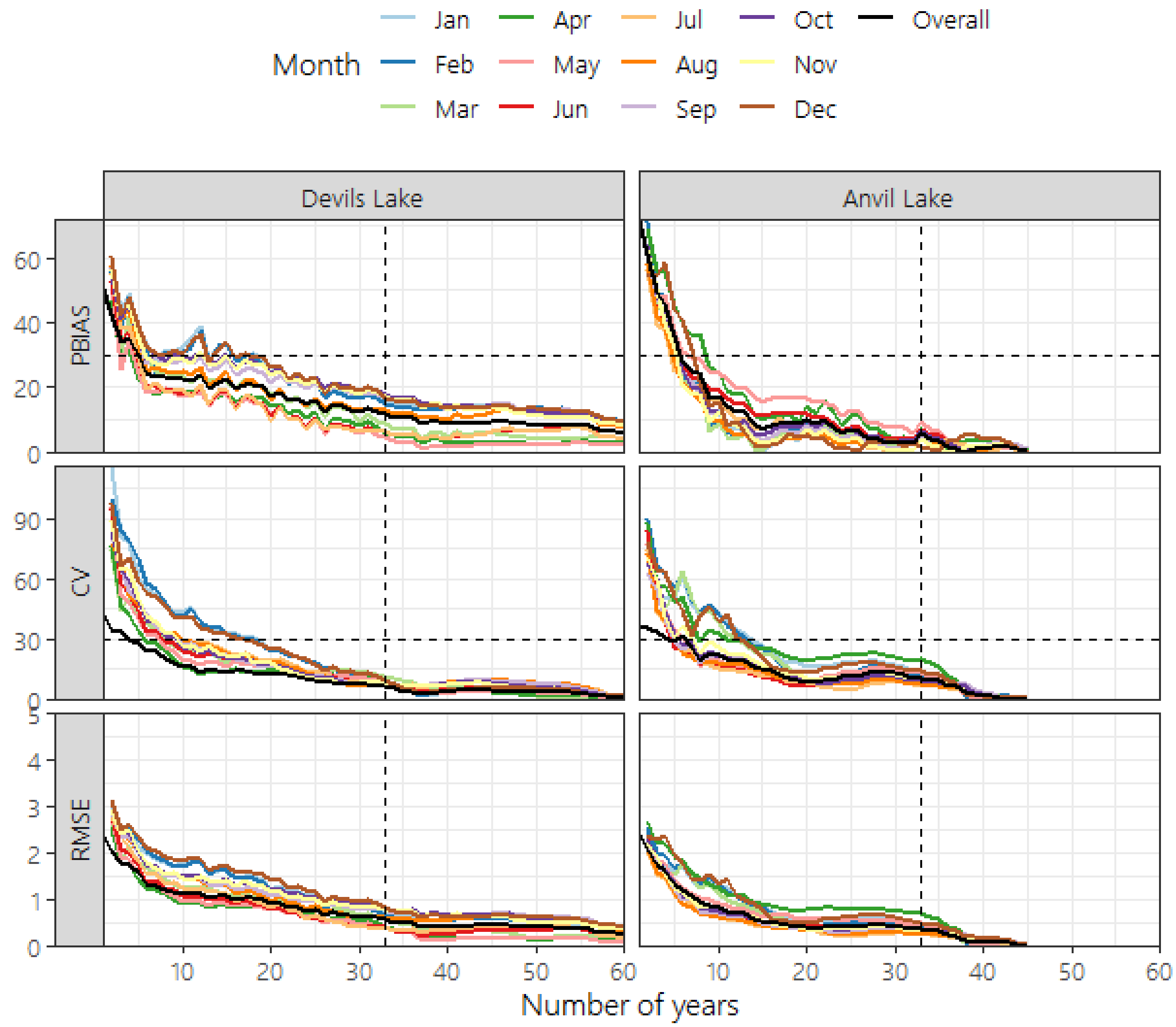


Figure A1. Time series length sensitivity of median levels. Bias (PBIAS), precision (CV), and accuracy (RMSE) for each lake for the median lake level of the overall time series (Overall) and each month. Dashed vertical lines correspond to a 33-year time series. Dashed horizontal lines represent a PBIAS of 30%, CV of 30%, and RMSE of 0.5 ft.



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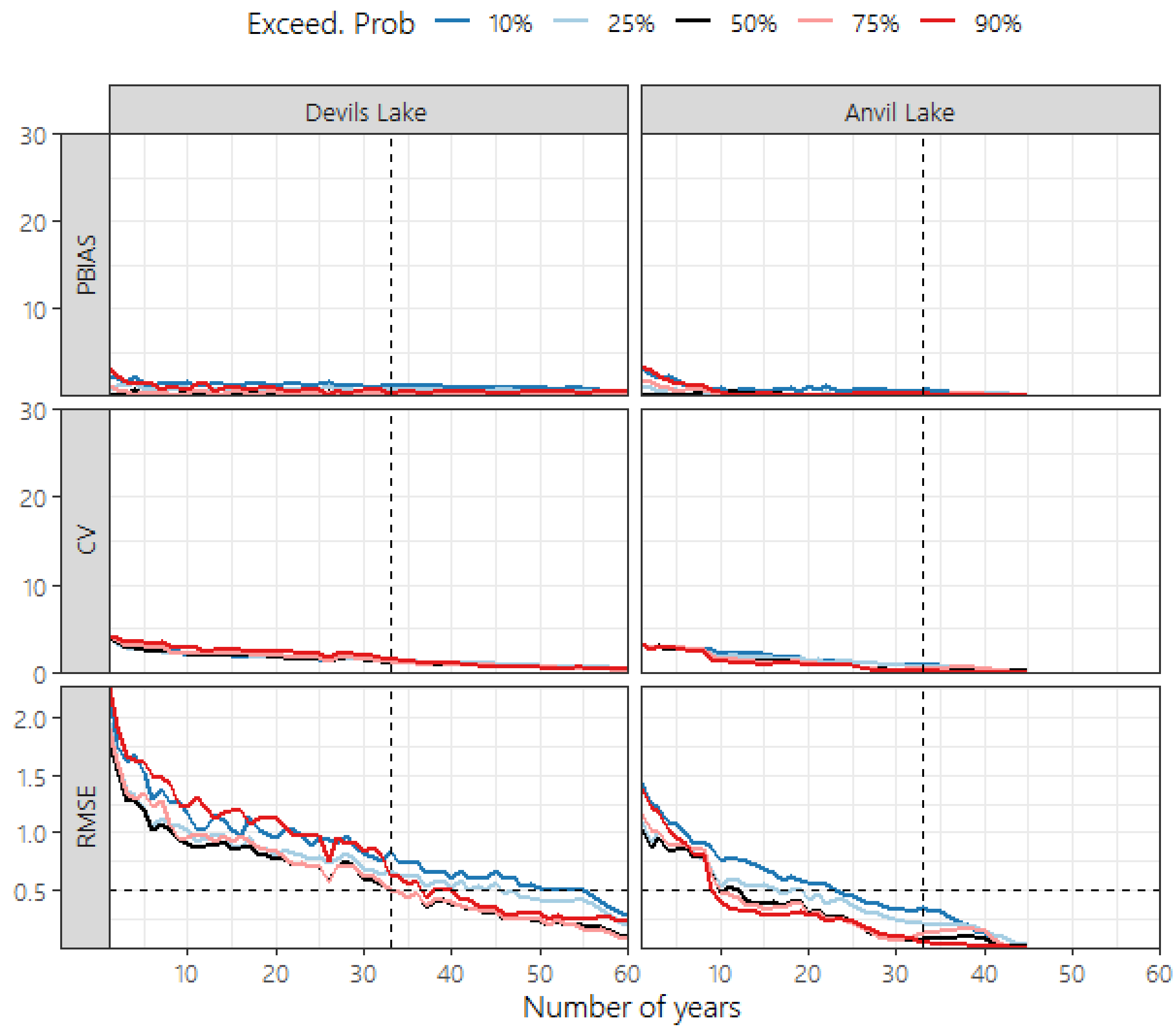

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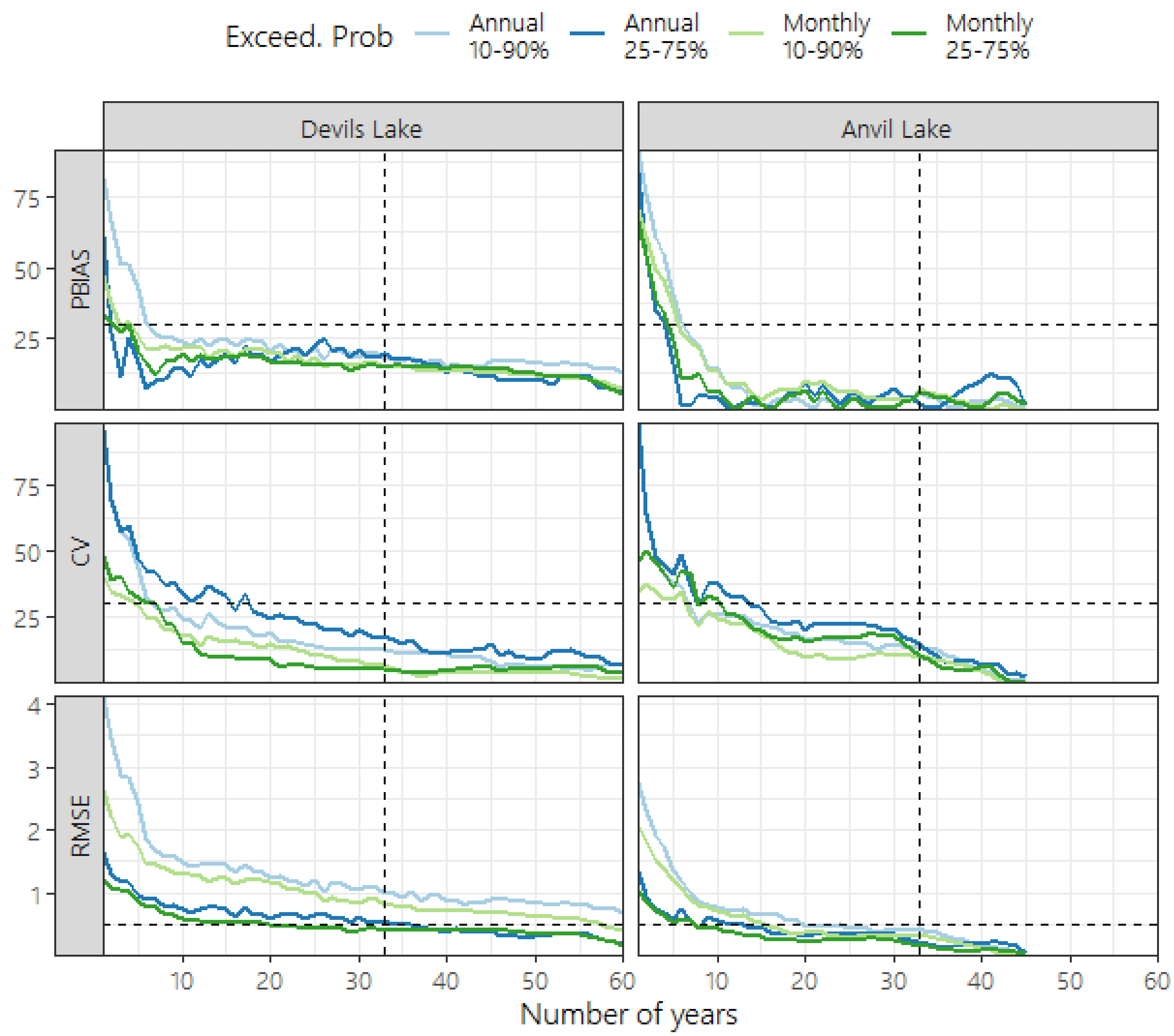

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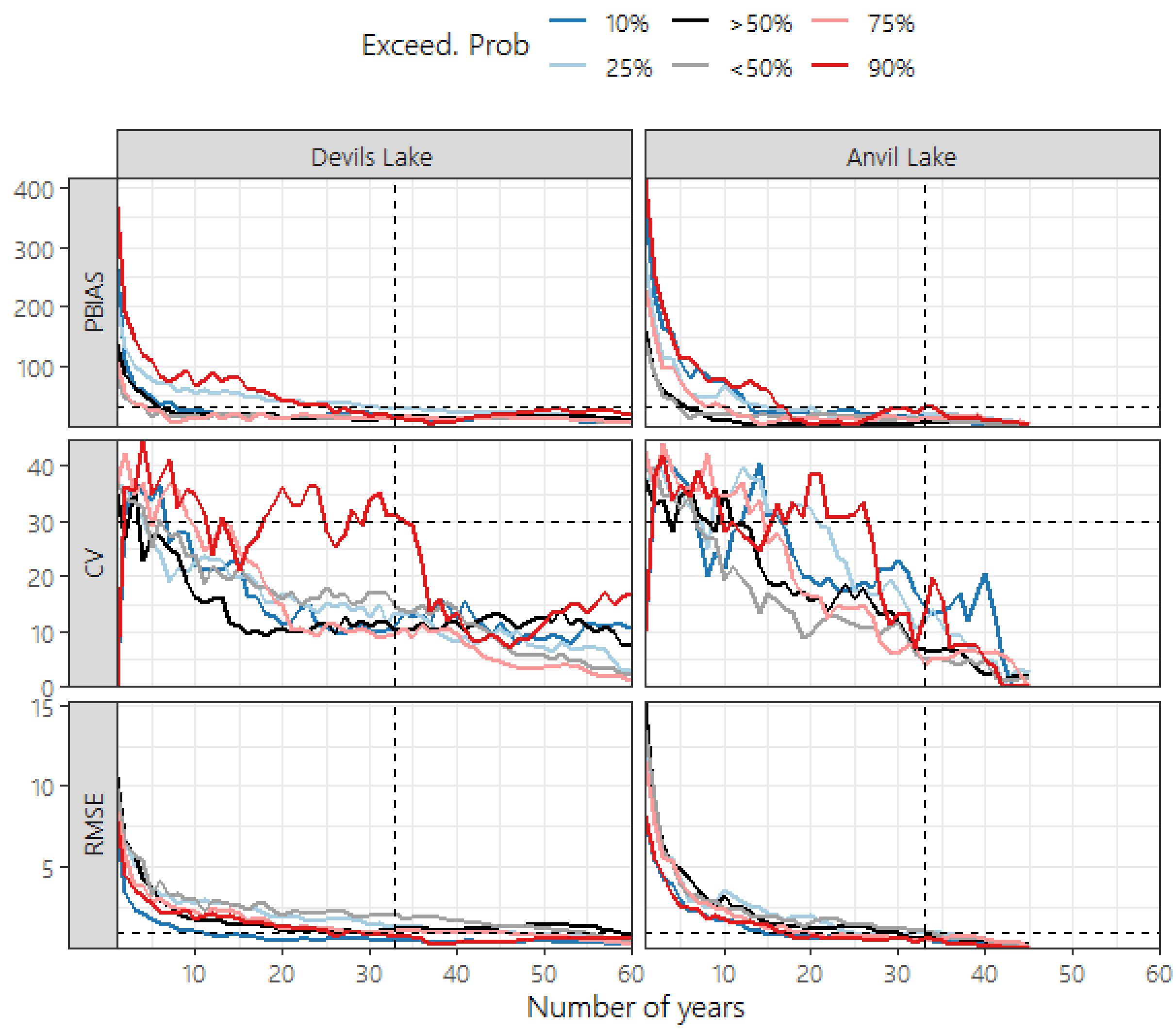

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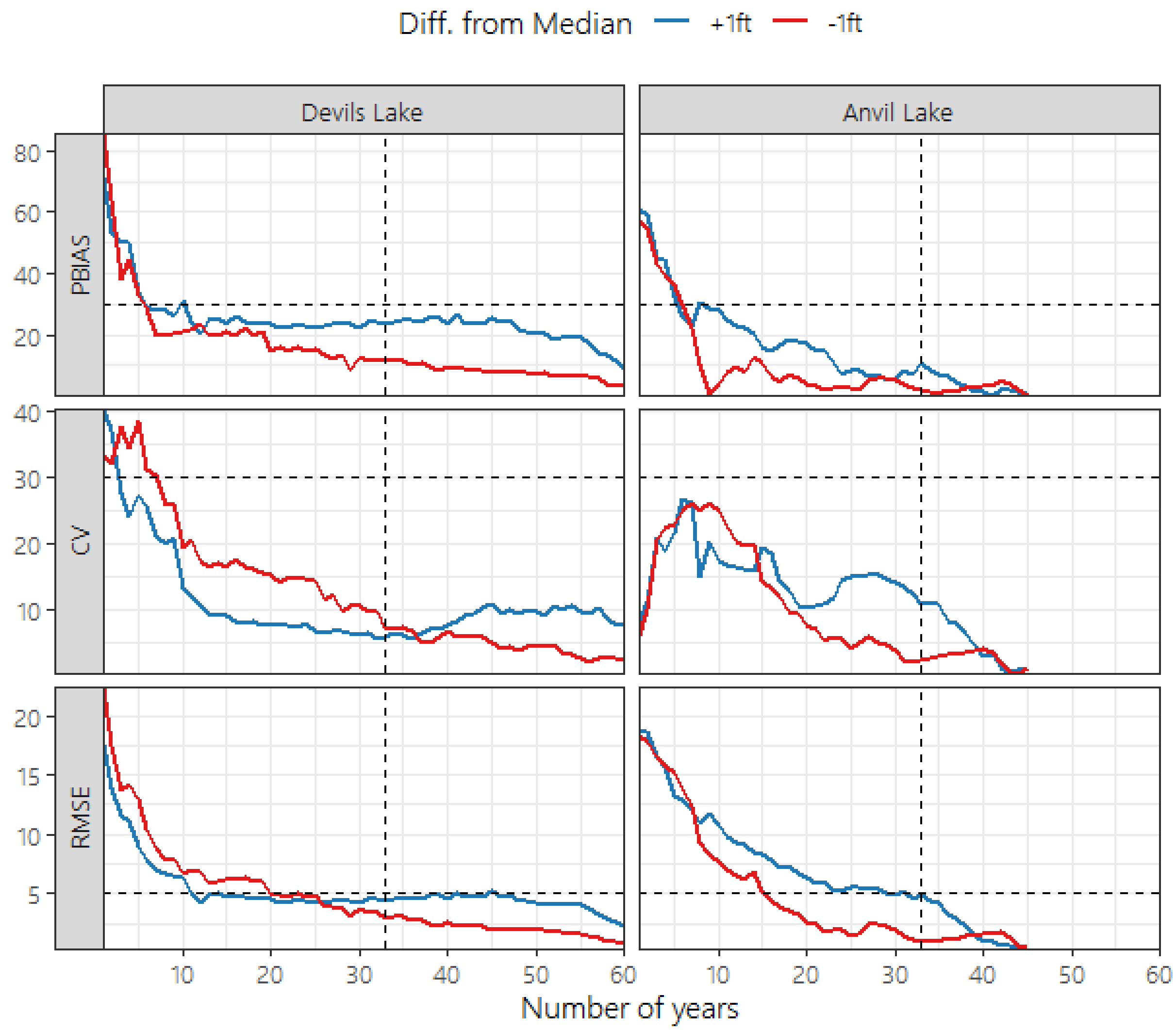

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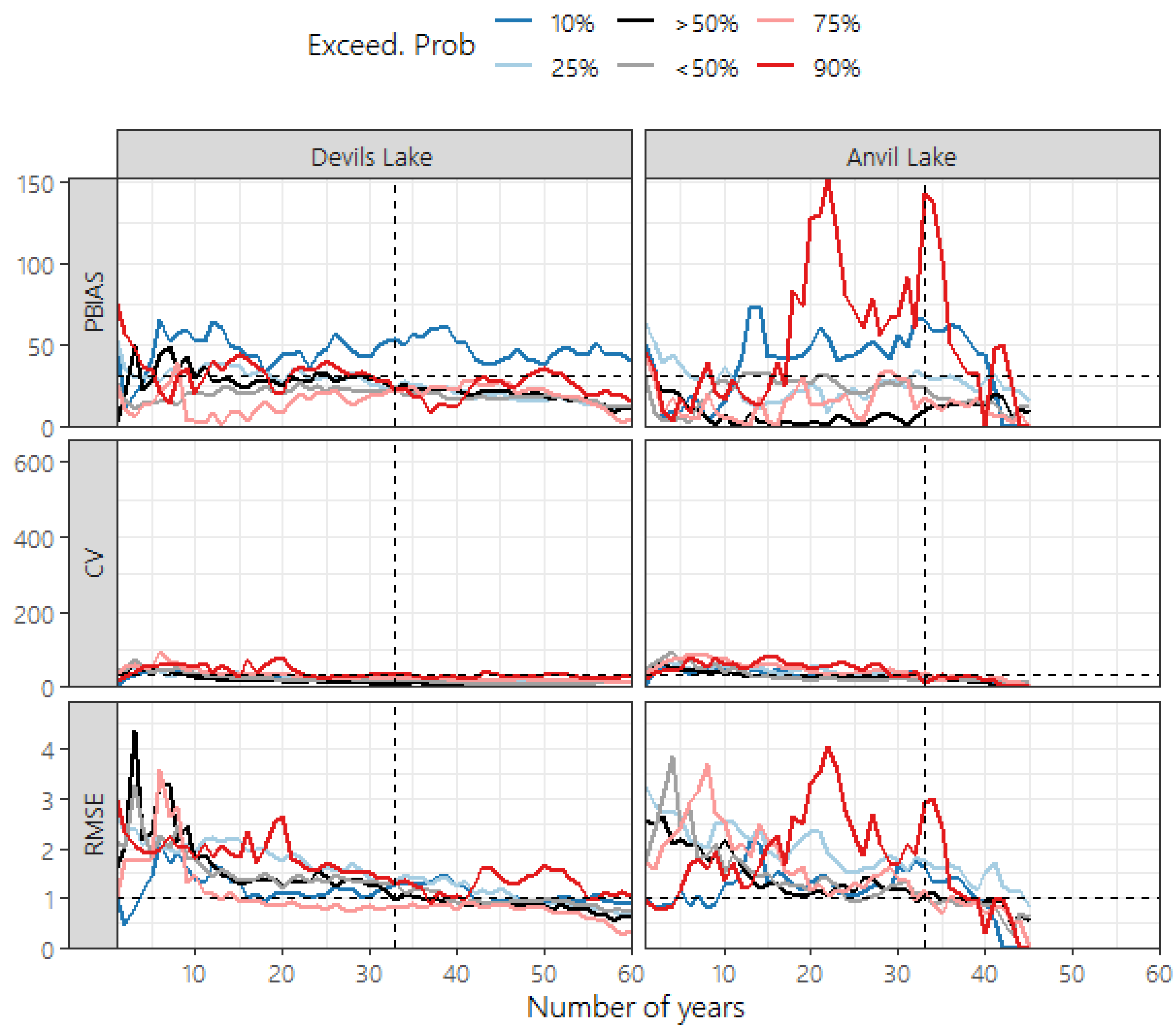

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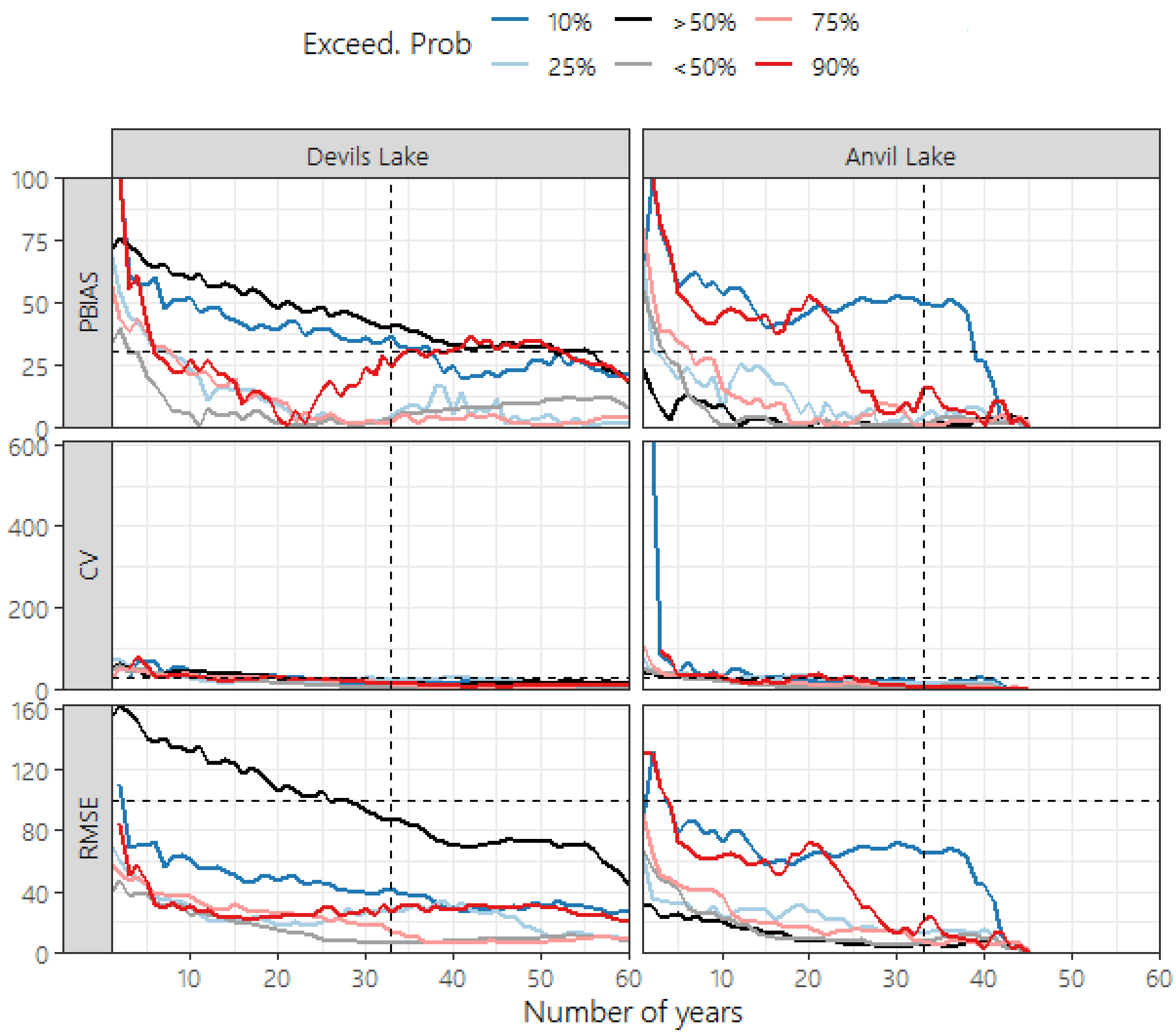

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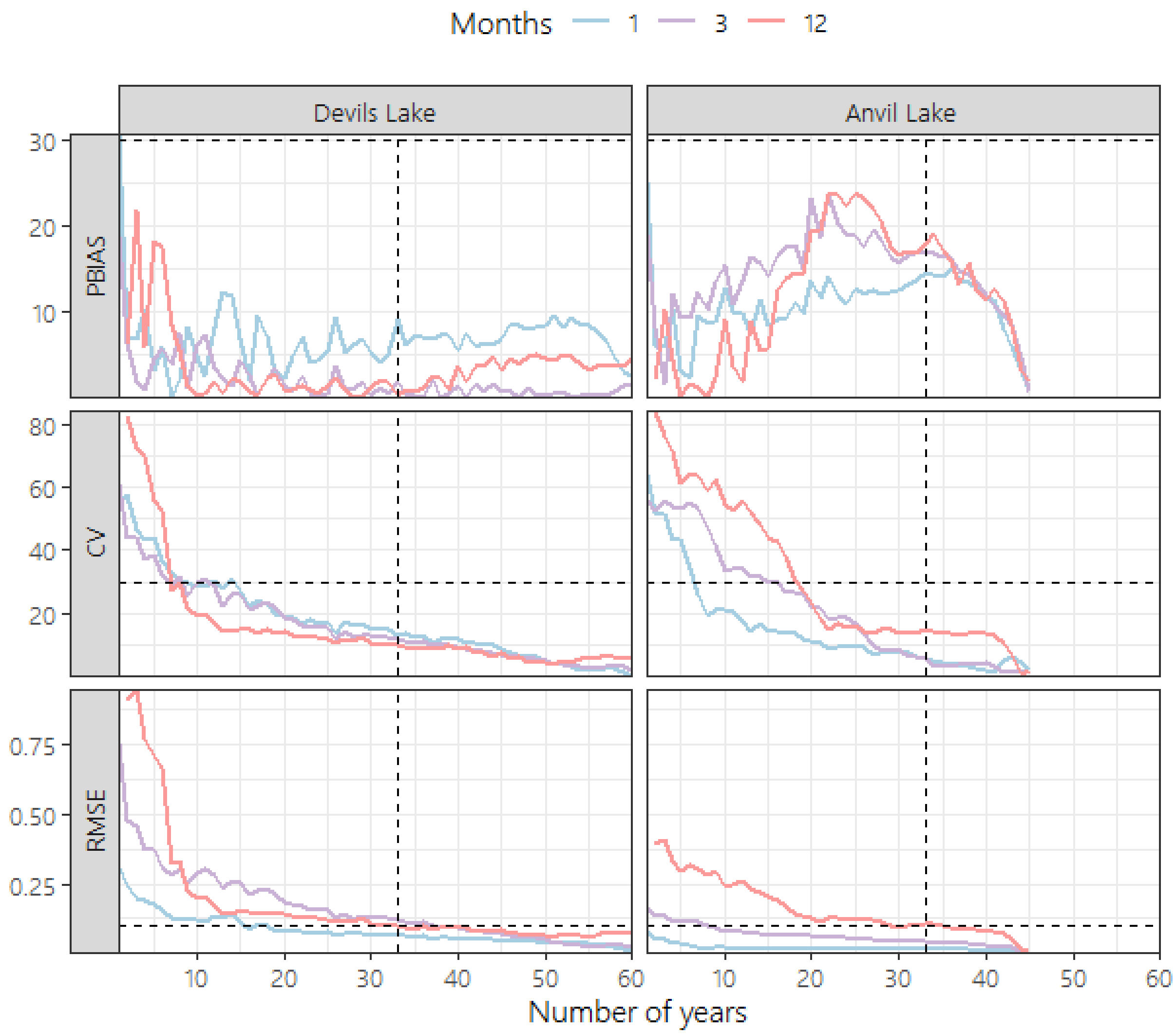

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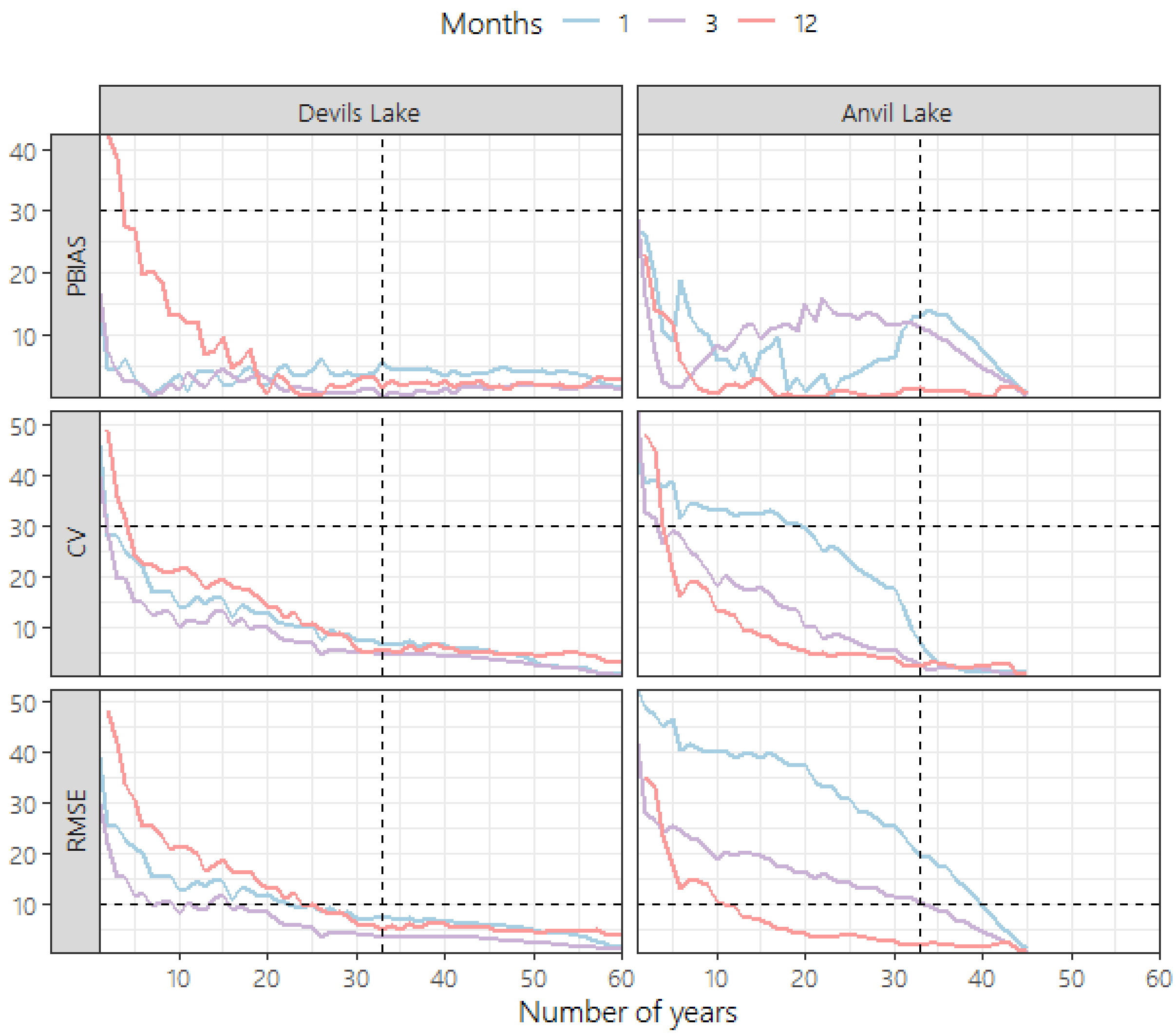

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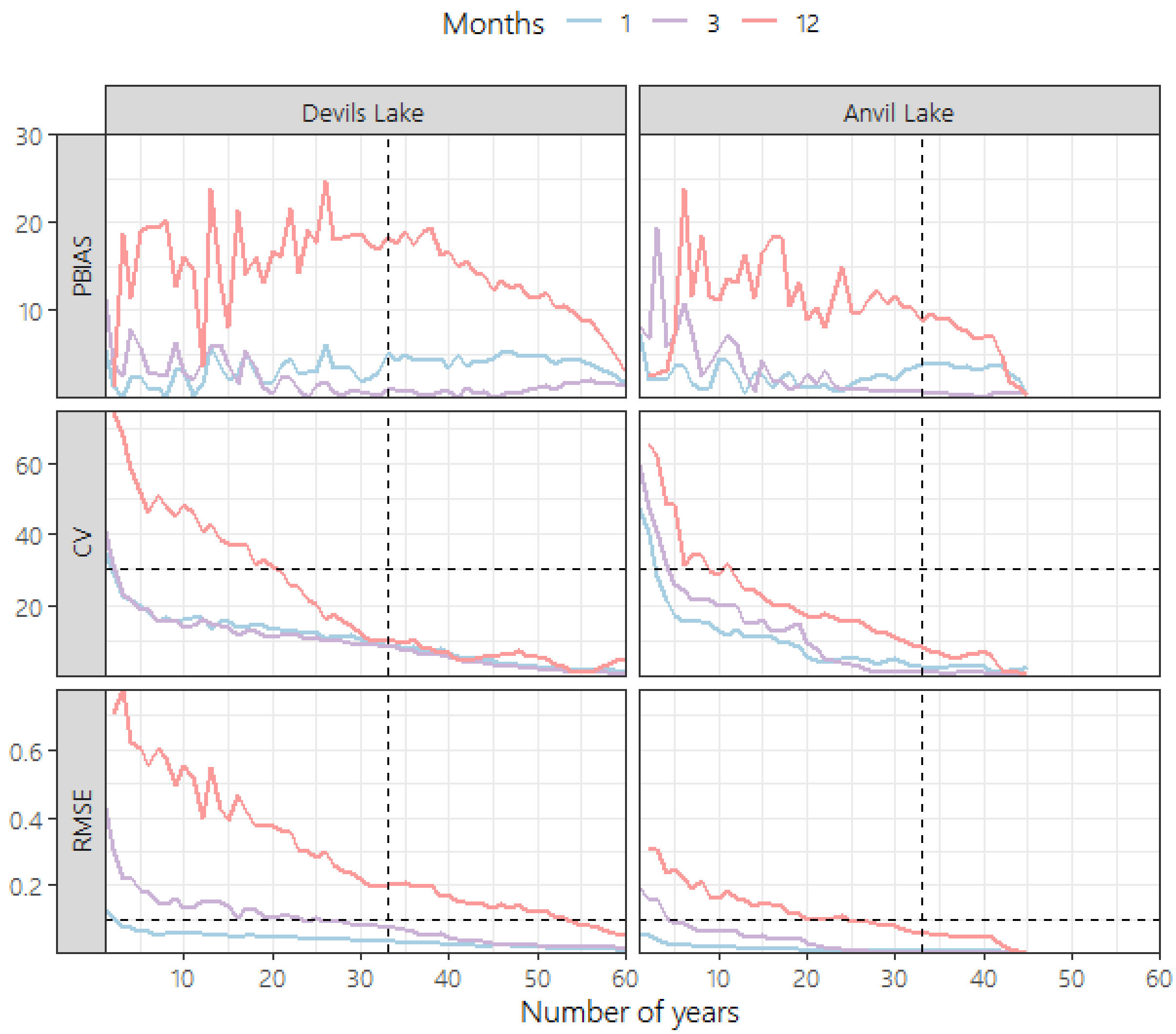

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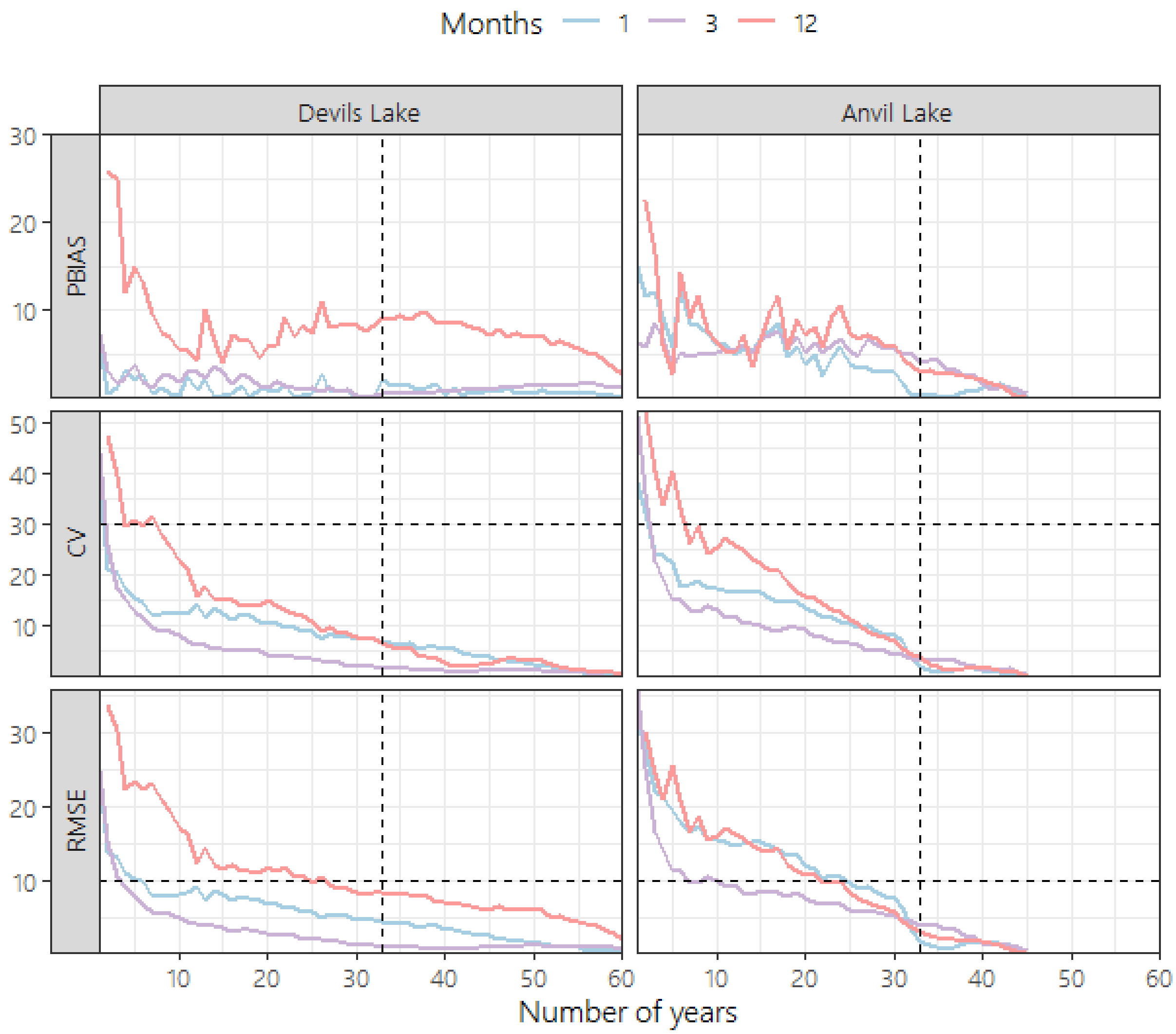

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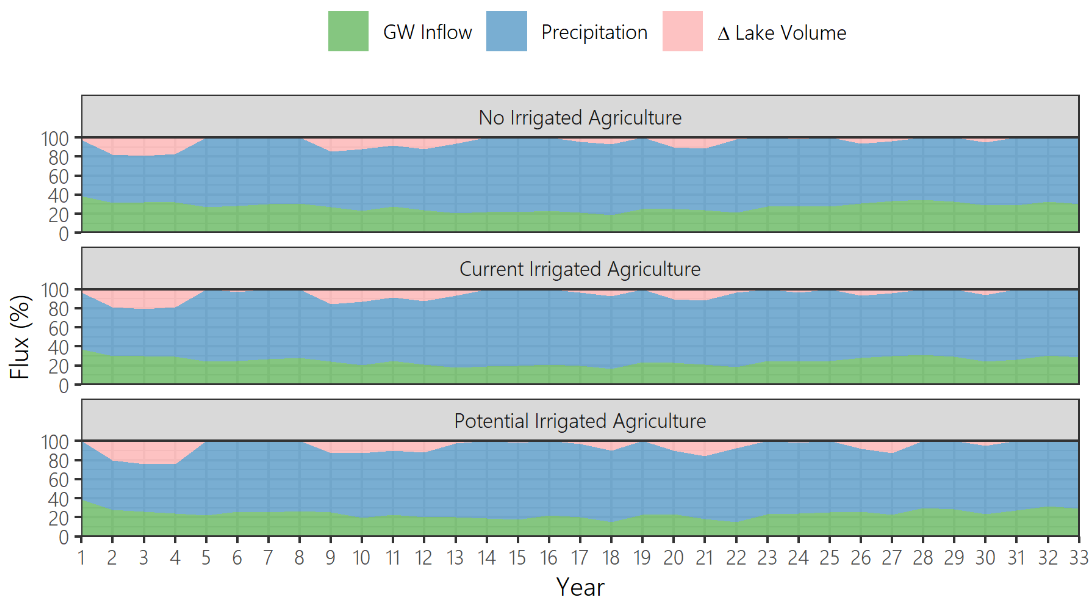


Figure B1. Modeled inflow as percent, Pleasant Lake. Annual precipitation, groundwater inflow, and change in lake volume as a percent of total inflow for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

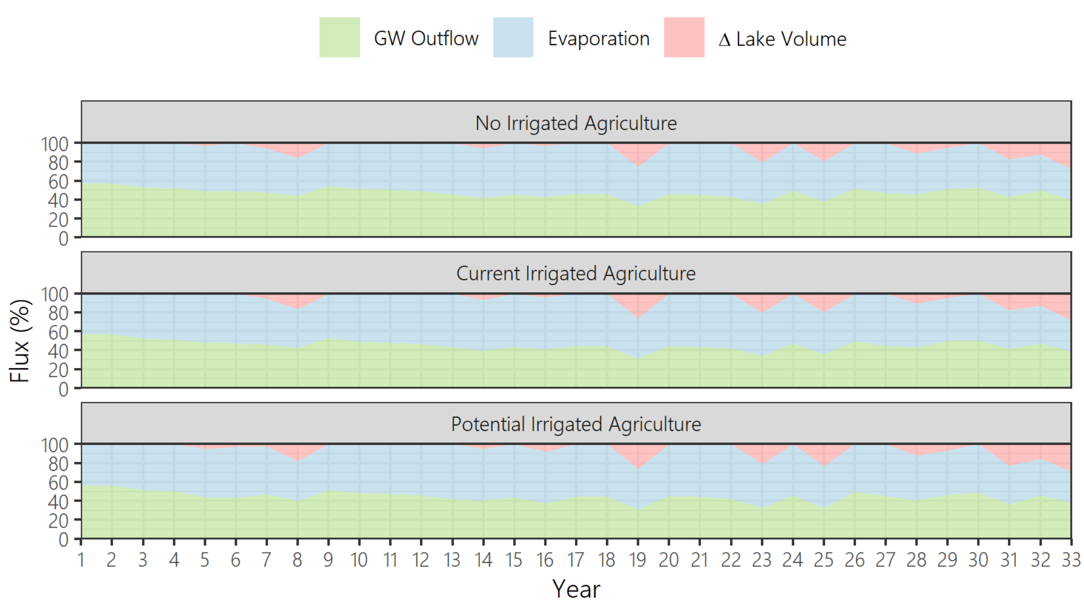


Figure B2. Modeled outflow as percent, Pleasant Lake. Annual evaporation, groundwater outflow, and change in lake volume as a percent of total inflow for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

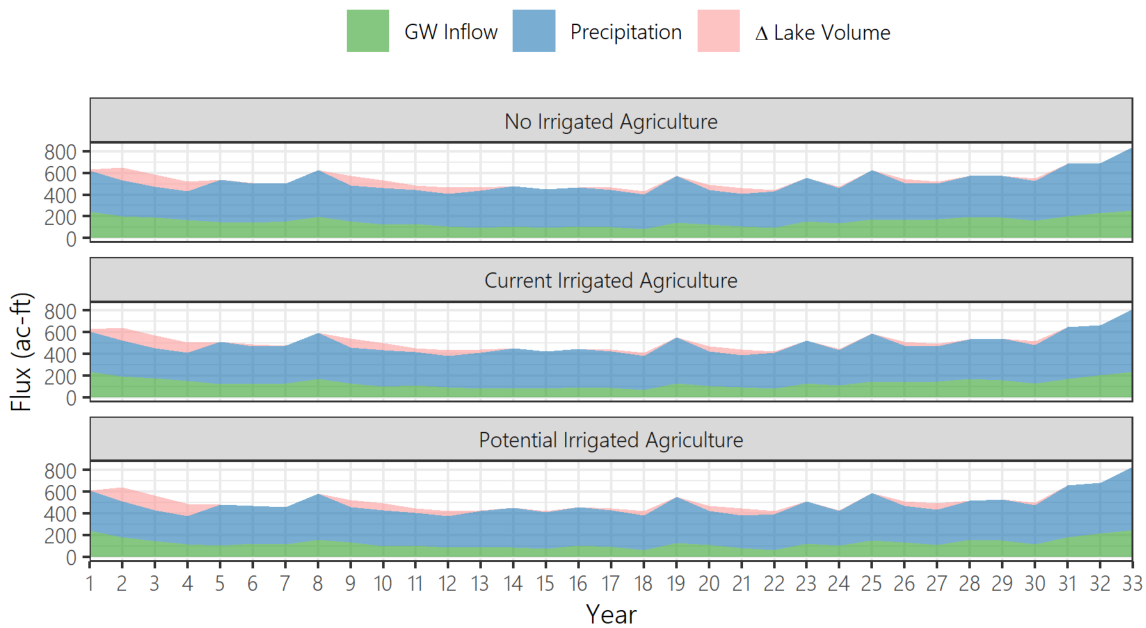


Figure B3. Modeled inflow as acre-ft, Pleasant Lake. Annual precipitation, groundwater inflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

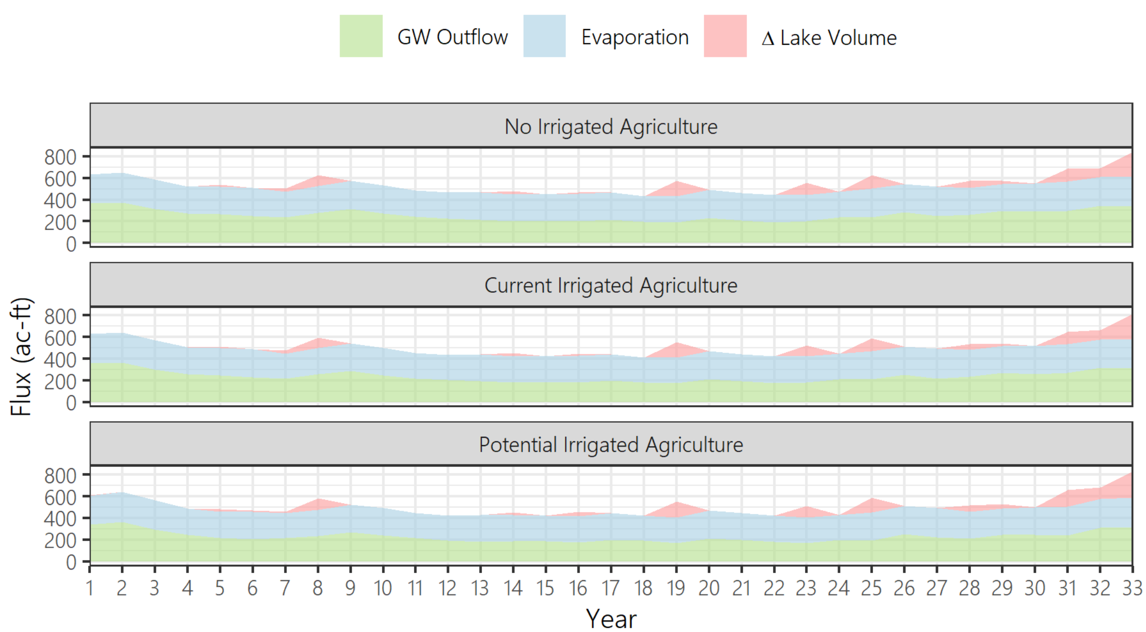
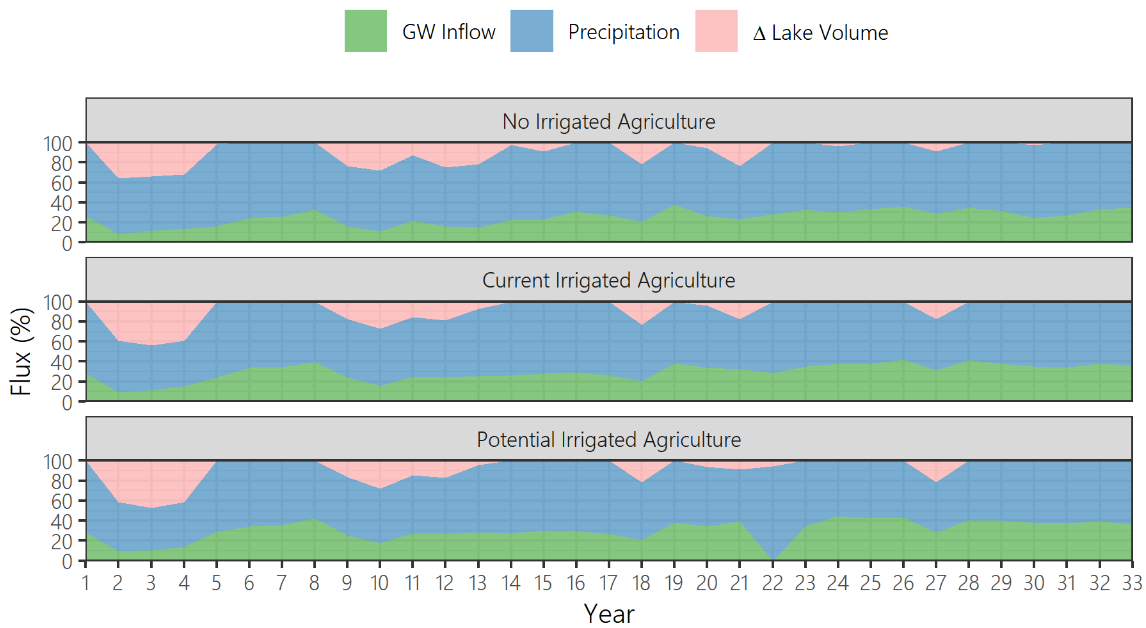


Figure B4. Modeled outflow as acre-ft, Pleasant Lake. Annual evaporation, groundwater outflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.



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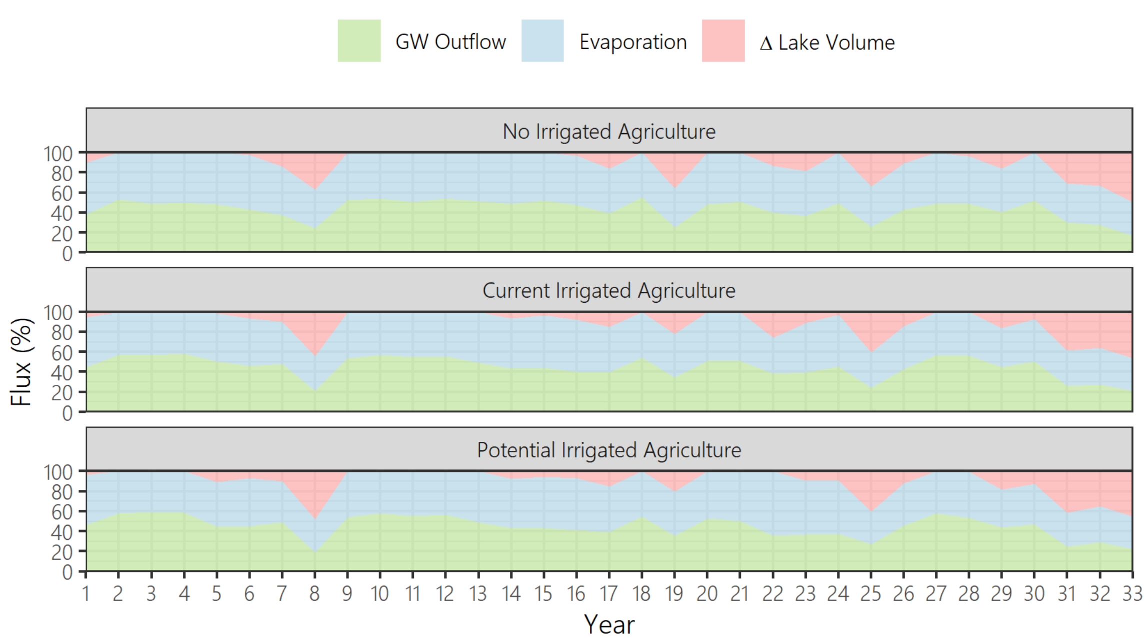

Figure B6. Modeled outflow as percent, Long Lake. Annual evaporation, groundwater outflow, and change in lake volume as a percent of total inflow for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

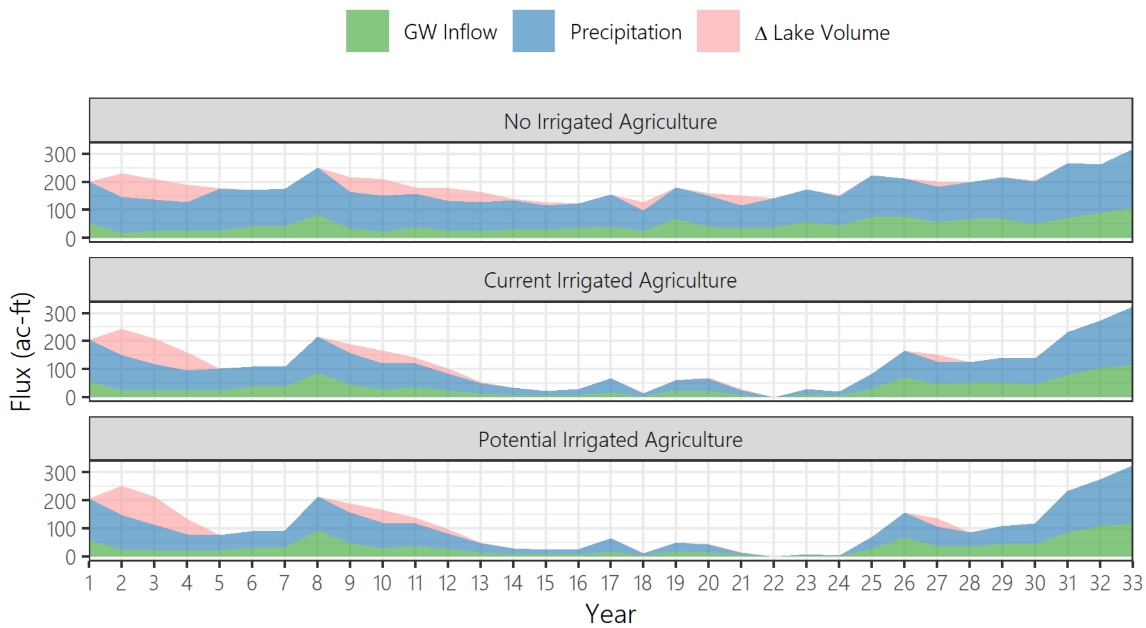

Figure B7. Modeled inflow as acre-ft, Long Lake. Annual precipitation, groundwater inflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

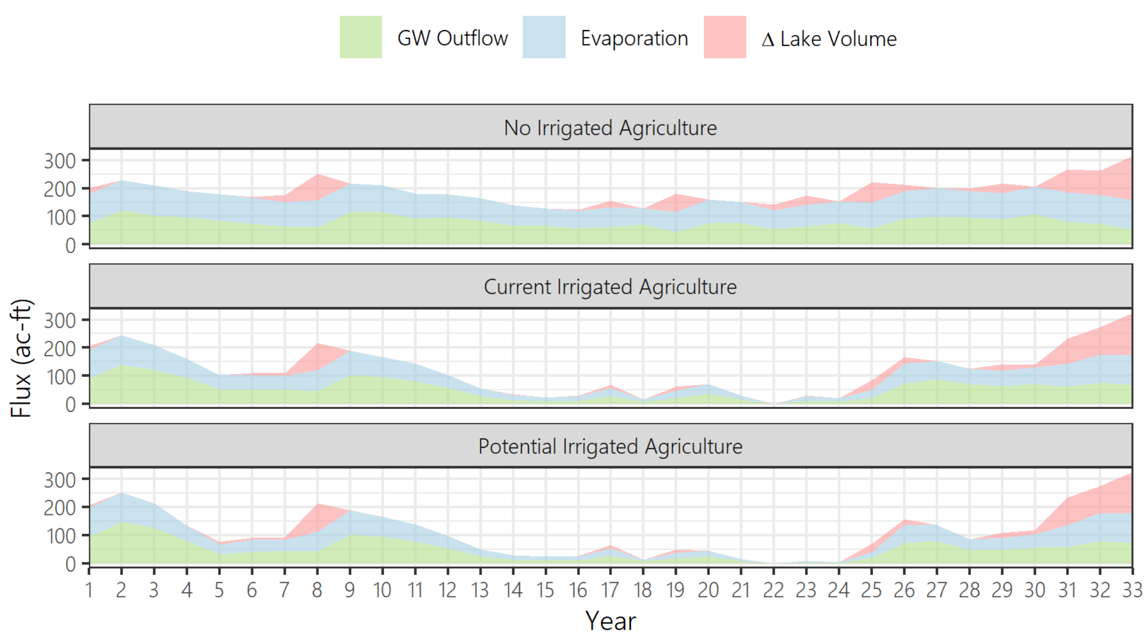

Figure B8. Modeled outflow as acre-ft, Long Lake. Annual evaporation, groundwater outflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

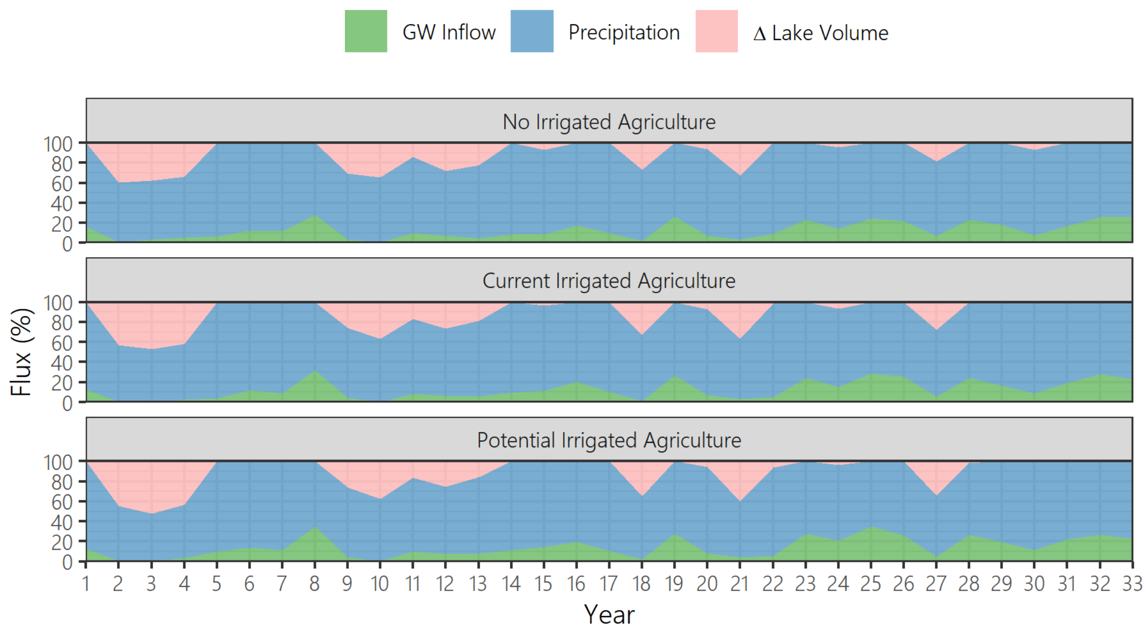

Figure B9. Modeled inflow as percent, Plainfield Lake. Annual precipitation, groundwater inflow, and change in lake volume as a percent of total inflow for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

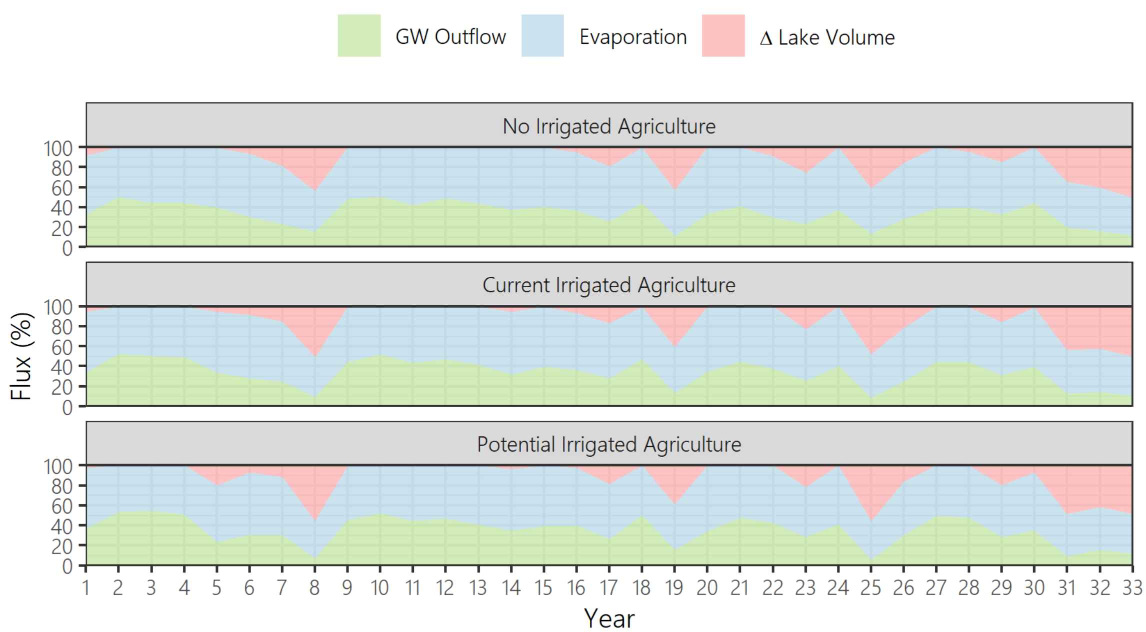

Figure B10. Modeled outflow as percent, Plainfield Lake. Annual evaporation, groundwater outflow, and change in lake volume as a percent of total inflow for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

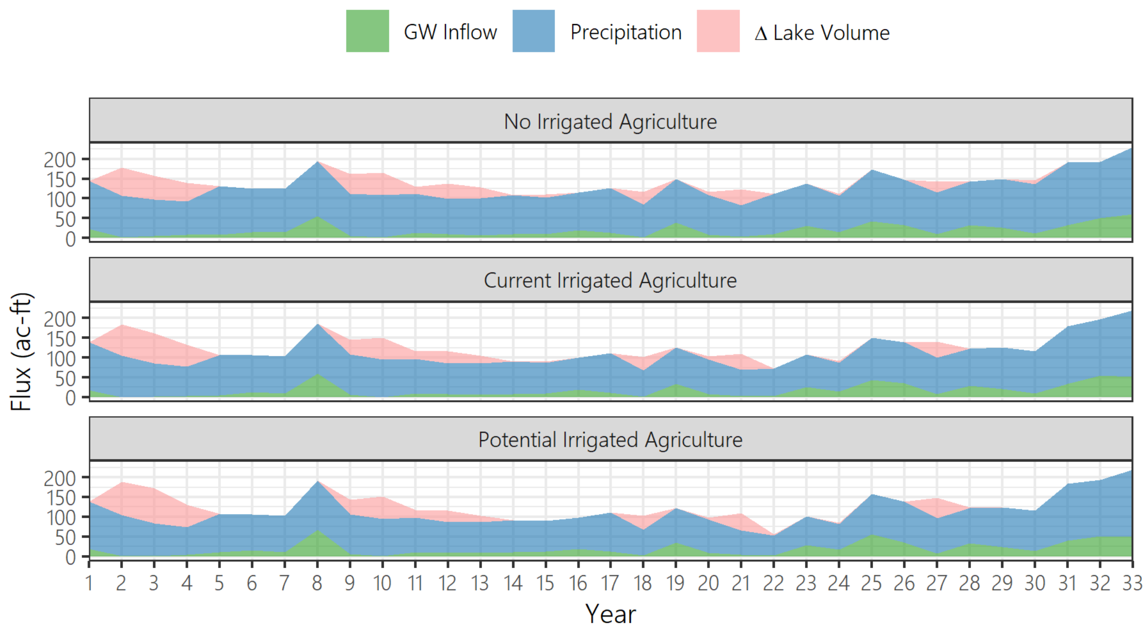

Figure B11. Modeled inflow as acre-ft, Plainfield Lake. Annual precipitation, groundwater inflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

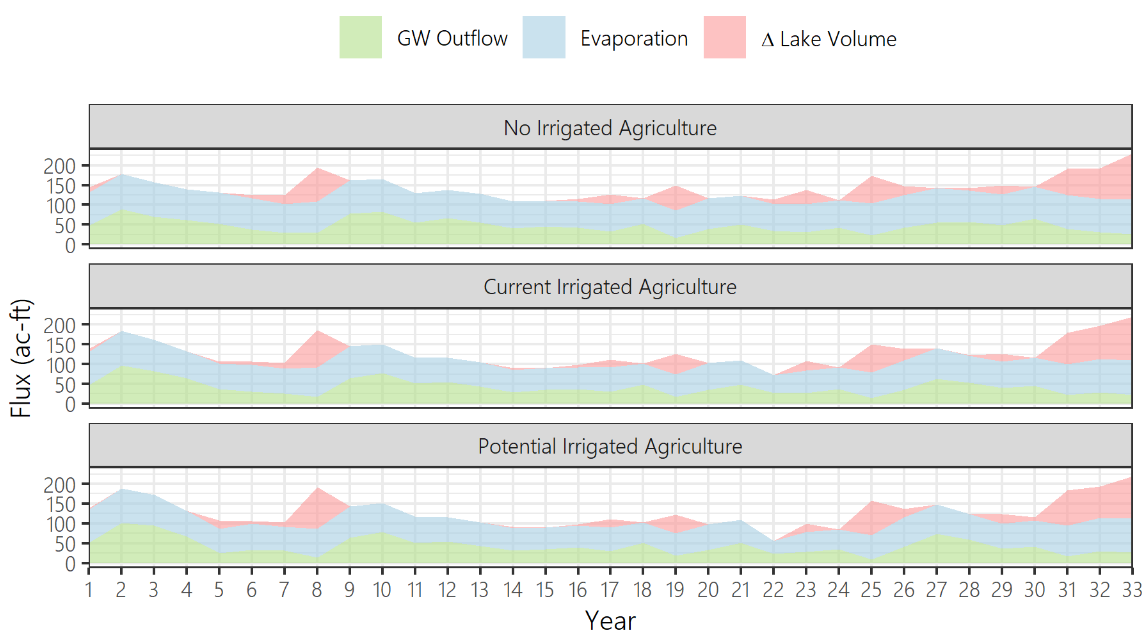

Figure B12. Modeled outflow as acre-ft, Plainfield Lake. Annual evaporation, groundwater outflow, and change in lake volume as acre-ft per year for each modeled irrigation scenario. Change in lake volume is grouped with inflows when lake volume decreases and with outflows when lake volume increases.

Errata Addendum to Appendix B: Central Sands Lakes Study Technical Report: Lake Ecosystem Characterization and Response
November 15, 2021
Catherine L. Hein

The reference list lacks one reference cited in the text:
Sutela, T. and T. Vehanen. 2008. Effects of water-level regulation on the nearshore fish community in boreal lakes. Hydrobiologia 613: 13-20.

Two in-text references name the incorrect year:
Oele et al. 2019: in-text reference should be 2019, not 2018
Lawson et al. 2011 – in text ref should be 2011, not 2001

References by the same author in the same year are not differentiated
Stuber, R.J., Gebhart, G. and Maughan, O.E., 1982a. Habitat suitability index models: Bluegill. FWS/OBS, (82/10.8).

Stuber, R.J., Gebhart, G. and Maughan, O.E., 1982b. Habitat suitability index models: largemouth bass. Western Energy and Land Use Team, Office of Biological Services, Fish and Wildlife Service, US Department of the Interior.

On page 185, both Stuber et al. 1982a and Stuber et al. 1982b should be referenced in text.