Impacts of and Adaptation Strategies for Climate Change on Wisconsin's Water Resources

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Introduction

The two driving forces of climate change that will most affect water resources are increased temperature and shifting precipitation patterns. Wisconsin has become warmer, wetter, and has had more extreme precipitation events since the 1950's. Climate models forecast that these trends will continue in the future: rising air temperatures, more precipitation in winter, spring and fall (less certainty in summer), and more frequent and larger extreme precipitation events. These changes in temperature and precipitation will affect Wisconsin's water cycles, with major impacts on lakes, streams, groundwater and wetlands. Some of the physical responses we can expect to see include:

- Increase in average surface water and shallow groundwater temperatures
- Shorter period of ice cover on lakes and streams
- Decrease in the thickness of lake ice cover
- Increase in evapotranspiration rates during the longer growing season
- Increase in freeze-thaw events
- Change in groundwater recharge (water that infiltrates the saturated zone of an aquifer)
    - recharge may increase due to increases in winter and spring precipitation
    - recharge may decrease due to more freeze-thaw events
- Changes in groundwater recharge and discharge based on whether precipitation falls as rain or snow
- Increased high water events causing flooding

In the sections below, we summarize the latest information regarding the impacts of warming and changing precipitation patterns on water resources. We also offer a wide variety of adaptation strategies for water resources. We encourage readers to revisit the 2011 WICCI assessment report for a comprehensive review of climate change impacts to water resources as the material in the 2011 report is still relevant. Here, we provide new information and updates to historical records presented in the 2011 report.

Key Takeaways

- Water temperatures are warming in concert with air temperatures
    - Lakes experience shorter periods of ice cover
    - Lake surface waters are warmer in spring and fall
    - Warm summers occur more frequently, but maximum summer surface temperatures are not increasing
    - Bottom temperatures are warming in some lakes and cooling in others
    - Stratification is stronger and occurs for a longer period of time
- Warmer water temperatures can result in:
    - loss of winter recreational opportunities on ice
    - increased risk of winter drownings due to unstable ice conditions
    - reduced dissolved oxygen in surface waters due to lower solubility in warmer waters and in bottom waters due to longer stratified periods with faster respiration rates
    - reduced cold-water habitat for fish in lakes due to warm surface waters and hypoxia in bottom waters
    - increased internal phosphorus loading due to prolonged periods of stratification and anoxia in bottom waters
    - more harmful algal blooms

    - shifts in fish distributions from cold- or cool-water species to warm water species (e.g., dominance shifting from walleye to largemouth bass)
    - changes in suitability for aquatic invasive species, with decreasing risk for cold-water species like spiny waterflea and increasing risk for warm-water species like the Asian clam
- Changing precipitation patterns affect water level fluctuations
    - Groundwater and lake levels go up and down on an approximate 13-year cycle. Lows occur after an accumulation of years with low precipitation and highs after many years of above-average precipitation
    - Changing precipitation patterns with changing temperatures could shift the balance between precipitation and evaporation, causing water levels to fluctuate at higher or lower levels than they have in the past
    - Greater climatic extremes may also cause water levels to fluctuate more dramatically
- More extreme precipitation impacts water resources in many ways:
    - groundwater flooding
    - increased stream baseflow and stream flooding
    - increased lake levels, sometimes to heights that flood septic systems, drinking wells, roads, and buildings
    - increased erosion and runoff, leading to increased nutrient loading to surface waters and reduced water quality
    - increased contaminant transport
    - loss of shoreland vegetation
    - increased risk of human health concerns due to flooded homes, contaminated drinking water sources, and flooded septic and sewage systems
- Drought impacts to water resources:
    - reduced groundwater discharge to surface waters
    - often warmer temperatures in surface waters
    - water quality changes in surface waters and drinking water
    - reduced or no water in drinking water wells and surface water bodies
    - decreased dissolved oxygen in some surface waters
- A wide variety of adaptation strategies are already being employed as part of typical water quality management activities, but the urgency and magnitude of these activities is enhanced by climate change
- While difficult to prevent lakes from warming, actions to protect and restore habitat and enhance water quality will make lakes more resilient to warming and minimize impacts
- A wide variety of strategies may be used to anticipate and accommodate high and low water levels, again making waters and humans more resilient to fluctuating water levels
- A combination of conservation strategies (e.g., wetland protection and restoration), and engineering solutions (e.g., green infrastructure) can minimize flooding caused by extreme precipitation events.

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Key Findings

- Lake water temperatures have warmed overall, but there are differences between lake types, surface and bottom waters, seasons, and historical time periods.
- Lake surface water temperatures have warmed at a similar rate as air temperatures, but some lakes warmed slightly faster and others slightly slower.
- Surface water warming trends vary seasonally, with post-1980 records indicating the most warming in fall, moderate warming in spring, and minimal to no warming in midsummer.
- Warm years occur more frequently, but maximum summer surface water temperatures are not increasing.
- Bottom water temperature trends vary widely across lakes. They are cooling on several Wisconsin lakes and in many lakes in the northern hemisphere, but bottom temperatures are warming at a similar rate as surface waters on other lakes.
- Bottom water temperature trends depend on lake size and depth, trends in wind speed, and water clarity, all of which influence processes that transfer heat downward.
- Seasonal differences in bottom water warming rates exist on some lakes, but monthly variation in warming rates is less than cross-lake variation.
- The strength and duration of summer stratification is increasing.
- Decreases in wind speed and water clarity can outweigh lake warming due to air temperature rise.
- Average rates of surface water warming are generally slower when examining records dating back to the early 1900's compared to records post-1980. Care should be taken when interpreting rates of temperature change from particular time periods.
- Future projected lake temperature profiles are available for thousands of lakes and indicate that future warming will likely have ecological consequences, such as changes in fish and invasive species distributions.

Introduction

Wisconsin lakes are warming. Warmer waters have a myriad of consequences: inducing shifts in species distributions and increasing hypoxia, internal phosphorus loading, and toxic harmful algal blooms. Although the warming trends and consequences are clear and strongly track warming air temperatures, lake thermodynamics are complex. Neighboring lakes respond differently to the same external drivers in large part due to their morphometry and water clarity. In this section, we summarize the state of the science on warming patterns in Wisconsin lakes. We break down lake warming patterns by the length and timing of the period of record observed, depth, and season. We also explain how lake-specific characteristics influence warming rates. Finally, we share future projections of lake water temperatures given climate change.

External drivers of lake thermodynamics include air temperature, solar radiation, and wind (Figure 1). Lake surface waters warm conductively through contact with the air. Solar radiation penetrates and warms the water. Thus, clearer lakes warm more and to greater depths. Wind mixes surface water downward, and large lakes with greater fetch will mix deeper because wind energy increases as it moves across the lake's surface. Lakes that are deep enough undergo a seasonal stratification cycle wherein they develop a warm shallow layer (epilimnion) and cold deep layer (hypolimnion) in summer, mix from the lake surface to the lake bottom after ice-out in spring and before ice-on in fall, and exhibit freezing temperatures near the surface and slightly warmer temperatures near the bottom when ice-covered. Conversely, shallow lakes maintain a relatively uniform water temperature profile during the ice-free season, sometimes with multiple, short periods of stratification in summer. Climate change also affects the stratification cycle.

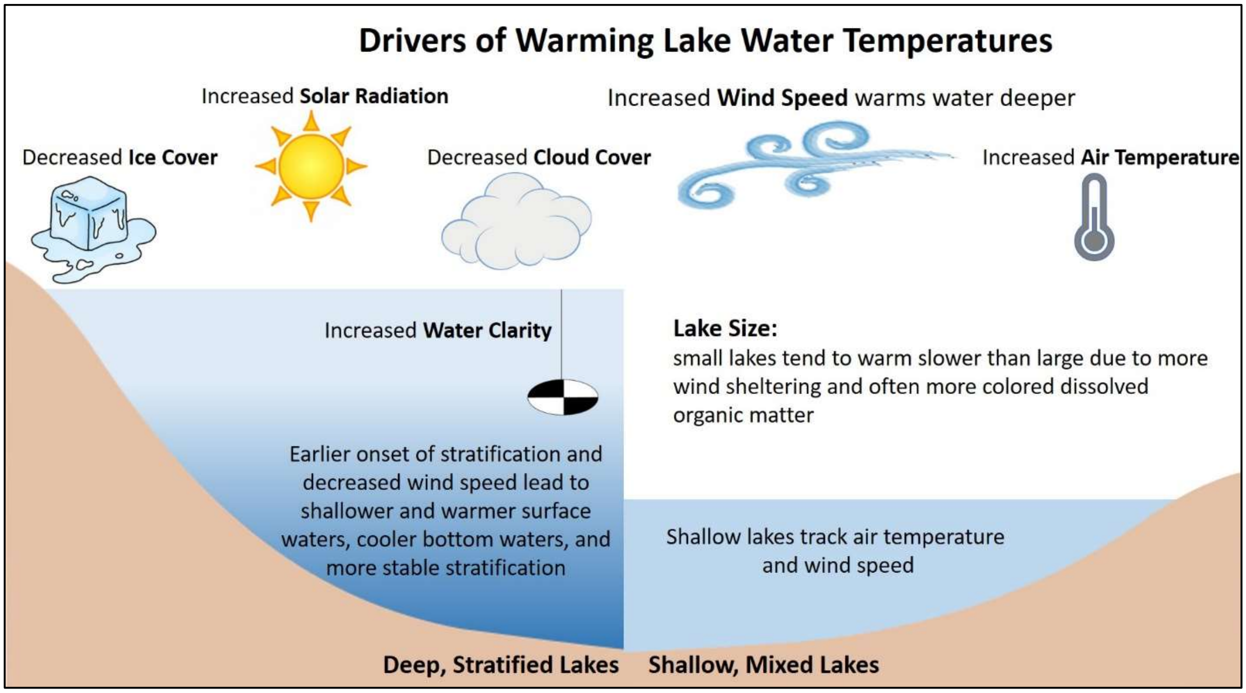

Figure 1. Drivers of warming lake water temperatures and differences between lakes based on size and depth. Art from various sources. Ice: https://drawinghowtos.com/ice-cube-8770/, Sun: https://www.pngall.com/?p=14409, Cloud: https://en.wikipedia.org/wiki/File:Cartoon_cloud.svg by Jean Victor Balin, Wind: https://www.freepngimg.com/png/87055-blue-weather-cloud-wind-electric-free-transparent-image-hd by Hannah Hill, Secchi Disk: Tyler Logan, Lake Profile: Carolyn Voter. Licenses: CC BY-SA and CC BY-NC.

Historical Time Period

The rate of surface water temperature change is not constant over time.[1,2] Most studies have focused on warming rates since the 1980's because that is when a lot of monitoring efforts began,[2,3,4,5,6] but two lakes in Wisconsin have surface water temperature records from the past century: Lake Mendota in the south (starting 1894) and Trout Lake in the north (starting 1914).[1] We summarize differences in warming rates between the full records and records post-1980 on these two lakes to consider the influence of time period,[1] but do not imply that warming rates changed beginning 1980. In fact, there was not a significant breakpoint in the July-August-epilimnetic warming trend on Lake Mendota.[7]

For many monthly metrics, more of the warming trends are statistically significant when analyzed over the full record, but the rate of change is more modest than that observed post-1980 (Figure 22).[1] For example, Trout Lake's September surface water temperature significantly increases in the full record only, but the rate is two times greater post-1980.[1] When analyzed on a century time scale, warming rates are less sensitive to the specific years included and the exact thermal metric. For example, Lake Mendota's epilimnetic midsummer warming rate (July 15 – August 15) is moderately significant at 0.1 °F/decade (simulated from 1911-2014),[8] which is similar to the observed epilimnetic July-August mean increase at 0.15 °F/decade (observed from 1894-2017 with some data gaps).[1] Simulated midsummer warming rates on neighboring Lake Wingra and Fish Lake were similar at 0.1 and 0.2°F/decade, respectively (1911-2014).[8]

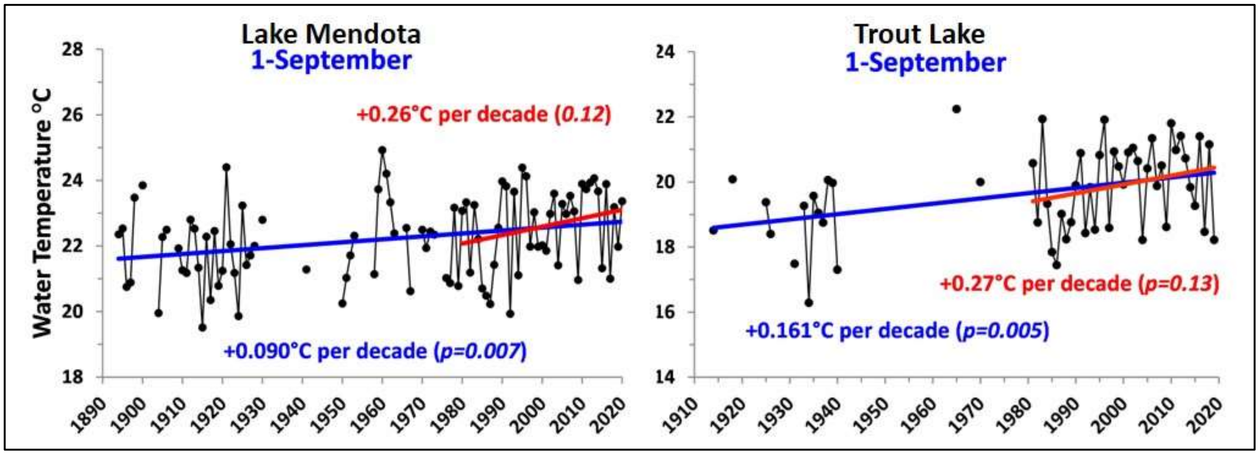

Figure 2. Epilimnetic water temperatures interpolated to September 1 on Lake Mendota and Trout Lake and linear trends over the entire time frame of available records (blue) and post-1980 (red). Source: [1]Lathrop & Robertson 2021

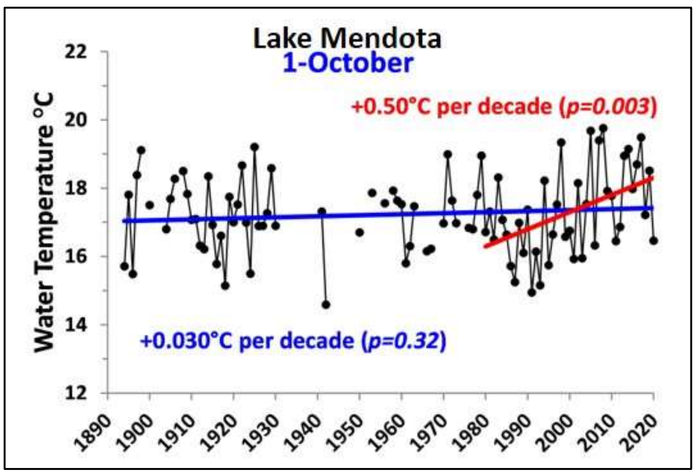

Figure 3. Epilimnetic water temperatures interpolated to October 1 on Lake Mendota and linear trends over the entire time frame of available records (blue) and post-1980 (red). Source: [1]Lathrop & Robertson 2021

Warming rates calculated over shorter time periods are more sensitive to which years are included in the record. For example, the significance and warming rates of a few monthly temperature metrics changed when the Lake Mendota and Trout Lake records that begin in the 1980s were expanded to include 2018-2020.[1,9] The addition of those three years almost halved the November warming trends and nearly doubled Trout Lake's July warming trend.[1,9] The long-term Mendota record shows that the October-1 warming rate is much faster during the short period of record than the long due to the cool October-1 years in the late 1980's (Figure 3). Thus, users should be aware that trends calculated from 30 to 40-year time periods can be sensitive to which years are included.

This comparison between 30+ and 100+ year records shows that temperature trends are not linear and constant over time. While observed warming rates are useful, one should consider the most relevant time frame for their specific application. A warm period occurred in the 1930's (e.g., Trout Lake was as warm then as it is now),[1,2] and a warming pause occurred globally from 1998-2012.[10] Lake surface water temperatures reflect air temperatures during these periods. Thus, the 100+ year record captures trends and variability reflecting both natural and anthropogenic climate drivers. Most of the global air surface temperature warming post-1950 stems from anthropogenic drivers, particularly increased greenhouse gas emissions.[11] Nationally, air temperatures have been increasing since 1964.[2] The following sections report trends observed given available data. Because only a few lakes have records dating back 100+

years, findings related to geography, lake morphometry and season are mostly limited to records dating back to *c.* 1980.

Depth

Climate change affects lake thermodynamics in a variety of ways, so it is helpful to individually examine changes in surface water temperature, bottom water temperature, and the average temperature of the entire lake volume. Globally, average summer (July through September) surface water temperatures (0 to 3.3 ft deep) on lakes increased by 0.6°F per decade from 1985-2009, but eight Wisconsin lakes monitored by the North Temperate Lakes Long Term Ecological Research (NTL-LTER) program warmed faster than that at a rate of 0.68 to 1.5°F/decade.[3] Lakes in the Great Lakes Region and in Northern Europe warmed faster than the global average (Figure 4).[3] In the northern hemisphere, simulated lake surface (0.3 ft deep) temperatures increased by 0.59°F/decade on average (1980-2016).[6] Nationally, average July-August surface water temperatures increased at 0.6°F/decade from 1981-2018, but Wisconsin lakes are warming more slowly than the national average in July and August, moderately in June, and as fast as the fastest lakes in the nation in September.[2] The fastest warming rates in Wisconsin lakes occur in September (see "Season" below), so including September in the summer average results in faster warming rates. Surface and epilimnetic warming rates vary across seasons and between lakes and will be described in more detail in the sections below.

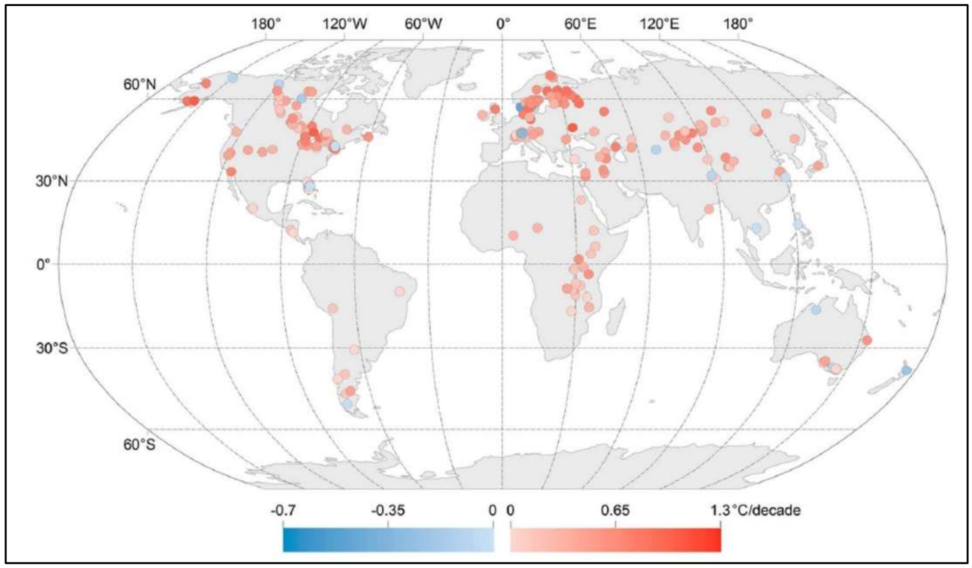

Figure 4. Trends in global lake surface water temperatures (July – September) from 1985 – 2009. Source: [3]O'Reilly et al. 2016

Bottom water trends are highly variable among lakes with some lakes exhibiting warming trends and others exhibiting cooling trends.[5,6,7,8] Across lakes in the northern hemisphere, bottom water at the deepest point decreased in temperature at an average rate of -0.13°F/decade from 1980-2016.[6] Mean bottom-water (deepest 6.6 ft) warming rates across five northern Wisconsin NTL-LTER lakes ranged from 0.1 to 0.7°F/decade, whereas Crystal Lake cooled at a rate of 0.9°F/decade (averaged from June to October, 1981-2015).[5] The simulated temperatures in the hypolimnions of Fish Lake and Lake Mendota cooled at rates of 0.1 and 0.2°F/decade, respectively (1911-2014).[8] The factors driving temperature trends in bottom waters will be discussed in detail below.

Among 142 Wisconsin lakes, the median pair-wise temperature trend across all depths was 0.76°F per decade from 1990 to 2012, which is slightly slower than the statewide air temperature (1.2°F per decade from 1990 to 2013)[4]. Here, pair-wise slopes were estimated for temperatures taken in separate years on the same lake at the same depth within the same week.[4]

Stratification

Warming surface waters and/or sometimes diverging trends between surface and bottom waters have led to increased stratification strength and duration over time.[5,6,7,8] Across hundreds of lakes in the northern hemisphere, simulated lake profiles show that the difference between the top and bottom water temperatures increased at an average rate of 0.2°F/decade and the number of stratified days increased by 4.13 days/decade on average (1980-2016).[6] This increase in thermal stability results from both warming air temperatures and a decrease in windspeed over time. Decreased windspeed results in warmer surface waters (accounting for 15% of warming), cooler bottom waters, and a greater differential between the two.[6] This pattern of diverging surface and bottom water temperatures and increased stratification strength and duration also occurred on Lake Mendota and Fish Lake in Wisconsin and largely resulted from decreased windspeed.[7,8] For example, the simulated difference between the epilimnion and hypolimnion temperature increased at a rate of 0.36°F/decade on Lake Mendota from 1911-2014 (Figure 5).[7]

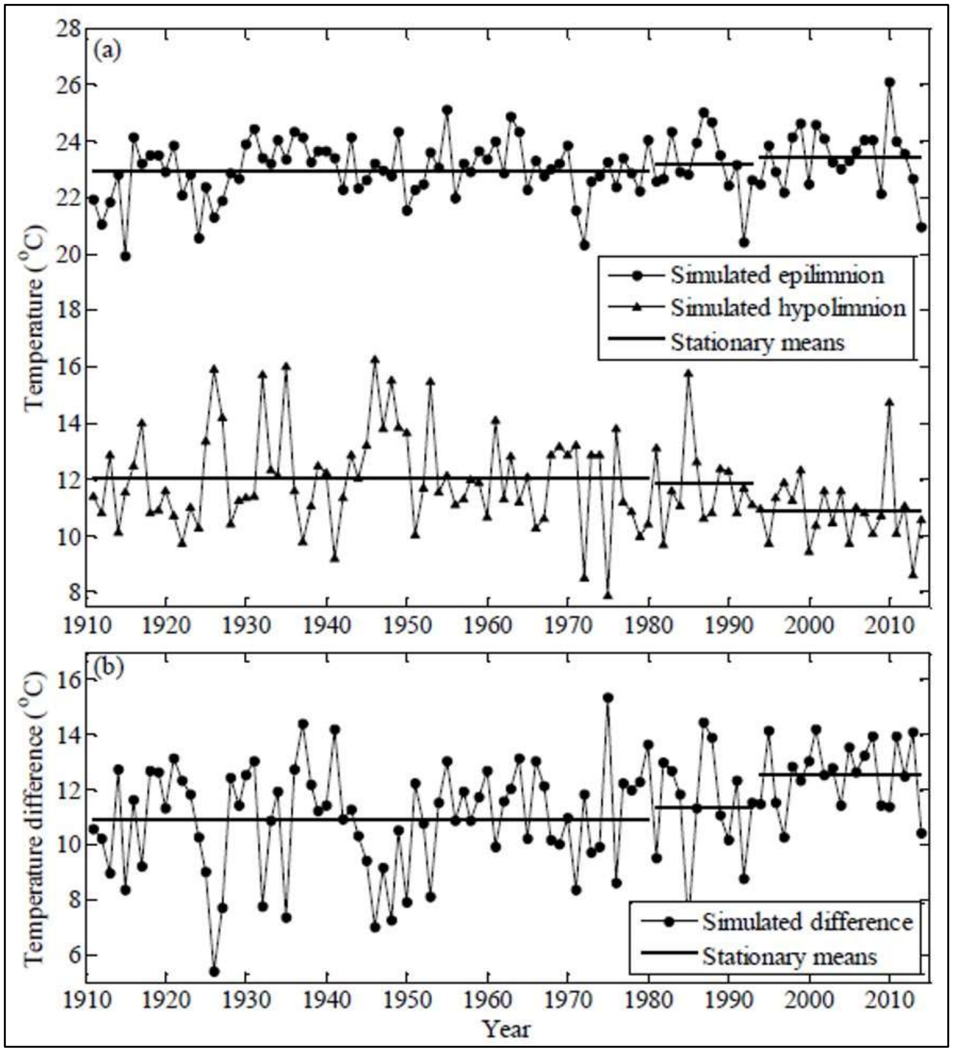

Figure 5. Simulated midsummer (July 16 – August 15) water temperatures on Lake Mendota over time. Though epilimnion water temperatures did not change, a cooler hypolimnion (a) also led to greater temperature difference between the epilimnion and hypolimnion and stronger stratification (b). Source: [7]Magee et al. 2016

Season

Generally, epilimnetic waters warm quickly in spring and rapidly cool after September 1, with shallow lakes warming and cooling faster and reaching a slightly warmer maximum temperature in summer.[1] The maximum temperature occurs sometime between the end of June and third week of August in southern Wisconsin lakes and between the second week of July and third week of August in northern Wisconsin lakes (Figure 6).[1] The preceding month's air temperature is a good predictor of lake surface water temperature and is better than the preceding month's surface water temperature, indicating that surface waters respond relatively quickly to changing air temperatures.[1] This seasonal pattern is coherent across lakes.[1]

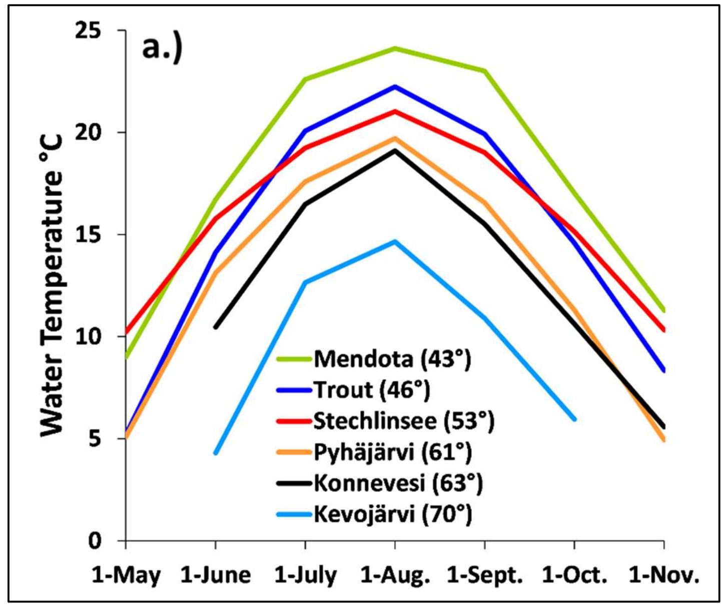

Figure 6. Seasonal patterns of median epilimnetic temperatures from 1980-2017. Lake Mendota is in southern Wisconsin and Trout Lake is in northern Wisconsin. Source: [1]Lathrop et al. 2019

Though the surface waters and epilimnetic waters of most lakes are warming over time, warming rates are not constant across seasons.[1,2,5,9] In general, the greatest surface/epilimnion warming rates occur in fall followed by spring.[1,2,5,8,9] Midsummer warming rates, when lakes reach their maximum temperature, are slowest, and midsummer trends are not always statistically significant.[1,2,5,7,8,9] For example, the surface waters of six NTL-LTER lakes in northern Wisconsin warmed slowest in August (mean 0.2°F per decade from 1981-2015) and fastest in September (mean 1.3°F per decade, Figure 7).[5] This pattern occurs nationally as well, with average warming rates across lakes of 0.6°F per decade in June, 0.6°F per decade in July, 0.4°F per decade in August, and 0.8°F per decade in September (1981-2018).[2] In general, the warm season begins slightly earlier in spring and extends much later into the fall; from 1981-2015, surface waters reached temperatures greater than 68°F six days earlier in spring and stayed above 68°F 18 days longer in fall.[5] This echoes air temperature patterns during the same time period; fall air temperatures warmed fastest, and winter and late spring air temperatures cooled.[5] Though maximum temperatures are not significantly increasing in most lakes, warm summers are occurring more frequently.[1] In addition, under-ice temperatures on Lake Mendota significantly increased at 0.09°F per decade (simulated from 1911-2014).[7] Unlike surface waters, bottom waters do not exhibit as much monthly variability in their decadal trends as they do between lakes, though warming rates still vary by month on some lakes.[5]

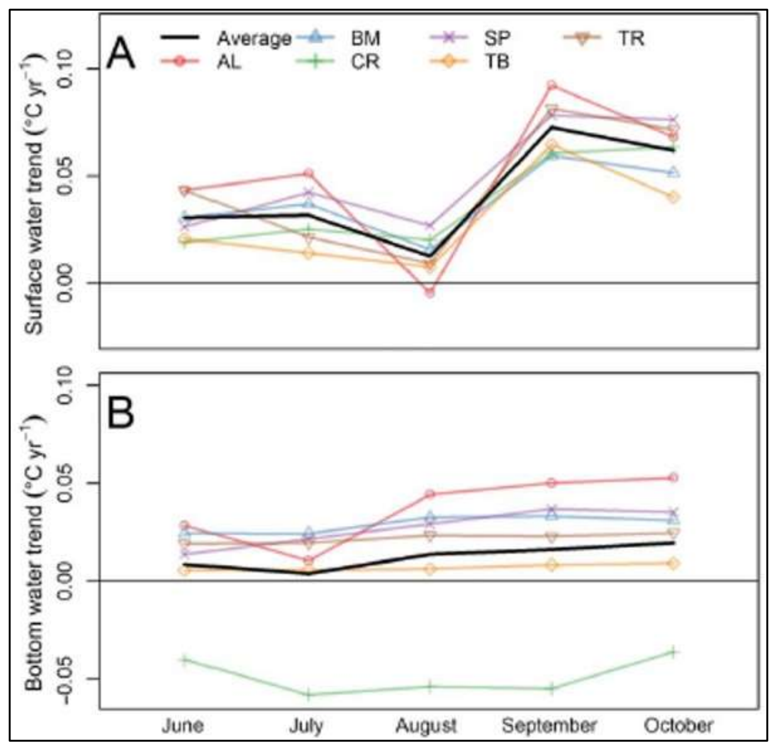

Figure 7. Monthly trends in average surface temperature (a) and bottom temperature (b) in northern Wisconsin lakes (AL=Allequash, BM=Big Muskellunge, CR=Crystal, SP=Sparkling, TR=Trout, TB=Trout Bog). Source: [5]Winslow et al. 2017

Lake Type

Lakes are warming worldwide, but warming trends between lakes are highly variable. Lake characteristics rather than proximity explain this variability. Globally, the surface waters of deep, ice-covered lakes are warming the fastest, and their surface waters can warm even faster than air temperature.[3] For example, average June – October surface water temperatures on six NTL-LTER lakes rose 0.8°F per decade while air temperatures rose 0.5°F per decade over the period from 1981-2015.[5] Earlier onset of stratification can lead to a shallower thermocline and smaller volume of water to heat. This combined with decreased cloud cover, increased summer air temperatures, and increased shortwave radiation in regions with ice-covered lakes can lead to surface waters warming faster than air.[3] However, summer thermal metrics indicate that July-August epilimnetic waters are warming slightly slower than June-August air temperatures, at 0.75 degrees for each degree of air temperature change from 1980-2017,[1] which is similar to the 0.86 slope observed between June-Sept lake surface water and air temperature nationally.[2] In general, the surface waters of ice-covered lakes warm at a rate similar to air temperature and this rate can be slightly faster or slower than air temperature depending on the lake characteristics, trend in wind speed, time period, and thermal metrics evaluated.

Given that all Wisconsin lakes are ice-covered in winter, the next most important characteristics are lake size, lake depth, and water clarity (Figure 1). In Wisconsin, large lakes (>124 acres) are warming faster than small lakes across all depths, at a rate of 0.9°F compared to 0.2°F per decade from 1990-2012.[4] Small lakes tend to have more wind sheltering, which prevents heat transfer to deeper waters.[4,6] They also tend to have higher dissolved organic carbon, which stains the water brown and prevents solar radiation from penetrating and warming deep water.[4] In fact, bottom waters of a small Canadian lake are actually cooling despite warming air temperatures because a tall canopy surrounding the lake limits wind mixing and water clarity is low.[12] Although greater wind mixing on large lakes can transfer heat to deeper waters, it can also moderate the warming of surface waters by mixing cold water toward the surface. For example, Lake Mendota is larger than Fish Lake, both of which stratify, and shallow waters warmed more slowly on Lake Mendota.[8] Mixing of shallow and deep waters, stratification strength and duration, and deep-water temperatures are all more variable in large lakes than small lakes, and this is especially true if wind speeds vary also.[8] In addition, the onset date of stratification and the deep-water temperature are less correlated with ice-off date in large lakes.[8]

Lake depth is also an important lake characteristic. Shallow lakes tend to track air temperature and short-term weather changes more closely as they have lower heat capacity and mix from the surface to the bottom.[3,8] In shallow lakes, wind can be more important for thermal structure and stratification stability than air temperature, whereas air temperature becomes more important in deep lakes.[6,8]

Finally, lake depth and water clarity interact, as clarity determines how much of the water column may be warmed through solar radiation. On shallow lakes that mix frequently, water clarity is of little importance for determining stratification strength and differences in warming rates between surface and bottom waters (though clear lakes will generally warm more).[13] Bottom water warming rates are relatively immune to water clarity differences in deep lakes because solar radiation does not penetrate to the bottom.[13] Bottom water warming rates are most sensitive to water clarity changes in lakes of moderate depth (10-59 feet), wherein increasing clarity can double bottom water warming rates.[13] Conversely, decreasing clarity can cool bottom waters and warm surface waters more dramatically than air temperature alone.[13] On lakes greater than 21 feet deep, water clarity decreases can be enough to offset climate warming across all lake depths and can actually result in cooling.[13]

Future Lake Temperatures

Although warming rates observed over any particular historical time period cannot be used to forecast future warming, previous observations indicate that future lake surface water temperatures should generally track future air temperatures. WICCI's low-end emissions scenario projects summer air temperatures to warm 1.5°-7.5°F by 2041-2060.

Researchers projected future lake water temperatures, from the surface to the bottom, on 10,774 Midwestern lakes, and these projections are available online: https://www.sciencebase.gov/catalog/item/57d30fd1e4b0571647d113e7. They used downscaled Global Climate Models (GCM) paired with the General Lake Model to project daily temperature profiles for two future time periods: 2040-2064 and 2065-2089.[14] The General Lake Model is a vertical, one-dimensional model that uses a combination of local meteorology and lake properties to predict lake temperature profiles. The United States Geological Survey just released updated hindcast model projections,[15] and summaries of projected lake temperatures are forthcoming.

Existing studies show that the expected amount of warming is ecologically significant. One study converted these projected lake water temperatures into degree days to explore how fish distributions might shift with climate change.[16] Degree days sum the degrees greater than a base temperature, 41°F in this case, across all days in the year. Degree days increase up to 17% by mid-century and up to 31% by late-century depending on the lake and GCM.[16] This is a large enough change in thermal habitat to greatly impact fisheries. For example, this amount of warming could result in walleye recruitment losses from 33-75% of lakes that previously supported naturally reproducing walleye populations.[16] Another study found that fewer lakes would provide suitable habitat for invasive spiny water fleas given future projected lake water temperatures.[17]

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Lake Ice Trends

Ice on inland lakes and rivers provide multiple cultural ecosystem services, including ceremonial services, artistic inspiration, education and research opportunities, outdoor recreation, and subsistence opportunities.[1] Outdoor recreational opportunities on ice-covered lakes and rivers are particularly important in Wisconsin and provide benefits like physical exercise, social connections, a sense of place, and source of tourism revenue during winter months. Ice fishing is a common pastime in Wisconsin, as are other opportunities like snowmobiling, ice skating, ice hockey, and cross-country skiing (Figure 8). Subsistence activities like ice fishing, using ice-covered lakes and rivers for hunting routes, and traversing ice-covered water bodies to access trapping sites are important for tribal communities.[1]

Figure 8. Ice boats on Lake Kegonsa.

In Wisconsin, records show that ice cover duration has decreased over the last century for both lake and river ice (Figure 9).[2–4] While other factors, like wind, precipitation, solar radiation and summer conditions[4] can play a role in ice formation and melting, air temperature seems to be the primary driver in determining whether a lake will be ice covered in any year.[5,6] Lake Mendota,[7] Fish Lake, and Lake Wingra, all in Dane County have had later ice-on (date that ice first forms across the whole surface of the lake) and earlier ice-off dates (when lake ice fully melts) over the last 100 years.[4] This has resulted in shorter overall ice cover durations on all three lakes.[4] Similarly, the same three lakes have seen decreases in the thickness of ice cover over the same time period.[4]

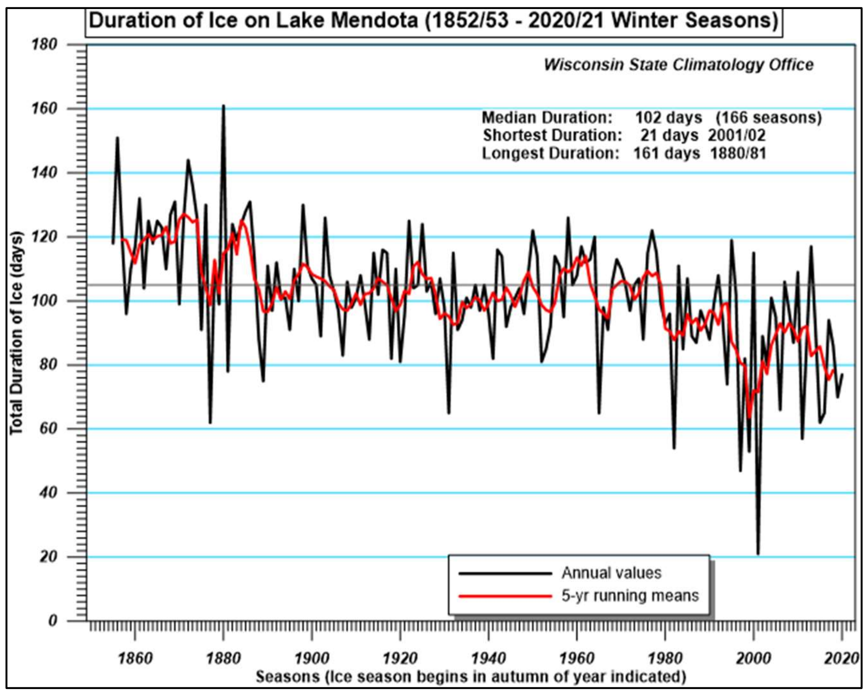

Figure 9. Decreasing trend in ice duration on Lake Mendota. Source: Wisconsin State Climatology Office, https://www.aos.wisc.edu/~sco/lakes/Mendota-ice.html

Lake Mendota now has about 31 fewer days of ice cover than it did in 1855, with the ten longest ice cover periods occurring before 1900 and most of the shortest ice cover periods happening since 1980.[7] The same is true for Lake Monona, which now has about 34 fewer days of ice cover than it did in the mid-1800s.[7]

Later ice-on, earlier breakup, and a shorter ice cover period have also been observed in lakes and rivers across the Northern Hemisphere,[6,8] with greater changes occurring in more southern portions of the region.[8] Rates of change in these three ice metrics are not uniform over time; more rapid change in recent years relates to more rapid increases in air temperature and more time overall with air temperatures above freezing.[6] Breakup date changed more rapidly than ice-on date, and ice-on date is related to lake-specific characteristics like lake volume.[6] Finally, an increase in mean temperature rather than increasing variance, explains the increased frequency of extreme warm years and decreased frequency of extreme cold years in most Northern Hemisphere lakes.[6]

Lake ice models under projected climate conditions indicate that these impacts to lake ice will continue and may increase through the next century. Lakes Mendota, Fish, and Wingra in Dane County are projected to have large decreases in ice cover duration and ice thickness under air temperature increases.[4] Projections for Crystal Lake in Vilas County show a 7-inch decrease in average ice thickness under the most likely climate scenario (SRES A1B climate scenario), with ice-on occurring 10 days later and ice-off almost 20 days earlier, resulting in a one-month shorter ice period.[9] Geneva Lake and Big Green Lake have been ice-free 4 and 1 years, respectively since 1800 with all 5 events occurring after 1995,[10] and both could have completely ice-free years a large percentage of the time by the end of the century or even completely ice-free conditions under the warmest climate projections.[10]

Lakes in southern areas will be more vulnerable to changes in ice cover than northern lakes.[10] With air temperature increases of 2°C (3.6°F), we expect many lakes in southern WI to have winters without ice

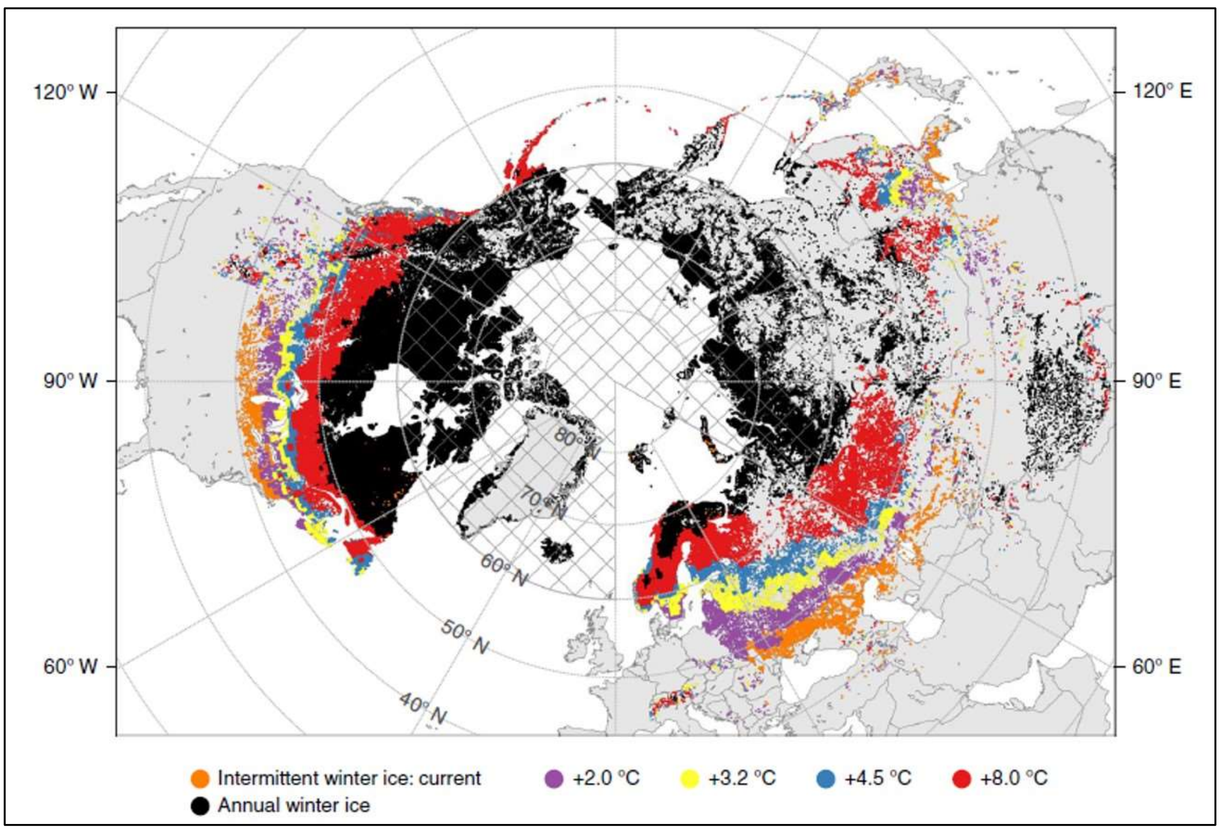

Figure 10. Distribution of Northern Hemisphere lakes that could experience intermittent winter ice cover under current conditions and potential future annual air temperatures. Source: [5]Sharma et al. 2019

cover, but lakes in northern Wisconsin may remain regularly ice-covered until air temperatures increase by 8.1°F (Figure 10).[5] For example, Lake Mendota, in southern Wisconsin, is predicted to have some years without ice cover as early as the year 2050, but Trout Lake, in northern Wisconsin, will likely remain ice covered each year through 2100.[5] Small and shallow lakes may be more resilient to temperature changes and have at least short periods of complete ice cover even with very large air temperature increases because these lakes respond more quickly to periods of cold air during the winter.[4]

We know less about the impact of climate change on river ice conditions, although evidence indicates that the extent of river ice will shift northward as winters warm.[3,11] Globally, average ice duration on rivers will decrease by over 16 days by the end of the century,[11] and may result in increasingly intermittent or completely ice-free conditions in rivers of all sizes.[3,11] Projections show that river ice in much of Wisconsin will see a decrease in duration.[11] For the Mississippi River, ice cover is expected only on the northern-most portions of the river by the year 2100 and ice cover duration along the Wisconsin border is projected to decrease.[3] Like lakes, much about the impact of loss of winter ice on rivers in unknown,[3] but it is likely that weaker ice could lead to increased drownings in areas where ice fishing or travel (snowmobile, etc.) on ice-covered rivers is common.

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Lake Warming Impacts

Temperature is a master factor, affecting physical processes like ice cover and evaporation, chemical processes like oxygen solubility, and biological processes like metabolism. Below, we summarize some of the many ecological consequences of warming lakes.

- **Loss of Winter Recreational Activities on Ice** - Reduced ice cover results in a shortened season or complete loss of winter recreational pursuits like ice fishing and ice skating. For example, in Minnesota, winter air temperature was positively related to the percentage of canceled ice-fishing tournaments, with higher cancelations occurring when average winter air temperatures were -4°C or warmer[1]. While this research has not been done in Wisconsin, we expect a similar relationship to hold true.
- **Increased Risk of Winter Drownings** - Consistently cold periods are required to form stable and thick ice, so warmer winters can also degrade ice conditions even when ice covers the lake. These degraded conditions increase risk of falling through the ice, with winter drownings increasing exponentially as winters warm.[2] Most drownings occur toward the end of winter when air temperatures are warmer, ice is thinner and weaker, and the sun is higher (which can cause faster ice melt).[2]
- **Cascading Effects of Ice Cover Loss on Lake Ecosystems** - Ice cover plays a key role in lake physics and biology for northern latitude lakes, so loss of ice cover will affect lake ecosystems both in winter and the traditionally ice-free period.[3] For example, loss of ice cover and/or ice thickness decreases albedo and water storage and increases productivity due to a longer growing season and greater light penetration.[4]
- **Widespread Dissolved Oxygen Declines** - Oxygen is less soluble in warmer water, and reduced solubility largely explains declining summer dissolved oxygen trends in the surface waters of temperate lakes (median DO decline of -0.11 mg/L/decade and median water temperature increase of 0.7°F/decade globally).[5] Dissolved oxygen (DO) concentrations in bottom waters of temperate, stratified lakes have declined at a similar rate (median: -0.12 mg/L/decade globally),

but the trend is not explained by reduced solubility.[5] Bottom water temperatures changed little over the same lakes and time frame (median: -0.01°C/decade globally).[5] Instead, a longer and more stable summer stratified period combined with increased respiration rates means that more oxygen is being consumed before it can be replenished during fall mixing.[5] Wisconsin lakes included in the global study represent the full range of dissolved oxygen trends, from -0.8 to 0.52 mg/L/decade in surface waters and from -1.37 to 0.72 mg/L/decade in bottom waters (Figure 11).[5] Decreasing surface DO trends occur in 9 of 20 lakes, and decreasing bottom DO trends occur in 9 of 14 lakes.[5] Low DO in bottom waters can increase internal nutrient loading by mobilizing phosphorus bound to lake sediments. It also reduces habitat for aquatic organisms.

- **Surface Dissolved Oxygen Increases in Developed/Agricultural Watersheds** - Some temperate lakes exhibit increasing epilimnetic DO trends over time despite warming surface water.[5] These lakes tend to be in agricultural and/or developed watersheds with low water clarity (Secchi depth < 6.6 feet) and very warm surface waters (> 75.2°F), likely fueling cyanobacteria blooms and thus, oxygen supersaturation.[5] Increasing surface DO concentrations occur in 10 of 20 Wisconsin lakes;[5] all nine lakes with slopes > 0.05 mg/L DO per decade occur in southern Wisconsin and have more than 23% developed and agricultural land uses in their watersheds (Figure 11). High concentrations of DO are not problematic, but they do pose a health concern if they are a symptom of more cyanobacterial blooms. More research on the mechanisms driving increasing DO trends on Wisconsin lakes is necessary.

Figure 11. Summer epilimnetic (top square) and hypolimnetic (bottom square) DO trends in Wisconsin lakes over a 16 to 35-year period (records begin as early as 1981 and end as late as 2017).[5] Left panel depicts lakes in southeastern Wisconsin monitored by the DNR, USGS, and UW NTL-LTER and the right panel depicts lakes in Vilas County monitored by the UW NTL-LTER.

- **Loss of Oxythermal Habitat for Cold-Water Fish**- The combination of warming surface waters and loss of oxygen from bottom waters results in an overall loss of oxythermal habitat for cold-water fish, which usually find water that is sufficiently cold and well-oxygenated in the metalimnion and upper layers of the hypolimnion.[6,7,8,9] Suitable oxythermal habitat for cisco (*Coregonus artedi*) is projected to decline by late century in lakes across Wisconsin, Michigan, and Minnesota; most lakes that provide the highest quality habitat will offer only adequate habitat, and half of those that offered adequate habitat will become marginal (Figure 12).[6] Although preventing further surface water warming is unlikely, protecting forested lands in the watershed and reducing nutrient loading can help mitigate oxythermal habitat loss by minimizing oxygen depletion from bottom waters.[7,8,9]

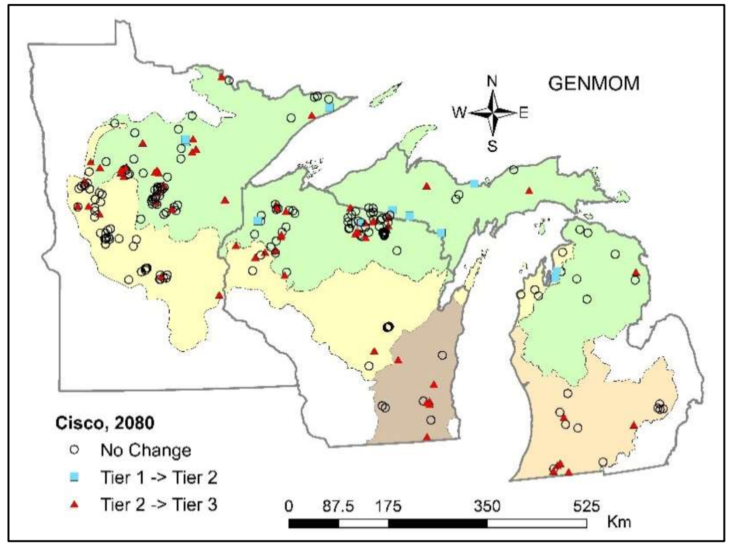

Figure 12. Change in cisco habitat from 1980-199 to 2070-2089 given projected land use change and air temperature increases (Tier 1=high quality, Tier 2=adequate, Tier 3=marginal). Source: [6]Herb et al. 2014

- **Changing Fisheries** - Water temperature affects fish in a wide variety of ways, including: habitat suitability, metabolism, growth rates, spawning, competition, and predation.[10] Warmer water temperatures are generally expected to shift fisheries toward warm-water species and away from cool- and cold-water species, though the effects on cool- and cold-water species are more variable and complex.[10,11] In Wisconsin, walleye recruitment success declines with increasing water temperature degree days and will likely decline given future warming projections (Figure 13).[12] Largemouth bass, a warm-water fish, exhibits the reverse relationship with water temperature degree days and will likely become abundant on more lakes (Figure 13).[12] Please visit WICCI's Fisheries Working Group for more details on fishery responses to climate change.

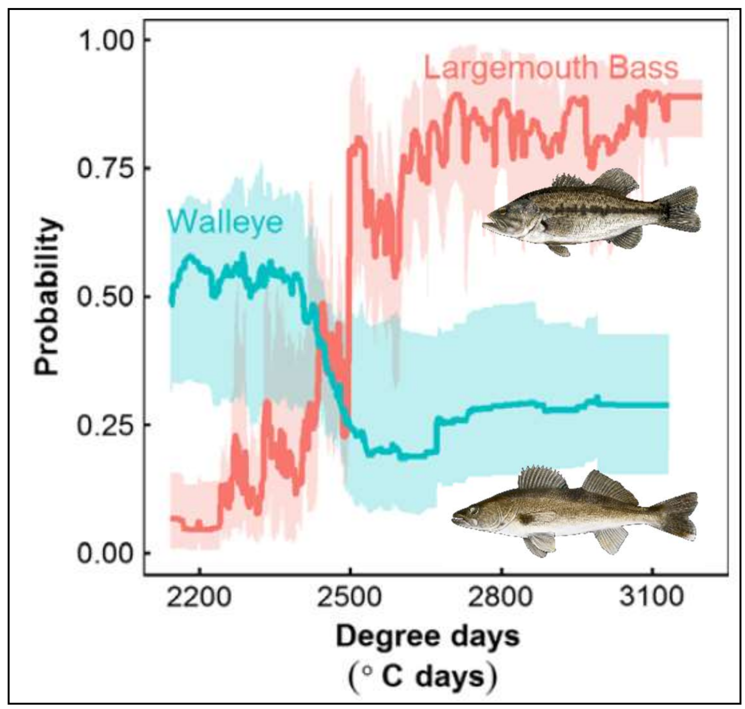

Figure 13. Temperature dependence of predicted walleye recruitment success and largemouth bass relative abundance (degree day base temperature 5°C, 1989-2014). Source: [12]Hansen et al. 2017. Fish illustrations: UW Zoology Museum

- **Changing Risk of Aquatic Invasive Species** – Water temperature is important for determining the distribution and abundance of many species and therefore, changing water temperatures will affect the suitability of Wisconsin lakes for aquatic invasive species. As with fish, species adapted to cooler climates may be of less risk to Wisconsin lakes in the future and species adapted to warmer temperatures will likely be of greater risk.[10] Spiny water fleas (*Bythotrephes cederstroemi*) prefer cooler temperatures, and models that use projected lake water temperatures predict that fewer lakes will be suitable for spiny water fleas in the future (Figure 14).[13] Conversely, a climate-matching model shows that, while not suitable now, Wisconsin's projected future climate will be suitable for new species like parrot feather watermilfoil (*Myriophyllum aquaticum*), inland silverside (*Menidia beryllina*), and scud (*Apocorophium lacustre*).[14,15] Though already present in Wisconsin, another model projects that Wisconsin will become more suitable for the Asian clam (*Corbicula fluminea*) given future climate projections.[16] The pathways of invasion will also change as human behavior adapts to climate change, with new shipping routes, longer boating seasons, and potentially assisted migration.[10] Given that a non-native species arrives and establishes in Wisconsin, climate change will also affect the likelihood that it becomes invasive.[10]

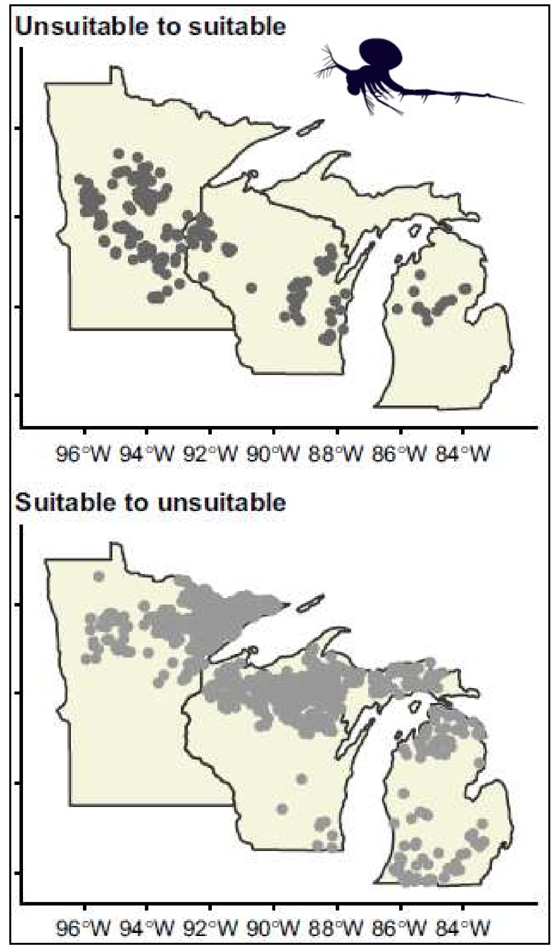

Figure 14. Late-century change in suitability for spiny water fleas in Wisconsin lakes based on projected water temperature and lake depth. Source: [10]Walsh et al. 2020

- **More Harmful Algal Blooms** - Warmer water temperatures, especially those >77°F, and a longer growing season favor cyanobacterial growth over diatoms and green algae.[17] Warmer water temperatures also result in stronger lake stratification, which enables buoyant cyanobacteria to form dense surface blooms and shade out other primary producers.[17] Thus, warming waters further exacerbate cyanobacterial blooms triggered by nutrient over enrichment. The impacts of harmful algal blooms are widespread. Cyanobacteria outcompete aquatic plants and other phytoplankton, and decomposition of senescing cyanobacteria can lead to oxygen depletion and fish kills.[17] Their toxin-producing capabilities draw the most attention with a variety of human and animal health risks including gastrointestinal, neurological, respiratory, and skin diseases.[17]

- **Seasonal Mismatch** - Many biological processes have strong seasonal patterns tied to water temperature (e.g., fish spawning). A mismatch in timing can occur if one organism responds to warming temperatures differently than an interdependent organism. For example, earlier lake ice-off dates resulted in warmer water temperatures earlier in spring and an earlier peak in phytoplankton abundance on Lake Washington.[18,19] However, *Daphnid* zooplankton abundance did not peak earlier in spring (hatching cues could relate to photoperiod instead of water temperature), and this mismatch in timing between *Daphnia* and their food resource led to a long-term decline in *Daphnia* abundance.[18,19] While this detailed study comes from Washington State, similar phenomena are likely occurring in Wisconsin as well and deserve further study. On Wisconsin's Lake Mendota and Lake Monona, an interplay of climatic and biological dynamics influence the timing of the spring clear-water phase (a period of low phytoplankton density following the spring peak).[20] Although there was not a linear trend in the timing of the spring clear-water phase in either lake from 1980 to 2017, warmer water temperatures and grazing by *Daphnia pulicaria* would make the clear-water phase occur earlier whereas grazing by *Bythotrephes* would make it occur later.[20]

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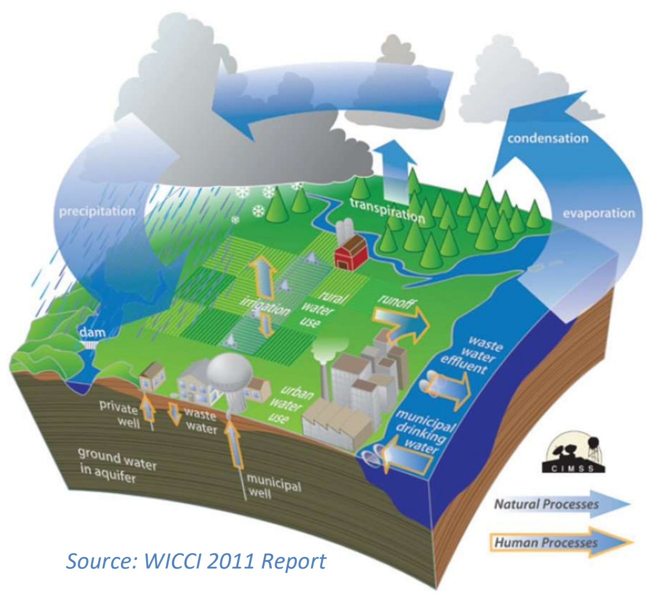
Precipitation and Water Levels

Wisconsin's water resources are diverse and strongly interconnected, including groundwater, wetlands, streams, rivers, and lakes. The hydrologic cycle describes the complex interactions that occur within and between each of these components. Most of the water entering the landscape arrives as precipitation that falls directly on surface waters, runs off the land surface and enters streams, rivers, wetlands and downstream lakes, or percolates through the soil, recharging groundwater that flows through the ground and reemerges into lakes, wetlands, streams, and springs. Water returns to the atmosphere via evaporation, evapotranspiration, and sublimation. The landscape, geology, soil type, amount and type of precipitation and extent of natural and manmade features all influence the rate of water movement as well as the chemical and physical composition of water throughout the system.[1,2,3,4] Understanding the interconnections and system components is critical when considering solutions to water-related challenges created or intensified by climate change.



Source: WICCI 2011 Report

"Climate change will affect how water moves through ecosystems in many ways, including more frequent heavy precipitation, a more variable snowpack, and changes in the timing of spring melt and runoff. These changes will have cascading effects on water quality and water availability."

[3]Tribal Climate Adaptation Menu

Naturally occurring cycles of high and low water levels driven by variable weather patterns affect all hydrologic systems throughout Wisconsin and are an important aspect of these ecosystems. For example, water level fluctuations are critical for maintaining diverse plant communities (Figure 15).[5,6] Changes in precipitation regimes related to climate change will affect the hydrologic cycle and may change the average and range of water levels observed in Wisconsin's groundwater, wetlands, lakes, and streams. In addition, extended periods of greater- or lower-than-average precipitation would result in more extreme high and low water levels. Because water levels affect many aspects of water resources, changes to their historic regime induced by climate change, especially more extreme highs and lows, will also alter and pose challenges for the natural and built environments.

WICCI's downscaled climate models predict above average precipitation throughout most of Wisconsin, particularly during winter, spring, and fall.[7] The additional precipitation is exhibited as individual events delivering large volumes of water over hours and as prolonged periods that may extend for months to years of wetter than normal conditions. In the sections below, we describe the phenomena and consequences of long-term water level increases, short-term water level increases, and long-term water level decreases. We also summarize the state of the science regarding groundwater and lake level fluctuations and the potential effects of climate change.

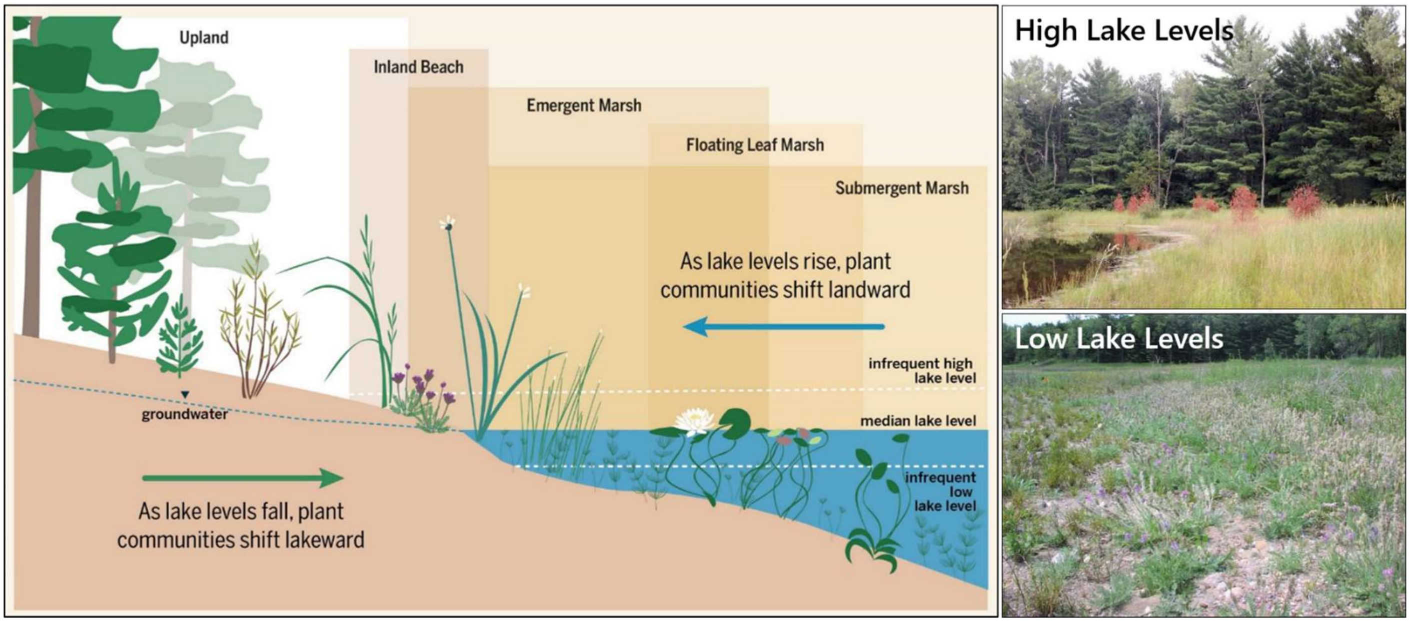


Figure 15. Fluctuating lake levels maintain a continuum of plant communities from the aquatic to terrestrial environment. High lake levels on Plainfield Lake prevent trees and shrubs from dominating riparian areas, allowing inland beach and emergent species to thrive during low water periods. Source: [6]Voter et al. 2021

Long-term, Gradual Water Level Increases

During prolonged periods of greater-than-average precipitation in regions of the state with permeable soils, precipitation seeps into the groundwater and flows across the landscape towards wetlands, streams, and lakes. As this cycle progresses, groundwater elevations increase with corresponding increases in the volume of groundwater discharging to surface water. The combination of increased precipitation, runoff, and groundwater discharge raise surface water levels. Elevated groundwater can inundate septic drain fields, creating substandard treatment of wastewater. High groundwater levels may also affect the water quality in private drinking water wells by overtopping the well casing or via preferred flow paths adjacent to the well. In these circumstances, microbial contamination is of greatest concern.

The additional precipitation occurring during these conditions increases leaching of natural and manmade compounds from the land's surface into the groundwater, altering the chemistry of the groundwater discharging to surface water. Depending on the characteristics of the landscape, these changes may have positive or negative effects on groundwater and surface water quality.[1] Land uses and more importantly, land management practices drive these differences; lands with higher contaminant loads have a greater potential to contaminate groundwater while landscapes with minimal contaminants provide high quality groundwater and may benefit receiving water bodies through the dilution of contaminants.

Settings with karst geology and fractured bedrock provide direct conduits to surface water with minimal filtration. In portions of the state with less porous soils, additional runoff directly to wetlands, lakes, and streams will occur. In these settings, greater water volume, warmer water temperatures, and higher concentrations of dissolved compounds and particulates will likely be discharged to surface water due to less subsurface flow and shorter travel times.

Lake shorelines, stream riparian areas, and floodplains become inundated at high water levels. Erosion can be problematic and is worse if vegetation has already been removed (Figure 16). Flooding and erosion during high-water phases are further exacerbated by extreme precipitation events. On many lakes, water clarity decreases when lake water levels are high.[8,9,10,11] This is especially true on oligotrophic lakes, which experience more algal growth due to increased nutrient and sediment loading. [8,9,10] Conversely, water clarity increases when water levels are high on eutrophic lakes or impoundments with short water residence times, likely due to dilution and flushing.[8] High lake levels are also correlated with more methyl-mercury in walleye, which likely stems from biogeochemical processes in nearshore areas that mobilize legacy mercury when dried lake sediments are reflooded.[12] This is in line with post-drought decreases in pH observed in Canadian lakes due to the flushing of sulfide-oxidation products.[13] At the same time, high water level phases can provide an ecological benefit, preventing encroachment by trees, shrubs, and other terrestrial species such that inland beach and emergent plants have space to establish once water levels recede (Figure 15).[5,6]

Figure 16. Erosion on Silver Lake, Barron County. Source: Robertson et al. 2009. USGS Report 2009-5077.

High water levels have recreational and economic impacts, often imposing no-wake restrictions on lakes and causing property damage. Many lake groups are seeking options for reducing water levels during prolonged flooded periods. Devils Lake in Sauk County provides an interesting case study.[14] Over the past 100 years, lake elevations infrequently exceeded the OHWM and even surpassed containment. [14] Changes to the former pattern began occurring in the late 1970s with even greater highs beginning around 2000.[14] In recent years, the higher lake elevations damaged structures. Devils Lake State Park installed a siphon that can be turned on as needed to reduce lake levels and prevent flooding of the park structure and other facilities (Figure 17). The siphon takes advantage of an existing elevational drop and does not require power, making it relatively affordable. However, reducing lake levels was unsuccessful on another nearby lake that rose more than 17 feet since the 1970's. Many homes around Fish Lake in Dane County are unlivable due to flooding (Figure 18). Flooding also allowed carp invasion, reducing water clarity.[14] The surrounding landscape is relatively flat, and the nearest stream is far away. Attempts were made to reduce lake levels with an electric pump, but it could not run at times because outfall water quality permit limits were exceeded, it was costly, and it ultimately was unable to pump enough water to solve the problem.[14] In cases like these, land purchases and conversion to natural areas may be the only remaining solution.

Figure 17. Installation of the siphon pipe in Devils Lake in August 2002. Source: [14]Lathrop 2021

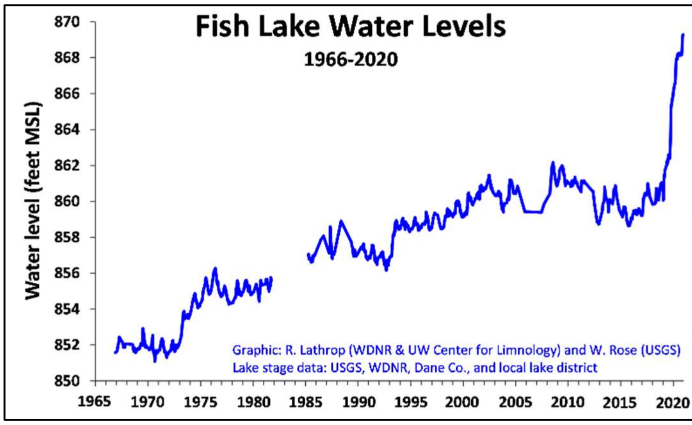


Figure 18. Rising water levels over time on Fish Lake (left) and flooded homes along Fish Lake's former western shoreline in June 2020 (right). Source: [14]Lathrop 202

Short-term, Rapid Water Level Increases

Wisconsin is experiencing extreme precipitation events more frequently, and these events will likely continue to occur more frequently in the future.[7] These events produce large amounts of rain or snow over relatively short periods. For much of Wisconsin, during large events, infiltration is restricted primarily due to soil pore space, compacted soil, and impervious surfaces. As a result, a large percentage of the precipitation remains on the landscape, flowing to areas of lower elevation. Wetlands, natural depressions on the landscape, and engineered swales and infiltration basins help reduce the extent of flooding and slow the delivery of floodwater to storm sewers and surface water bodies, reducing the erosive capacity of fast flowing water and contaminant delivery. Conversely, alterations to the natural landscape depressions and destruction of wetlands can lead to an increased water volume delivered to lakes and streams and enhanced erosive energy during these events. Regions with greater topographic relief are prone to increased erosion and altered landscapes exemplified by modified channel morphology and damage to roads, bridges, structures, and poorly vegetated lands, ultimately leading to risks for people and wildlife.

Flooding from rapid snowmelt events triggered by warmer air temperatures is similar to flooding from rain events. Additionally, ice jams may occur in flowing water and exacerbate flooding, particularly upstream of impediments such as bridges, culverts, and dams.

The amount and type of contaminants transported by flood waters are directly associated with the types of land use and the management practices employed within a watershed. In agricultural watersheds, nutrient and sediment runoff are common, contributing to long-term eutrophication problems and fueling harmful algal blooms (Figure 19).[15,16] Seventy-four percent of the annual phosphorus load to Lake Mendota comes from days with heavy rains or snowmelt, which only occur 29 days per year on average.[15] In urban areas like Milwaukee, sewage contamination of rivers and coastal areas following rainfall is widespread and is 10-fold higher following combined sewer overflows associated with extreme precipitation events.[17] The resulting contamination of GI pathogens is high enough to present a human health risk when swimming in rivers or on public beaches.[17] Trace organic contaminants like pesticides, flame retardants, polycyclic aromatic hydrocarbons, corrosion inhibitors, pharmaceuticals, petroleum products, and personal care products are also of concern both for aquatic organisms and human health.[18] At two urban storm sewers in Madison, a maximum of 30 and 34 organic contaminants were detected during storm events, and 30 trace organic contaminants were found ≥50% of the time from at least one site.[18] Even in forested watersheds, sedimentation due to erosion blankets cobble important for fish spawning and generally reduces water quality and habitat for aquatic organisms.[19]

Additional impacts within water bodies include reduced dissolved oxygen and water clarity, increased temperature and concentrations of toxic substances, and negative impacts on aquatic biota. Long-term changes in channel morphology and littoral habitat may also occur. Groundwater and drinking water quality in private wells may also be impacted through the introduction of microbes and other contaminants as floodwaters overtop poorly sealed wells or take preferential flow paths to groundwater, evading filtration through the soil column.

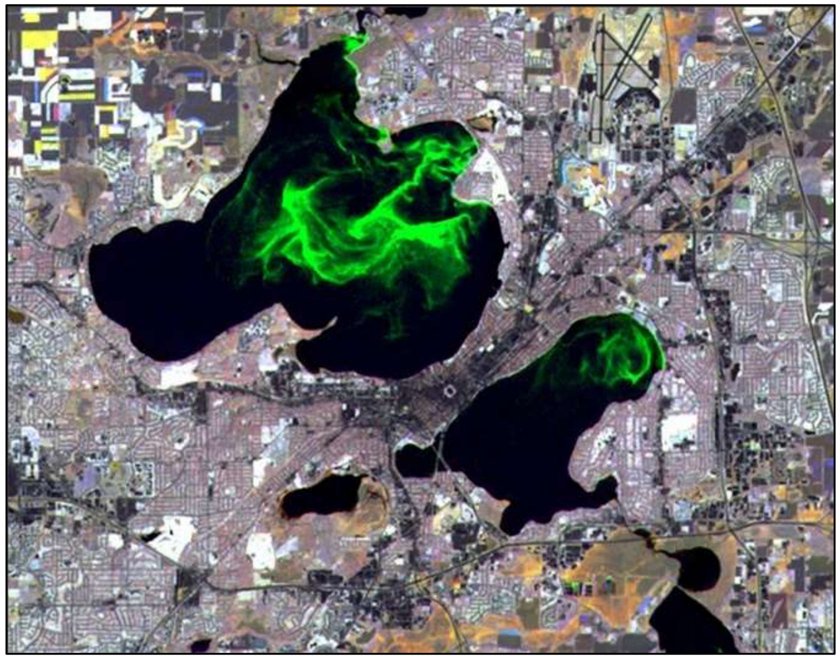


Figure 19. Landsat-7 composite images depicting an algal bloom on Lake Mendota and Lake Monona in October 1999. Note the extensive urban and agricultural environment surrounding the lakes. Source: lakesat.org/galleryindex.php

Long-term, Gradual Water Level Declines

During the early stages of a drought, less precipitation falls onto the landscape but many of the components of the hydrologic system continue to function. A similar volume of groundwater continues to discharge to surface water, providing cool pockets of water in the summer and maintaining areas of open ice in the winter. Wetlands continue to provide habitat for aquatic organisms and exchange water with adjacent surface water bodies.

As the duration of a drought increases and water levels are reduced throughout the system, lesser volume of groundwater discharges to surface water bodies, and wetlands may disconnect from adjacent water bodies, restricting their use by aquatic organisms. Reductions in groundwater inputs can contribute to warmer surface water temperatures, particularly in the zones nearest upwelling sites. The disappearance of cooler micro-climates in a waterbody may negatively impact temperature sensitive aquatic biota. In lakes with short residence times, the geochemistry can be altered due to reductions in groundwater volume and associated dissolved minerals, which in turn can alter the composition of diatoms.[2,20]

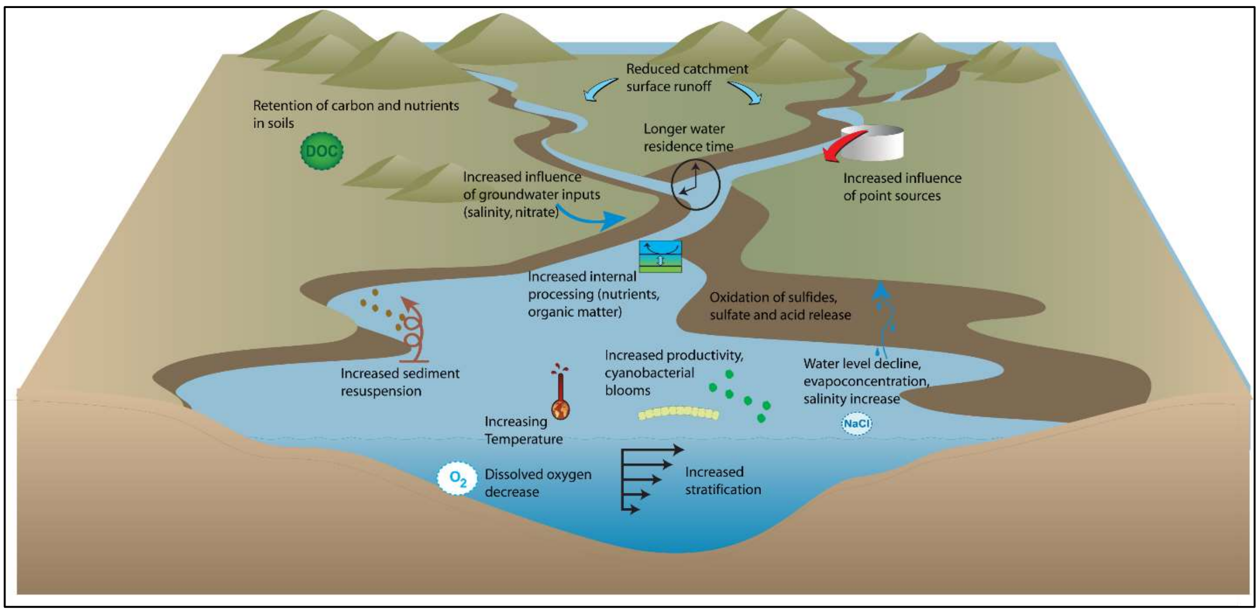


Figure 20. Processes that may influence water quality during drought. Source: [13]Mosley 2015

A variety of ecosystem responses to drought occur, and these responses differ between water bodies (Figure 20). Increased temperature is common on rivers but more variable in lakes and reservoirs.[13] Increased salinity and nutrient concentrations result from decreased water volume and evapoconcentration, also enhancing algal blooms and decreasing water clarity on some water bodies.[13,30] In northwest Wisconsin, water clarity decreases on shallow, eutrophic systems, but increases in deep, oligotrophic lakes due to reduced runoff of nutrients and sediment (Figure 21).[8,9,10] A similar dichotomy occurs in rivers, with improved water quality during drought due to

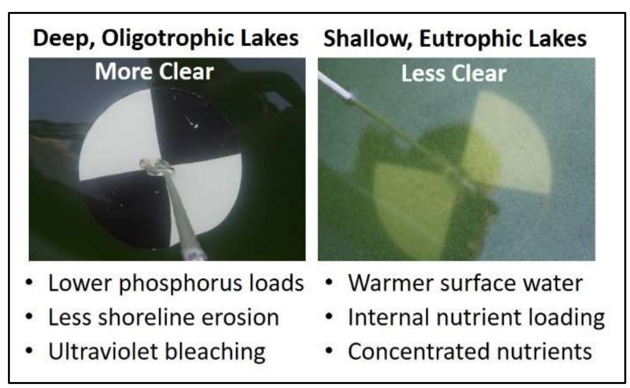


Figure 21. Processes likely responsible for the dichotomy between oligotrophic and eutrophic lakes in their response to drought. Source: [8]Lisi and Hein 2019

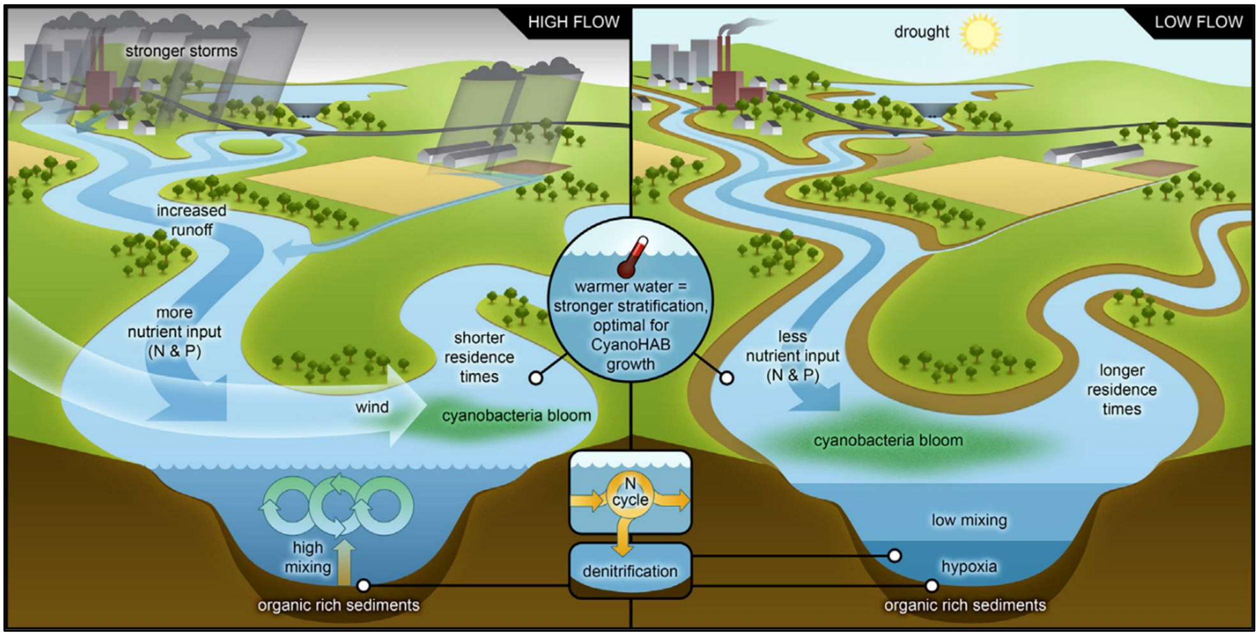


Figure 22. Processes that can exacerbate cyanobacterial harmful algal blooms (HABs) in shallow water ecosystems under high and low flows. At high flow, greater nutrient loading and mixing positively affect HABs, but greater flushing helps offset the increase. Although runoff is less problematic during drought, more stable vertical stratification allows buoyant cyanobacteria to dominate and increases deep-water hypoxia and internal nutrient loading. Source: [30]Hans Paerl, UNC-Chapel Hill, Institute of Marine Sciences

reduced loading, but reduced water quality in polluted watersheds due to less dilution and more stable stratification, favoring cyanobacteria (Figure 22).[13,30] Salinity changes in lakes depend in part on landscape position; lakes lower in the landscape increased in calcium mass during drought due to a greater proportion of groundwater input.[21] During periods of ice cover, the reduced lake water volume paired with reduced groundwater inflow can result in more anoxia, particularly towards the end of the ice-on period. Additionally, the lack of groundwater inflow can limit open water, which has direct atmospheric contact and provides areas of oxygen-rich water for aquatic organisms when dissolved oxygen is low.

Low water levels also strand coarse woody habitat above water (Figure 23), reducing refugia for prey fish like yellow perch (*Perca flavescens*).[22] On Little Rock Lake, largemouth bass (*Micropterus salmoides*) rapidly decimated the perch population and then lacked prey, slowing growth rates dramatically.[22] At the same time, low water levels are important for emergent plants like bulrush (*Schoenoplectus spp.*) to establish and inland beach plants like a federally threatened plant to germinate and reproduce (Figure 15).

Figure 23. Stranded coarse woody habitat along Little Rock Lake's shoreline on October 13, 2007. Loss of habitat made yellow perch vulnerable to largemouth bass predation, crashing the perch population and reducing largemouth bass growth rates. Source: [22]Gaeta et al. 2014

During periods of lower groundwater elevations, shallow drinking water wells may become partially or completely dry and contaminated with viruses, protozoa, bacteria, nitrates, and arsenic. Freeze-thaw conditions are predicted to increase in Wisconsin due to warmer winter temperatures, which may result in reduced groundwater infiltration and increased runoff.[23]

Lake and Groundwater Level Fluctuations

Lake water levels fluctuate over decadal time scales.[10,24,25] For example, records dating back to 1936 show that 10 to 15-year cycles of approximately 1 m occur on Anvil Lake.[10,24] However, in the late 1980s, lake elevations quickly dropped and by 2008, were reduced by 2 meters (Figure 24).[24] Around 2014, elevations began increasing and have rebounded to previously recorded high water levels.[24] Modeling suggests that precipitation is the primary driver, but not the only driver, of water level fluctuations, and net changes in groundwater volumes either exacerbate or modify the extent of lake elevation changes.[24]

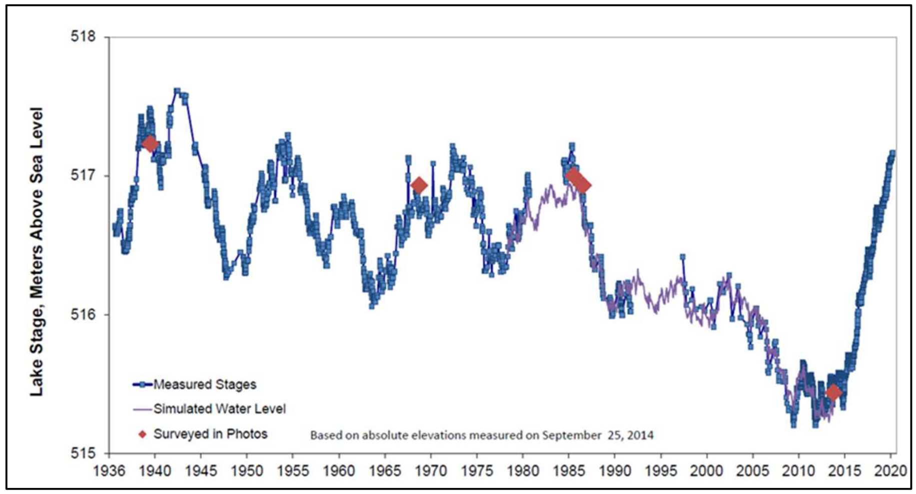


Figure 24. Water levels on Anvil Lake over time. Source: [24]Robertson 2021

These long-term fluctuations are coherent across inland lakes, groundwater wells, and even the Great Lakes (Figure 25).[25] In Wisconsin's glacial outwash regions, most seepage lakes and rivers correspond with water table elevations, so coherence in water level fluctuations between groundwater and surface water can be expected. The broad geographical coherence across lakes likely reflects large-scale atmospheric circulation patterns,[25] particularly precipitation.[26]

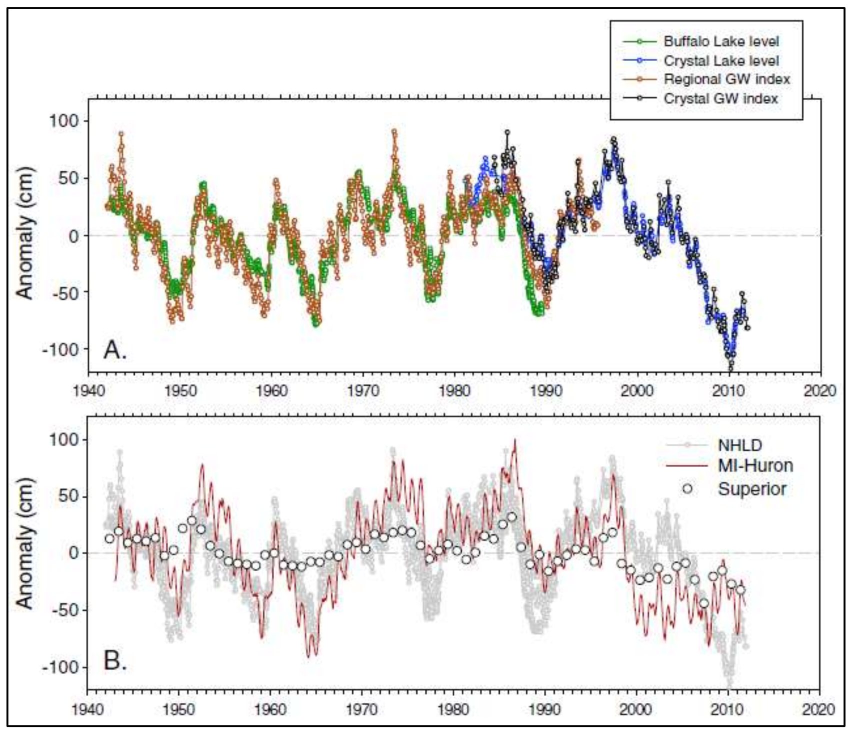


Figure 25. Water levels on two inland lakes and two sets of groundwater wells in the Northern Highland Lake District (NHLD) and upper Wisconsin River watershed (A) and in Lake Superior and Lake Michigan-Huron (B). Timeline is scaled to match that in Figure 24 for comparison with Anvil Lake. Source: [25]Watras et al. 2014

Given the relatively large water volume and multi-year water residence times of lakes and aquifers, these decadal water level cycles do not reflect single precipitation events, but instead, the accumulation of repeated years of higher or lower than normal amounts of precipitation. In fact, the cumulative deviation in precipitation over a 5-year time period is moderately to strongly correlated with groundwater level fluctuations in 54% of wells across Wisconsin.[26] There are no regional or other differences between wells except that deeper wells in sandstone aquifers are not as strongly correlated with precipitation.[26] Though the best fit in the period over which precipitation is accumulated may differ from 5 years for an individual well, time periods longer than 5 years generally smooth the cumulative deviation in precipitation too much to match observed groundwater level fluctuations.[26] Conversely, shorter time periods (e.g., 12 months) do not smooth it nearly enough.[26]

The cumulative deviation in precipitation is also a good predictor for lake level fluctuations.[27] Because the spatial patterns of accumulated precipitation are dynamic over time, regional coherence across Wisconsin lakes and groundwater wells largely depends on the precipitation patterns over the specific time period of interest. Over the time period 2001-2015, there is strong coherence among lakes in the north versus south.[27] While northern Wisconsin experienced a drought (*c.* 2008) and low water levels (Figures 23-26, 28), southern Wisconsin experienced record high water levels (Figure 26).[27] Lake Delton even broke through its banks.

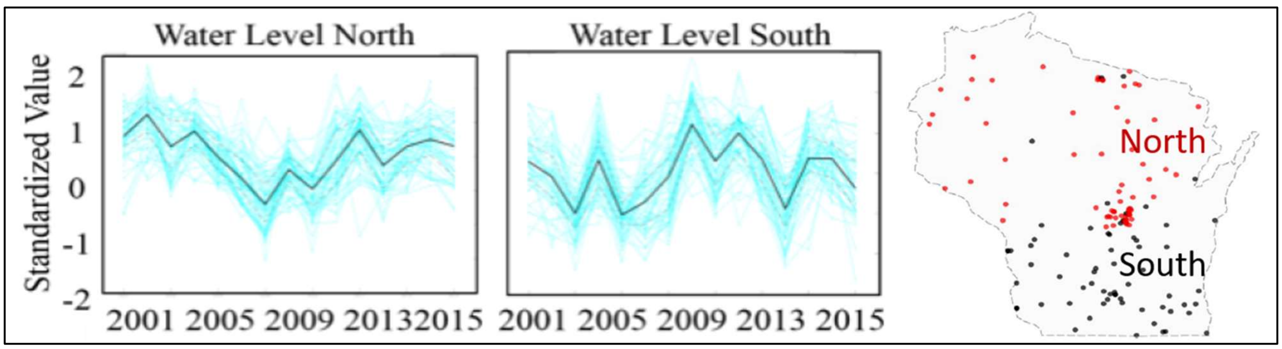
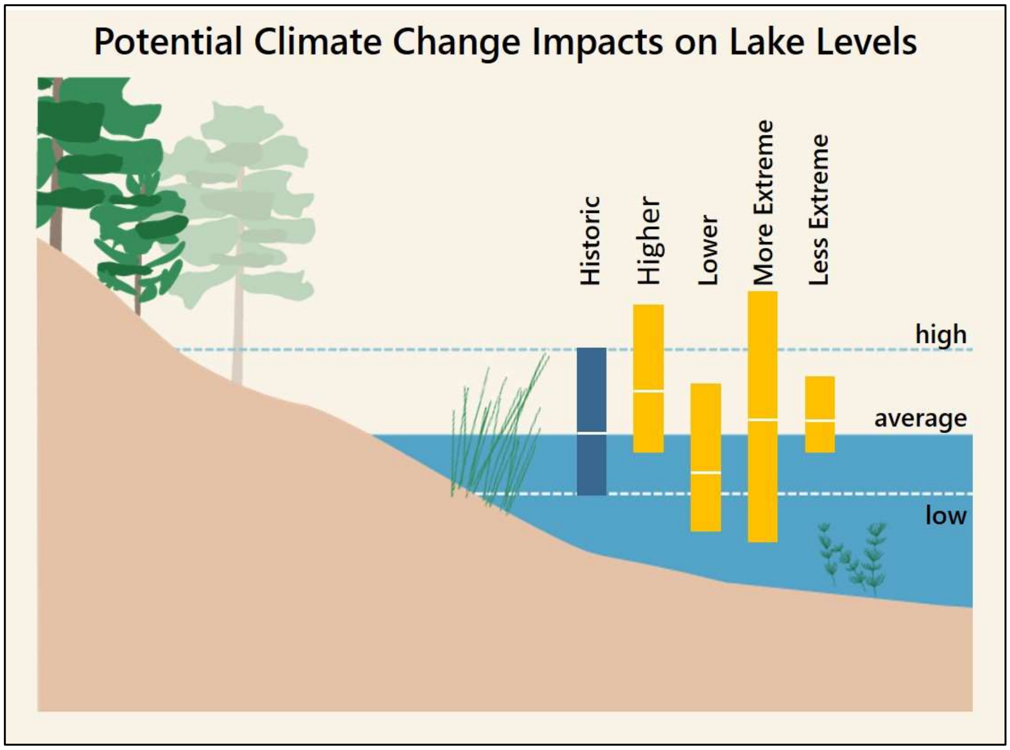


Figure 26. From 2001 to 2015, lakes and groundwater wells in northern Wisconsin exhibit coherence in water level fluctuations as do lakes and groundwater wells in southern Wisconsin, but the two regions display opposite patterns from one another. Source: [27]Lottig et al. 2019

At time scales of several years, changes in lake volume are still moderately correlated with one another over time but are quite variable with some lake pairs highly correlated and others not.[28] In Wisconsin, the distance between lakes did not explain the degree of correlation between lakes.[28] The shorter time span reflects annual and sub seasonal patterns in lake storage, and variation at this time scale is likely driven more by localized weather events. Further research regarding the drivers and spatial coherence of lake level fluctuations at different temporal and spatial scales is necessary.

Given the strong effect of precipitation on lake and groundwater levels, the projected increase in future precipitation will likely increase water levels (Figure 27). Water levels would still undergo highs and lows, but the overall stage at which they vary may become higher. However, evaporation is an important part of the water cycle as well and may increase with warmer water and air temperatures, resulting in water level fluctuations at a lower stage. The magnitude of fluctuations could also change: 1) more extreme decadal water level fluctuations will occur if the difference between accumulated precipitation and evaporation over multi-year periods becomes greater, 2) water level fluctuations will be less variable if this difference becomes smaller. Thus, projecting future lake and water levels is difficult and uncertain. We can say with certainty that lake and groundwater levels vary and are

Figure 27. Conceptual diagram displaying how lake level fluctuations might change under a future climate. If the net change in the difference between precipitation and evaporation is positive, the full range of lake levels would rise, but they would decline if the net change is negative. More extreme highs and lows would occur if the difference between accumulated precipitation and evaporation over multi-year periods becomes greater, whereas dampened high and lows would occur if this difference becomes smaller. Figure modified from [6]Voter et al. 2021.



inextricably linked to climate, especially the accumulation of wet or dry periods over time. A changing climate will likely alter the balance between precipitation and evaporation, and thus, water levels.

The water level fluctuations of some lakes are more sensitive to climatic patterns, and thus climate change, than others. Seepage lakes high in the landscape fluctuate more dramatically than drainage lakes lower in the landscape, which are modulated by streamflow (Figure 28).[29] Low conductivity lakes with little surrounding wetlands and highly permeable soils are also more sensitive to climate change.[29] One of the best climate-ready solutions related to lake levels is to preserve natural habitat along lake shorelines, giving them room to change and minimizing damage to infrastructure. These efforts can be focused on the most sensitive lakes using the characteristics described above.

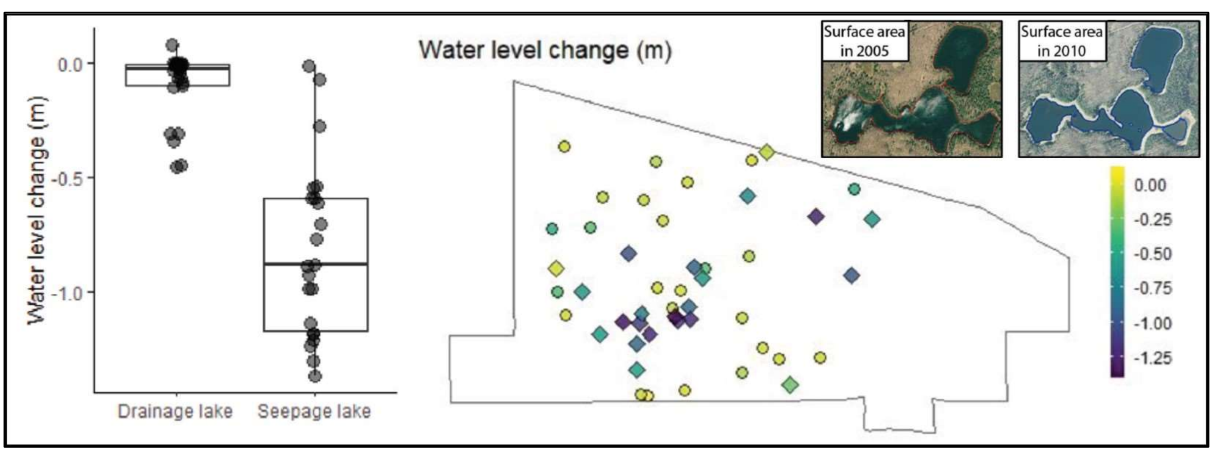


Figure 28. Change in lake level from the 2005 high to the 2010 drought (see Figure 21) in drainage lakes (circles) and seepage lakes (diamonds) in Vilas County. Box plot show the median, first and third quartiles. Source: [29]Perales et al. 2020

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Adaptation Strategies

Many of the adaptation strategies we suggest below are good practices to improve and protect water resources with or without climate change, but they are even more important with a changing climate. For example, many activities aimed at reducing nutrient loading and improving the water quality of the Yahara watershed are underway. They help offset the impacts of extreme precipitation events, which deliver even more nutrients to the lakes and streams.[1] Instead, our typical water management strategies can be viewed through a climate lens. The additional stressor of climate change magnifies the need for conservation and restoration actions. We organize adaptation strategies under a general category and three themes of climate impacts to water resources: warming waters, high and low water levels, and flooding and runoff associated with more extreme precipitation. Many of the strategies listed stem from an inland lakes climate adaptation workshop the WICCI Water Resources working group hosted in 2018,[2] additional Water Resources working group meetings and collaborations, and the 2011 WICCI report.[3] We also rely on a couple of management frameworks for climate adaptation.[4,5] Under the RAD (Resist-Accept-Direct) framework, resistance approaches prevent or reduce the likelihood of changes from occurring and/or restore conditions when change occurs.[4] Accept allows ecosystems to change into new conditions, and direct helps transform ecosystems such that they better fit the new climate.[2] Another framework categorizes adaptation as resistance, resilience, and response.[5] Here, resilience is distinct from accept in that the adaptation strategies allow change to occur in response to disturbance, but they help the ecosystem return to its desired state.[5] Response is similar to direct, facilitating change to a new state.[5]

General

- Disseminate findings from climate assessment studies to water resource managers, municipalities, academics and conservation and environmental organizations.
- Develop water resource climate adaptation menus for water resource managers, local government, and other organizations
- Establish a long-term monitoring network of groundwater, streams, inland lakes, wetlands, and nearshore sites on the Great Lakes to track response to climate change
- Establish the Wisconsin Surface Water Applied Research Program to incentivize and enable the state's research community to solve surface water challenges related to climate change

Warming Waters

Little can be done to prevent lakes from warming, so most adaptation strategies here focus on non-resistance techniques. For example, climate change threatens cold-water fish by warming surface waters and exacerbating hypoxia in deep waters that are still cold enough. Although we do not have resistance strategies to stop surface waters from warming, we do have a wide variety of techniques to reduce nutrient loading to lakes, thereby reducing the risk of hypoxia in deep waters and increasing the lake's resilience. On the aquatic invasive species front, we can prepare for changing patterns of risk based on warming water temperatures and adapt to focus our prevention efforts on species and pathways likely to be of highest risk as climate changes. Below, we list strategies to employ in response to warming waters in relation to water quality, fisheries, and aquatic invasive species.

Water Quality

- Improve shoreland and watershed management to minimize runoff (see Flooding and Runoff)
- Constructed water treatment wetlands and detention ponds
- Artificial aeration to prevent anoxia and internal nutrient loading and enhance oxygen for fish
- Maintain beach usage through enclosed swimming and treatment systems
- Develop statewide standards for algal toxins and take action to protect public health
- Create a harmful algal blooms surveillance program to collect data, issue warnings, and identify how climate change may increase human and animal exposure to harmful algal blooms
- Develop tools for predicting risk of harmful algal blooms and toxins
- Employ a variety of techniques in the watershed (e.g., nutrient reduction, wetland development, dam regulation) and within the waterbody (e.g., enhance mixing, food web manipulation, sediment dredging) to reduce harmful algal blooms (Figure 29).[6]

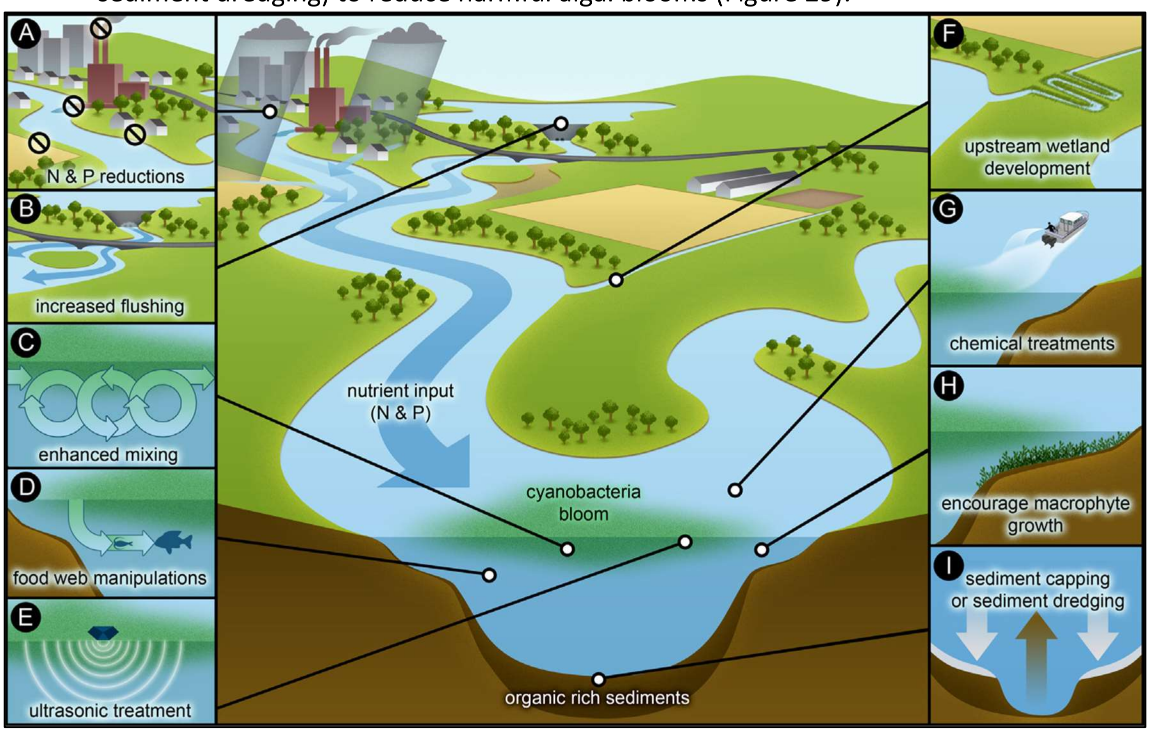

Figure 29. Strategies for controlling cyanobacterial harmful algal blooms at the scale of the watershed and individual water bodies. Nutrients that fuel algal blooms can be reduced via improved watershed practices, wetland capture, macrophyte growth and removal, and sediment dredging. Increased flushing and mixing dilute algae and prevent formation of concentrated, floating blooms. Herbivory, ultrasonic treatments and chemical treatments (e.g., copper salts and hydrogen peroxide) kill the algae. Source: [6]Hans Paerl, UNC-Chapel Hill, Institute of Marine Sciences

Fisheries

- Enhance understanding of human role on fisheries systems under climate change
- Set management policies to protect/enhance fishery under climate change
- Encourage and/or enhance manager and stakeholder partnerships
- Set realistic expectations and goals for fish communities based on lake conditions
- Harvest regulations (length and bag limits, closed seasons) to reduce exploitation rates
- Stock genetically resilient strains
- Cost-benefit analysis of stocking policies for maintaining the fishery
- Alter inland fishery management to what the lake can currently support
- Continue long-term monitoring programs of sentinel lakes
- Protect forested watersheds, restore headwater wetlands, and minimize groundwater withdrawals for cold-water fish species
- Purchase land in watersheds of resilient lakes with high-value fisheries
- Add structural habitat
- Reduce nutrient loading
- Aerate lakes with low dissolved oxygen
- Plow snow on lake ice to encourage oxygen production via photosynthesis and mitigate low winter oxygen
- Re-establish upper watershed wetland acreage and function to increase storage & infiltration, which will help maintain baseflow
- Reconnect floodplains

Aquatic Invasive Species

- Continue outreach efforts to maintain 100% compliance with AIS prevention efforts
- Expand youth education and community-based social marketing to achieve higher compliance rates
- Develop proactive long-term monitoring and studies
- Develop regulations that close existing and potential future transport vectors
- Proactively incorporate AIS management into regulation regarding water quantity management
- Incentivize invasive species harvest at the edge of invasion
- Promote strategies to increase surface water quality and increase resilience to AIS
- Restore watershed hydrology to prevent proliferation of invasive plants
- Develop local-scale prediction and prevention strategies
- Adjust ballast water regulations to decrease risk of invasion
- Alter standards for boat manufacturers that require design for AIS prevention and decontamination
- Recreational boat and shipping vessel decontamination
- Fish passage barriers
    - Electric barriers
    - Physical barriers (dams)
    - Acoustic deterrents
    - Carbon dioxide deterrent
    - Chlorinated locks to prevent AIS from passage

Ice Safety

- Educate the public on ice safety to prevent winter drownings[7]
- Introduce ice safety legislation and enforcement (e.g., limit ice activities when ice is too thin)[7]
- Provide ice safety guidelines (e.g., avoid ice at night, while intoxicated, in large groups)[7]
- Use ice safety equipment (e.g., ice picks, flotation devices, hypothermia protective clothing)[7]
- Better parental supervision of young children, especially near ice-on and ice-off[7]

Threatened and Endangered Species

- Consider stocking threatened and endangered species in new water bodies that will be more suitable in the future to prevent extinctions

High and Low Water Levels

Similar to warming waters, most strategies related to changing precipitation fall into the non-resistance categories. High and low water levels result from a shift in the balance between evaporation and precipitation. Water level fluctuations occur naturally and are ecologically important, but climate change will likely change the frequency and duration of these fluctuations. We can prepare for and moderate water level fluctuations by protecting and restoring riparian areas, floodplains, and wetlands throughout the watershed. Engineering solutions like water control structures and pumps can sometimes be effective at resisting change but are often insufficient for the volume of water in question. More economical approaches anticipate highs and lows, building adaptable infrastructure out of harm's way and relying on wetlands and vegetation to increase infiltration and evapotranspiration.

- Set expectations for fluctuating rather than static lake levels
- Monitor and define the range of lake levels expected; identify seepage lakes with large lake level fluctuations
- Repair or restore headwater wetland storage and infiltration to provide more stable summer discharge
- Promote integrated water management planning using long-term projections of supply and demand, tied to land use and economic growth forecasts.
- Encourage large water users to locate in areas with sustainable water sources (e.g., near large rivers, Great Lakes)
- Incentivize and regulate agricultural and urban development practices that minimize water use and encourage water infiltration, including restoring and repairing upper watershed wetlands
- During the non-growing season, direct agricultural drain water into wetlands and other infiltration areas to facilitate groundwater recharge
- Limit groundwater extraction to maintain minimum lake levels during drought
- Add woody and other habitat to deep water so it is available when lake levels are low
- Protect woody and other habitat stranded above water so it is available when lake levels rise
- Protect and restore wetlands and lake habitat in riparian and littoral zones
- Build adaptable/temporary structures, such as rolling or floating piers
- Set zoning regulations that protect the riparian zone from development
- Set insurance policies based on future climate projections to minimize building below the high-water mark

Flooding and Runoff

Extreme precipitation events are larger and more frequent, and this trend is likely to continue. We can work at the watershed scale to minimize runoff during these events and protect water quality. Even if enough practices are employed to counteract runoff from widespread impervious surfaces, groundwater flooding can still be problematic. In that case, enhancing storage in the watershed with wetlands and removing water via evapotranspiration are helpful.

- Emphasize watershed based hydrologic assessment, planning, restoration, and monitoring.
- Use grade control and other low impact practices to reverse bed and bank erosion and re-establish floodplain connection and functions.
- Enhance the ability of ecosystems to retain water.
- Protect and restore wetlands, especially in the upper watershed, the riparian/floodplain, and urban areas to enhance water storage and infiltration and capture nutrients and sediment.
- Enhance infiltration by reducing impervious surfaces in urban/riparian areas and improving land management practices.
- Protect recharge/infiltration areas and riparian buffers from overland flow of polluted runoff.
- On lakes with water control structures, set lake level targets to anticipate future highs and lows
- Design infrastructure to accommodate extreme events and increased stormflow (e.g., manure storage facilities, wastewater facilities, stormwater drains, and culverts) and when possible select green infrastructure options.
- Incorporate working lands into flood management strategies.
- Incentivize companies and farmers to reduce nutrient runoff in the watershed using best management practices:
    - Limit fertilizer application
    - Grazing and pasture management
    - Riparian and buffer zones
    - Saturated buffers to reduce phosphorus and nitrate loads entering streams from tile-drained agricultural fields
    - Manure digesters
- Continue implementation of total maximum daily load (TMDL) programs and adapt to account for more high flow events.
- Dredge legacy phosphorus in impacted stream reaches.
- Reevaluate water quality and permitting standards to reduce phosphorus, chloride, and fecal contaminants.
- Remove combined storm overflows in urban areas.
- Reduce road salt application during winter months.
- Incorporate climate change scenarios into modeling and planning efforts (e.g., watershed management, restoration plans, community plans).
- Provide local units of government with the technical and financial assistance needed to assess and mitigate their vulnerabilities to potential high-water conditions.
- Help local governments by developing regional continuous hydrologic simulation models for both surface and groundwater.

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