Michigan Department of Transportation

Infrastructure Protection and Rehabilitation Response to High Lake Levels

MDOT OR21-013

Appendix A: Expanded Literature Review of Long-Term Lake Level Trends, Including Climate Change Effects

March 2022 (Final)

Infrastructure Protection and Rehabilitation Response to High Lake Levels

MDOT OR21-031

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March 2022 (Final)

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1 Natural Climate Variation and Historic Lake Level Variability

The Great Lakes water levels naturally show significant variability, both seasonally and across years or decades. Annual swings are relatively predictable, with higher water levels in summer and lower water levels in winter. However, these annual fluctuations in water levels are smaller than the fluctuations seen across years. Lake levels fluctuate between periods of relative high water levels and periods of relatively low water levels. Historically, between years, water levels vary three times more than within a year (Hanrahan et al. 2010). While these fluctuations are driven by natural climate variation, the seemingly random unpredictable extremes over time have plagued those dependent on the Great Lakes since record keeping began in 1895. Table 1 indicates the overall variation between highs and lows seen across lakes.

Table 1. Lakewide Monthly Averages Across Period of Record – Historic Highs and Lows

Lake	Minimum Water Level (feet IGLD) / Date	Minimum Water Level (feet IGLD) / Date	Net Difference (feet)
Superior	599.47 *(April 1926)*	603.37 *(October 1985)*	3.9
Michigan-Huron	576.02 *(January 2013)*	582.35 *(October 1986)*	6.33
Erie	568.17 *(February 1935)*	574.6 (June 2019)	6.43

IGLD = International Great Lakes Datum

Source: NOAA Office of Coastal Management, 2021

Varying water levels can have seemingly disparate impacts. Lower water levels observed in the 1980’s led to a rise in concerns over impacts to shipping and the potential long-term impacts of diversions. In contrast, elevated water levels observed in the last decade have led to shoreline erosion increases and loss of beaches. Variations in water levels across time are depicted in Figure 1.

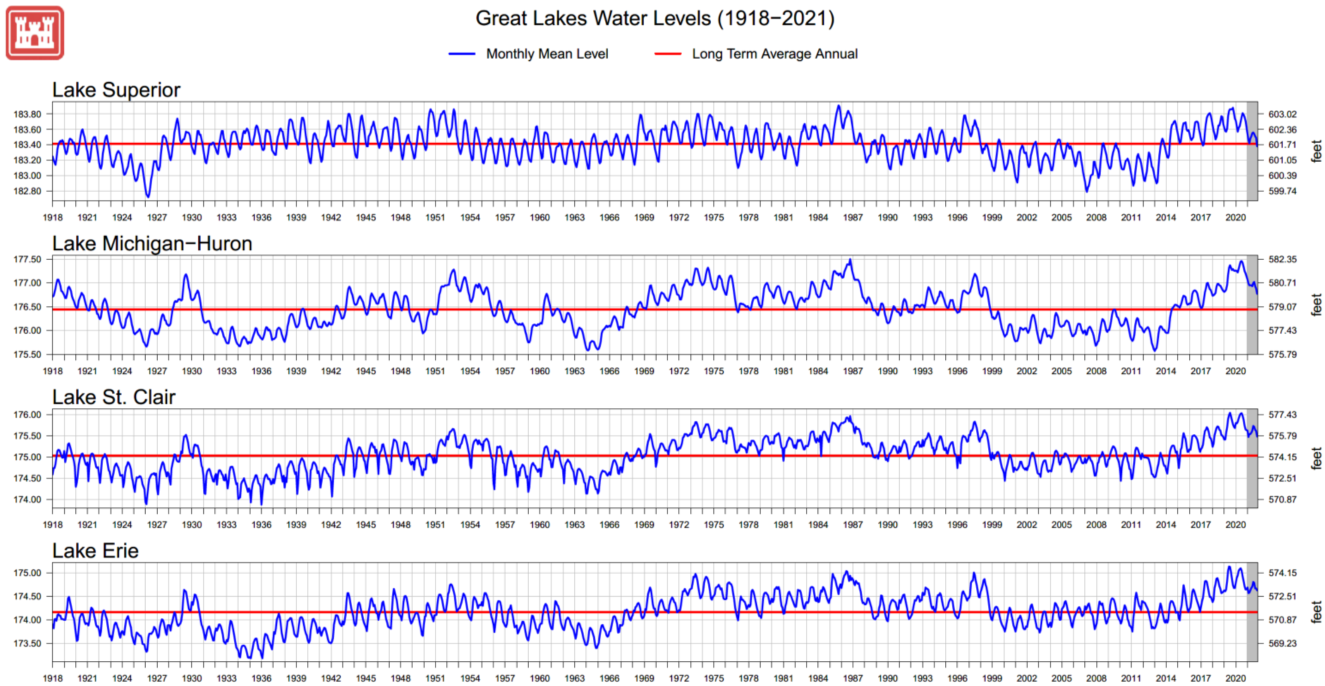

Figure 1. Historic lake level variability for Lakes Superior, Michigan – Huron, St. Clair, and Erie across the period of record. Source: USACE Detroit District, 2021a.[1]

While longer term multidecadal (between decades) and interannual (between years) trends have been identified qualitatively in the literature since 1976, only recently was the historic record long enough (statistically speaking) to verify these historic patterns. Two dominant longer-term water level cycles have been identified, one at around 80 years, and one at around 30 years. Both patterns are driven regional climate patterns. The 80-year trend has been associated with the Atlantic Multidecadal Oscillation (AMO) which captures multidecadal trends in sea surface temperature patterns in the North Atlantic, which in turn affect the regional climate.[2] This pattern explains approximately 7.1 inches of lake level variation between cycles. The 30-year pattern is in fact an interaction between two interannual cycles, an 8-year and a

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[1] USACE updates projections regularly, the most recent version of this graphic can be found online: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/

[2] The AMO has an estimated period of 60-80 years, over which time the North Atlantic Ocean sees natural swings of sea surface temperature (Trenberth et al., 2021). 1916-1924, and again in 1973-1991, the AMO was colder than average, while in 1932-1967 it was warmer. These variations in surface temperature are thought to indirectly impact the water levels of the Great Lakes through changes in precipitation. On average, annual totals were around 7.1 inches (18 cm) higher during colder phase of the AMO than the warmer AMO years (Hanrahan et al., 2010).

12-year cycle. Both are driven by regional weather cycles, with the 8-year cycle linked to the air pressure cycles of the North Atlantic Oscillation, and the 12-year cycle linked to regional precipitation patterns driven by North Atlantic sea surface temperatures (Hanrahan et al., 2010). It is important to note when interpreting these historic time-series trends, there is generally a high signal-to-noise ratio, meaning that while trends exist, there is also a lot of random variation around these trends (ELPC, 2019)

When looking at the amount of variation explained by long-term trends (around 7 inches), versus the total fluctuation across the historic record (around 4 – 6.5 feet depending on the lake), there remains a significant "randomness" to the variations seen across years and decades. Historically, this variation could at least be correlated with precipitation. Prior to the 1980s, the long-term lake level variability very closely matched historic precipitation records (Figure 2) (Hanrahan et al., 2010). While this correlation did not help with longer term predictions of lake level swings, it at least meant that the driving input for lake levels was understood.

However, after around 1980 evapotranspiration began having a significant impact on long-term water level variations, due to climate change and rapid global warming (Figure 2). While before, evaporation did not vary much from year to year, the area began seeing large variations in evaporation across years, with increases especially notable in summer months (Hanrahan et al., 2010). In terms of predicting future lake levels, this shift means that it is uncertain whether historically identified multidecadal and interannual patterns in lake levels will hold into the future, as well as which factor (precipitation or evaporation) will be the driving input for lake levels in the future.

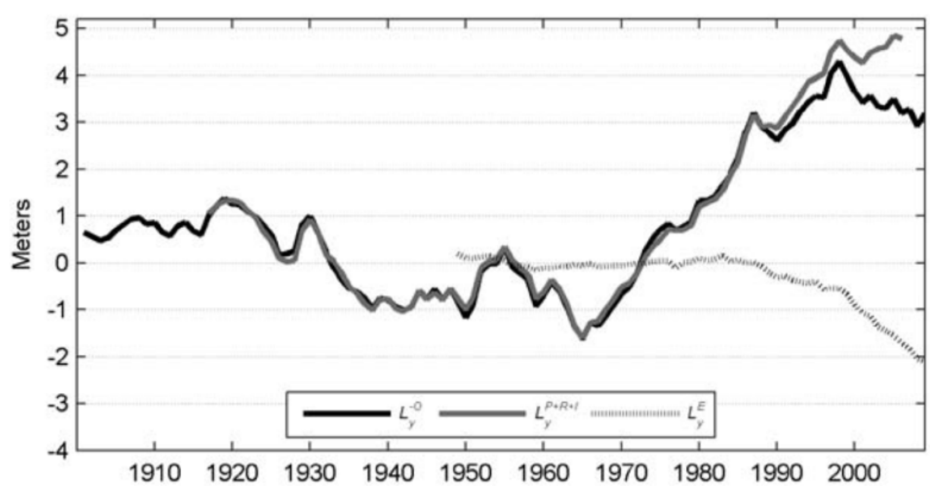

Figure 2. Outflow removed lake level curve (black) closely followed the precipitation driven components of net basin supply curve (gray; includes overlake precipitation, runoff, and

inflows) prior to the mid 1980s, after which the lake level trends decreased, following the evapotranspiration curve (dotted). Source: Hanrahan et al., 2010.

1.1 Additional Factors

Two additional factors (outside of climate) that impact the historic record should be mentioned, though both play a smaller role in overall water level variations:

- **Human Intervention.** When looking at the historical lake level record, human interventions in the landscape must also be noted. The Great Lakes have two points of regulated flow, with regulation of Lake Superior via the Compensation Works having begun in 1921, and regulation Lake Ontario via the Moses-Saunders Dam having begun around 1960. While outflows from Lake Superior are regulated, the impact on water levels of Lake Superior are not as great as those of Lake Ontario, with Lake Superior still seeing swings between high and low levels across years (Gronewold et al., 2013). Additionally, three inter-basin diversions are large enough to potentially have basin-scale impacts. The Ogoki Diversion and the Long Lac Diversion shift water from the Lake Superior watershed to the Hudson Bay watershed, while the Chicago Sanitary and Ship Canal transfers water from Lake Michigan to the Illinois and Mississippi River basins (ELPC, 2019). Both regulation and diversion flows are accounted for in lake level projections (see below). Similarly, dredging may minor role in water level variations.[3]
- **Differential Glacial Isostatic Rebound.** The Great Lakes region was formed by glaciers, and the soil is still slowly expanding from the decrease in pressure since their retreat. This is happing at varying rates around the shoreline, changing the water-land relationship. Some sites increase in elevation relative to the lake's equipotential surface, and some sites decrease.[4] This is generally accounted for by periodically adjusting the lake datums, of which the current iteration is the International Great Lakes Datum (IGLD) 1985 (Lee and Southam, 1994; Gronewold et al., 2013). The next update to the datum is the 2020 IGLD, which is scheduled to be implemented in 2025.

[3] While some older literature points to dredging as causing the significant water level decreases in the late 1980s, it now is generally agreed that changing climate was the dominant cause of lake level variations.

[4] When considering Lake Superior for example, on the high end, Michipicoten Ontario is rising at a rate of 0.95 feet per 100 years, while on the low end, Duluth Minnesota is falling at a rate of 0.77 feet per 100 years (relative to Pt Iriqous, Michigan) (Lee and Southam, 1994).

1.2 Observed Climate Change Impacts

As noted above, the historic long-term trends are becoming less reliable as a means of forecasting potential future lake levels. Climate change is likely to drive new patterns not recorded or represented in the historical lake level data set. Already, global climate change has begun to modify the regional climate. Key observed regional trends include:

- **Temperature.** The Great Lakes basin has seen an increase in annual average temperature of **1.6°F** when comparing present day (1986-2016) and the first half of the last century (1901-1960), slightly higher than the contiguous US average (ELPC, 2019).[5] Spatially, more northern latitudes experienced greater annual average increases, as seen in Figure 3.
- **Precipitation**. Annual precipitation for present-day (1986-2016) has generally increased relative to 1901-1960 across the Great Lake Basin, with an average trend of a 10.0% increase. However, as seen in Figure 4, there is significant spatial variation, with much of the coastal lower peninsula seeing increases between 10-20%, but the western half of the upper peninsula seeing a 5% *decrease* in precipitation over the same timeframe. Seasonally, across the Great Lake states the largest increases have been seen in fall (15.8%), then summer (9.9%), with lower increases in winter (7.7%) and spring (7.0%) precipitation (ELPC, 2019).
- **Snowfall.** While increased precipitation may lead to more snowfall during an individual event, winter warming leads to more precipitation coming as rain instead of snow. In total, there had been little effect on historic average annual snowfall across the region, with the Great Lakes Basin seeing a modest 2.25% decrease (from 1886 – 2013 compared to 1954 – 1983). Some areas affected by lake effect snow have actually seen significant *increases* in snowfall.[6] More notable is perhaps the reduced seasonal duration of snow cover, and corresponding increase in frost-free days and a longer growing season (ELPC, 2019).

[5] The Environmental Law and Policy Center *Assessment of the Impact of Climate Change on the Great Lakes* (2019) builds of the 4th U.S. National Climate Assessment, bringing in additonal updated literature and focusing the spatial extents on the Great Lake states and Great Lakes Basin. Per the National Climate Assessment, present day is defined as 1986-2016, and 1901-1960 as the first half of the last century.

[6] Lake effect snow happens when cold air from Canada flows across unfrozen, relatively warm Great Lakes. The lake moisture and temperature contrast lead to heavy snow in areas downwind of the lakes. Climate change may lead to greater lake effect snow events in the future (ELPC, 2019).

Additional climate variables, such as decreased cloud cover and increased evapotranspiration, also play a key role in lake levels.

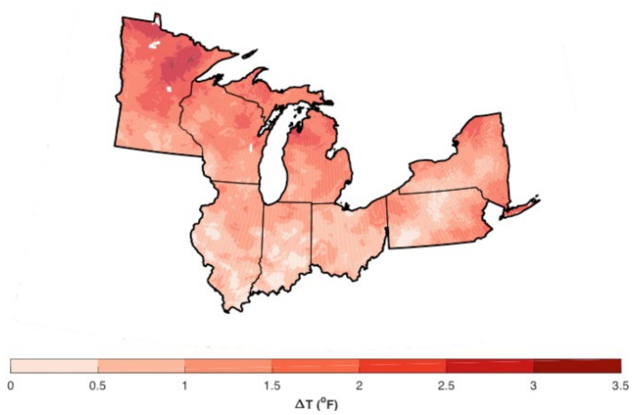

Figure 3. Observed changes in annual average temperature (°F) between 1986-2016 (present day) compared to 1901 – 1960 in the Great Lakes states. Source: NOAA/NCEI as referenced in ELPC, 2019.

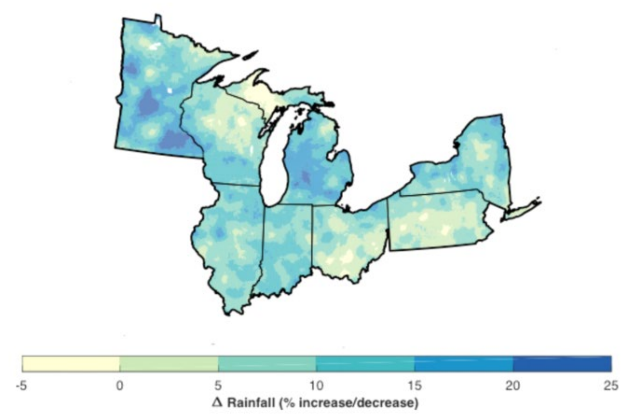

Figure 4. Observed changes in annual average precipitation (%) changes between 1986-2016 (present day) compared to 1901 – 1960 in the Great Lakes states. Source: NOAA/NCEI as referenced in ELPC, 2019.

Climate change not just impacting the regional climate, but also changing affecting the Great Lakes themselves. Fundamentally, the exchange of heat between the atmosphere and the Great Lakes is being altered – by both increasing the direct heat input into the lakes and inhibiting the loss of heat from the lakes to the air. This alters lake temperature, ice cover, and timings of overturning (or seasonal mixing of waters) (ELPC, 2019). To date, the following patterns have been observed:

- **Summer surface water temperature.** Similar to regional climate trends, the increase in summer surface temperature varies spatially across and within the lakes. Within the lakes, the greatest increases occur in deeper water, as shown in Figure 5. While all the Great Lakes have seen increases in surface water temperature from 1994 – 2013, Lake Superior shows the largest rate of change (ELPC, 2019).
- **Stratification and overturning.** Deep water temperatures of the lakes are rising in winter, as evidenced by Lake Michigan (Anderson et al., 2021). The Great Lakes see two surface to bottom mixing events each year – one in fall and one in spring. During the fall overturn, as the surface water cools it falls and the water column mixes, warming the subsurface water temperatures. Over the winter, the lake experiences inverse stratification (with the top being cooler than the bottom), but the deep waters still

experience a period of cooling. In spring once ice melts, there is another full overturn of the lake. Then as summer waters warm, the lakes again become stratified. Climate change is causing changes to this thermal regime. The fall overturn has been delayed with fall warming trends, decreasing the winter cooling period of deep water. This results in increasing deep water temperatures, and an earlier onset of summer stratification. As these yearly patterns weaking, it leaves open the possibility of a mixing regime shift in the lakes (Anderson et al., 2021).

- **Ice cover.** As seen in Figure 6, Lakes Superior, Huron, and Erie saw the greatest loss of ice cover from 1973 - 2013. Spatially, the greatest decrease in duration of ice cover is seen near the shorelines, with smaller rates of decrease in the deeper, central areas of the lakes (note, deeper areas of Michigan and Ontario rarely see winter ice cover). While Figure 6 shows a significant decrease in ice coverage, when accounting for the extremely cold winters of 2013-14 and 2014-15, these negative trends are somewhat tempered (ELPC, 2019).
- **Over-lake precipitation.** While it was noted above that precipitation over the Great Lakes Basin as a whole saw recent increases (considering both land and water), the actual over-lake precipitation decreased by 7.9% over Lake Superior, 6.8% for Lake Erie, and 2.0% for Lakes Michigan-Huron, when comparing 1984-2013 to 1954-1983 (ELPC, 2019).

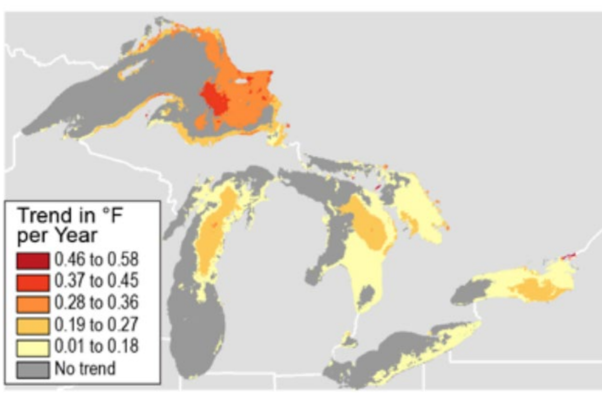

Figure 5. Observed rate of change in summer surface water temperature (°F) between 1994-2013 in the Great Lakes. Source: Adapted from Mason et al. (2016) by NOAA GLERL as referenced in ELPC, 2019.

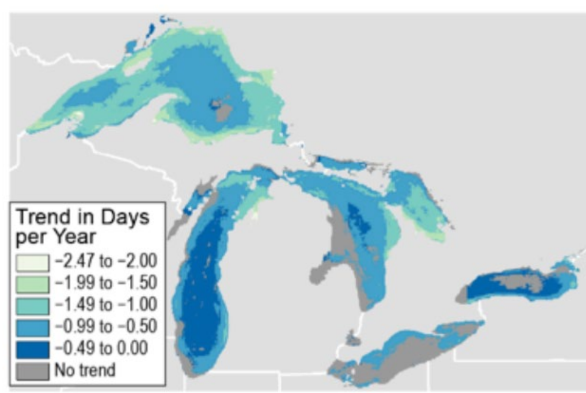

Figure 6. Observed rate of change in ice cover duration (days) between 1973-2013. Source: Adapted from Mason et al. (2016) by NOAA GLERL as referenced in ELPC, 2019.

These changing trends regarding the lakes themselves add an additonal layer of complexity in predicting future water levels.

Additionally, similar to the United States as a whole, there is strong evidence that weather events are increasing in intensity. The Midwest has seen extreme weather events in terms of heatwaves and extreme precipitation (ELPC, 2019). Looking forward, changes in Artic snow and ice cover and weaking of the polar jet stream and changes to the Artic Oscillation may be fundamentally changing and slowing weather patterns in North America, leading to more persistent droughts, heat waves, cold spells, and storms (Francis et al., 2018; Gronewold and Rood, 2019).

2 Modeling Lake Levels and Future Trends

While it was noted above that historically lake levels generally followed precipitation trends, there are a significant additonal number of variables that go into determining the actual water levels. On top of multiple, complex inputs, uncertainty around future climate trends complicate predicting long-term lake level trends.

This section first discusses the process and inputs to estimate long-term Great Lake water levels, and then reviews key projections available. It concludes by discussing the implications for planning and proposing a maximum high future water level scenario for the Michigan Department of Transportation (MDOT) to consider.

2.1 Lake Level Modeling Context

Overall, lake levels are calculated by predicting net basins supply, and then translating that into lake levels by stimulating channel flow between the lakes and accounting for diversions (Gronewold et al., 2017; Notaro et al., 2015). Net basin supply is calculated as:

Equation 1: Net Basin Supply = Drainage Basin Runoff + Overlake Precipitation – Lake Evaporation

There has been an established body of literature going back to the mid-1980s that has attempted to predict future long-term lake levels. While this body of literature overwhelming relies on a suite of models developed by the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) (the GLERL suite) [7] to simulate net basin supply components, the climate models used to predict future conditions

[7] The GLERL suite includes the large basin runoff model (LBRM), large lake thermodynamic model (LLTM), and the coordinated Great Lakes regulation and routing model (CGLLRM).

have been more varied (MacKay and Seglenieks, 2012; Notaro et al., 2015). As this body of literature developed, there have been a couple significant limitations identified that call into question the results of earlier studies.

First, early reliance on global climate models (GCMs) only modeled the regional climate at a very coarse level, and generally did not include the impacts the Great Lakes themselves have on the regional climate (MacKay and Seglenieks, 2012; Notaro et al., 2015). For example, GCMs do not capture lake effect storms, which mitigate any projected increase in evaporation, as the storms recycle the water back into the system. Additionally, coarse resolution GCMs don't accurately capture precipitation over relatively small watersheds, and seasonal variability is only weakly captured (MacKay and Seglenieks, 2012). This limitation has been addressed in more recent studies by using downscaled GCMs just to establish the boundary conditions for higher resolution regional climate models. These regional climate models can either directly incorporate the Great Lakes, or be run in conjunction with a lake model.

Second, Lofgren et al (2011) identified a serious flaw in how overland evapotranspiration was handled in the GLERL suite. Air temperature was being used as a proxy for overland evapotranspiration in the GLERL suite, however the energy balance between ingoing and outgoing energy to the system was not being enforced between the GCM inputs and the offline hydrologic models.[8] Various studies after 2011 have addressed this in different manners, either through estimating evapotranspiration directly from a regional climate model or making updates to the GLERL suite.

Both of these factors led to significant overestimation of evaporation (and evapotranspiration), and "dire" predictions of long term lake level declines – with some estimates predicting an average decrease of over 5 feet in the coming decades (Notaro et al., 2015). More current projections (discussed more below), result in a much more tempered view. While climate models agree that temperatures will increase, this will lead to both increased precipitation and increased evaporation (and evapotranspiration). Either of these components of net basin supply could dominate, and as such, currently the literature does not show a clear trend – lake levels may, on average, show moderate decreases or moderate increases, depending on the climate projection.

2.2 Lake Level Modeling Steps

In order to appreciate the layers of uncertainty and weight that should be given to predictions in terms of decision making, it is useful to understand the general process that is followed

[8] Specifically, GLERL's Large Basin Runoff Model (LBRM), which is used to calculate overland runoff.

when estimating long-term water levels. While various papers iterate and improve on portions of the process, the general steps are outlined below.

The first step is to identify meteorological inputs and account for future climate impacts on weather. Meteorological inputs can either be historical data or predicted through climate models.[9] These inputs are estimated at quite a fine timescale (such as daily). Generally, the hydrologic models require the following inputs:

- The inputs of daily maximum, average, and minimum air temperature, precipitation, and solar radiation are used to model the overland components of snowpack accumulation and melt, infiltration, evapotranspiration, and runoff, in order to get to total drainage basin runoff (Gronewold et al., 2017, MacKay and Seglenieks, 2012).
- The inputs of daily maximum, average, and minimum air temperature, surface wind speed, cloud cover, and dew point temperature are used to model the overlake components of lake sensible and latent heat fluxes, heat storage, and surface temperature in order to get total lake evaporation (Gronewold et al., 2017, MacKay and Seglenieks, 2012).

Newer modeling techniques that also consider the effects of the lakes themselves are able to better predict seasonal ice cover and lake surface temperature, with lake surface temperature highly dependent on lake stratification and mixing cycles (see Section 1.2 above). While the impacts the Great Lakes themselves have on regional climate has been addressed at some level in more recent projections by incorporating finer scale regional climate models, fully capturing the two-way interaction between the lakes and the climate inputs is still a limitation of the research to date.

The second step is to run overland and overlake hydrological models and calculate net basin supply. The inputs discussed in the previous step are then used in the appropriate hydrological models. The physical inputs that drive net basin supply (drainage basin runoff, overlake precipitation, and lake evaporation) are modeled based on climate factors. For example, when rain falls over a watershed that feeds into the Great Lakes, only a portion of the surface water or groundwater eventually flows into the Great Lakes, much is intercepted and returns to the atmosphere through evaporation or is taken up by vegetation (transpiration).

Traditionally, GLERL’s Large Basin Runoff Model (LBRM) was used to calculate overland runoff. However, as noted above, as this model was “offline” from the climate inputs, it led to over-estimation of evapotranspiration. Since this issue was identified by Lofgren et al., 2011,

[9] When climate models are used for future predictions, it is still best practice to baseline the models with historical data. Additionally, as discussed below, USACE uses historical data for one of their 5-year forecast predictions.

there have been various methods of addressing this in the literature – from calculating evapotranspiration outside of the LBRM to modifying to updating the model itself. Similarly, while virtually all of the earlier literature relied on GLERL's Large Lake Thermodynamic Model (LLTM) to calculate the overlake components of precipitation and evapotranspiration, regional climate models are being used more and more to directly calculate these inputs at a finer resolution.

Bringing these inputs together, net basin supply (or the amount of water feeding into each of the Great Lakes) is determined by for each lake by adding the drainage basin runoff and overlake precipitation, and then subtracting the overlake evaporation.

The third step is to run multiple simulations of potential future net basin supply. Given the historic variability and time dependence between yearly water levels, there are many possible future outcomes. Water level predictions rely on a distribution of probable future net basin supply, and then report the most likely outcome. One method of doing so is taking multiple multi-year samples (1,000+) of the historic time series (preserving all its statistical properties such as mean, standard deviation, and time dependence), and then adjusting those values by expected changes future climate will have (Notaro et al., 2015).

The final step is to incorporate routing and regulation models. There is one final step between knowing how much water is flowing into each of the Great Lakes and calculating a mean monthly water level. The surface area of the lakes and the flows between each lake need to be considered. This is done with the Coordinated Great Lakes Regulation and Routing Model (CGLRRM), which simulates flows through connecting channels.[10] The CGLRRM considers lake to lake differences in water levels, channel characteristics, "retardation factors" (such as ice and weeds), and operation of control structures on the St Mary's and St Lawrence Rivers (Gronewold et al., 2017). Within the model, groundwater acts as temporary storage, eventually draining to the lakes, so does not affect the over water budget, just the timing of the water's release into the lakes (Notaro et al., 2015).

As the process illustrates, translating weather and climate to water levels is complex. There are many points where uncertainty can be compounded. Still, with the introduction of regional climate models, and incorporating the impacts of the lakes themselves, the literature has shown great advancement since the mid-1980s.

[10] This model was developed by NOAA/GLERL, USACE, and Environment Canada.

3 Relevant Water Level Projections

Given the unreliability of the earlier predictions, Arcadis focused on the available projections after 2011. While there are additonal papers that address just regional climate projections or estimate net basin supply, there are limited number that take the final step to predict lake levels. As such, three projections were reviewed in-depth and considered in the recommendation for a future high water scenario for MDOT's planning purposes:

- MacKay and Seglenieks, 2012;
- Notaro et al., 2015, and
- U.S. Army Corp of Engineers' (USACE's) 5-year projections

All these report projections seasonally.

3.1 MacKay and Seglenieks, 2012

One of the first papers to address the key limitations in the literature discussed above was MacKay and Seglenieks' 2012 "On the simulation of Laurentian Great Lakes water levels under projections of global climate change." They dynamically downscaled a Canadian GCM, to a regional climate model (Great Lakes Regional Climate Model) that did include a simple lake model, and bias-corrected the results.[11] Because of the finer-scale of the climate data used, land-surface atmosphere feedback is represented in the climate data, and monthly variation in predictions are captured (MacKay and Seglenieks, 2012).

Long-term future water level trends are projected a seasonal scale for 2021-2050. Overall, the yearly lake-wide average is predicted to decrease by 3 cm for Superior, 5 cm for Huron – Michigan, and 6 cm for Erie. The decreases are not seen uniformly across the annual cycles, with winter showing greater decreases in lake levels than summer– seasonal cycles are slightly amplified. While the model predicts that Superior is expected to see slight summer increases and the greatest seasonal amplification, the model fit for lake Superior is also is the weakest, showing seasonal peaks 2-3 months earlier than historical values (Figure 7) (MacKay and Seglenieks, 2012).

While this paper corroborates that the likely long-term trends are much more tempered than the early literature, these projections were not directly considered in the potential future

[11] The regional climate model was based on Environment Canada's GCM (CGCM3), and the Canadian Regional Climate model (CRCM). These models draw on the "observed 20th century" emissions scenario for 1961 – 2000, and the SRES A2 emission scenario for 2001 – 2100. This emission scenario is near the highest of IPCC's projections for mid-century, but not the highest.

maximum for this planning project, due both to lack of model fit and the conclusion that with the exception of Superior, seasonal summer decreases are expected.

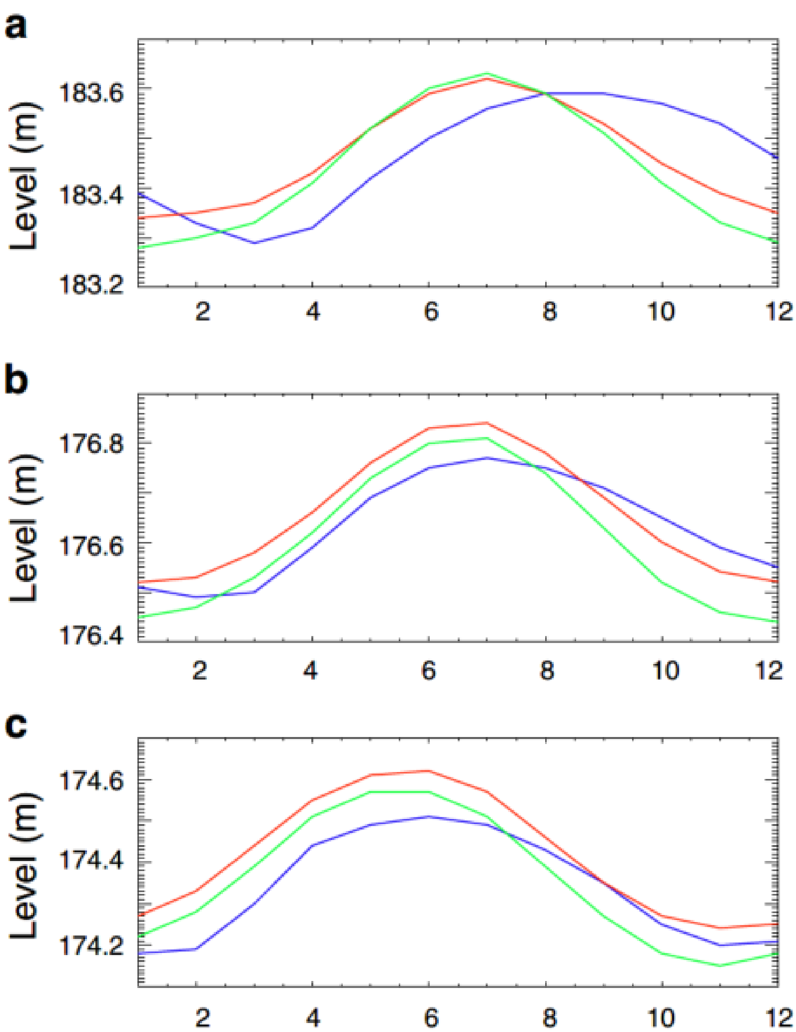

Figure 7. Lake level mean season cycle for: a) Lake Superior, b) Lake Michigan – Huron, c) Lake Erie. Blue = observed from 1962 -1990; Red = model fit from 1962 -1990; Green = model prediction for 2021 - 2050. To interpret expected long term trends, compare Red to Green (showing a decrease in lake levels). Units (m) referenced in IGDL 1985. Source: MacKay and Seglenieks, 2012.

3.2 Notaro et al., 2015

The most useful projections identified during the literature review process for MDOT's planning purposes are Notaro et al.'s 2015, "Dynamically Downscaling-Based Projections of Great Lakes Water Levels." Similar to MacKay and Seglenieks, Notaro et al.'s methodology address the previous shortcomings in the literature. Additionally, the paper reports projections from two climate projections for two different timeframes, 2040-59 (mid 21 century) and 2080-99 (late 21 century), again reporting at a monthly scale that captures seasonal variation. Additionally, the mean and standard deviation are reported, allowing for an interpretation of how these average long term trends may vary across the years (Notaro et al., 2015).

The authors downscaled two Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs using a regional climate model coupled with a one-dimensional lake model, in order to represent the effects of the lakes themselves.[12] While the representation of the Great Lakes is greatly improved from what is included in the GCMs, when comparing model predictions to historical data, there are still limitations in how well this representation accounts for lake temperature and ice cover. As evapotranspiration is calculated directly from the regional climate model, the previously noted issues with using the GLERL suite are avoided (Notaro et al., 2015).

The two climate projections were chosen to be representative of two different potential future warming trends. The high-end warming model (MIROC5) has peak warming occurring in spring, which is less typical of the CMIP5 GCMs. More typical is a low-end warming model with peak warming occurring in winter (represented by CNRM-CM5). The two climate scenarios both project future increases in air temperature and precipitation, and corresponding increases in over-lake precipitation, base-wide runoff, and lake evaporation. However, the projected long term water level trends are of opposite signs. The high-end warming scenario estimates ***moderate decreases*** in lake levels (Figure 8, top row), and the low-end warming scenario estimates ***relatively large increase*** in lake levels (Figure 8, bottom row). This is due to the relative magnitudes of the inputs into net basin supply, and whether increases in precipitation (lake levels trend up) or increases in evaporation/transpiration (lake levels trend down) dominate (Notaro et al., 2015).

Considering the low-end warming scenario, lake levels may see an annual lake level changes of +3.0 inches for Lake Superior to +7.1 inches for Lakes Michigan – Huron by the mid 21st century, roughly doubling to +5.3 inches for Lake Superior to +16.5 inches for Lakes Michigan – Huron by the late 21st century. Seasonally, the largest increases are expected in spring for Lakes Superior and Michigan – Huron, and summer for Lake Erie. Considering the high-end warming scenario, expected decreases are slightly smaller, with annual lake level changes of -0.9 inches for Lake Superior to -5.2 inches for Lakes Michigan – Huron by the mid 21st century,

[12] While the authors reviewed a total of 33 CMIP5 GCM simulations, two were chosen to generate boundary conditions for the regional climate model based on the needed inputs, absence of bias, the overall spatial resolution. They both represent the high-emissions scenario of RCP8.5.

increasing to -3.8 inches for Lake Superior to -11.7 inches for Lakes Michigan – Huron by the late 21st century. For this scenario, the largest water level declines occur in summer for Lake Erie, late summer/early fall for Lake Superior, and fall for Lakes Michigan – Huron.

As the low-end warming scenario is more indicative of the full suite of CMIP5 scenarios, and given the scope of this analysis, Arcadis focused on potential future increase in lake levels. Table 2 summarizes these predicted water levels.

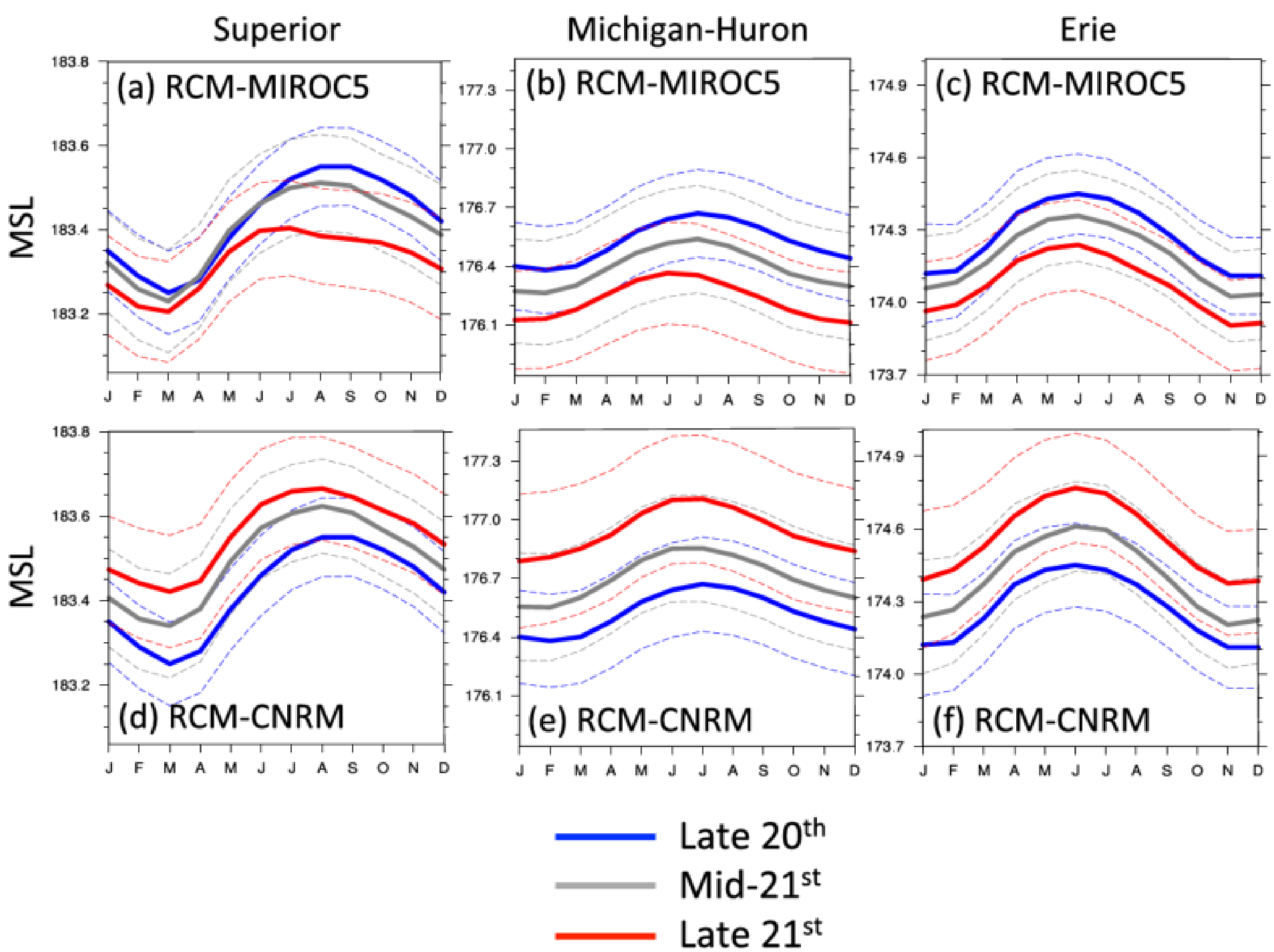

*Figure 8. Mean seasonal cycle of water levels (solid), in meters IGLD85, on: (a),(d) Lake Superior; (b),(e) Lake Michigan – Huron; (c),(f) Lake Erie. Blue = observed from 1948 -12006; Gray = model prediction 2040-59; Red = model prediction for 2080-99. Dashed lines indicate the interannual variability – namely **+/-1 standard** deviation in lake levels for each time period. Source: Notaro et al., 2015.*

Table 2. Low-End Warming Scenario (CNRM-CM5, peak warming in winter) Maximum Mean Monthly Water Level predictions (+/- one standard deviation)

Peak Month	Month of data reported below	September (Baseline); August (Projections) (feet IGLD)	July (feet IGLD)	June (feet IGLD)
Mean Monthly Water Level	Baseline	602.2 (601.9 – 602.5)	579.6 (578.8 – 580.4)	572.3 (571.8 – 572.9)
	Mid-century 21st Century (2040-59)	602.4 (602.1 – 602.8)	580.2 (579.3 – 571.1)	572.9 (572.3 – 573.5)
	Late-century 21st Century (2080-99)	602.6 (602.2 – 603.0)	581.1 (580.0 -582.1)	573.4 (572.7 – 574.1)
Changes from Baseline	Increase by 2040-59 (feet)	0.2 (0.2 – 0.3)	0.6 (0.5 - 0.7)	0.5 (0.5 – 0.6)
	Increase by 2080-99 (feet)	0.4 (0.3 – 0.5)	1.4 (1.2 – 1.7)	1.0 (0.9 – 1.2)

3.3 USACE Long-Term (5-year) Forecast

In addition to the available mid to end of century long term trends available in the literature, NOAA/GLERL and the USACE have developed an unofficial (or experimental) 5-year forecast, which is updated monthly (USACE Detroit District, 2021b; Gronewold et al., 2017; USACE Detroit District, 2018).[13] These forecasts were specifically developed to help hydropower authorities with decision support around flows along the Niagara and St. Lawrence rivers. While they don't provide estimates of long-range trends, they are useful cross-check, and as an ongoing resource for MDOT for monitoring and management.

A key benefit of the USACE 5-year forecast is that it provides two predictions – one based on historic climate data, and one based on projected future climate data. Instead of just considering one or two future climate scenarios, the projections are based on aggregating

[13] Official projections only extend 6 months. See: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Water-Levels/Water-Level-Forecast/Monthly-Bulletin-of-Great-Lakes-Water-Levels/

predictions from 19 bias-corrected downscaled CMIP5 GCMs, using the RCP 4.5 scenario (as there is minimal difference between the 4.5 and 8.5 scenario in the near future of 5 to 10 years). While the projections are downscaled, a specific regional climate model was not employed, and so representation of the lakes themselves varies based on however they were initially represented in the various GCMs. However, the future conditions projections due incorporate initial conditions and seasonal outlooks for the first several months of the projection. The modeling relies on the GLERL suite of models (LBRM, LLTM, and CGLRRM), but the current projections rely on an updated version of the Large Basin Runoff Model (LBRMv2.0) which addresses the earlier shortcomings of estimating evapotranspiration (Gronewold et al., 2017).

As shown below in Figure 9, these results are reported at a monthly basis for the first year, and then on a yearly basis for years two through five. When relying on historic supplies, the annual average lake levels are expected to decrease over the next five years, while this trend reverses when considering future supplies, which predict annual averages increasing in the next five years. Figure 9 underscores the large range of uncertainty with these estimates.

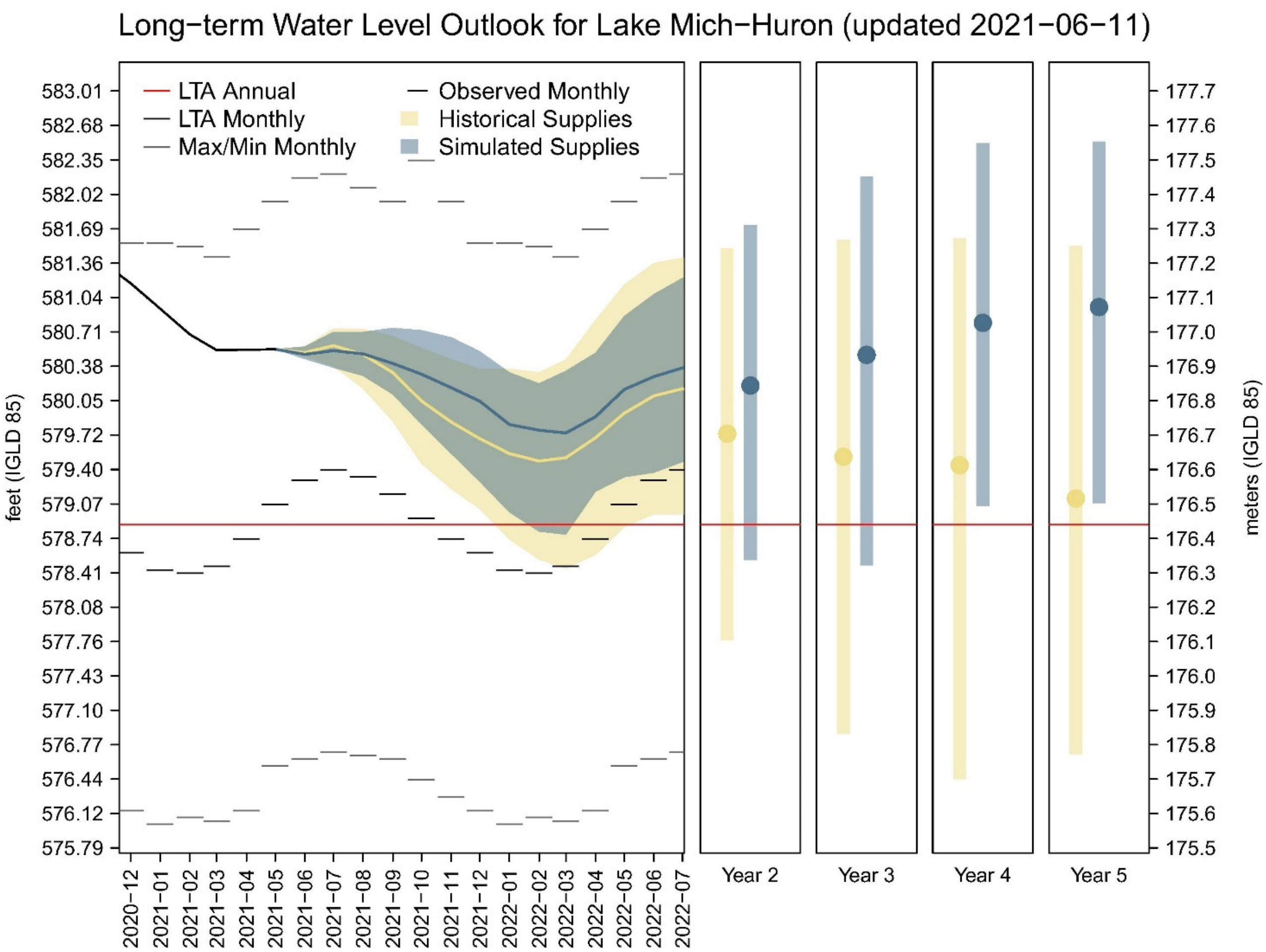

Figure 9. Example USACE 5-year Forecast for Lakes Michigan – Huron. The largest and furthest left panel depicts the monthly mean water levels that are projected for the next 12 months using the two alternative net basin supply modelling approaches. The shaded areas show the 95% confidence interval of monthly mean water levels, while the solid line shows the median outlook, for both historical and simulated supplies.

The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent 12-month periods of the outlook *horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).*

Source: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Water-Levels/Water-Level-Forecast/Long-Term-Forecast/; (USACE Detroit District, 2018).

4 Planning for and with Uncertainty

In summary, it is well established that climate change is already affecting Michigan through increased temperature, less ice cover, and later-season winter overturning and stratification of lake waters. While climate models agree that temperatures will increase, researchers also agree that this will lead to ***both*** increased precipitation and increased evaporation (and evapotranspiration). Different climate warming scenarios (maximum temperature increase occurring in winter versus spring) will determine which of these factors will play the dominate role in long-term water levels and whether the lake levels will, on average, show moderate decreases or moderate increases. If increased precipitation proves to be the dominant driver and lake levels trend upwards, current models suggest an upper end of approximately 6 inches to 1 foot increase of average water levels by 2050. This may double to 1 foot to 2 feet on average by 2090.

Given the overall fluctuation of lake levels established above, MDOT will need to plan for both unprecedented high and low water levels in the Great Lakes, regardless of long-term trends. While not quantified in the literature to date, it is noted that given emerging weather patterns and observed extreme events to date, water levels are likely to show increased variability in the future (Gronewold and Rood, 2019). This is schematically depicted in Figure 10, which demonstrates that even if long term lake levels trends downward, MDOT will likely see years of high water, that may even result in peaks above those in the historical record.

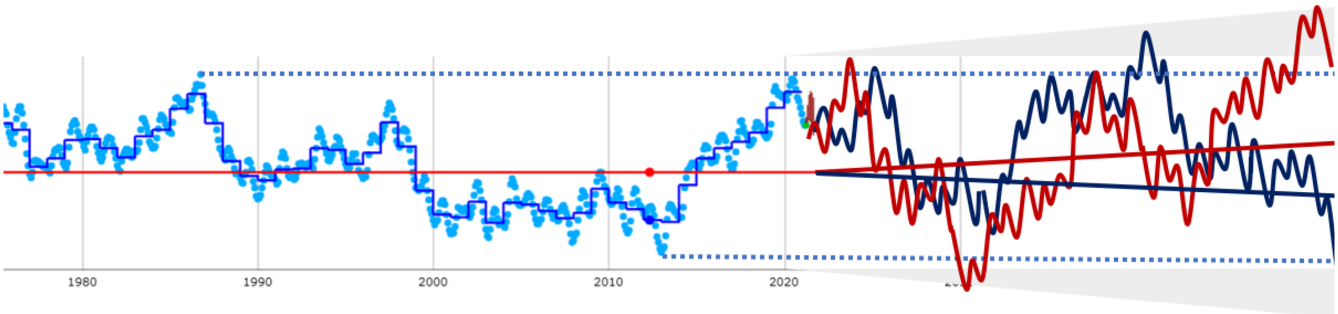

Figure 10. Schematic depiction of potential variability around an increasing long-term lake level average and a decreasing long-term lake level average. Base graphic source: Great Lakes Water Level Dashboard, NOAA/GLERL.

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6 Acronyms and Abbreviations

AMO	Atlantic Multidecadal Oscillation
CGLRRM	Coordinated Great Lakes Regulation and Routing Model
CMIP5	Coupled Model Intercomparison Project Phase 5
GCM	global climate models
GLERL	Great Lakes Environmental Research Laboratory
IGLD	International Great Lakes Datum
LBRM	Large Basin Runoff Model
LLTM	large lake thermodynamic model
MDOT	Michigan Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
USACE	U.S. Army Corps of Engineers

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