US Army Corps of Engineers®
St. Paul District

Appendix D

Qualitative Assessment of Climate Change Impacts

Pool 5 Dredged Material Management Plan

Upper Mississippi River

Wabasha and Winona Counties, Minnesota

Buffalo County, Wisconsin

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Pool 5 Qualitative Climate Assessment

1 Purpose

United States Army Corps of Engineers (USACE) projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural climate variability over their operating life spans. Recent scientific evidence shows that in some places, and for some impacts relevant to USACE operations, climate change has shifted the climatological baseline about which natural climate variability occurs, and may be changing the range of that variability as well. This is relevant to the USACE because the assumptions of stationary climatic baselines and a fixed range of natural variability, as captured in the historic hydrologic record, may no longer be appropriate for long-term projections of risk to the USACE Navigation.

Long-term, natural fluctuations in climate or anthropogenic driven climate change have the ability to alter regional precipitation, temperature, hydrology patterns, and ecosystem functions. This study seeks to provide qualitative information which can be used to determine how hydrologic variables have responded to climate change in the past and may respond to climate change in the future. The purpose of this analysis is to provide a qualitative assessment to determine if climate change is relevant to navigation projects in the Upper Mississippi River Watershed and make recommendations about how to incorporate the findings of this assessment. The results of this qualitative assessment can be used to increase the resilience of existing and proposed water resources projects in the watershed.

2 Project Background Information

The purpose of this Dredged Material Management Plan (DMMP) is to prepare a coordinated, long-term plan for managing dredged material in Lower Pool 5 of the Upper Mississippi River for the purposes of continued operation and maintenance of the 9-Foot Navigation Channel Project. This plan was initiated because permanent dredged material placement sites previously used in Lower Pool 5 have reached capacity. Dredged material placed at island transfer sites will need to be offloaded to permanent sites. Therefore, additional permanent sites are needed to accommodate the Corps' dredging needs in Lower Pool 5 over the next 40 years. Costs associated with managing the dredged material have increased significantly over the past 20 years, so the DMMP also looked for ways to reduce cost. Lower Pool 5 has six active dredge cuts where maintenance dredging has occurred. These dredge cuts are expected to generate 4.7 million cubic yards (CYs) of dredged material over the next 40 years, or about 117,000 CYs annually.

The Tentatively Selected Plan (TSP) for the Lower Pool 5 DMMP has been identified as the "Federal Standard". The Federal Standard is defined as "the dredged material disposal alternative or alternatives identified by the Corps which represent the least costly alternatives consistent with sound engineering practices and meeting the environmental standards established by the 404(b)(1) evaluation process…" (33 C.F.R. § 335.7). The DMMP study includes the use of the existing West Newton Chute site as a transfer site prior to hauling the material to the selected Rolling Prairie Site. The combined sites are capable of accepting material placed hydraulically and mechanically from Pool 5 for more than 40 years.

Use of land-based transfer sites reduces the need to periodically offload material from island transfer sites. Additionally, several other property locations have been identified for future dredged material placement opportunities within Pool 5.

Three island sites used in the past for temporary placement are retained in the Recommended Plan. Above West Newton, Fisher Island, and Lost Island would remain available in the future if the permanent placement sites are at capacity, become unavailable for some unforeseen reason, or if it's operationally more feasible to use the island sites. Finally, no dredge material will be used to make islands, beaches, or added back into the Mississippi River.

Climate change impacts on the hydrology of the Upper Mississippi River Basin were considered in accordance with the USACE Engineering Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs and Projects* (USACE, 2018a), as well as USACE Engineering Technical Letter (ETL) 1100-2-3 *Guidance for Detection of Nonstationarities in Annual Maximum Discharges* (Friedman et al., 2016).

The goal of a qualitative analysis of potential climate threats and impacts to USACE hydrology-related projects and operations is to describe the observed present and possible future climate threats, vulnerabilities, and impacts of climate change specific to the study goals or engineering designs, in this case, the TSP for dredge material from Pool 5. This includes consideration of both past (observed) changes as well as potential future (projected) changes to relevant climatic and hydrologic variables. This analysis uses a weight of evidence based approach to make a qualitative assessment of climate change impacts to dredging in the Upper Mississippi-Black-Root River Basin (Hydrologic Unit Code 'HUC' 0704) which contains the project area at Mississippi River Pool 5.

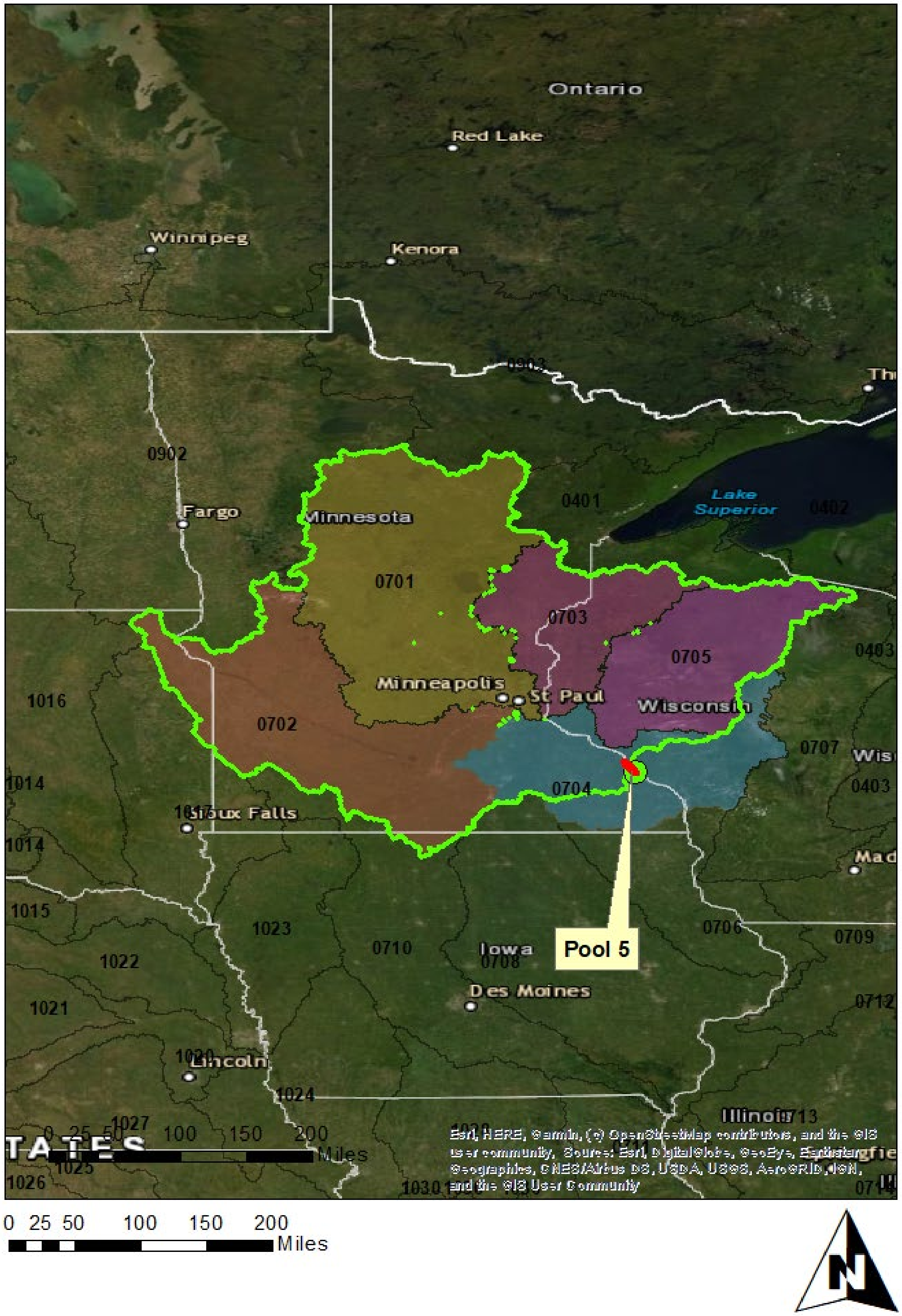

Figure 1 Pool 5 and Contributing Watershed Map with HUC4 Watersheds.

3 Literature Review

Both historical, observed hydro-meteorological datasets, as well as projected, climate-changed hydro-meteorological data was reviewed to support qualitative statements about how to incorporate resilience from impacts of climate change over the minimum 20-year DMMP. Important, driving hydro-meteorological variables include streamflow, precipitation, and temperature. The magnitude, seasonal and inter-annual variation, duration, and rate of change of these variables can affect the volume and frequency of dredging sediment material.

The Upper Mississippi River Region is also referred to as Water Resources Region 07 (2-digit hydrologic unit code, or HUC, 07). The Upper Mississippi-Black-Root River watershed (encompassing the project area) falls within the 2-digit HUC07 region. A synthesis of peer reviewed climate literature is available from the Corps of Engineers for the Upper Mississippi River Region and is referenced as the primary source of information in this literature review (USACE, 2015). The report concludes that increased average annual precipitation in the region may lead to increases in streamflow. A change in flow regime could affect dredging in the area. Increased annual precipitation can also lead to an increase in erosion and promote additional sediment transport (Melillo et al., 2014). Increased sedimentation would impact the demand for dredging and affect future planning for dredged material placement. These conclusions were based on a large body of research cited which is summarized in the sections below.

3.1 Precipitation

3.1.1 Observed Precipitation Trends

The fourth National Climate Assessment (NCA) considers the science and impacts of climate change within the Continental United States (CONUS) and at a regional scale (Melillo et al., 2014). A map of regions defined in the third (and subsequently the fourth) NCA is shown in Figure 2 below. On a national scale, average precipitation in the United States increased by approximately 4% since 1900 (USGCRP, 2017). Precipitation in the Midwest region (encompassing the study area) increased by 9% since 1991 (Pryor et al., 2014).

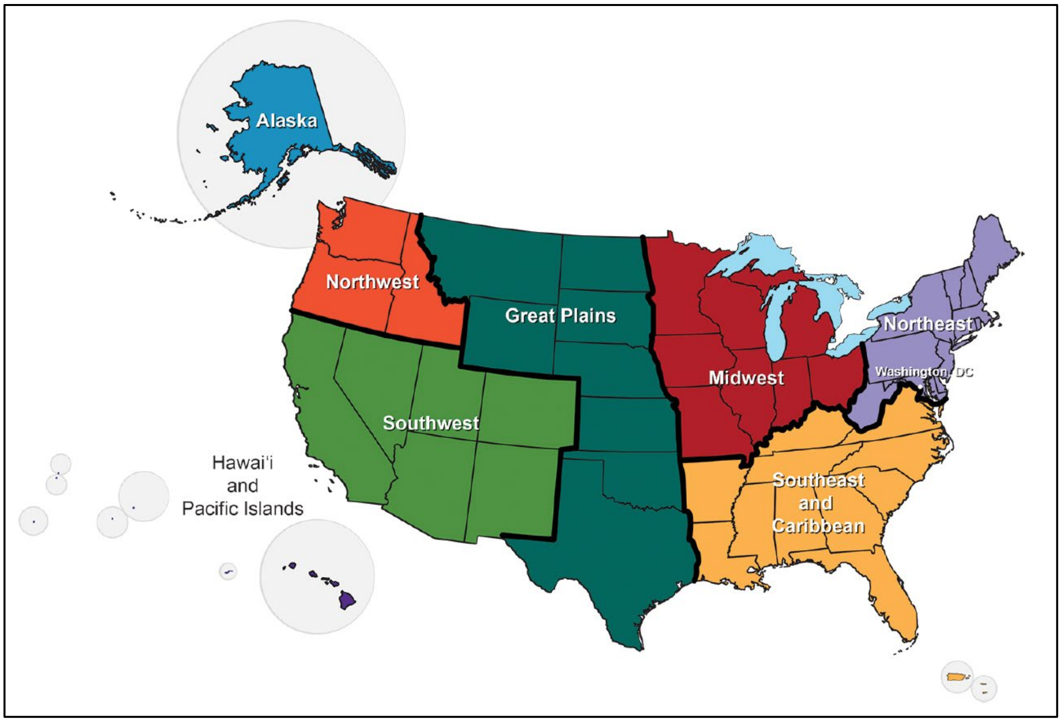

Figure 2 Third National Climate Assessment regional boundaries in CONUS (Melillo et al., 2014)

Increases in the amount of precipitation are primarily driven by intensification of the heaviest rainfall events (Melillo et al., 2014). Heavy, extreme rainfall events are more frequent now than in the past, particularly in the Midwest and Northeast United States during summer and fall months (Melillo et al., 2014). The amount of rain falling in heavy precipitation events in the Midwest is 30% greater than it was relative to a 1901-1960 average. Frequency of heavy precipitation events in the Midwest have increased nearly 37% from 1958-2012 (Pryor et al., 2014). A corresponding increase in frequency of flood events has also been noted in the Midwest United States, where the frequency of heavy rainfall events is greatest (Melillo et al., 2014).

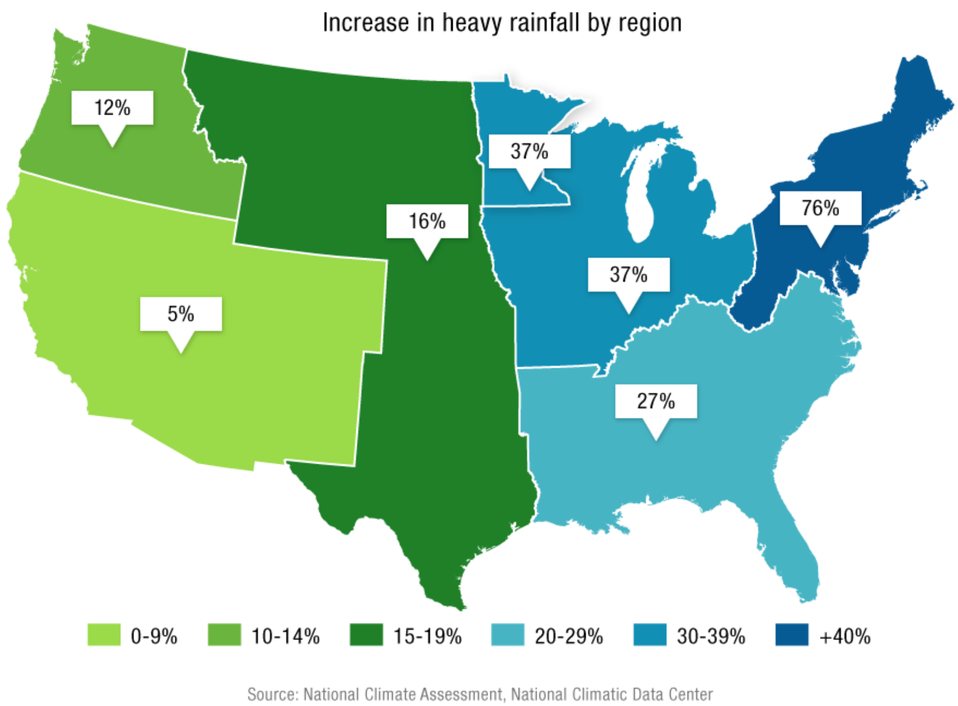

Figure 3 Regional heavy rainfall increases.

Using historical records, multiple authors have identified significant increasing trends in total precipitation for the Upper Mississippi River Basin, which contains the project area. Palecki et al. (2005) quantified statistically significant increases in winter storm precipitation totals for the 1972 to 2002 time period in the Upper Mississippi River Region. Grundstein (2009) identified significant positive linear trends (period 1895-2006) in both annual precipitation and the soil moisture index for multiple sites within the Upper Mississippi River Region. Wang et al. (2009) identified an increasing precipitation trend from 1950-2000 for late summer and fall in central regions of the United States. A study by McRoberts and Nielsen-Gammon (2011) found that the positive trend in annual precipitation indicates an increase on the order of 5%-20% per century (1895-2009 period of record) for the Upper Mississippi River Region.

3.1.2 Projected Precipitation Trends

According to the third NCA, at a global scale, climate models show consistent projections of future increases in precipitation for northern climates under a range of greenhouse gas (GHG) emissions scenarios (Melillo et al., 2014). In addition to increases in annual precipitation, the frequency of heavy storm events is expected to increase relative to current conditions (Melillo et al., 2014). Under a high greenhouse gas emissions scenario (A2 scenario), GCMs project average winter and spring precipitation in 2071-2099 to increase between 10% and 20% for the Midwest United States relative to a 1971-2000 baseline condition (Pryor et al., 2014). Increases in summer and fall precipitation are not expected to be greater than the natural observed variation. Regional climate models (RCMs) for the Midwest using the same emissions scenarios as the previously mentioned study are projected to increase spring precipitation by 9% for the 2041-2062 timeframe relative to the 1979-2000 time period (Pryor et al., 2014). Projected changes in the Northern United States are a consequence of a warmer atmosphere (temperatures, see Section 3.2), which can hold more moisture, and changes in large scale weather patterns. Climate model projections for the Midwest region of the United States indicate a significant increase in annual precipitation (2.4-4.0 inches) by the middle of the 21st century (Melillo et al., 2014). The fourth NCA findings were consistent with findings from the third NCA, with more detail cited in the third edition.

At a regional scale, projections generally showed an increase in average annual precipitation. Projections based on global circulation models (GCMs) assessed by Johnson et al. (2012) for the Upper Mississippi River Basin showed average annual precipitation changes for the 2055 planning horizon compared to a historic baseline. The projections showed an increase in average annual precipitation of 5%-15%. A study by Liu et al. (2013) investigated maximum air temperatures in the Upper Mississippi River Region using a single GCM, which assumes an A2 (high) greenhouse gas emissions scenario. The study forecasted droughts in the region will be more severe in the future, because the effects of projected temperature (see Section 3.2.2) and evapotranspiration increases are expected to outweigh increases in precipitation. Drought severity in the Upper Mississippi River Basin is also anticipated to increase in the future as a result of projected temperature (see Section 3.2.2) and evapotranspiration increases (USACE, 2015).

3.2 Air Temperature

3.2.1 Observed Air Temperature Trends

According to the fourth NCA, observed temperature in the United States increased 1.2-1.8 degrees Fahrenheit since 1895, and the largest proportion of this increase occurred since 1970 (USGCRP, 2017). Much of the warming occurred in recent decades, with the most recent decade at time of the publication being the nation's hottest on record. Since 1991, temperatures rose 1.0-1.5 degrees Fahrenheit over most of the United States relative to a 1901-1960 time period.

Recent work by Pryor et al. (2014) for the Upper Mississippi River Region estimates that from 1895-2012, temperatures in the region increased by an average of 1.5 degrees Fahrenheit. The largest increases by season occurred during the winter and spring months (USGCRP, 2017). Wang et al. (2009) also found a statistically significant trend of increasing air temperature for the winter, spring, and summer months for the 1950-2000 time period across Minnesota; however, a slight decreasing trend was observed in the fall. Johnson and Stefan (2006) identified numerous trends in 20th century hydro-climate data for sites across Minnesota suggestive of a warming climate. These include earlier ice-out dates and later ice-in dates for lakes and earlier spring runoff.

The length of the frost-free season has gradually increased since the 1980s. The last occurrence of freezing temperatures presently occurs earlier in the spring and later in the fall, which suggests a change in the frost-free season length and a potential shift in the timing of seasons (USGCRP, 2017). Nationally, the average frost-free season from 1991-2011 is ten days longer relative to an earlier 1901-1960 timeframe. When compared to the typical season length, the frost-free season length increased by 9 days in the Midwestern United States (USGCRP, 2017). An increase in frost-free season would impact the duration and demand for dredging, as dredging season generally occurs ice-out to ice-in.

3.2.2 Projected Air Temperature Trends

Future temperature projections are estimated using GCMs and various greenhouse gas emissions scenarios. According to the fourth NCA, warming is projected for all parts of the United States during the next century (USGCRP, 2017). Estimates indicate the magnitude of warming will be 2-4 degrees Fahrenheit over the coming decades (Melillo et al., 2014). Even under a lower greenhouse gas emissions scenario, which incorporates assumed reductions in greenhouse gas emissions, by the end of the century it is estimated that temperatures will be roughly 3-5 degrees Fahrenheit greater than present day temperatures. For higher greenhouse gas emission scenarios, warming is anticipated to increase by 5-10 degrees Fahrenheit by the end of the 21st century. The largest temperature increases are expected in the upper Midwestern United States and Alaska (USGCRP, 2017).

In the Midwestern region of the United States, an increase in both annual average temperature and the number of extreme heat days is expected over the next century (Pryor et al., 2014). Increases in extreme heat days has the potential to increase the frequency and duration of droughts in the Midwest (Pryor et al., 2014). By applying a worst case greenhouse gas emissions scenario, Liu et al. (2013) projected an average temperature increase of 2.7-8.1 degrees Fahrenheit in the Upper Mississippi River Region by 2055 compared to a historic study baseline from 1971-2000. It is important to note there is a high degree of uncertainty associated with temperature estimates due to the use of GCMs, the natural variability of temperature, and assumed greenhouse gas emissions scenarios. However, in general, consensus among peer-reviewed studies indicates projected temperatures in Minnesota will rise over the next century, and drought conditions are likely to become more prevalent (USACE, 2015).

3.3 Hydrology

3.3.1 Observed Hydrologic Trends

The fourth NCA (NCA) indicates the magnitude of floods has changed in many parts of the United States (USGCRP, 2017). Due to variations in climate across the country, there is no national trend in flood magnitude; however, flood magnitudes at the regional level have increased in the Midwestern United States (USGCRP, 2017). The regional trends in observed flows are consistent with regional observed climate trends. As precipitation and the frequency of extreme precipitation has increased in the Midwest, so have the number of flood events. Extreme precipitation events now occur more frequently during the summer and fall months. Although the frequency of summer and fall floods has increased, these events are less likely to produce floods as large as spring snowmelt driven floods, in part because the water storage capacity of the soil is typically greater during the summer and fall months (USGCRP, 2017). Spring snowmelt floods can also be exacerbated by the combination of snowmelt and rainfall to produce large scale flooding.

Xu et al. (2013) studied trends in streamflow for multiple gages in the Upper Mississippi River Region using Model Parameter Estimation Experiment (MOPEX) data for 1950-2000. The study found that of 302 watershed gages across the United States, 20%-30% of sites used in the study showed significant increases in streamflow and baseflow and 65% of sites showed non-significant trends. Most of the sites which showed significant increases in streamflow and baseflow are concentrated in the Midwestern United States (Xu et al., 2013). This finding is consistent with what is presented in the fourth NCA: northern climates tend to show increases in streamflow.

At the regional level, Novotny and Stefan (2007) studied 20th century streamflow data from 36 gages in the state of Minnesota. A total of 11 gages were observed in the Upper Mississippi River Basin, including gages near the Pool 5 project site. Trend analysis of flow metrics including mean flow, 7-day low flow, and peak flows were used in the study. The majority of Minnesota stream gages exhibited a statistically significant trend of increasing flows for the period of 1913-2002 (Novotny and Stefan, 2007). Figure 4 below shows a summary of trends in streamflow for several large river basins in Minnesota (Novotny and Stefan, 2007). A strong consensus was found showing an upward trend in mean annual flow, low flows (example: 7-day low flow), and peak streamflow. There is a reasonable consensus among multiple studies that trends show an increase in flow in the Midwest and the Upper Mississippi River Basin (USACE, 2015). Increases in flow may lead to more low-magnitude but high-frequency flood events. These high frequency events are within a sediment transport prompting flow regime, which would affect sedimentation in the project area.

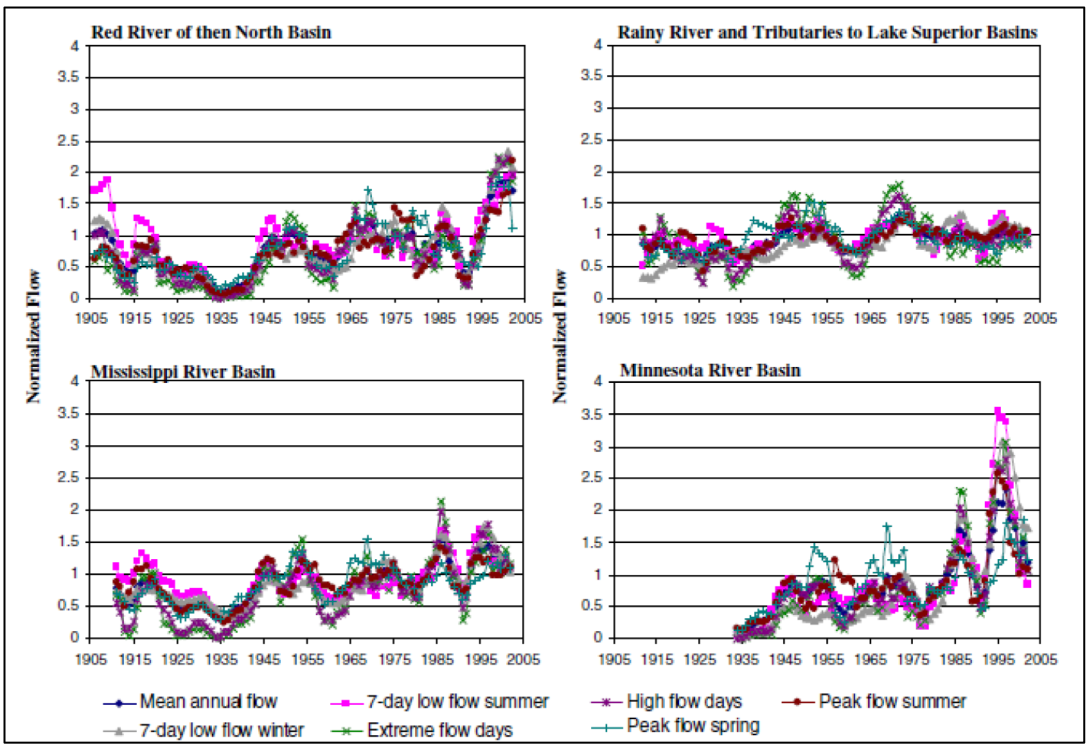

Figure 4 Five year running mean of streamflow statistics averaged for major rivers in Minnesota (Novotny and Stefan, 2007)

3.3.2 Projected Hydrologic Trends

The fourth NCA (NCA) states extreme rainfall events and flooding have increased during the last century (see Sections 3.1.1 and 3.3.1) and these trends are expected to continue in the future (USGCRP, 2017). Large scale flooding in the Midwest Region is typically caused by spring snowmelt and the associated runoff, which can be exacerbated by rainfall. The NCA notes that high magnitude snowfall years are less frequent than in the past, but large-scale flooding is expected from increases in extreme precipitation.

Jha et al. (2006) used Soil and Water Assessment Tool (SWAT) models to assess the effects of potential future climate change on the hydrology of the Upper Mississippi River Basin. The study assessed the effects of nine 30-year (1968-1997) sensitivity runs and six climate change scenarios relative to a baseline scenario. The study noted that precipitation trends in the United States over the past century indicate that average precipitation nationwide has increased by 5%-10% and that the average increase in the Upper Mississippi River Basin is greater than this. The model results indicated a substantial amount of uncertainty in the current GCM projections for the region and, consequently, Jha et al. (2006) did not make definitive conclusions about how changes in climatic variables impact streamflow. Jha et al. (2006) did note it is likely that snowmelt and rainfall have the potential to increase in January, which would result in both an earlier melt and increases in spring streamflow, signaling a potential shift in seasonality.

Notaro et al. (2011) applied 15 different GCMs using three different greenhouse gas emissions scenarios of varying severity (B1, A1B, and A2) to assess the impact of climate change on snow pack in Wisconsin. The results indicated that warmer and wetter winters are anticipated in the future. Snow pack is anticipated to be reduced and earlier snowmelt is expected, resulting in a shortened snow season. As noted above, the frequency of high magnitude snowfall in the Midwest is decreasing, and the frequency of summer and fall floods is increasing. Collectively, these effects could result in a change in seasonality of maximum annual flood peaks from being primarily snowmelt driven in the spring to being primarily rainfall driven in the summer and fall.

The complex interaction between precipitation, temperature, and hydrology make it difficult to state with certainty how climate change will affect future hydrology and streamflow. Increases in precipitation have the potential to increase streamflow; however, corresponding increases in temperature and evapotranspiration could outweigh effects of increased precipitation. As the studies above indicate, no definitive statement can be made to describe how climate change will impact hydrology and streamflow in the region; however, it can be stated with relative certainty that climate change has the ability to alter basin hydrology.

3.4 Sedimentation

High rates of sedimentation increase the need for navigation channel dredging, an important factor in the Pool 5 DMMP project. Studies have been conducted to observe sediment transport in the Upper Mississippi River Basin and the lower Minnesota River Basin, a primary source of sediment to the Mississippi River. Engstom (2009) collected 25 sediment core samples across the flow axis of Lake Pepin. Lake Pepin is located in Pool 4 of the Mississippi River. The study found that sediment accumulation rates have increased by over a magnitude from the beginning of European settlement in 1830 to the 1990s. This increase in sediment accumulation is detailed by a doubled increase at the time of European settlement, followed by a gradual increase at the beginning of the twentieth century and then a sharp rise from 1940 to 1960 (Figure 5). Sediment accumulation rates then plateaued during the 1970s, but were observed to have peak values from the preceding two decades, when the study was completed.

Changes in land use should be taken into account when observing the data. Settlement in Minnesota significantly impacted the landscape as agriculture increased, which is separate from climate change.

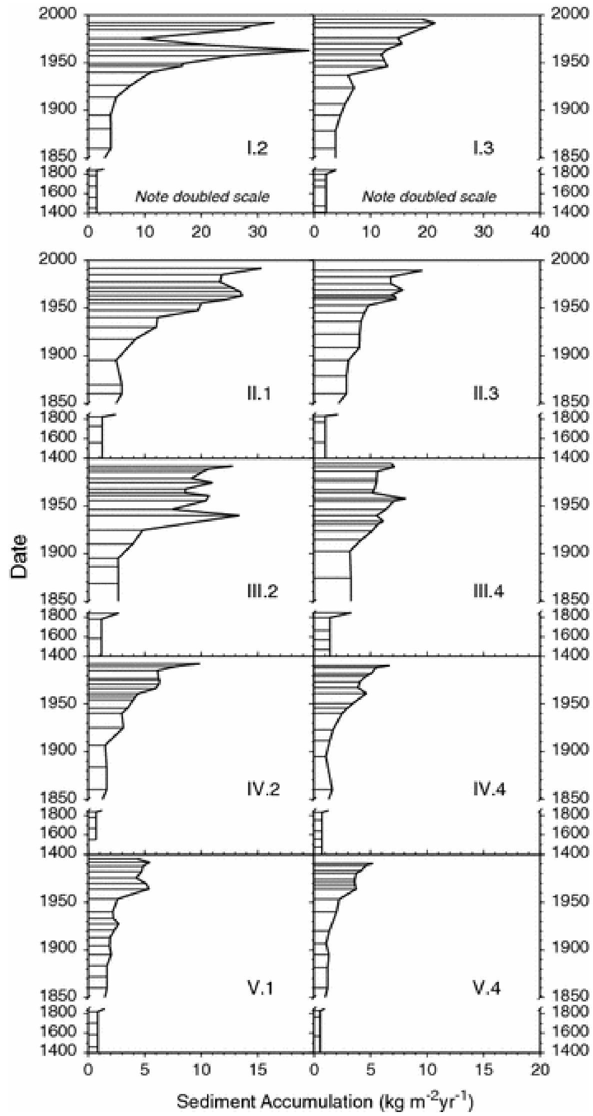

Figure 5 Sediment accumulation rates versus sediment age for 10 detailed cores (Engstrom et al. 2009)

Johnson et al. (2015) studied 20 large watersheds in the United States (including the Minnesota River Basin) and assessed the response of watershed runoff and water quality to several projected climate change scenarios. The study used six climate change scenarios adopted from the North American Regional Climate Change Assessment Program (NARCCAP) and dynamically downscaled for climate model output. Two time periods were simulated in the SWAT model, 1971-2000 and 2041-2070 for past and potential conditions. Variance between the simulated changes in total suspended solids, total phosphorus load, and total nitrogen load among the studied watersheds were related to different sediment and nutrient sources, soil erosion, and biogeochemical cycling. Based on the six NARCCAP scenarios, the mean increase in simulated annual total suspended solids load for the Minnesota River basin was approximately 50% by 2070. The mean increase in simulated annual total phosphorus load was approximately 25%. The mean increase in simulated annual total nitrogen load was approximately 45% (Johnson et al., 2015). According to the study, 78% of land surrounding the Minnesota River is used for agriculture. This could account for the projected increases in sediment and nutrient loads. Due to the influence of the Minnesota River on sedimentation in the Mississippi River, total suspended solids could be expected to increase in the Mississippi River and consequently study area under the assumed conditions of the modeled scenarios.

The link between climate change and sedimentation is not well studied, and it is difficult to draw conclusions regarding how climate change will impact sediment load to a watershed (Johnson et al., 2015). The magnitude of precipitation and frequency of storm events has increased over the observed period of record and is expected to increase in the future (Walsh et al., 2014). Increases in precipitation intensity may increase erosion and promote additional sediment transport (Melillo et al., 2014). The study conducted by Novotny and Stefan found increases in mean annual flow for the Upper Mississippi River. Mean annual flow and low flow relates to flow regimes that can advance sedimentation in the project area.

3.5 Summary

A summary of the findings from the *Recent US Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Water Resources Region 07, Upper Mississippi* is included in Figure 6 below. In general, temperature, precipitation, and streamflow have increased over the observed period of record for the region. Projected increases in temperature and precipitation are anticipated in the future. Projections of future hydrology are uncertain due to the complex interaction between temperature, evapotranspiration, and soil moisture deficits. Projected increases in precipitation could increase streamflow; however, increases in temperature and evapotranspiration could outweigh additional runoff from precipitation causing streamflow to decrease. An increase in streamflow would promote sedimentation and sediment transport from project area tributaries, as low and normal flow conditions are projected to increase. It should be noted that changing land use since settlement in the 1830s has also impacted observed increases in erosion and streamflow, a separate mechanism from climate change. All of these projected variables would have an impact to the study area and dredging activity for the future.

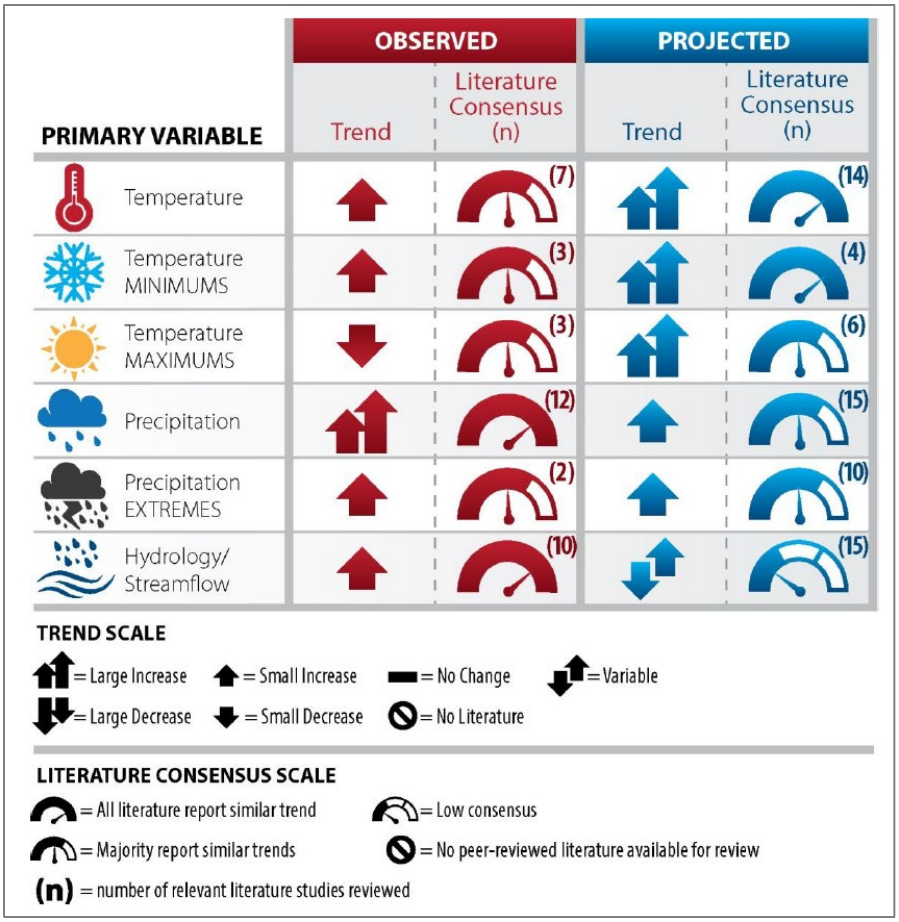

Figure 6 Summary matrix of observed and projected climate trends and literary consensus (USACE, 2015)

4 Trends in Observed Records

The important hydrologic variables affecting the project include water surface elevation (stage) and river discharge (water surface elevation is directly proportional to river discharge). Discharge can give indication to behaviors of potential sediment transport, as it is the main driver of how sediment travels through a system. There is limited data available on sediment transport, particularly in the study area so conclusions are best drawn from discharge trends. The concept of sediment transport is important in dredging because it reflects the amount of material in the river channel.

Besides fluctuations in climate, stage can be influenced by long-term geomorphic change, changes to Lock and Dam operating plans, and gage relocation. Discharge can be influenced by changes in upstream water storage due to dam construction, changes in land-use, and measurement techniques. These factors make it difficult to determine the role of climate change in affecting the hydrologic signal at the project scale. The relevant question to answer at the project scale is whether there has been, or will be, a hydrologic change that will affect dredging frequency for the future. Discharge was selected as the primary hydrologic variable to analyze for this project.

4.1 Gage Data

The Mississippi River at Winona, MN USGS gage (ID 05378500) is the best representation of streamflow for the project area (Pool 5) and is used for the climate assessment. The continuous period of record for daily discharge and annual instantaneous peak flow at this site is 1928-2018, in full water years. The gage recorded sediment data from 1975-1987. This short period of record was difficult to draw conclusions for trends in sediment transport so it was not included in the assessment.

The USGS gage at Winona, MN is approximately 12.0 miles downstream of Lock and Dam 5 and Pool 5. The USGS gage at Prescott, WI was considered; however, the gage at Winona was selected due to the relatively similar watershed size and inclusion of the Zumbro and Chippewa River (Wisconsin) as significant tributaries. The records at the Winona gage are considered good, according to the USGS website. Nonetheless, flow is influenced by power operations at the Prairie Island Power Plant, located upstream in Pool 3 of the Mississippi River. Additionally, there are various power and flood control projects located along the Chippewa and Flambeau Rivers that are tributaries just upstream from Pool 4. The drainage area for Pool 5 is estimated to be approximately 59,277 mi^2 and the drainage area above the Winona gage is approximately 59,620 mi^2.

None of the Locks and Dams upstream or along the Mississippi River itself are thought to adversely impact the annual peak discharges seen at Pool 5. Since the hydraulic structures in the area do not store water, they are not anticipated to have an impact on the annual average discharge for the Mississippi River at Winona, MN USGS gage. In fact, when flows are high enough, the gates of the Locks and Dam affected by high flows are lifted out of the water column after which the flow has a free run of the river.

The Chippewa River at Durand, WI USGS gage (ID 05369500) is a tributary of the Mississippi River into Pool 4. The gage has a period of record from 1930-2019. The stream has considerable influences from regulation and reservoir operations, so cannot be used for comparison of peak flow data and non-stationary. However, annual volumetric flow, which is not affected by flood control or power regulation, can be examined for patterns of change over the period of record and will be presented in sections following with the Winona analysis.

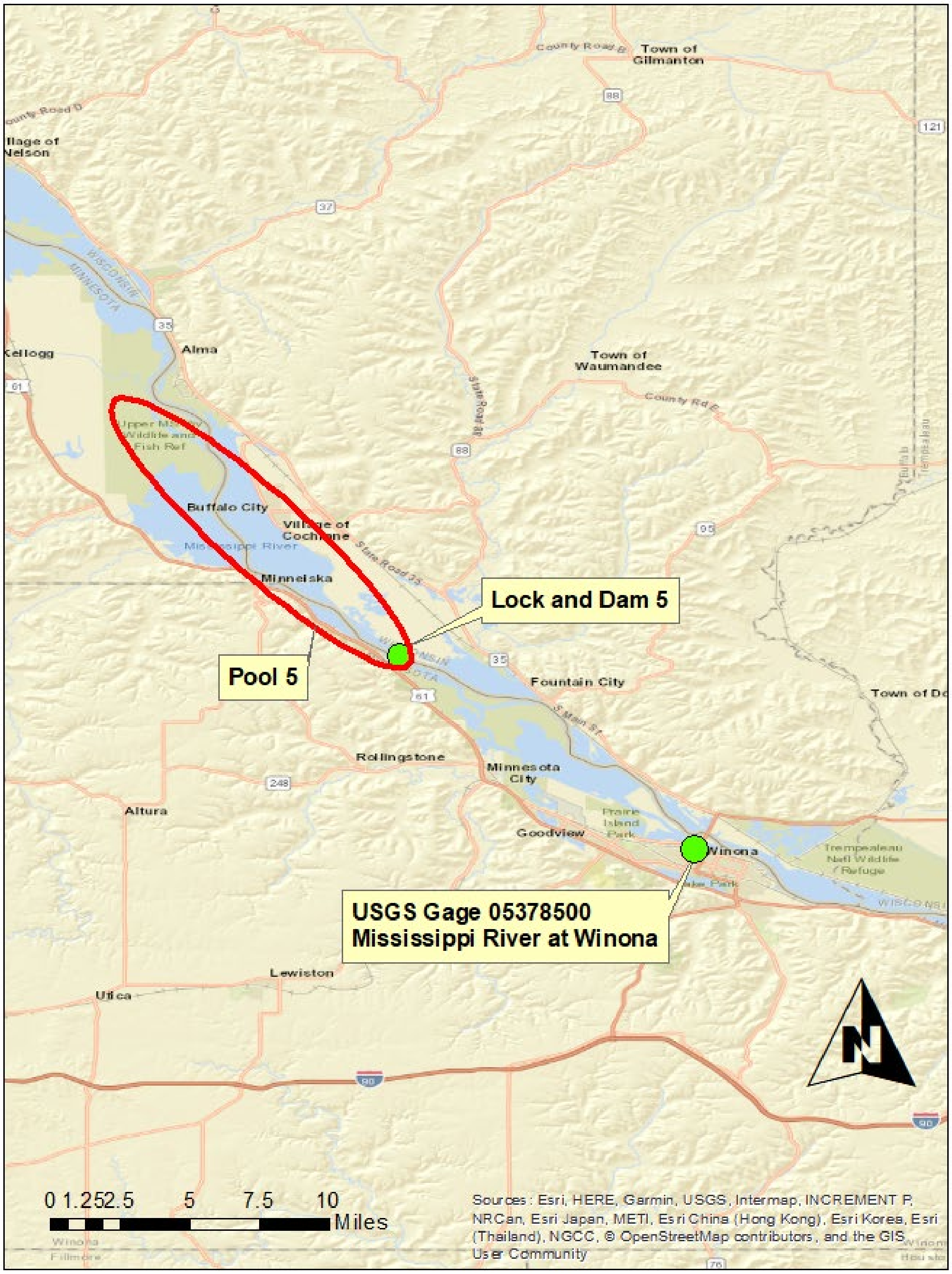

Figure 7 Streamflow gage used for analysis (Department of the Interior 2019b)

4.2 Peak Streamflow

Annual peak flow data was analyzed to determine if there are any patterns in observed discharge that might provide insight into future hydrologic conditions in the project area. Peak streamflow is relevant to navigation projects because it could indicate changing high flow regimes in the area. As noted in the USGS information on the Winona gage, peak streamflow is a good representation for natural flow conditions in the area, i.e. unregulated. The stationarity of the flow record at the Mississippi River at Winona, MN USGS gage (ID 05378500) is assessed by applying a series of twelve statistical test to the observed peak flow record using the USACE Nonstationarity Detection (NSD) tool with default settings in the Timeseries Toolbox (USACE, 2019a). These settings apply statistical tests to detect the presence of nonstationarities in data. The statistical tests can be grouped into mean-based, variance-based, and distribution-based. The results can be seen in Figure 8 below. Trend lines are fit to the data using regression techniques. The relative strength of a detected nonstationarity is evaluated using criteria of consensus, robustness, and magnitude.

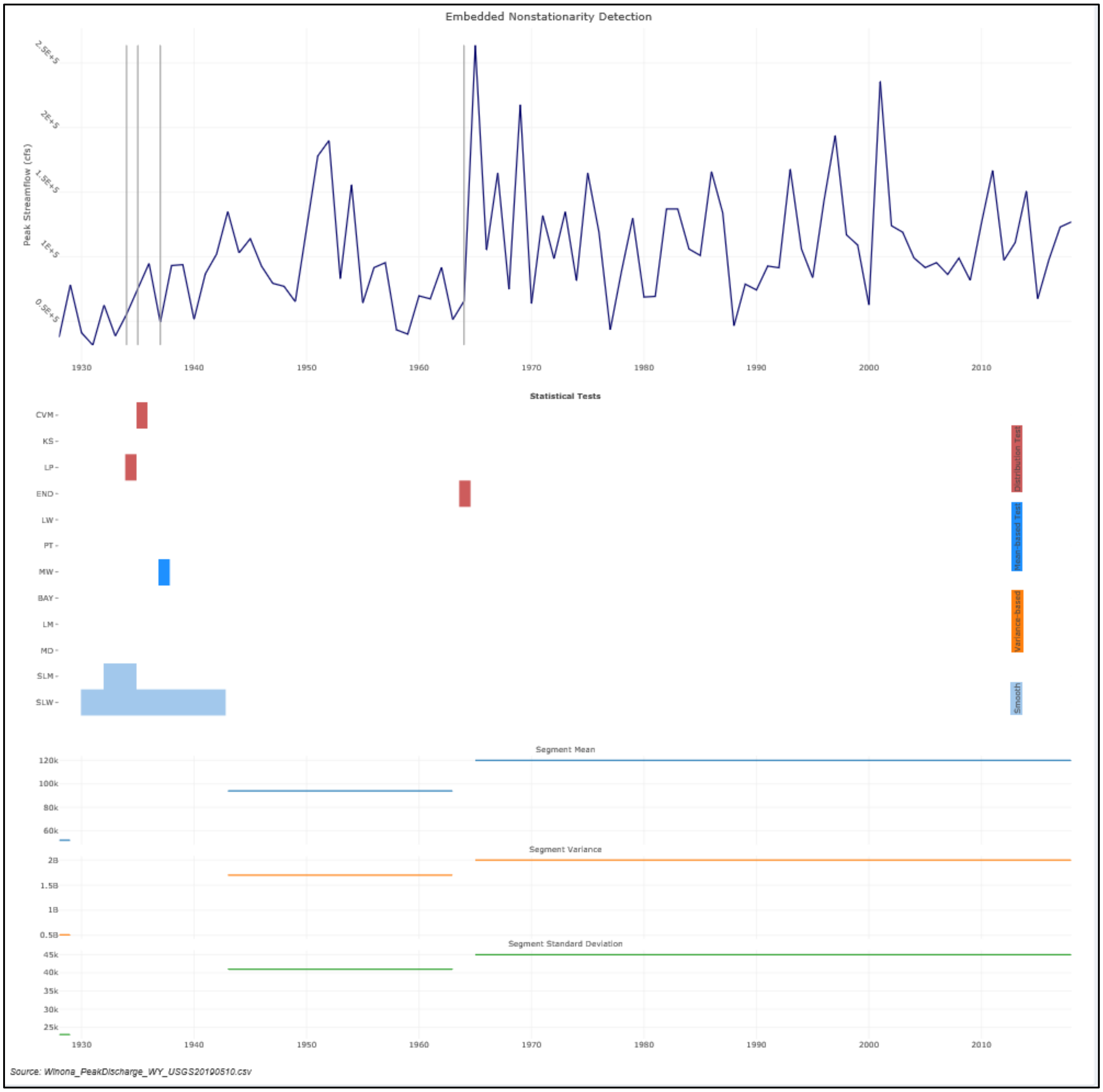

Figure 8 Nonstationarity detection results for Mississippi River at Winona, MN USGS gage (ID 05378500)

Nonstationarities were detected in 1934, 1935, 1937, and 1964. The relative strength of each nonstationarity is determined by considering the level of consensus between different statistical tests targeted at detecting the same type of nonstationarity (e.g. a change in the variance/standard deviation, mean, or distribution) in the flow data series. If consensus is not found for a given year or a short period of time, it is reasonable to discount the nonstationarity (Friedman et al., 2016). In accordance with the guidance, the 1934, 1935, and 1937 change points are under the same consideration to meet the criteria for consensus, because they are within five years of each other. Consensus between two different statistical tests showed changes in distribution for the two change points.

A second criterion for adopting nonstationarities as significant indicators of change is robustness. Robustness is achieved when tests targeting changes in two or more different statistical properties (mean, variance/standard deviation, and overall distribution) indicate a statistically significant nonstationarity. For example, robustness would be achieved if at least one test indicated a change in the mean and another test indicated a change in standard deviation in the same year. Again, 1934, 1935, and 1937 meet the criteria of robustness because significant changes in the mean and distribution of the annual peak flows were detected.

A third criterion for detection of significant nonstationarities is a change in magnitude of the annual peak flows. Changes in magnitude are noted in the segment mean, variance, and standard deviation for 1965. Since the 1965 change point did not meet the consensus and robustness criteria, it is not considered a strong change point. The 1934, 1935, and 1937 change points could not be determined for magnitude changes because the segmented statistical properties were not plotted. This could be due to the Smooth Lombard Wilcoxon being applied at the start of the period of record to 1943, where the first segment mean, variance, and standard deviation begins.

Using the strong nonstationarity indicators detected in 1934, 1935, and 1937, a monotonic trend analysis was performed for annual peak streamflow recorded at the Mississippi River at Winona, MN USGS gage (ID 05378500) for two periods: 1928-2018 (systematic record) and 1938-2018 (post latter change point). A p-value less than 0.05 is generally accepted as statistically significant, and this threshold is adopted for this assessment. For the 1928-2018 time period (the entire period of record), both the Mann-Kendall Test and Spearman Rank Order Test determined a statistically significant positive trend, with p-values of 0.00037 and 0.00023, respectively. See Figure 9 and Figure 10 for the annual peak flow monotonic trend analysis results for the Mississippi River at Winona, MN gage from 1928-2018.

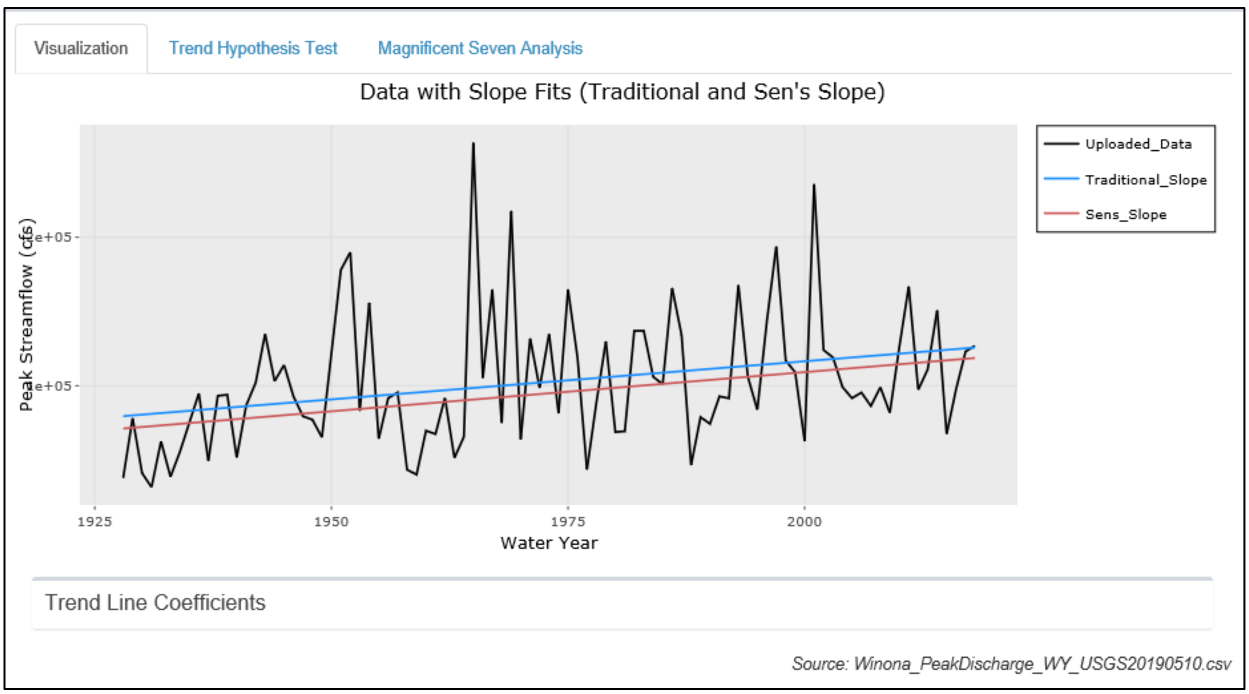

Figure 9 Annual peak flow monotonic trend analysis for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500), 1928-2018

Visualization | Trend Hypothesis Test | Magnificent Seven Analysis

Test	P.Value
t-Test	0.0035601
Mann-Kendall	0.00036788
Spearman Rank-Order	0.00023036

- **A statistically significant trend (at the alpha = .05 level) was detected by the Mann-Kendall Test.**
- **A statistically signifnicant trend (at the alpha = .05 level) was detected by the Spearman Rank-Order Test.**

Source: Winona_PeakDischarge_WY_USGS20190510.csv

Figure 10 Annual peak flow monotonic trend analysis for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500), 1928-2018

Figure 11 and Figure 12 shows the annual peak flow monotonic trend analysis results for the Mississippi River at Winona, MN gage from 1938-2018. For this timeframe, both the Mann-Kendall Test and Spearman Rank Order Test did not detect a significant trend with p-values of 0.1045 and 0.0864, respectively. Looking at the post change point monotonic trend analysis provides evidence that a significant trend is not observed amongst annual peak flows for the Mississippi River at Winona, MN USGS gage (ID 05378500).

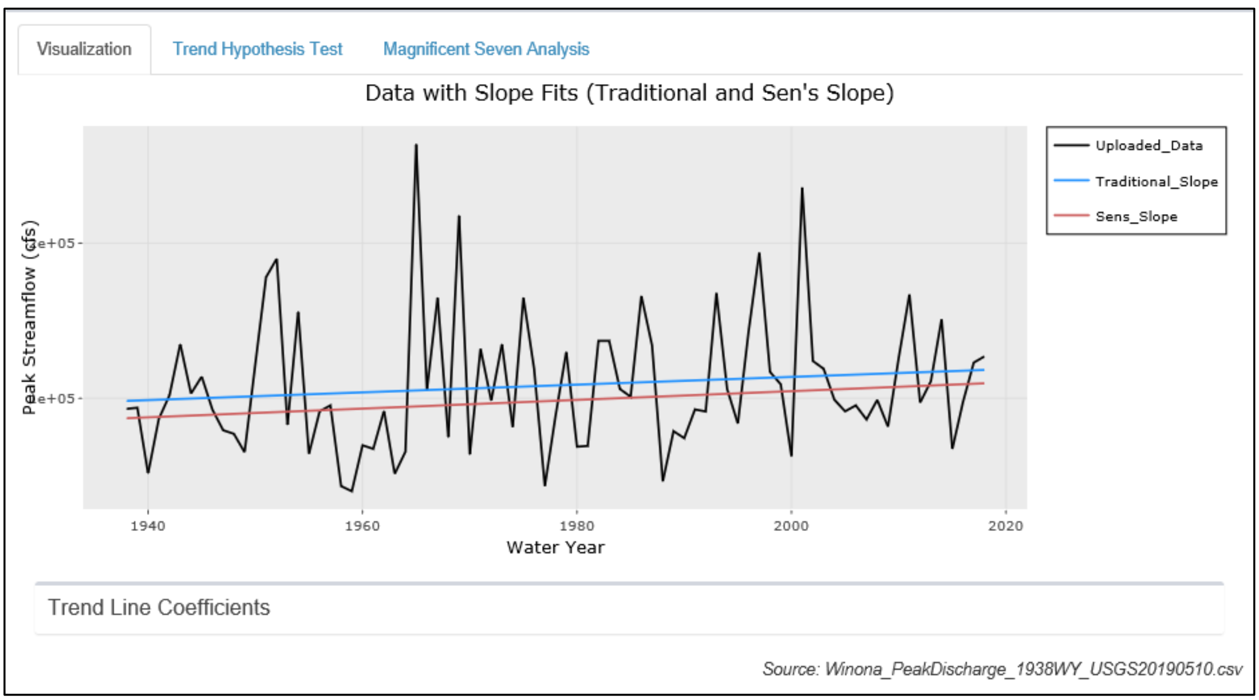

Figure 11 Annual peak flow monotonic trend analysis for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500), 1938-2018 (post change point)

Visualization | Trend Hypothesis Test | Magnificent Seven Analysis

Test	P.Value
t-Test	0.23294
Mann-Kendall	0.10453
Spearman Rank-Order	0.086419

- **A statistically significant trend (at the alpha = .05 level) was NOT detected by the Mann-Kendall Test.**
- **A statistically signifnicant trend (at the alpha = .05 level) was NOT detected by the Spearman Rank-Order Test.**

Source: Winona_PeakDischarge_1938WY_USGS20190510.csv

Figure 12 Annual peak flow monotonic trend analysis for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500), 1938-2018 (post change point)

4.3 Annual Average Discharge

Observed annual average discharge for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500) was analyzed for trends in streamflow (Department of the Interior, 2019a). The USGS indicates that low and medium flow regimes at the gage are influenced by upstream regulation. Regulation is from the Prairie Island power plant (they use water for cooling) and impoundments on tributaries. The Prairie Island power plant is not used to store water and therefore is unlikely to have any impact on the natural flow regime of the river. The drainage area of tributary streams which are affected by regulation is considerably smaller than the drainage area at the Mississippi River at Winona, MN USGS gage and have a negligible impact on the annual average discharge volume. Regulation began in Pool 5 with the construction of the locks and dams in 1936, so the majority of the period of record should reflect consistent operation. In other words, trends in flow could still indicate changing flow regimes outside of regulation, like climate change.

Microsoft Excel 2013 was used to calculate average annual discharge using the water year and apply a test for statistical significance. Over the entire period of record (1928-2018), a statistically significant positive trend was identified, as shown in Figure 13. The p-value of 4.45×10^{-8} was significantly lower than the generally accepted threshold for significance of less than 0.05, which indicated a strong trend when the entire period of record is used. It should also be noted that regulation and operation of reservoirs often lower flow, so an increasing trend could indicate other affecters in higher flows, like changes in land use or climate.

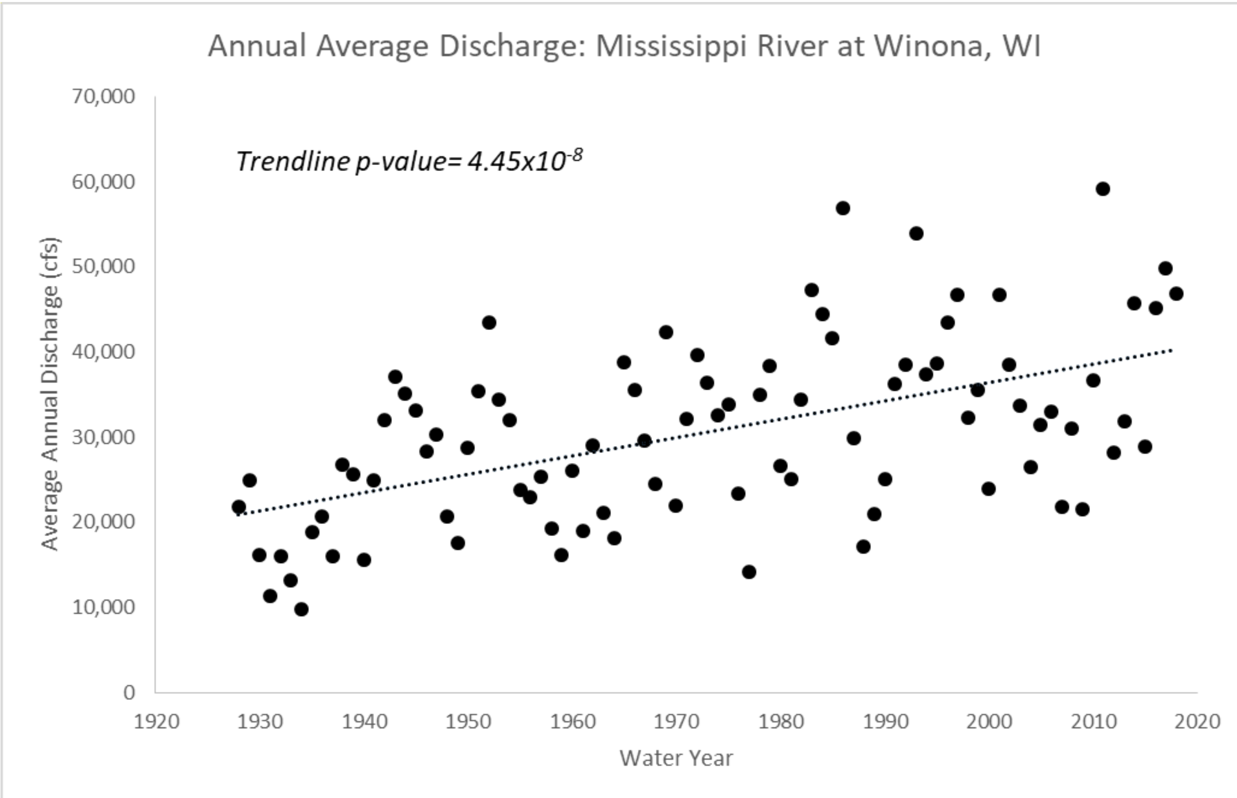

Figure 13 Annual average discharge for the Mississippi River near Winona, MN USGS Gage (Gage ID 05378500), 1928-2018

A separate qualitative assessment of climate change was prepared for the Pool 3 North and Sturgeon Lakes in 2016 (USACE, 2016a). According to the *Qualitative Assessment of Climate Change for Mississippi River North and Sturgeon Lakes*, the 1930s and early 1940s were a periods of extremely low flows (drought) on the Mississippi River, corresponding with dry climatic conditions across the Upper Midwest and Great Plains region (USACE 2016a). Engstrom et al. (2009) indicated that discharges in the Mississippi River were persistently low in the 1920s and 1930s and substantially higher beginning in the early 1940s, especially during the 1980 to present time period (Engstrom et al., 2009). The plot in Figure 13 Annual average discharge for the Mississippi River near Winona, MN USGS Gage (Gage ID 05378500), 1928-2018

13 shows that flows were generally greater after the early 1940s. The NSD tool uses linear regression modeling to determine if there are breakpoints to segment the data for separate analysis. A breakpoint was detected in 1940, which supports the notion that the dust bowl era flows are not part of the stationary period of record.

Due to the effects of the dry conditions in the 1930s and early 1940s, a separate trend analysis of average annual flows is performed for the period of record from 1940-2018 and is shown in Figure 14. The low p-value in Figure 13 may be potentially influenced from the large number of low flow years in the early period of record (1928-1940). When the 1941-2018 period of record is considered (excluding the dry years), the positive trend produces a p-value of 0.0013 which is still less than the accepted significant threshold of 0.05. The 1941-2018 period of record also includes years after construction of the locks and dams. This exclusion of dry years and consistent period of locks and dams operation validates the statistical significance of the average annual flow for the entire period of record.

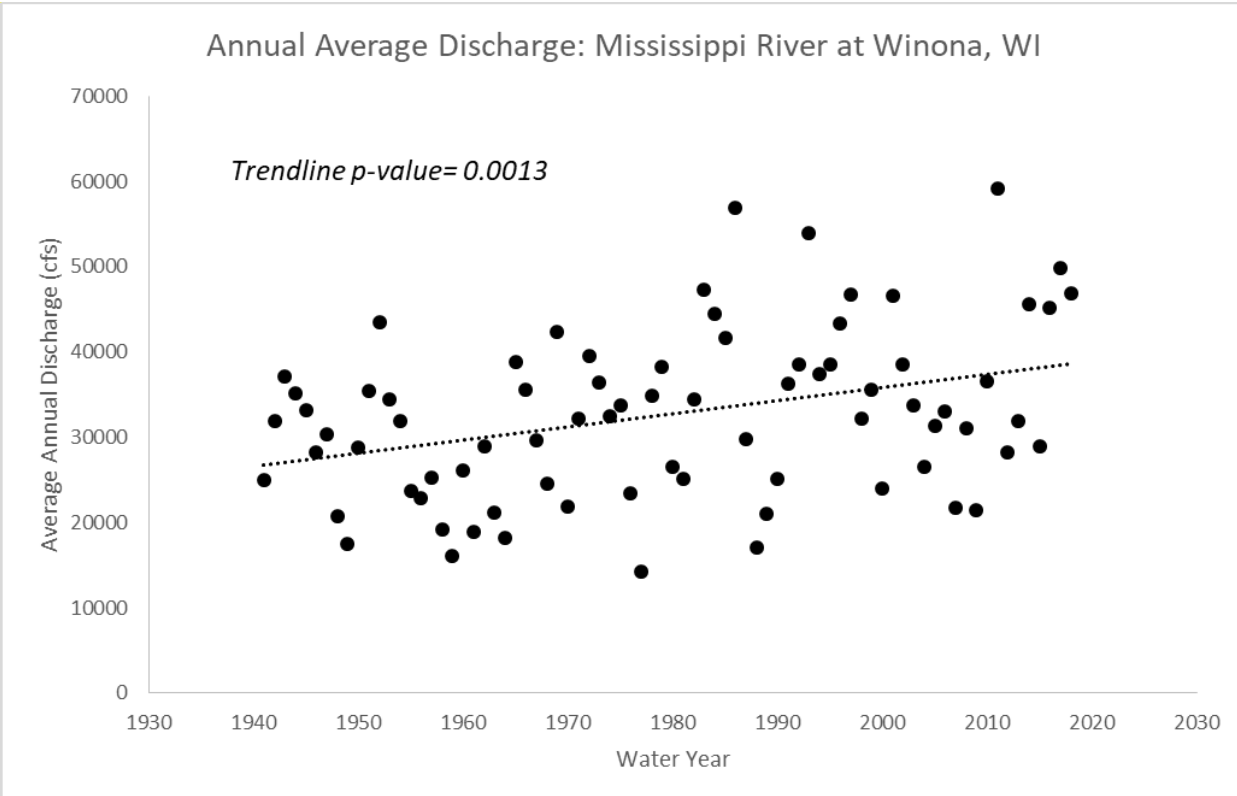

Figure 14 Annual average discharge for the Mississippi River near Winona, MN USGS Gage (Gage ID 05378500), 1941-2018

Additionally, an analysis was done on the annual average discharge for the Trempealeau River at Dodge, WI, one of the tributaries that flows into Pool 6, but is downstream of the Winona gage. The entire period of record for the gage is 1914-2018, however, there is a gap of no recorded data from 1920-1933 so the period from 1934-2018 was analyzed. There is a positive trend in the observed annual average streamflow for the tributary with an accepted statistical significance (p-2.38×10^{-7}). With no locks and dams operation affecting the data from the Trempealeau River at Dodge, WI gage, this increase in natural streamflow supports the concept of an increase in flow which is driven by climate and land use rather than hydraulic structures.

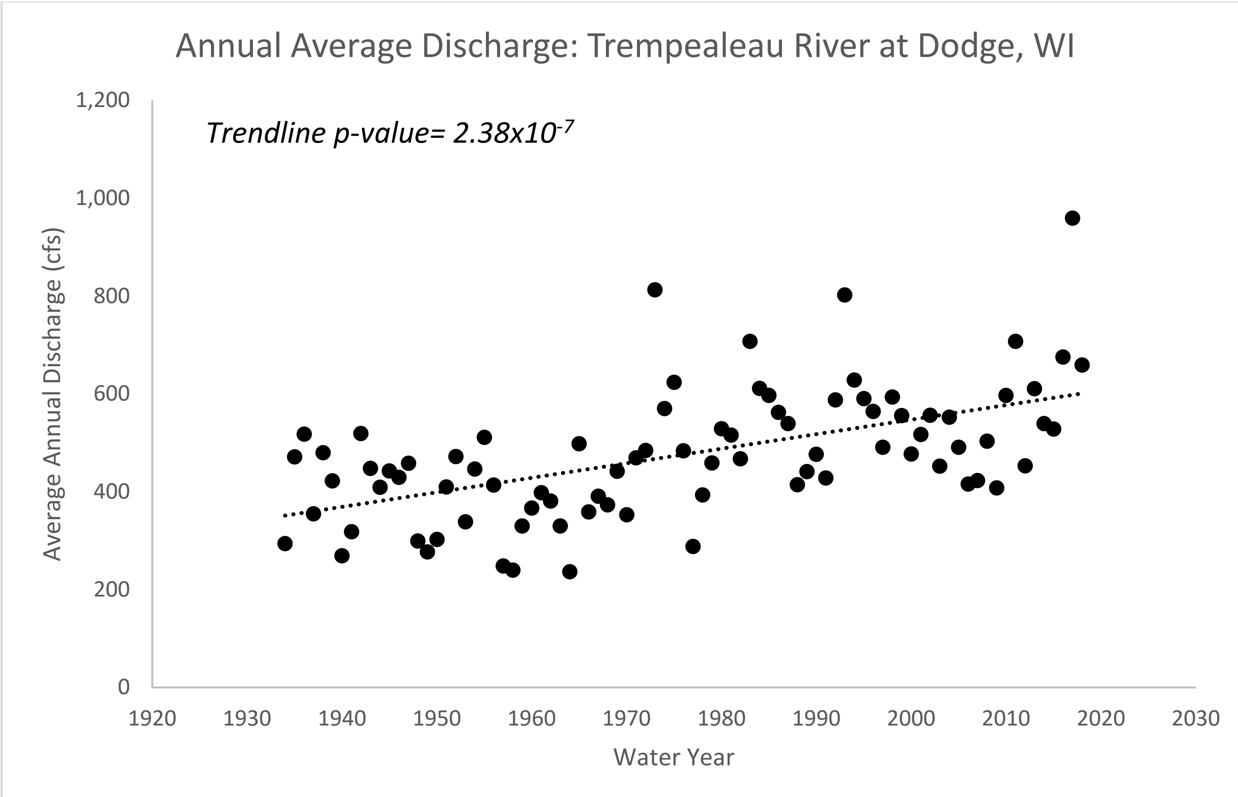

Figure 15 Annual average discharge for the Trempealeau River near Dodge, WI USGS Gage (Gage ID 05379500), 1934-2018

In the Upper Mississippi River Region, the general consensus is that recorded flows during the latter part of the 20th century were higher than flows during the first part of the 20th century (see Section 3.3.1). In prior work, the USACE and Engstrom et al. (2009) identified the year 1980 as a useful break point when comparing the early and late portions of observed flow records (USACE, 2014). The average annual discharge for the Mississippi River at Winona, MN (Gage ID 05378500) was compared between the time periods: 1928-1980, 1981-2018, 1941-1980, 1928-2018, and 1941-2018 to observe any changes in the project area. Summary statistics for these periods are shown in Table 1: Annual average discharge for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500)

Time Period	Mean	Standard Deviation	P-Value	Trend Significance
1928-1980	26,312	8,477	0.0012	Yes
1981-2018	36,462	10,423	0.7004	No
1941-1980	28,950	7,585	0.8371	No
1928-2018	30,550	10,502	4.45E-08	Yes
1941-2018	32,610	9,779	0.0013	Yes

below.

There was a 28% increase in the average annual flow for the 1981-2018 time period compared to the 1928-1980 time period. A significant positive trend was identified for the period 1928-1980, 1928-2018, and 1941-2018. No significant trend was identified for 1981-2018 or 1941-1980. The inter-annual variability in annual average discharge increased for 1981-2018 relative to 1928-1980 (1981-2018 standard deviation: 10,423 cfs, 1928-1980 standard deviation: 8,477 cfs). The inter-annual variability in annual average discharge increased for 1981-2018 relative to 1941-1980 (1981-2018 standard deviation: 10,423 cfs, 1941-1980 standard deviation: 7,585 cfs). The mean discharge increased for the 1941-2018 time period relative to the 1928-2018 time period but the variability decreases. The identified drought years early in the period of record would account for the decreased inter-annual variability.

Shorter duration records often have more variability, but it could also indicate a change in average discharge over time. It can be observed from Table 1 that time periods that end later in the period of record show increased average annual discharges and variability. The study by Engstrom observed an increase in flow starting in the 1940s, with the trend becoming more apparent from the 1980s to the present day. The article noted that changes in land use after the European settlement in the 1830s and climate change could be factors in the increase of discharge over time. Increases in discharge variability poses issues in dredged material planning and navigation. This increase in discharge could impact the frequency of dredging due to sedimentation, depending on the flow regime.

Table 1: Annual average discharge for the Mississippi River at Winona, MN USGS gage (Gage ID 05378500)

Time Period	Mean	Standard Deviation	P-Value	Trend Significance
1928-1980	26,312	8,477	0.0012	Yes
1981-2018	36,462	10,423	0.7004	No
1941-1980	28,950	7,585	0.8371	No
1928-2018	30,550	10,502	4.45E-08	Yes
1941-2018	32,610	9,779	0.0013	Yes

Finally, annual discharge volume was examined at the Chippewa River at Durand gage, which is approximately 17 miles upstream from the confluence with the Mississippi River where it empties into Pool 4. Figure 16 shows the upward trend observed in the gage record at Durand. The p-value significance is 0.015, which indicates a significant trend toward greater discharge volumes at the gage. The observations at the Durand gage are in agreement with the other gage analyses in the area that show higher discharge volumes over time. Higher discharge volumes are linked to greater potential for sediment transport and potentially greater sediment loading to Pool 4, directly upstream of Pool 5.

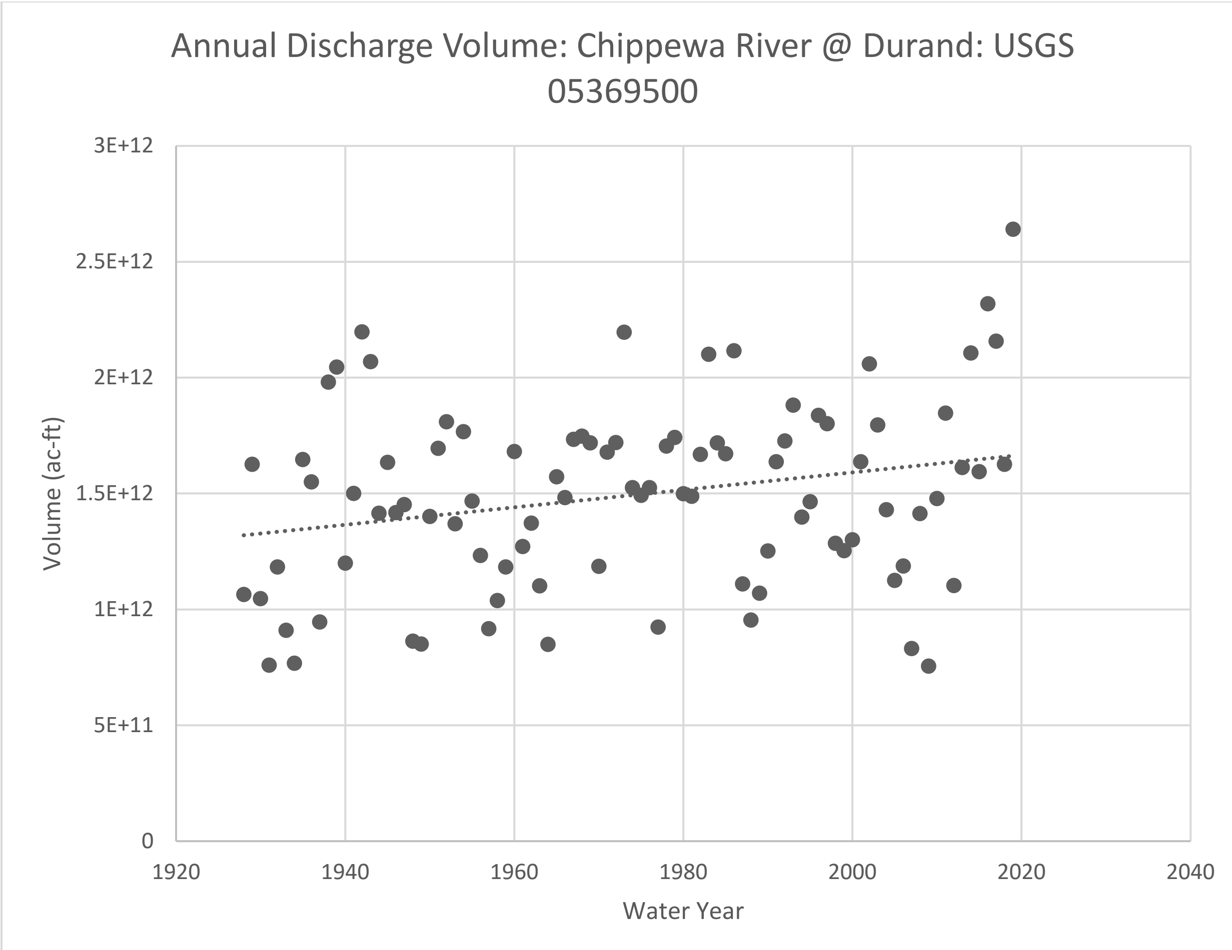

Figure 16: Annual average discharge for the Chippewa River near Durand, WI USGS Gage (Gage ID 05369500), 1930-2018

5 Projected Trends and Watershed Vulnerability

5.1 USACE Climate Hydrology Assessment

The USACE has developed tools to project future streamflow and assess vulnerability to climate change at a regional scale. These tools were used to project changes to basin hydrology in response to climate change that are relevant to navigation projects. HUC4 0704, the Upper Mississippi-Black-Root watershed shown in Figure 16, encompasses the project area and was used for this analysis.

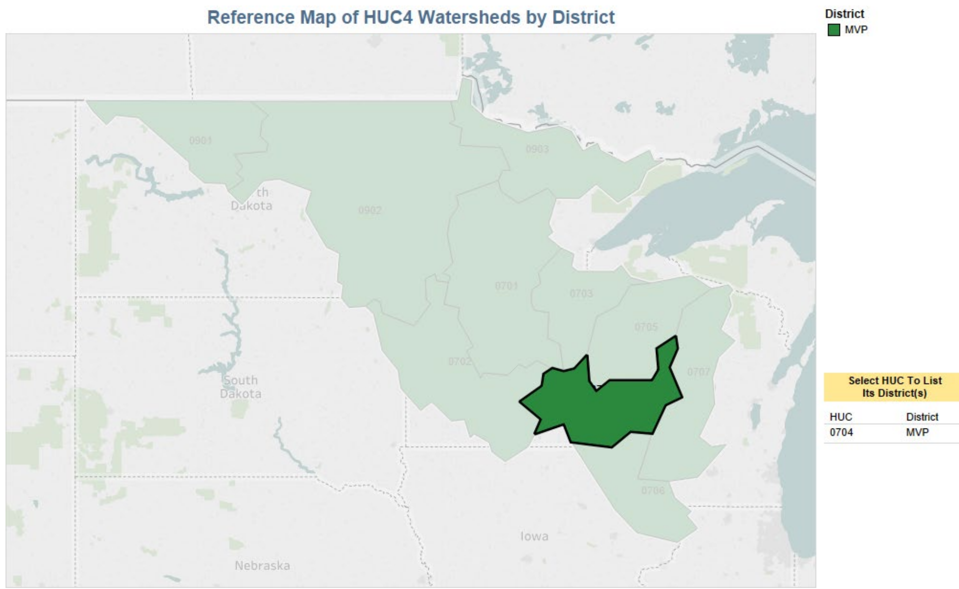

Figure 17 Reference map of HUC2 and HUC4 watersheds

The USACE Climate Hydrology Assessment Tool (CHAT) was used to investigate potential future trends in streamflow for the HUC4 0704 watershed. Hydrologic model output is generated using meteorological inputs derived based on 93 different combinations of representative concentration pathways (RCPs) of greenhouse gas emission scenarios and Global Circulation Models (GCMs). Couplings of RCPs and GCMs are used to project precipitation and temperature data into the future. These meteorological outputs are spatially downscaled using the bias corrected spatially downscaled (BCSD) statistical method and then inputted into the Variable Infiltration Capacity (VIC) precipitation-runoff model, developed at the University of Washington (Liang, et al., 1994). The VIC model (and thus the climate assessment tool and vulnerability assessment tool) simulates unregulated basin conditions.

Figure 17 displays the range of projected annual maximum monthly streamflows computed from 93 different climate-changed hydrologic model runs for the period 1980-2099. There was considerable but consistent spread in the projected annual maximum monthly flows. This spread is indicative of the high degree of uncertainty associated with projected, climate-changed hydrology.

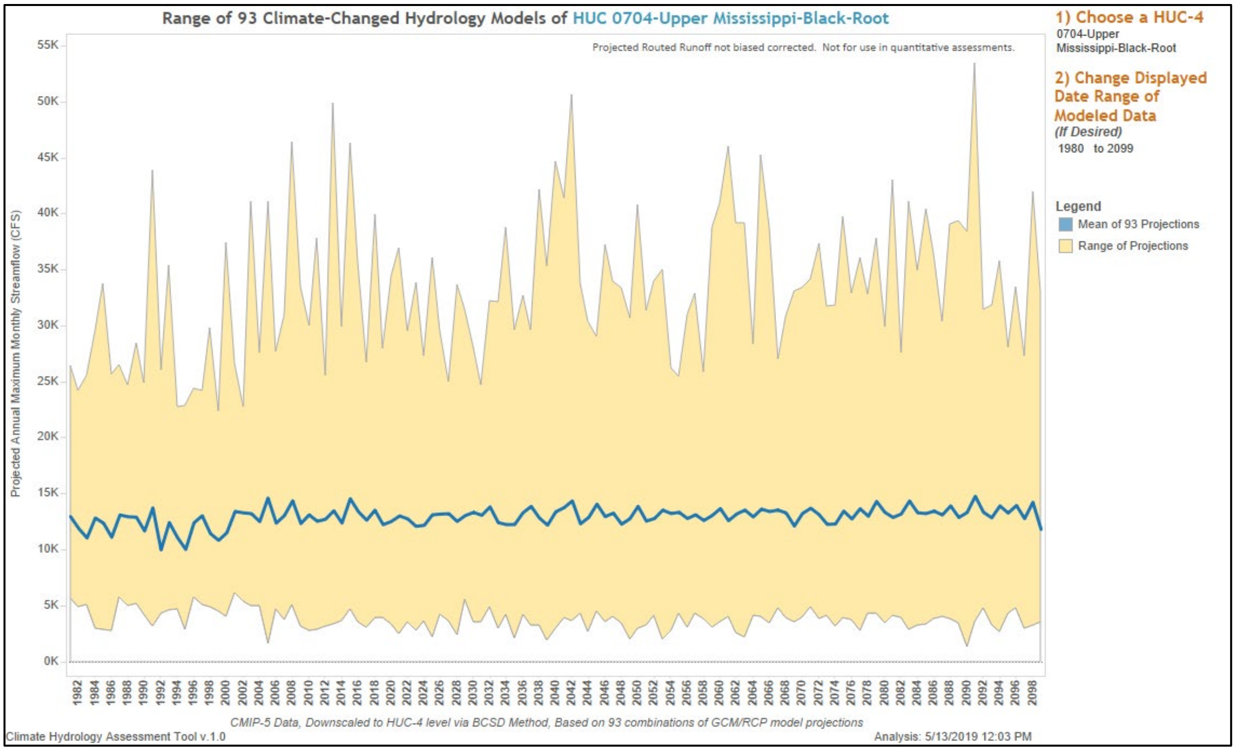

Figure 18 Range of projected maximum monthly streamflow for years 1980-2099 within HUC4 0704

The overall trend in the mean projected annual maximum monthly streamflow (the blue line) is shown above in Figure 17. The trend was statistically significant with a p-value of less than 0.0001 (much less than the generally accepted significance threshold of 0.05). A positive trend suggests there is potential for annual maximum monthly streamflow to increase in the study area over the next century, relative to current conditions. However, even though flows are projected to increase, this trend may not be operationally significant. The CHAT tool uses the best available climate information to make an assessment of whether or not flows will increase in the future. However, due to the nature of the climate models and the high degree of uncertainty associated with the models, a quantitative increase cannot be determined. Based on the information presented, it is likely that flows average annual maximum monthly streamflow will increase in the region. This could promote erosion and sediment transport through the project area. The increase in maximum streamflow and promotion of sediment transport would impact dredging activity in Pool 5. Sedimentation to the area would increase the need for dredging in the area and require more planning for material placement.

5.2 USACE Watershed Climate Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment (VA) Tool was used to compare the relative vulnerability to climate change of the HUC4 0704 watershed to the 130 navigable HUC4 watersheds across the continental United States (CONUS) with respect to Navigation. The tool facilitates a screening level, comparative assessment of how vulnerable a given HUC4 watershed is to the impacts of climate change. The tool can be used to assess the vulnerability of a specific USACE business line, such as Navigation, to projected climate change impacts. Assessments such as these help to identify and characterize specific climate threats, at least in a relative sense, across regions and business lines.

The VA tool uses the Weighted Order Weighted Average (WOWA) method to represent a composite index of how vulnerable a given HUC4 watershed is to climate change specific to a given business line. This WOWA index is also known as the Vulnerability Score. The HUC4 watersheds with the top 20% of WOWA scores are flagged as being vulnerable. Indicators considered within the WOWA score for Navigation include: change in sediment load, two indicators on low flow runoff exceeded 90% of the time, drought severity index, flood magnification (indicator of how much high flows are projected to change over time), mean monthly runoff, low flow reduction, area of floodplain in 0.2% Annual Exceedance Probability (AEP), and percentage of urban/suburban land cover.

When assessing future risk projected by climate change, the USACE Climate Vulnerability Assessment Tool makes an assessment for two 30-year epochs centered at 2050 and 2085. These two periods were selected to be consistent with many of the other national and international analyses. The tool assesses how vulnerable a given HUC4 watershed is to the impacts of climate for a given USACE business line using climate hydrology based on a combination of projected climate outputs from the global circulation models (GCMs) and representative concentration pathway (RCP), resulting in 100 traces per watershed per time period. The top 50% of the traces are called “wet,” and the bottom 50% of traces are called “dry.” Meteorological data projected by the GCMs is translated into runoff using the Variable Infiltration Capacity (VIC) macroscale hydrologic model. For this assessment, the default National Standards Settings (NSS) were used to carry out the vulnerability assessment.

Figure 18 shows the results of the USACE Watershed Climate Vulnerability Assessment Tool. Based on these results, the Upper Mississippi-Black-Root (HUC4 0704) watershed is not vulnerable to the impacts of climate change on navigation projects relative to the other 129 HUC4 watersheds in the continental United States. For the Upper Mississippi-Black-Root watershed, the major drivers of the computed vulnerability score are Flood Magnification, the Runoff/Precipitation Ratio, Monthly Low Flow 90% Exceedance, and Low Flow Reduction. Table 2 shows the vulnerability scores for the two 30-year epochs. The scores are relatively constant between both epochs as well as between their wet and dry scenarios. This consistency in scores between both scenarios and epochs could be an indicator for a projected wetter climate susceptibility for the Upper-Mississippi-Black-Root watershed. Table 3 lists the vulnerability score contribution from each indicator for the 2050 epoch. The dominating indicators for the wet and dry scenarios were flood magnification and low flow reduction, respectively. The flood magnification indicator score for the wet scenario indicates an increase in flood flow occurrences. The dry scenario score on the low flow reduction indicates an increased value for low flow conditions. While the HUC4 0704 watershed is not vulnerable in a relative sense, it may still be vulnerable in an absolute sense.

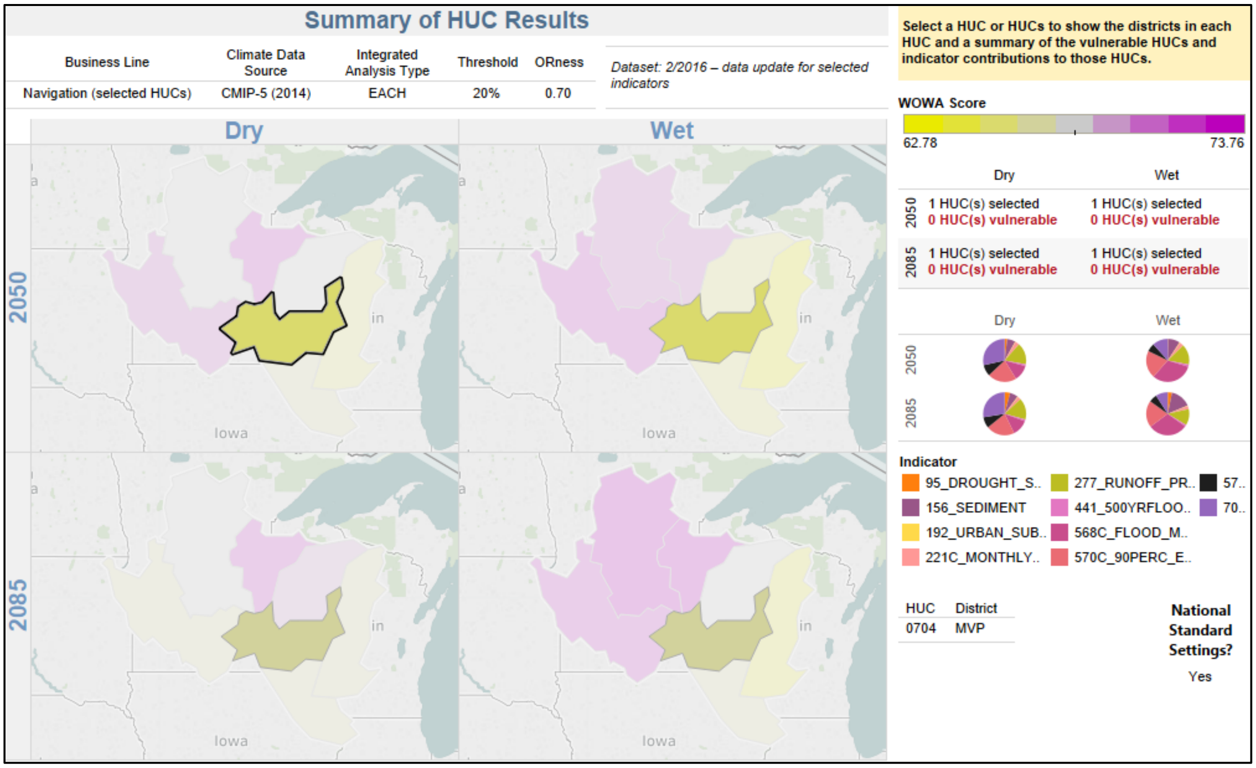

Figure 19 Projected vulnerability for the HUC4 0704, Upper Mississippi-Black-Root watershed

Table 2 Projected vulnerability with respect to navigation for HUC4 0704

HUC4 Watershed	Navigation Vulnerability (WOWA) Score			
	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Upper Mississippi Black Root	66.3	65.88	66.748	66.96

Table 3 Comparison of indicators for navigation for HUC4 0704, 2050 epoch

Indicator	Contribution to WOWA Score	
	Wet	Dry
Flood Magnification- Cumulative	20.898	7.893
Drought Severity Index	0.207	1.237
Cumulative Monthly Low Flow 90% Exceedance	13.61	14.46
Sediment	5.908	4.173
Low Flow Reduction- Cumulative	7.68	18.94
Runoff/ Precipitation Ratio	10.126	10.843
Local Monthly Low Flow 90% Exceedance	4.055	5.586
Mean Monthly Runoff- Cumulative	1.9646	2.009
Area in 0.2% AEP Floodplain	1.115	0.905
Land Cover Urban/Suburban	0.3104	0.2521

There is a moderate degree of uncertainty with the climate-changed hydrology projected by the vulnerability assessment tool, as each of the tool's inputs has uncertainty. The uncertainty associated with projected hydrologic data includes errors in temporal downscaling, errors in spatial downscaling, errors in hydrologic modeling, errors associated with emissions scenarios, and errors associated with GCMs. Some of the uncertainty associated with the tool can be visualized, because the tool separates results for each of the scenarios (wet versus dry) and epoch (2050 versus 2085) combinations rather than presenting a single, aggregate result (USACE, 2016b). Beyond the uncertainties associated with inputs to the vulnerability assessment tool, the analysis also contains substantial uncertainty inherent in the exact level of risk aversion selected (ORness factor) and the importance weights applied. Some users may elect to use a higher level of risk aversion while others may not. The importance weights of the indicator variables used to compute the WOWA (vulnerability) scores are subjective, and there is no way to quantify which indicator variables are more important than others when making projections about vulnerability. The user should note that the uncertainty with climate-changed hydrology projects is high and is currently not readily quantifiable; however, the VA tool can help to indicate which watersheds may be more vulnerable than others to impacts from climate change.

6 Risk Assessment

Identified risks to the project can be observed in Table 4. With the project being a DMMP, the main measures assessed for risk are dredging and dredged material placement. Future DMMPs for Pool 5 should consider the potential increases in dredged material and assess material placement location capabilities.

Table 4 Climate risk identifiers for Pool 5 DMMP

Feature or Measure	Trigger	Hazard	Harm	Qualitative Likelihood
Channel Dredging	Increased precipitation	Increases in low and normal flow regimes.	Changes in flow regimes could have an effect on channel accessibility for dredging.	Likely
Dredged Material Placement	Increased precipitation	Increases in low and normal flow regimes.	Increased sediment transport and sedimentation in the channel could occur with increases in flow regimes, potentially increasing the demand for dredged material placement.	Likely

7 Conclusion

USACE Watershed Climate Vulnerability Tool indicates that the Upper Mississippi-Black-Root watershed is not highly vulnerable to the impacts of climate change on navigation projects relative to other HUC4 watersheds in CONUS. However, it is still vulnerable in an absolute sense. The climate change literature review concluded that an increased average annual precipitation in the region may lead to variation in the flow regime, which could affect dredging in the area. An increase in precipitation and annual discharge volumes would promote erosion and increased sediment transport, also affecting dredging activity and future planning for dredged material placement. Available literature suggests a warmer and wetter climate in the future. Observed increases in air temperature could impact durations of future frost-free seasons. Observed trends in average annual discharge of the Mississippi River at Winona, MN were analyzed for statistical significance and concurred with findings in the literature review. Over the period of record (1928-2018), a statistically significant positive trend was identified in average annual discharge. Analysis was also done for the years 1941-2018 to account for dry years in the 1930s and 1940s, as well as regulation for the basin. A statistically significant positive trend line was observed for the discharge for this time period as well. This positive trend line was also observed on the Chippewa River at the Durand gage, as well as on the Trempealeau River gage. Changing flow conditions will likely have effects on future dredging efforts in Pool 5, although the extent of those effects cannot be known with great accuracy. Based on this assessment, the recommendation is to treat the potential effects of climate change and long-term natural variability in climate as occurring within the uncertainty range calculated for the current hydrologic analysis.

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