US Army Corps of Engineers®
St. Paul District

Appendix I – Climate Change Assessment

Riverbank Stabilization Project Feasibility Report and Integrated Environmental Assessment

Section 203 Tribal Partnership Program

2023

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Attachment

1 Qualitative Assessment of Climate Change

This assessment discusses potential climate vulnerabilities facing the Upper Sioux Community and Lower Sioux Community Tribal Partnership Program (TPP) streambank erosion protection projects along the Minnesota River. The locations of each TPP streambank erosion protection project is shown in the attached Plate I. This assessment highlights the project's existing and future challenges due to climate change, following Engineering Construction Bulletin *(ECB) 2018-14*, revised 19 Aug 2022. Background information on each TPP project is listed in their respective main reports. Information on climate-affected risks to projects and assessments thereof can be found in *ECB 2018-14*.

Both TPP projects evaluate how to stabilize and protect a streambank from continued erosion, from both high river velocities and overtopping of the bank. The most important variable which affects erosion at the project sites is discharge and the high velocity of flow from the Minnesota River. Increased discharge results in increased velocity and stage which promotes erosion and sediment transport. High flow conditions can be a function of spring snowmelt runoff or flooding from rainfall events. The relevant variables considered in this climate assessment are temperature, precipitation, and how they affect streamflow. Streamflow is also a relevant climate change variable. The Minnesota River hydrologic unit code (HUC-4) 0702 basin is in the Upper Mississippi River Region (HUC 07), shown in Plate I.

The objective of both TPP projects is to reduce erosion and land loss along the Minnesota River in order to conserve natural resources and improve access to the river to support tribal cultural practices. Both TPP projects analyze alternatives consisting of erosion protection (riprap) at the top of the bank, erosion protection at the toe of the bank, installation of bendway weirs (see Figure 7 in main report), bank reshaping, and vegetation plantings. A rock overflow section was also considered for the Upper Sioux Community TPP project. The residual risk tables at the end of this report note which features are included in the Tentatively Selected Plan (TSP) for each project.

1.1 Literature Review

A literature review of peer-reviewed sources assesses how climate change affects temperature, precipitation, and runoff from the watershed. The primary source of information included in the literature review is the *2018 Fourth National Climate Assessment*, or *NCA* (USGCRP, 2017, 2018). Findings from the *2015 Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions* (USACE, 2015) and regional and local sources are included to supplement information from the *Fourth NCA* as needed.

1.1.1 Temperature

The observed annual average air temperature between 1986-2016 for the Midwest has increased by 1.26°F relative to the 1901-1960 period (USGCRP, 2017). Work by Pyror et al. (2014) for the Upper Mississippi River region estimates that from 1895-2012, temperatures in the area increased by an average of 1.5°F (Pryor et al., 2014). Wang et al. (2009) verified Prior et al.'s (2014) findings, which found positive, statistically significant trends in observed mean air temperature for most of the United States for 1950-2000. A similar trend is observed for the winter, spring, and summer months, with a slightly decreasing trend in air temperatures observed during the fall months (H. Wang et al., 2009).

An analysis of spring temperatures and ice-out dates using climate gages in Minnesota by Johnson and Stefan (2006) shows earlier ice-out dates and later ice-in dates for lakes and earlier spring runoff throughout Minnesota. The results from this study correlate well with observed increases in air and water temperature across Minnesota and suggest a change in seasonality in the region, potentially extending the warm season length and shortening the cold season length (S. Johnson & Stefan, 2006). A longer warm season could mean more precipitation events falling in the form of rain rather than snow which would contribute to the erosion of the TPP projects.

Millet et al. (2009) analyzed weather station temperature data from 1906-2000 within the prairie pothole region encompassing the Minnesota River basin. The findings indicate that mean temperature increased throughout the 20th century by 1.8 degrees Fahrenheit (Millett et al., 2009). Johnson and Stefan (2006) show that temperatures generally increased in the prairie pothole region throughout the last century; however, daily minimum temperatures warmed while daily maximum temperatures cooled, which reduced the diurnal temperature range. The mean temperature increased throughout the region, even though the maximum daily temperatures cooled slightly (Johnson and Stefan, 2006).

The Minnesota Department of Natural Resources (MN DNR) notes that Minnesota has warmed by 2.9°F between 1895 and 2017 (MN DNR, 2019). Temperatures are increasing, especially during the winter months (MN DNR, 2019). Since 1970, the winter has warmed 13 times faster than summer, and the nights have warmed 55% faster than the days (MN DNR, 2019). Overall, there is consensus among multiple sources that mean air temperatures increased in the United States and the Upper Mississippi River region, including the Minnesota River (USACE, 2015).

The *2018 Fourth National Climate* Assessment applies downscaled general circulation model (GCM) results from Coupled Model Intercomparison Project Phase 5 (CMIP5) suite of models to project temperature. Annual average temperature is projected to increase in the Midwest (USGCRP, 2017). The average annual temperature is expected to rise by 4.21°F by mid-century (2036-2065) and 5.57°F by late-century (2071-2100) relative to the baseline period of 1976-2005 under an RCP 4.5 emissions scenario. Warming is projected to increase 5.29°F by mid-century and 9.49°F by late-century under a higher RCP 8.5 GHG emissions scenario relative to the baseline period (USGCRP, 2017).

By applying a worst-case greenhouse gas emissions scenario (A2), Liu et al. (2013) projected an average temperature increase of 2.7 to 8.1 degrees Fahrenheit in the Upper Mississippi River region by 2055 compared to a historic study baseline from 1971-2000 (Liu et al., 2013). 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. In general, the consensus among the studies indicates that projected temperatures in Minnesota will rise over the next century, and drought conditions are likely to become more prevalent (USACE, 2015).

1.1.2 Precipitation

Average precipitation in the United States has increased 4% from 1901-2015, and heavy precipitation events in most parts of the United States have increased in intensity and frequency since 1901 (USGCRP, 2017). Annual average precipitation in the Midwest has increased 5%-15% for the 1986-2015 period relative to the 1901-1960 period (USGCRP, 2018). Fall precipitation increased the most for these same periods with a 15% increase (USGCRP, 2017). This finding is supported by Wang et al. (2009), who studied climate trends across the United States using gridded records from 1950-2000. The authors identified significant positive trends in annual precipitation for the Upper Mississippi River region, particularly in the summer and Fall (H. Wang et al., 2009). Trends in annual precipitation for Minnesota show that the state has become an average of 3.4 inches wetter from 1895 to 2017 (MN DNR, 2019). Increases in precipitation may potentially contribute to higher runoff and streamflow, contributing to erosion at the TPP project sites.

The amount of heavy precipitation falling in daily events that exceeded the 99th percentile of all non-zero precipitation data (i.e., top 1% of daily events) increased by 42% from 1958-2016

(USGCRP, 2017). The frequency of extreme events has also increased. The number of 2-day precipitation events exceeding the mean for a 20% exceedance probability (5-year recurrence interval) event, expressed as a percentage difference from the 1901-1960 computed mean precipitation, is displayed in Figure 1-1 below and shows an increase in the number of heavy precipitation events throughout the record, especially after 1970 (USGCRP, 2017).

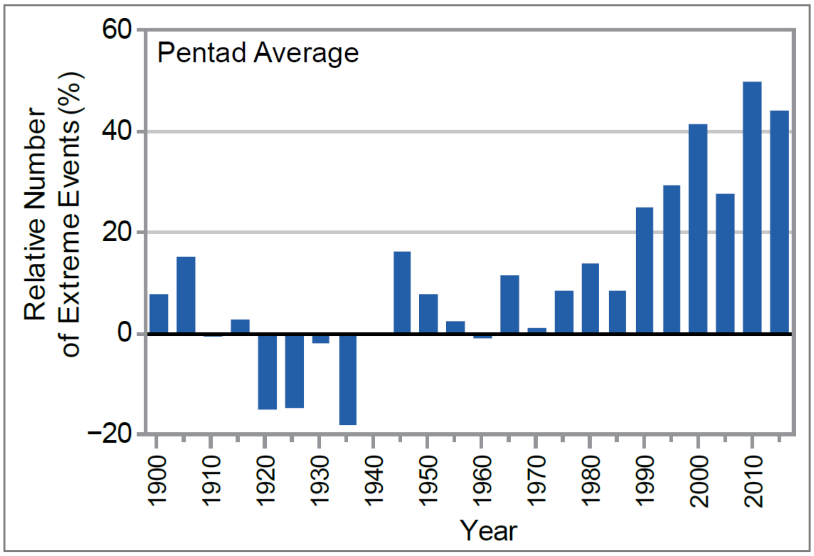

Figure 1-1 2-Day Precipitation Events Exceeding the 20% exceedance probability (5-Year Recurrence Interval) (USGCRP, 2017)

Wang and Zhang (2008) used historical data and downscaled GCMs to study changes in extreme precipitation across North America, focusing on changes in the frequency of the 5% exceedance probability (20-year recurrence interval) maximum daily event. The authors found a 33% increase in the 5% exceedance probability (20-year recurrence interval) event between the early record (1949-1976) and the later period (1977-1999) for the Upper Mississippi River region (J. Wang & Zhang, 2008).

The frequency and intensity of heavy precipitation events are projected to increase over the 21st century (USGCRP, 2017). It is anticipated that many parts of the United States will see a shift to precipitation falling as rain rather than snow during the cold season within the central United States (USGCRP, 2017).

According to the *2018 Fourth NCA*, The number of days with precipitation amounts greater than the 95th percentile of all non-zero precipitation days is anticipated to increase by more than 25% nationally. Climate projections indicate a shift to more precipitation falling during heavy, extreme events and less precipitation falling during typical events (USGCRP, 2017).

The *2018 Fourth NCA* studied how the 5% exceedance (20-year) daily precipitation event will change using Locally Constructed Analogs (LOCA) downscaled data and a lower GHG emissions scenario (RCP4.5) and a higher GHG emissions scenario (RCP8.5) for the mid and late 21st century. Under a lower emissions scenario, the projected change in the 5% exceedance (20-year) event daily precipitation amount is estimated to increase by 10% and 11% by mid-century and late-century, respectively (USGCRP, 2017). Under a higher emissions scenario, the 5% exceedance (20-year) event daily precipitation is anticipated to change by 13% and 20% by mid-century and late-century, respectively (USGCRP, 2017). The same study indicates that increases in daily precipitation for the 1% exceedance (100-year) event will be about 30% greater by the end of the century under a higher RCP8.5 emission scenario (USGCRP, 2017). Increases in extreme rainfall events can contribute to a rapid runoff response of the Minnesota River watershed and increased high flow conditions that would erode the streambanks along the Minnesota River.

GCM based projections assessed by Johnson et al. (2012) for the Upper Mississippi River Basin show average annual precipitation changes for the 2055 planning horizon compared to a historical baseline. The projections show an increase in average annual precipitation of 5% to 15%. Collectively, the studies indicate that yearly precipitation, extreme precipitation totals, and event frequency are likely to increase within the Upper Mississippi River region and the Minnesota River Basin.

Drought severity is also anticipated to increase (T. Johnson et al., 2012). Increases in drought could hinder the establishment and survival of vegetation on the banks which protects the project from streamflow erosion. Drought conditions may also increase erosion from the land to the water which would impact the health of the ecosystem.

1.1.3 Hydrology and Sediment Transport

The hydrologic cycle is a dynamic relationship between temperature, precipitation, and evapotranspiration that strongly influences trends in streamflow. Changes in watershed land use also influences the hydrologic cycle in a watershed. The majority of the Minnesota River basin under pre-European settlement conditions consisted of deciduous forest, native grassland prairie, and wetlands which have been converted to row crops and pasture (U.S. Army Corps of Engineers St. Paul District, 2020). Large-scale improvements to surface and subsurface drainage networks have occurred throughout the watershed since European settlement, with many improvements to subsurface drainage beginning in the 1940s. Around 1940, a shift in cropping patterns occurred where corn and soybeans replaced small grains (MPCA, 2015). This expansion in row crop agriculture was coupled with increased construction of artificial drainage networks that influenced local and regional hydrology (MPCA, 2015).

The artificial drainage network, especially subsurface tile drains, has resulted in increased runoff and sediment transport to the Minnesota River (U.S. Army Corps of Engineers St. Paul District, 2020). Artificial drainage established hydrologic connectivity to previously isolated prairie potholes and wetlands, decreased the amount of time it takes for runoff from the watershed to reach the rivers, and increased average annual discharge. Greater discharge has caused more frequent bank-full conditions which destabilizes streambanks and increases sediment load to the Minnesota River (U.S. Army Corps of Engineers St. Paul District, 2020).

Analysis of annual maximum streamflow shows statistically increasing trends in the Upper Mississippi River Valley (USGCRP, 2017). These increases in streamflow and corresponding flood risk are mainly attributed to observed increases in total annual precipitation and extreme rainfall events occurring more frequently than in the past (USGCRP, 2017). The 1930s and early 1940s were a period of extreme drought in the Midwest known as the “Dust Bowl” era. This period was defined by extremely low streamflow in the basin with marked increases starting in the early 1940s (Engstrom & Almendinger, 2009).

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 in the Midwestern United States (Xu et al., 2013). This finding is supported by Novotny and Stefan (2007), who studied 20^{th}-century streamflow data from 36 gages in Minnesota. Trend analysis of various flow metrics of the mean flow, 7-day low flow, and peak flows are used in the study. The majority of Minnesota stream gages exhibited a statistically significant trend of increasing flows for 1913-2002 (Novotny & 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 (Novotny & Stefan, 2007). There is a reasonable consensus among multiple studies that trends show increased flow in the Midwest and the Minnesota River region (USACE, 2015).

The *Mississippi River Geomorphology and Potamology Program (MRG&P)* studied variables of interest including annual water yield and median annual suspended sediment yields for each 4-digit HUC watershed in the Mississippi River basin (MRG&P, 2020). The study utilized multiple USGS gages per HUC-4 watershed in the analysis and normalized the results by drainage area to assess trends in the variables of interest. Normalized data at the HUC-4 watershed scale for the period of record 1912-2014 identified statistically significant increases in annual water yield (MRG&P, 2020). Normalized data for the period of 1905-2015 at the HUC-4 watershed scale showed statistically significant trends in median annual suspended sediment yields for the Minnesota River watershed, HUC 0702 (MRG&P, 2020).

Global and national scale studies attempt to predict future changes in hydrology through a combination of GCMs and macro-scale hydrologic models. Many variables contribute to the uncertainty of the models, including error in temporal downscaling, error in spatial downscaling, errors in the hydrologic modeling, errors associated with emissions scenarios, and errors related to GCMs.

A multiple watershed study of 20 large watersheds in the United States by Johnson et al. (2016) (including the Minnesota River Basin) assesses the response of watershed runoff and water quality to several projected climate change scenarios. The study's six climate change scenarios are adapted from the North American Regional Climate Change Assessment Program (NARCCAP). They are downscaled for climate model output (T. Johnson et al., 2016). A combination of GCMs and regional climate models (RCM) was used to simulate results for the baseline period of 1971-2000 and a future period of 2041-2070 at a spatial resolution of 50 km (T. Johnson et al., 2016). A Soil and Water Assessment Tool (SWAT) model was developed for each study watershed. The use of watershed models provides an effective tool for assessing the response of various watersheds to climate change and facilitates a consistent comparison between watersheds in different United States locations.

The mean increase in simulated total streamflow response of the six NARCCAP scenarios for the Minnesota River basin is approximately 30%. The mean increase in simulated, annual, average, seven-day minimum streamflow response of the six NARCCAP scenarios for the Minnesota River basin is 60%. The mean increase in simulated, one-day, maximum streamflow response of the six NARCCAP scenarios for the Minnesota River basin is approximately 25% (T. Johnson et al., 2016).

A study by Liu et al. (2013) investigates maximum air temperatures using a single GCM which assumes an A2 (high) greenhouse gas emissions scenario. The spatial scale of the study is the Upper Mississippi River region, and the study forecasts that droughts in the area will become more severe in the future because the effects of projected temperature and evapotranspiration increases are expected to outweigh increases in precipitation. Increased evapotranspiration (ET) because of increased air temperature could lead to decreased streamflow (see Section 1.1.2). As ET increases, water demand rises from landscape vegetation, crops, animal consumption, and human consumption and there will be less runoff in the river. Withdrawals from the river would also likely increase, further reducing streamflow. There is little to no consensus in the literature regarding projected, future streamflow changes in the Upper Mississippi Region (USACE, 2015).

1.1.4 Summary

Increases in average temperature, precipitation, and streamflow have been observed within the study region over the past century. There is consensus that maximum air temperatures have decreased slightly in the Upper Mississippi River region; however, average temperatures and minimum temperatures increased. The frequency and magnitude of significant storm events have increased, particularly in the summer and fall months.

Future air temperatures are expected to trend upward. Annual total precipitation and the frequency and intensity of high precipitation events may also increase. Projected changes in temperature, soil moisture, and precipitation indicate an increase in the severity of droughts and extreme precipitation events. Streamflow has increased over the past century; however, a clear consensus is lacking regarding projections in future hydrology. Increases in temperature and evapotranspiration could outweigh projected increases in precipitation and result in a decline in streamflow. Figure 1-2 summarizes observed and projected climate variables relevant to the Minnesota River basin and TPP projects.

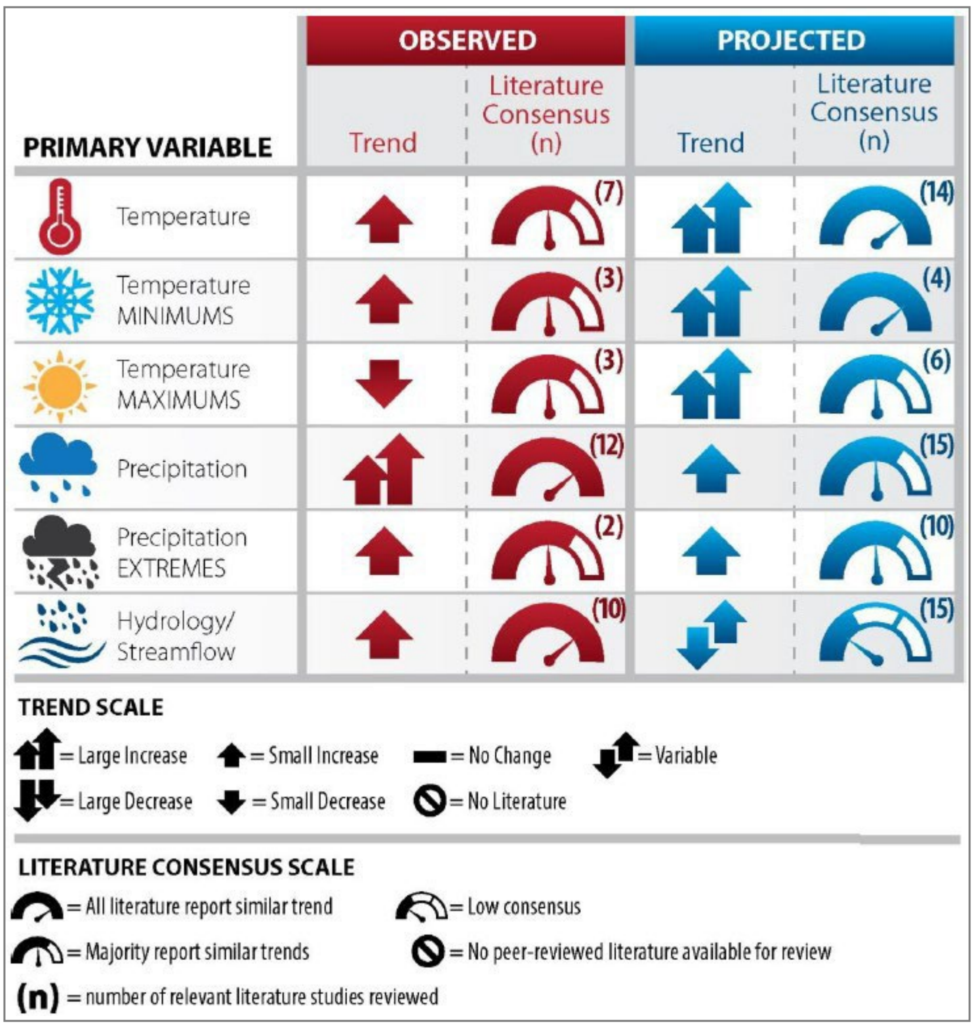

Figure 1-2 Summary matrix of observed and projected climate trends for the Upper Mississippi River Region 07

1.2 Trend Analysis

Peak streamflow is an essential parameter for both the Upper Sioux and Lower Sioux TPP projects because it can cause damage under existing conditions and with-project conditions. The Climate Hydrology Assessment Tool (CHAT) applies linear regression to annual peak streamflow data (1903-2019) measured at the Minnesota River at Mankato, MN USGS gage (ID 05325000). Figure 1-3 below shows the regression analysis. The p-value is significantly lower than the adopted significance level of 0.05, indicating that the trendline has a statistically significant slope at the 95% confidence level.

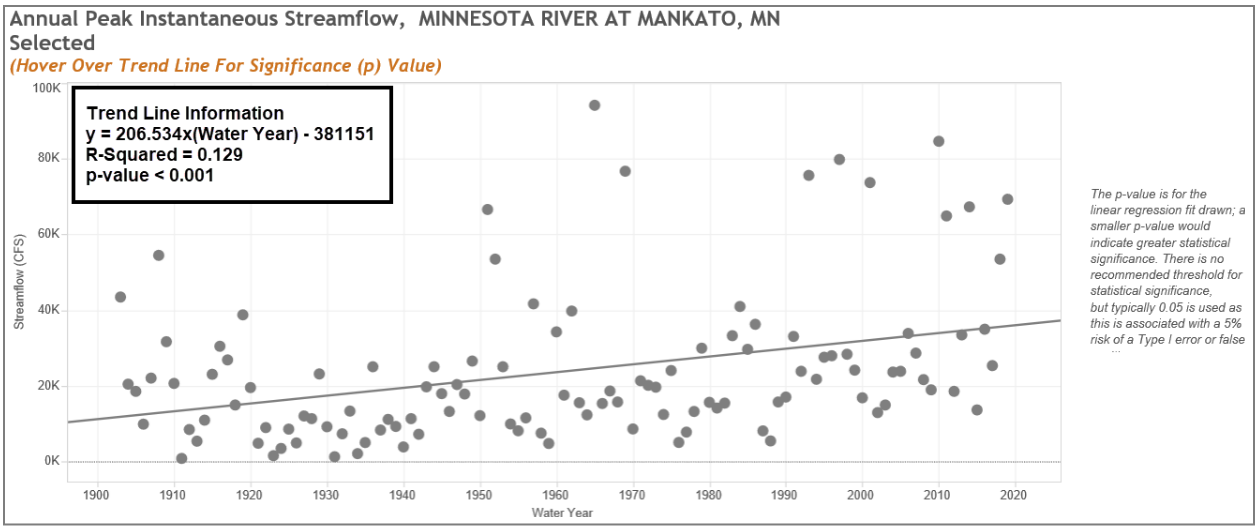

Figure 1-3 Trend analysis of AIP streamflow for the Minnesota River at Mankato, MN USGS gage (1903-2019)

1.3 Nonstationarity Detection

The assumption that discharge datasets are stationary underlies traditional flow frequency analysis. Statistical tests can be used to test this assumption using techniques outlined in *ETL 1100-2-3*. The Nonstationarity Detection (NSD) tool is a web-based tool to perform these tests on annual peak streamflow datasets at USGS streamflow gages unaffected by regulation, making these tests easier, faster, and more repeatable compared to custom implementations. The NSD tool also includes statistical tests for monotonic (i.e., increasing/decreasing) trend analysis for a specified period of record.

High flow conditions at the Upper Sioux Community and Lower Sioux Community projects can cause damage to the streambank. Peak streamflow can represent future trends in how high flow will continue to impact the project site.

The Upper Sioux Indian Community and Lower Sioux Indian Community project sites are influenced by regulation from Big Stone Lake, Lac qui Parle Dam, Highway 75 Dam, and Marsh Lake Dam. These structures can provide storage and flood risk reduction benefits. The project sites are far enough downstream in the watershed and there is enough intervening drainage area that the effect of regulation is likely reduced at the project sites.
Rainfall events on the intervening drainage area is also uncontrolled and can influence flow conditions at each project site. For this assessment, the NSD tool was applied using annual instantaneous peak (AIP) streamflow data from the Minnesota River at Mankato, MN USGS Gage (ID 05325000), which encompasses a drainage area of 14,900 mi².

The USGS water year summary for the Mankato, MN USGS gage (05325000) states no evidence flows at Mankato are affected by regulation from dams (USGS, 2021). Previous analysis also indicates that discharge at the Mankato USGS gage is unaffected by regulation (U.S. Army Corps of Engineers St. Paul District, 2017). This gage was selected to assess how climate will influence the natural flow regime. The default settings of the tool were used. The record at the Minnesota River at Mankato, MN USGS gage (05325000) is 117 years, extending from 1903-2019.

The stationarity of the flow record within the Minnesota River Basin is assessed by applying a series of eleven nonparametric statistical tests and one Bayesian, parametric statistical test to the observed peak flow record. All change points detected by the tool are considered statistically significant. The relative strength of a nonstationarity is evaluated using criteria of consensus (multiple tests detect a change in the same statistical property), robustness (change detected in multiple statistical properties), and magnitude (appreciable change in magnitude of the mean or standard deviation). These statistical tests are discussed in *ETL 1110-2-3* (U.S. Army Corps of Engineers, 2017).

As shown in Figure 1-4, USGS gage 05325000 shows strong evidence of a nonstationarity in water years 1942 and 1990, which meet the criteria of consensus, robustness, and a change in magnitude. Note that the user should be wary of relying on the stationarity assumption in this basin because the Smooth Lombard Wilcoxon test indicates that the statistical properties of the dataset are currently in flux.

Attributing the Nonstationarities to specific drivers can be challenging because a watershed is a complex, dynamic system. Often time, the change points can be attributed to multiple factors like climate and land use changes. Based on the information identified in the literature review, the 1942 change point could be attributed to the end of the Dust Bowl era drought or increases in subsurface tile drainage. Changes in agriculture from small grains to row crops like corn and soybeans also occurred around 1940 in the watershed. It is possible a combination of these factors each contributed to the identified change point.

The nonstationarity detected in 1992 could be attributed to the increase in the number of extreme precipitation events identified in Figure 1-1. Please note that the attribution of Nonstationarities to particular drivers is qualitative only. There is considerable uncertainty when connecting nonstationarties to specific drivers. Additional study would need to be performed to determine the significance between these potential drivers and how they impact the identified nonstationarity.

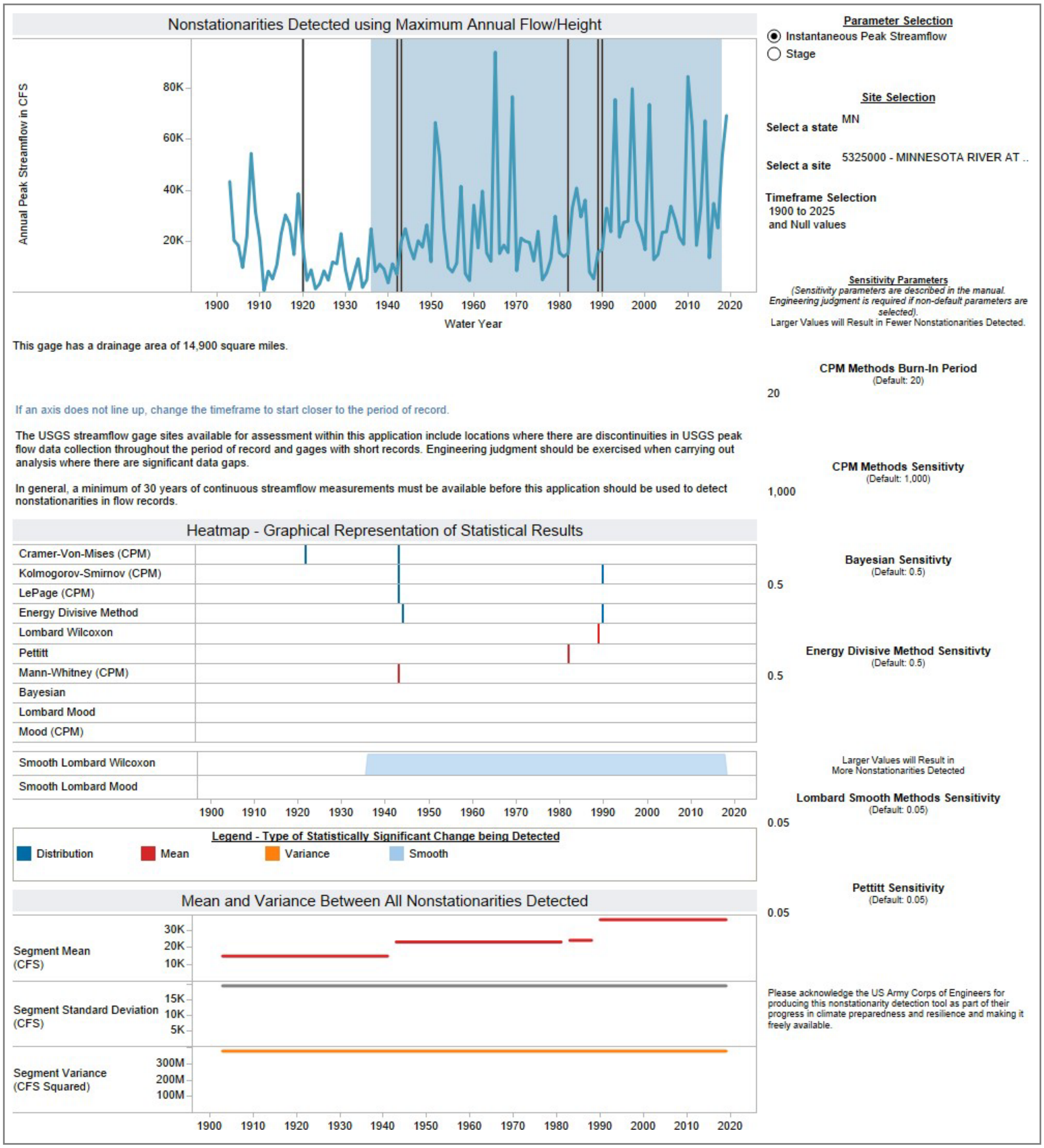

Figure 1-4 Output of NSD tool for the Minnesota River at Mankato, MN USGS gage (05325000)

Monotonic trend analysis using the Mann-Kendall and Spearman Rank Order tests and a 0.05 level of significance is included to identify statistically significant trends in the annual instantaneous peak flow dataset for the periods in between the detected Nonstationarities and the whole period of record. Detailed information about the monotonic trend analysis tests is discussed in the *US Army Corps of Engineers Nonstationarity Detection Tool User Guide* (USACE, 2016). Table 1 summarizes the monotonic trend analysis results for the 1903-2019, 1903-1942, 1943-1990, and 1991-2019 periods. A statistically significant positive trend is found when considering the whole period of record from 1903-2019. A statistically significant positive trend is found when considering the 1903-1942 period. This period coincides with the Dust Bowl era of the 1920s and 1930s, which likely explains the negative trend. No statistically significant trends were calculated for the 1943-1990 or 1991-2019 periods surrounding the identified Nonstationarities in 1942 and 1990.

Table 1 Summary of Maximum Annual Flow - Monotonic Trend Analysis Results

Gage Name	Analysis Period	Was a Statistically Significant Trend Detected (i.e., p-value ≤ 0.05)?		What Type of Trend Was Detected?	
		Mann-Kendall Test	**Spearman Rank Order Test**	**Parametric Statistical Methods**	**Robust Parametric Statistical Methods**
Minnesota River at Mankato, MN USGS gage (05325000)	1903-2019	Yes (p-value < 1.0E-3)	Yes (p-value < 1.0E-3)	Positive Trend	Positive Trend
	1903-1942	Yes (p-value = 0.014)	Yes (p-value = 0.007)	Negative Trend	Negative Trend
	1943-1990	No (p-value = 0.582)	No (p-value = 0.512)	No Trend	No Trend
	1991-2019	No (p-value = 0.626)	No (p-value = 0.607)	No Trend	No Trend

1.4 Projected Hydrology Assessment

The USACE *Climate Hydrology Assessment Tool (CHAT)* is used to investigate potential future changes and trends to the annual maximum of mean monthly stream flows for the Upper Sioux Indian Community (HUC 07020004 Hawk-Yellow Medicine Basin) and Lower Sioux Indian Community (HUC 07020007 Middle Minnesota Basin). The threshold for significance of a trend selected in this analysis is a p-value of less than 0.05.

The inter-model range includes 64 CMIP-5 based projections of climate changed hydrology produced by an ensemble of 32 GCMs driven by the Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5. CHAT runs a trend analysis for the historic simulation (water years 1950-2005) and projected future simulation (water years 2006-2099). Historic simulations assume observed greenhouse gas emission levels, while projected simulations represent the projected, climate changed meteorology from the selected RCP scenarios. These meteorological outputs are spatially downscaled using the Localized Constructed Analogs (LOCA) method and then inputted in the Variable Infiltration Capacity (VIC) precipitation-runoff model. The VIC model is a macro-scale model representative of unregulated basin conditions and is used to generate a streamflow response. Additional information about the CHAT software can be found online (U.S. Army Corps of Engineers, 2021).

As expected for this type of analysis, there is a considerable, but consistent spread in the inter-model, inter-scenario range of projected annual maximum average monthly flows (Figure 1-5 and Figure 1-6). This spread is indicative of the uncertainty associated with climate changed hydrology.

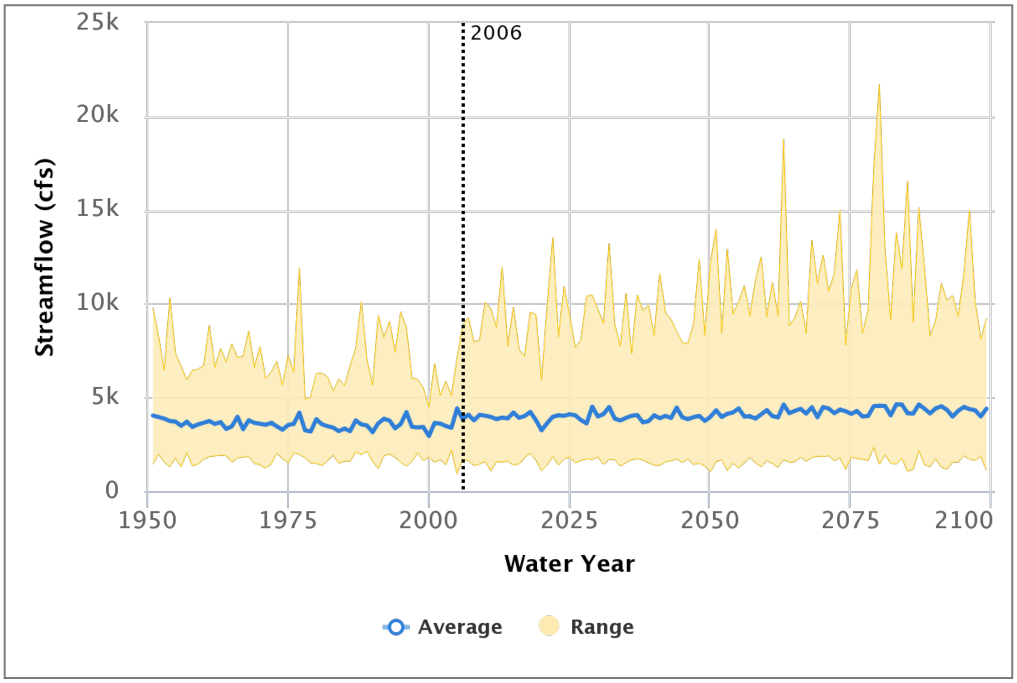

Figure 1-5 Range of 64 Climate-Changed Hydrology Model Output for HUC 07020004 Hawk-Yellow Medicine River Basin

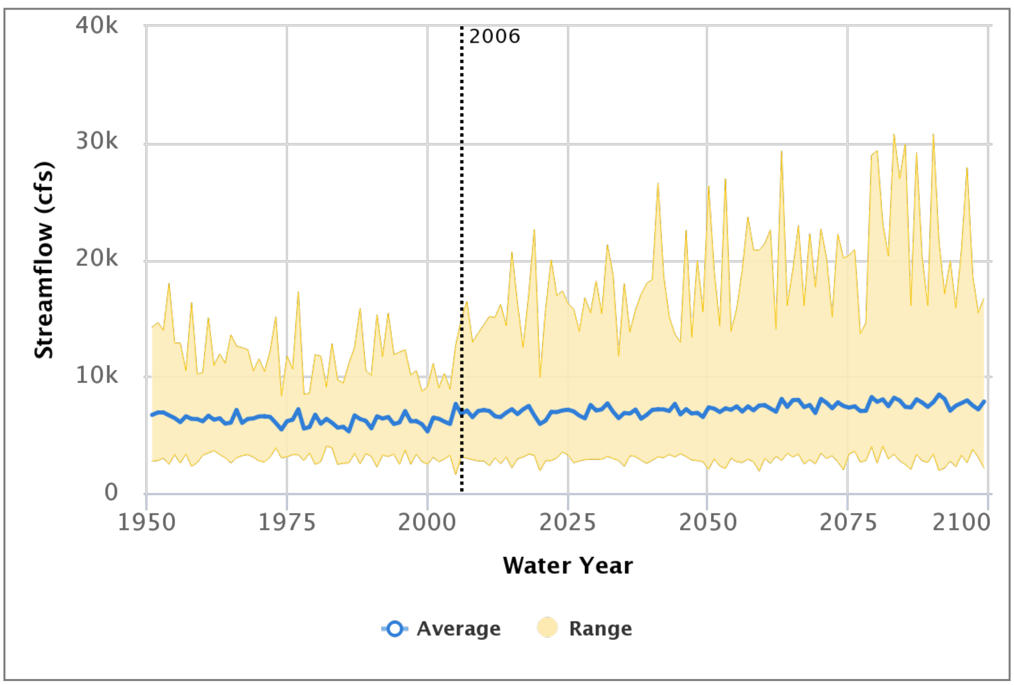

Figure 1-6 Range of 64 Climate-Changed Hydrology Model Output for HUC 07020007 Middle Minnesota River Basin

The CHAT projections in Figure 1-7 for the HUC 07020004 (Hawk-Yellow Medicine) indicate a statistically significant trend in projected 2006-2099 mean annual maximum of average monthly streamflow. The p-values associated with the t-test (p-value << 0.05), Mann-Kendall test (p-value << 0.05), and Spearman Rank-Order test (p-value << 0.05) are all well below the threshold for statistical significance (p-value ≤ 0.05) for the projected case. The modeled output for the hindcast period (1950-2005) produces conflicting results. The p-value associated with the t-Test (p-value = 0.207) and Spearman Rank-Order (p-value = 0.051) indicate that a statistically significant trend is not evident at the 95% level of confidence. Please note that the p-value associated with the Spearman Rank-Order test is only slightly outside the adopted threshold for significant of a p-value ≤ 0.05 for this analysis. The p-value of the Mann-Kendall (p-value = 0.028) indicates that a statistically significant decreasing trend is present in the hindcast period.

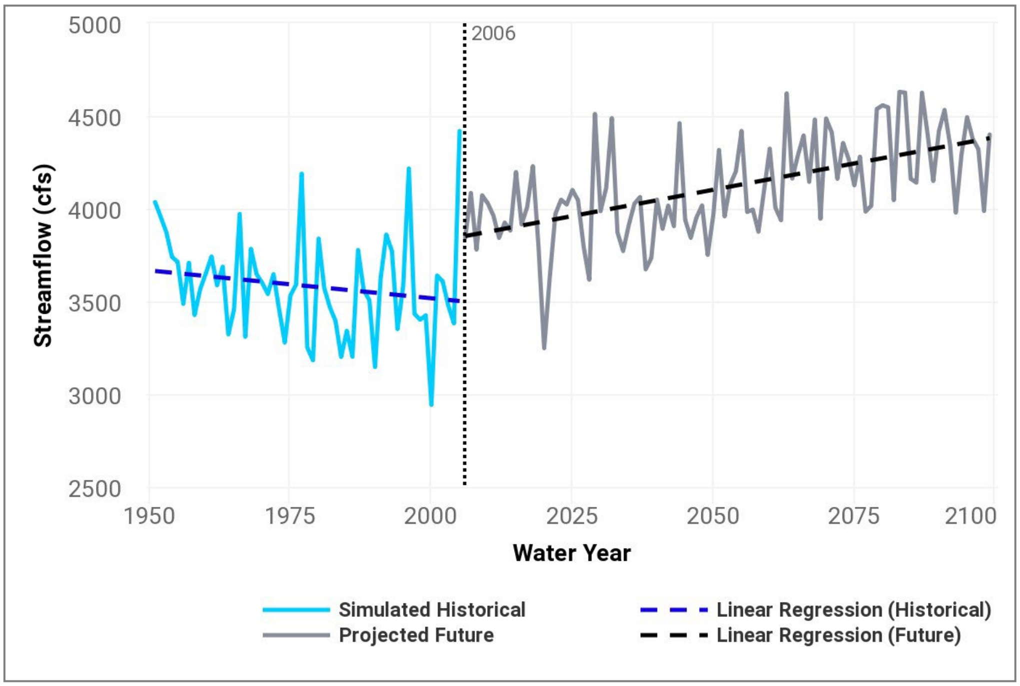

Figure 1-7 Projected and historical mean annual maximum monthly flows for HUC 07020004 Hawk-Yellow Medicine River Basin

The CHAT projections in Figure 1-8 for the HUC 07020007 (Middle Minnesota) indicate a statistically significant trend in projected 2006-2099 mean annual maximum of average monthly streamflow. The p-values associated with the t-test (p-value << 0.05), Mann-Kendall test (p-value << 0.05), and Spearman Rank-Order test (p-value << 0.05) are all well below the threshold for statistical significance (p-value ≤ 0.05) for the projected case. The modeled output for the hindcast period (1950-2005) produces conflicting results. The p-value associated with the t-Test (p-value = 0.131) indicates that a statistically significant trend is not evident at the 95% level of confidence. The p-value of the Mann-Kendall (p-value = 0.027) and Spearman Rank-Order (p-value = 0.037) each indicate that a statistically significant decreasing trend is present.

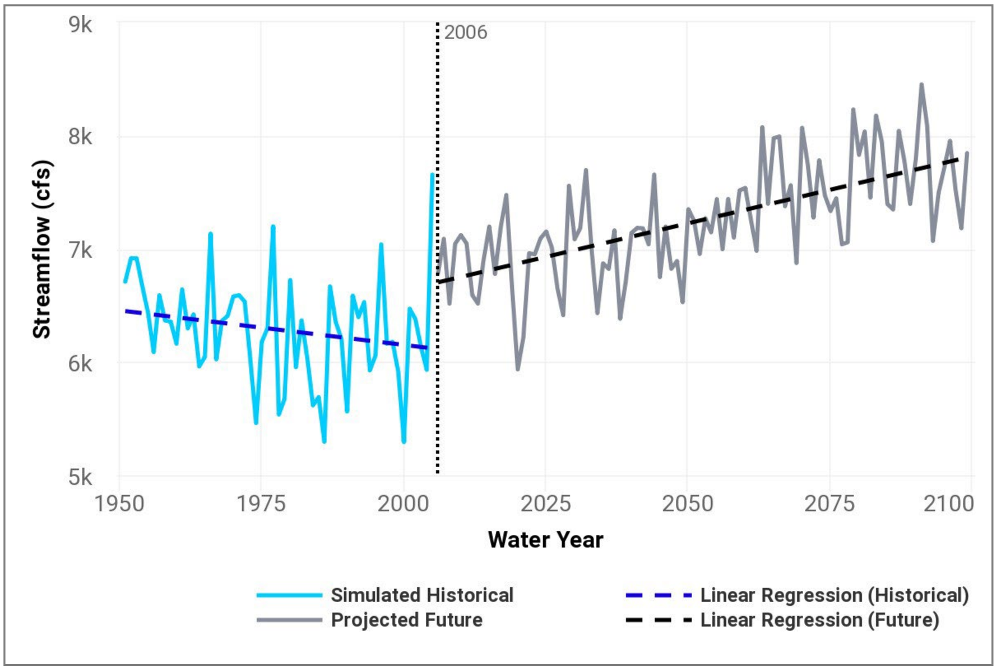

Figure 1-8 Projected and historical mean annual maximum monthly flows for HUC 07020007 Middle Minnesota River Basin

1.5 Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment (VA) Tool facilitates a screening level, comparative assessment of the vulnerability of a business line in a HUC-4 watershed to the impacts of climate change relative to the other HUC-4 watersheds represented by that business line within the continental United States (CONUS). It uses the CMIP5 GCM-BCSD-VIC dataset (2014) to define projected hydrometeorological inputs, combined with other data types to define a series of indicator variables to define a vulnerability score.

Vulnerabilities are represented by a weighted-order, weighted-average (WOWA) score generated for two subsets of simulations (wet and dry) and two 30-year epochs (centered on 2050 and 2085). The top 20% of WOWA scores (across CONUS watersheds) are flagged as vulnerable. All VA Tool analyses performed for this assessment use the default National Standard Settings. Additional information about the VA tool can be found in the User Guide (U.S. Army Corps of Engineers, 2016).

The HUC 0702 Minnesota River Basin is used for this assessment. The Flood Risk Reduction Business line and Ecosystem Restoration Business lines are used in the vulnerability assessment. Each of these business lines contains indicator variables relevant to streambank erosion protection projects. The primary variables of interest when considering vulnerability are discharge and sediment transport. These variables provide the most valuable information about vulnerability of the project to projected changes in climate.

1.5.1.1 Flood Risk Reduction Business Line

The primary purpose of the Lower Sioux Indian Community and Upper Sioux Indian Community projects is to address streambank erosion issues. Discharge is the most important variable to consider when addressing erosion because it is the cause of erosion. Indicators within the WOWA score for Flood Risk Reduction relevant to erosion control and streambank protection include the coefficient of variation in cumulative annual flow, runoff elasticity (ratio of streamflow runoff to precipitation), and flood magnification (how flood flow is projected to change in the future) (US Army Corps of Engineers, 2016). These indicator variables related to discharge are the most important variables to considering when interpreting results from the vulnerability tool because they impact erosion at the site.

The VA tool results for the Minnesota River watershed (HUC 0702) are summarized in Table 2, Table 3, and Figure 1-9 below. The Minnesota River watershed is not identified as vulnerable relative to other watersheds in the CONUS. For both the wet and dry scenarios, the dominant indicator variable for each epoch is the Flood Magnification Factor. This indicator variable contributes 48.93% of the total score for the 2050 epoch and 48.38% of the total score for the 2085 epoch in the wet scenario. The Flood Magnification factor contributes 44.33% of the total score for the 2050 epoch and 44.43% of the total score for the 2085 epoch in the dry scenario.

Table 2 VA Tool Results – Flood Risk Reduction Business Line

VA Tool Results - Flood Risk Reduction Vulnerability Score (WOWA)				
	2050		2085	
Watershed	Wet	Dry	Wet	Dry
Minnesota River Basin (HUC 0702)	54.85	45.62	56.55	45.28

Table 3 below shows the indicator values for the Flood Magnification Factor. Values greater than 1.0 indicate that flood flow is expected to increase in the basin. For both the wet and dry scenarios, the value of this indicator variable is anticipated to increase with time, indicating that the monthly flow that is exceeded 10% of the time will change in the future. The flow value exceeded 10% of the time for the Upper Sioux and Lower Sioux projects are approximately 7,630 cfs. This flow exceedance value was estimated using daily flow measurements and a period of record from 01 October 2000 – 28 November 2020 from the Minnesota River at Morton, MN USGS gage (ID 05316580). Appendix C contains more details about the hydrology for this study. Projected wet conditions could increase the 10% exceedance discharge resulting in higher discharge and stage at the site for longer durations. Increased flooding will impact conditions at the project site by resulting in higher stages and potentially faster flows, promoting erosion, especially if no action is taken to stabilize and protect the stream bank.

Table 3 VA Tool Results – Flood Risk Reduction Dominant Indicator Variable

Flood Risk Reduction Business Line 568C (and 568L) Flood Magnification Factor			
Scenario	**2050 Epoch**	**2085 Epoch**	**% Change In Indicator Variable**
Wet	1.335	1.361	1.94%
Dry	0.982	1.035	5.39%

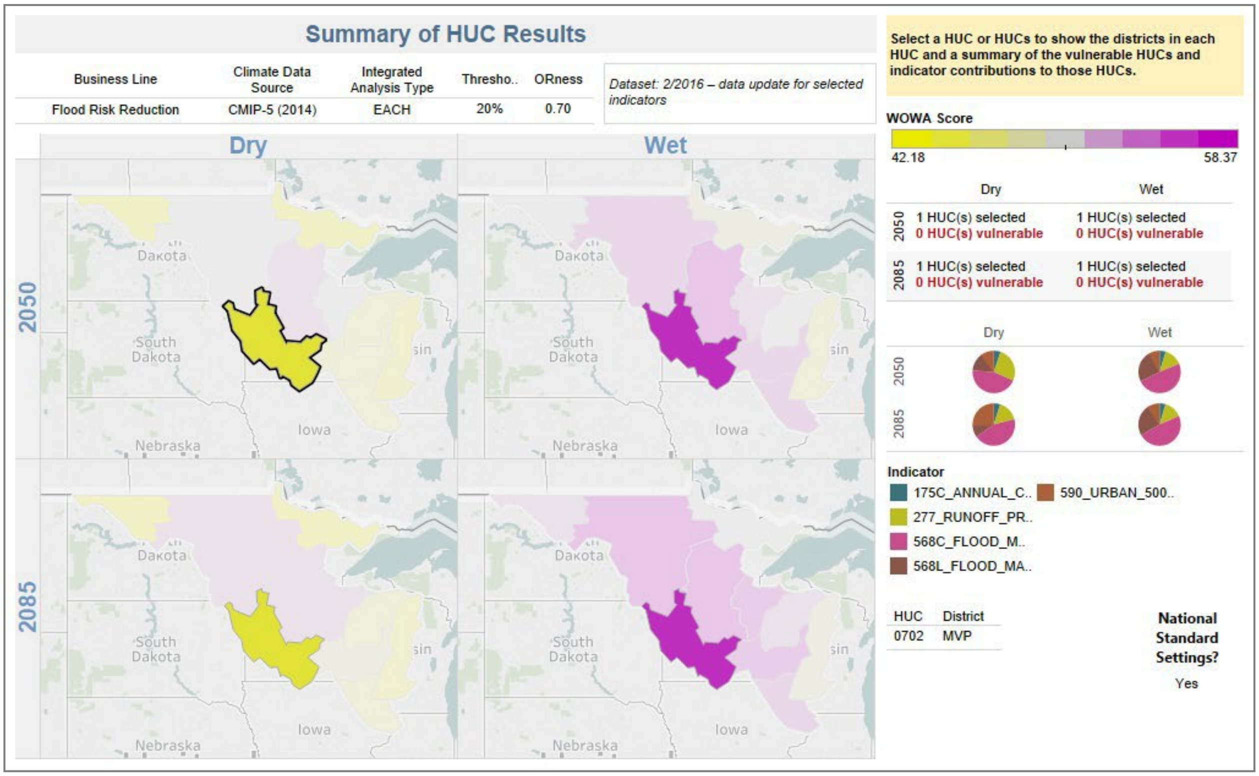

Figure 1-9 VA Tool results for the Flood Risk Reduction business line (HUC 0702)

1.5.1.2 Ecosystem Restoration Business Line

The Ecosystem Restoration business line contains indicator variables relevant to the project. Sediment transport is the variable of interest for the Ecosystem Restoration business line because the most significant contributors to sediment in the Minnesota River are from ravines, bluff, and streambanks (Minnesota Pollution Control Agency, 2021). Increases in projected sediment may indicate that conditions for streambank erosion will be more common in the future. Indicator variables considered within the WOWA score for Ecosystem Restoration relevant to a streambank erosion project include the change in sediment load due to change in future precipitation, monthly coefficient of variation in runoff, percent change in runoff divided by percent change in precipitation, flow magnification and mean annual runoff. Additional information about each indicator variable and how they are used to determine a WOWA score (vulnerability score) is described in the Vulnerability Assessment User Manual (U.S. Army Corps of Engineers, 2016).

Table 4 summarizes the WOWA score for the ecosystem restoration business line. Due to future precipitation changes, the change in sediment load comprises 2.89% and 2.80% of the

WOWA score for the 2050 and 2085 epochs, respectively, during the dry scenario. Due to future precipitation changes, the difference in sediment load comprises 3.27% and 3.52% of the WOWA score for the 2050 and 2085 epochs, respectively, during the wet scenario. Although the sediment load indicator variable is not a significant contributor to the overall vulnerability score, the value of the indicator variable under a wet scenario increases substantially. The percent change in the sediment indicator variable (156 Sediment) is a +75.14% increase from the 2050 to 2085 epoch, suggesting that sediment transport in the watershed may increase under wet conditions.

Table 4 VA Tool Results – Ecosystem Restoration Business Line

VA Tool Results - Ecosystem Restoration Vulnerability Score (WOWA)				
	2050		2085	
Watershed	Wet	Dry	Wet	Dry
Minnesota River Basin (HUC 0702)	68.11	66.92	68.30	66.46

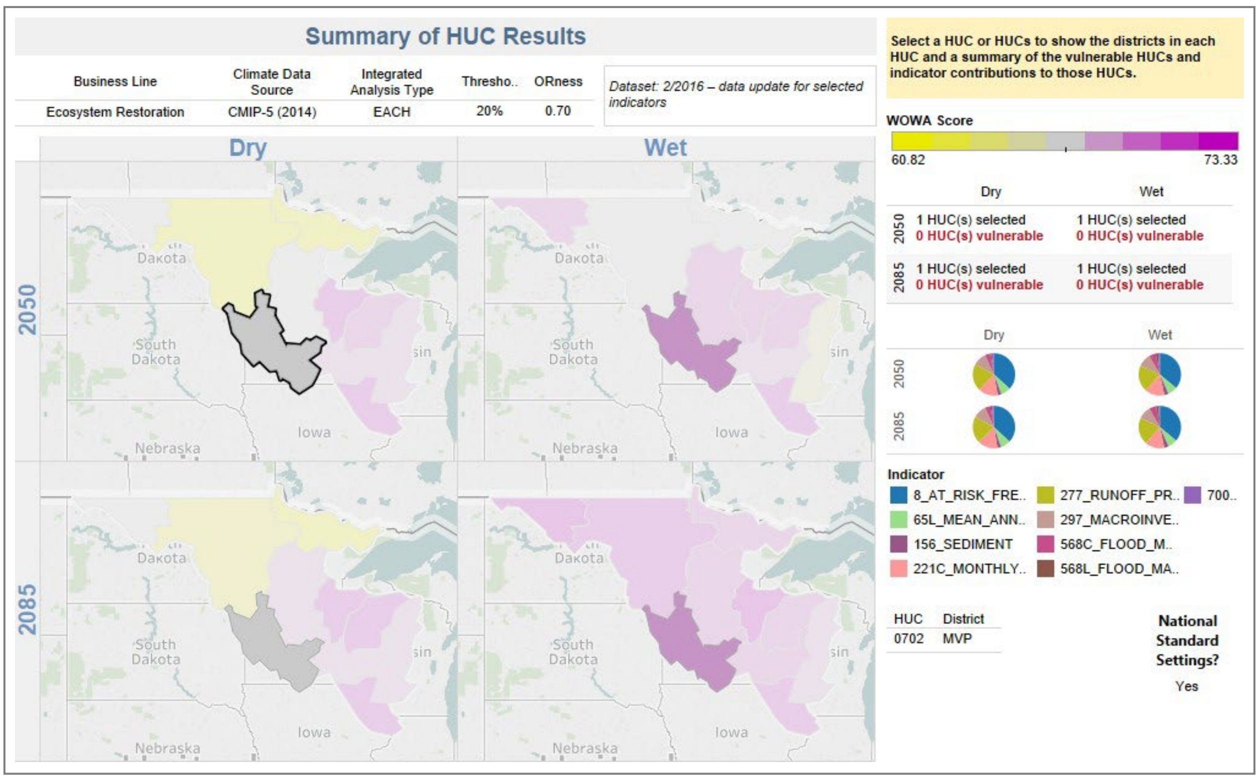

Figure 1-10 VA Tool results for the Ecosystem Restoration business line (HUC 0702)

1.6 Conclusion

The literature review notes that an increase in the frequency and magnitude of observed intense rainfall events and future climate projections indicates that the frequency of severe rainfall events will become more prevalent. Statistically significant increases in observed peak annual streamflow are present in the Minnesota River watershed, promoting conditions for erosion.

The CHAT tool projects that streamflow will increase in the Minnesota River watershed through the water year 2099. Projections indicate that streamflow may increase but increases in air temperature and evapotranspiration may offset increases in potential runoff. There is little consensus in the literature about how hydrology will change in the future. There is a high probability that erosion at each of the TPP project sites will continue in the near term and deteriorate if no action is taken.

The current streamflow record in the Minnesota River basin is considered nonstationary. Additionally, the NSD tool identified that the annual peak streamflow record for the Minnesota River is currently in flux. Since the current streamflow record exhibits nonstationary characteristics, it is recommended that each TPP project be monitored to evaluate the effectiveness of the designs considered to protect the bank.

The objective of both TPP projects is to reduce erosion and land loss along the Minnesota River in order to conserve natural resources and improve access to the river to support tribal cultural practices. Both TPP projects analyze alternatives consisting of erosion protection (riprap) at the top of the bank, erosion protection at the toe of the bank, installation of bendway weirs, bank reshaping, and vegetation plantings. A rock overflow section was also considered for the Upper Sioux Community TPP project. Table 6 and Table 5 indicate potential residual risks for this project due to climate change along with a qualitative rating of how likely those residual risks are to occur for the Upper Sioux Community and Lower Sioux Community TPP projects, respectively. The primary driver of risk due to climate change is higher river flows contributing to increased erosion. For the Lower Sioux Community project, a scale factor (SF) of 1.5 was applied to the riprap size. This SF was selected based upon the text in EM 1100-2-1601 Section 3-7.c.(1). This text recommends increasing the scale factor above the minimum value of 1.1 when large debris may impact the project site. Observed large trees within the channel during multiple site visits led to the use of a SF of 1.5. While not expressly driven by climate change considerations, the application of a SF will increase climate change resilience of the riprap protection measures. Consideration of increasing frequencies of flood events possibly driven by climate change could subject the site to more frequent large debris impacts. The proposed gradation's D_{30} exceeds the calculated D_{30} by approximately 50%, and the design thickness should provide added robustness against frequent flow and debris impact events. In lieu of a climate adaptation plan, instructions for monitoring and guidance suggesting when project features should be adjusted or redesigned should also be included in the project's Operation and Maintenance manual to improve the resiliency of the project.

Table 5 Residual Climate Risks to Upper Sioux Community TPP Project

Residual Risk Summary Table - Upper Sioux Project					
Project Feature	**Trigger (Variable which Causes Risk)**	**Environmental Hazard**	**Potential Harm to Project**	**Qualitative Likelihood (Low/ Moderate/ High)**	**Qualitative Justification for Likelihood Rating**
Top Elevation – Erosion Protection	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in high flow conditions at the site resulting in increased shear stress and flow velocity	Floods could overtop the riprap protection more frequently and exacerbate erosion	Low	The top elevation of the riprap is set to the elevation of the existing bank and the riprap was upsized. A rock overflow section allows for controlled overtopping, reducing any adverse impacts to the project due to more frequent overtopping of the riprap. Projections in hydrology are uncertain and increases in temperature and evapotranspiration could offset increases in future streamflow.
Riprap	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in high flow conditions at the site resulting in increased shear stress and flow velocity	Increased and prolonged loading promotes erosion and undermines project integrity	Low	The riprap was upsized from the gradation the design originally called for, which would likely be sufficient to handle present and some projected increases in discharge.
Rock overflow section for designated overtopping of the bank with larger rock than what is currently in place at the site	Increase in snowmelt runoff or runoff from heavy rainfall events	More frequent overtopping of overflow section	Frequent overtopping can damage and undermine the integrity of the project	Low	The inclusion of a designed overtopping section acts to increase the project's resilience because the overtopping section allows for managed overtopping instead of uncontrolled overtopping. The USACE design alternative will decrease the frequency of overtopping at this location. Projected increases in streamflow are uncertain and could be offset by corresponding increases in air temperature and evapotranspiration.
Bendway weirs (in addition to riprap protection of the streambank)	Increase in snowmelt runoff or runoff from heavy rainfall events. Decreased ice cover and rising temperatures increase ice movement/jamming during cold weather months.	Increase in frequency of high flow conditions and increases in shear stress on bendway weirs. Increases in ice impacts damaging the bendway weirs.	Bendway weirs are designed with current seasonal mean water and low water elevations, which could be higher in the future. Increased frequency and duration of high flow conditions could damage the bendway weirs and/or exceed their ability to redirect flows away from the streambank. Increased frequency of ice movement during cold weather months could also damage the bendway weirs.	Low	The bendway weirs would be designed for flows expected at the site; however, they are not commonly used in the Northern United States, and their performance in cold environments is uncertain. This project would combine bendway weirs with riprap protection on the streambank. Projections in hydrology are uncertain and increases in temperature and evapotranspiration could offset increases in future streamflow. The larger riprap gradation accounts for additional, projected ice impacts. Changing ice conditions that may prematurely degrade bendway weirs should be monitored.
Reshaping the bank	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in frequency of high flow conditions and increases in shear stress on bendway weirs	Increased flows would promote conditions conducive to erosion.	Low	Laying back the bank to a 1V:3H slope will increase its stability and resiliency compared to existing conditions at the site. Filter fabric will be included to reduce wash-out of fine material. Larger riprap will also be used on the streambank.
Bank vegetation	Increases in temperature and drought (increased evapotranspiration)	High temperatures and drought conditions may hinder survival of vegetation intended to protect the bank.	Lack of vegetative cover would make the project more susceptible damage from streamflow erosion	Moderate	Increases in temperature are the strongest indicator of climate change in the future. There is consensus in the literature that warming will continue which may contribute to more frequent drought conditions.

Table 6 Residual Climate Risks to Lower Sioux Community TPP Project

Residual Risk Summary Table - Lower Sioux Project					
Project Feature	**Trigger (Variable which Causes Risk)**	**Environmental Hazard**	**Potential Harm to Project**	**Qualitative Likelihood (Low/ Moderate/ High)**	**Qualitative Justification for Likelihood Rating**
*Top Elevation - Erosion Protection	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in high flow conditions at the site resulting in higher channel depth and flow velocity	Floods could overtop the riprap protection more frequently and exacerbate erosion	Low	The top elevation of the riprap is set to the elevation of the existing bank and the riprap uses a conservative scale factor of 1.5. Projections in hydrology are uncertain and increases in temperature and evapotranspiration could offset increases in future streamflow.
*Riprap	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in frequency and duration of high flow conditions, increase in shear stress and velocity in the channel	Increased frequency and duration of high flow conditions would increase the potential for erosion at the site, causing damage.	Low	The riprap uses a conservative scale factor of 1.5 and can withstand flow velocities from the estimated 1% AEP event. Projections in hydrology are uncertain and increases in temperature and evapotranspiration could offset increases in future streamflow.
*Bendway weirs (in addition to riprap protection of the streambank)	Increase in snowmelt runoff or runoff from heavy rainfall events. Decreased ice cover and rising temperatures increase ice movement/jamming during cold weather months.	Increase in frequency of high flow conditions and increases in shear stress on bendway weirs. Increases in ice impacts damaging the bendway weirs.	Bendway weirs are designed with current seasonal mean water and low water elevations, which could be higher in the future. Increased frequency and duration of high flow conditions could damage the bendway weirs and/or exceed their ability to redirect flows away from the streambank. Increased frequency of ice movement during cold weather months could also damage the bendway weirs.	Low	The bendway weirs would be designed for flows expected at the site; however, they are not commonly used in the Northern United States, and their performance in cold environments is uncertain. This project would combine bendway weirs with riprap protection on the streambank. Projections in hydrology are uncertain and increases in temperature and evapotranspiration could offset increases in future streamflow. The riprap scale factor of 1.5 would account for additional, projected ice impacts. Changing ice conditions that may prematurely degrade bendway weirs should be monitored.
Reshaping the bank	Increase in snowmelt runoff or runoff from heavy rainfall events	Increase in frequency of high flow conditions and increases in shear stress on bendway weirs	Increased flows would promote conditions conducive to erosion.	Low	Reshaping the bank to a 1V:3H slope will increase its stability and resiliency compared to existing conditions at the site. Filter fabric will be included to reduce wash-out of fine material. Larger riprap will also be used on the streambank.
Bank vegetation	Increases in temperature and drought (increased evapotranspiration)	High temperatures and drought conditions may hinder survival of vegetation intended to protect the bank.	Lack of vegetative cover would make the project more susceptible to damage from streamflow erosion	Moderate	Increases in temperature are the strongest indicator of climate change in the future. There is consensus in the literature that warming will continue which may contribute to more frequent drought conditions.

**Indicates project feature is included in the TSP*

1.7 References

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Attachment

Plate I: Watershed Map