US Army Corps of Engineers

Lower Missouri Jefferson City L-142 Flood Risk Management Study

Draft Integrated Environmental Assessment and Feasibility Report

Appendix A2 Climate Change

November 2024

MISSOURI
DEPARTMENT OF
NATURAL RESOURCES

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1 INTRODUCTION

1.1 TIER 1, ECB 2018-14 ANALYSIS OF POTENTIAL CLIMATE CHANGE VULNERABILITY

This Flood Risk Management (FRM) assessment highlights existing and future climate change-driven risks facing the study area. The assessment follows United States Army Corps of Engineers' (USACE) Engineering Construction Bulletin (ECB) 2018-14, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects, revised August 19, 2022. The assessment identifies potential climate change vulnerabilities to flood risk management alternatives for the L-142 Levee Feasibility Study at Jefferson City, Missouri in relation to the Lower Missouri River basin (United States Geological Survey [USGS] Hydrologic Unit Code [HUC] 1030). The immediate study area, consisting of the Capital View Levee Drainage District in Jefferson City, Missouri, is located on the Missouri River left bank between River Miles (RM) 139.8 to 144.5. The main report and H&H Hydrology Appendix provides background information on the study. For more information on climate change-driven risk, see ECB 2018-14.

1.2 STUDY BACKGROUND

The Lower Missouri Jefferson City L-142 FRM Study effort evaluates alternatives to be considered for levee modifications and construction on the left bank of the Missouri River through Jefferson City. The study evaluates alternatives and ultimately selects a plan to propose for design and construction that manages flood risk and resiliency and addresses flood impacts to critical public infrastructure. The proposed L-142 levee is an unconstructed unit that is authorized by the 1941 and 1944 Flood Control Acts and Section 216 of the Water Resources Development Act of 2020. Both structural and nonstructural measures to address existing challenges associated with the Capital View leveed area are considered. Future climate conditions may impact the flood frequency of the study reach of the Lower Missouri River Basin. The objective of this climate assessment is to better understand the future conditions and determine potential resilience of proposed project design alternatives in the Flood Risk Reduction business line. The key climate-related variable relevant to this study is peak streamflow, which is influenced by other variables including precipitation, and to a lesser degree temperature, will also be considered.

Annual peak flow-frequency curves were developed by the *Missouri River Flow Frequency Study – Yankton, South Dakota to Hermann, Missouri* (USACE 2023) and support the design of the L-142 flood risk management project. Future climate conditions may impact the design of project features and incorporation of resiliency measures. However, a qualitative climate assessment does not direct adoption of revised future without project hydrology to adopt climatic risk factors. The hydrologic variable most relevant to flood risk management is peak streamflow. Thus, to analyze the effects of climate change on flood risk management, the assessment evaluated the annual maximum streamflow variables which is influenced by other variables including temperature and precipitation.

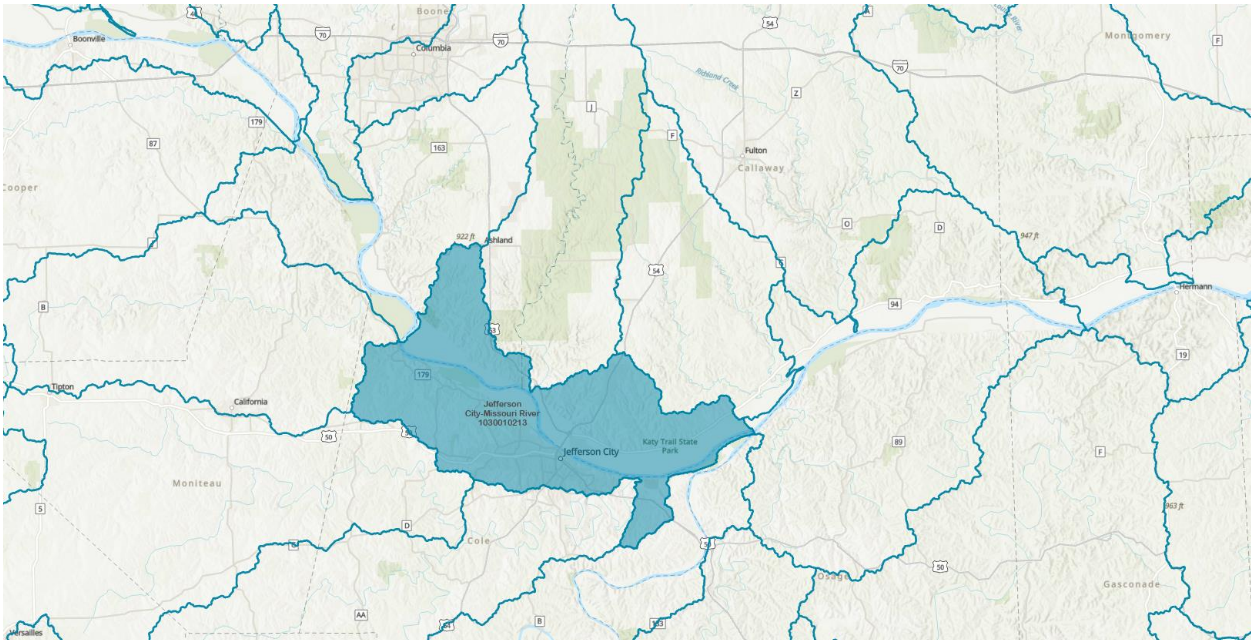
2 LITERATURE REVIEW

2.1 PROJECT SITE AND BACKGROUND

The drainage area of the Missouri River at Jefferson City is approximately 507,500 square miles. The immediate study area is located within the Hydrologic Unit Code 10 (HUC-10) Jefferson City - Missouri River watershed 1030010213, outlined in **Figure 1**.

The Missouri River watershed above Jefferson City is generally rural and used for agriculture. The Missouri River overbank through central Missouri is restricted by locally constructed and operated levees and/or bluffs. The drainage areas immediately upstream of Jefferson City along the Missouri River mainstem are unregulated, with the nearest upstream, mainstem dam at Gavins Point. Therefore, large precipitation events, typically occurring in spring and summer, are a predominate driver of flood events in the lower Missouri River Basin at Jefferson City.

Figure 1: Jefferson City - Missouri River Watershed (HUC 1030010213)



Mainstem Missouri River flows are the source of flooding for the study area, with 96% of the total Missouri River watershed located upstream of Jefferson City as shown in **Figure 2**. The greater Missouri River Basin is greatly affected by snowmelt (USACE 2023). Snowmelt is not a driver for localized flooding within the studied HUC-10 watershed.

Figure 2: Missouri River Basin and USACE Projects (USACE, 2023)

The Lower Missouri Jefferson City L-142 FRM Study at Jefferson City is a standalone spin-off of the overall Lower Missouri River Basin Flood Risk and Resiliency Study, including the *Missouri River Flow Frequency Study – Yankton, South Dakota to Hermann, Missouri* which was released in June 2023 and includes a system-wide climate assessment defined as “Appendix J”.

2.2 LITERATURE REVIEW

Literature review for the project site on the Lower Missouri River includes a combination of sources to best discuss observed and projected trends for the Missouri River in Jefferson City. References of this literature review include:

1. Missouri River Flow Frequency Study – Yankton, South Dakota to Hermann, Missouri, Appendix J: Qualitative Climate Change Analysis (USACE 2023). Report correlating to the overall Lower Missouri River System Study, focusing on trends for the mainstem Missouri River and systematic analysis of future project impacts.
2. Fifth National Climate Assessment (NCA) (Crimmins et al. 2023). Report consolidating discussion of climate projections, including changes in temperature and precipitation, for specific regions. The Lower Missouri River is located in the Midwest region.
3. NOAA National Centers for Environmental Information State Climate Summaries (NOAA 2022). State-level climate information utilized for the production of the NCA. Includes a historical record to 2020 and includes historical climate variations and trends and future climate model projections.
4. USACE Water Resources Region 10: Missouri River (USACE 2015). Report focusing on regional summaries of peer-reviewed climate literature for 2-digit United State Geologic Survey, hydrologic unit code (HUC) watersheds.

These resources summarize trends in historic temperature, precipitation, and streamflow records and provide indication of future, climate change-influenced hydrology based on the outputs from Global Climate Models (GCMs)/Earth Systems Models (ESMs). For this assessment, background on observed and projected temperature and precipitation is provided as context for the impact they have on observed and projected streamflow.

In many areas, temperature, precipitation, and streamflow measurements have been taken since the late 1800s. These records provide insight into how the hydrology in the study area changed over the past century. To model future climate, this assessment used GCMs/ESMs in combination with different Representative Concentration Pathways (RCPs)/Shared Socioeconomic Pathways (SSPs) reflecting projected radiative forcings up to year 2100. Radiative forcings encompass the change in net radiative flux due to external drivers of climate change, such as changes in carbon dioxide or land use/land cover. Projected temperature and precipitation results can be transformed to regional and local scales (a process called downscaling) for use as inputs in precipitation-runoff models (Graham, Andreasson, and Carlsson 2007).

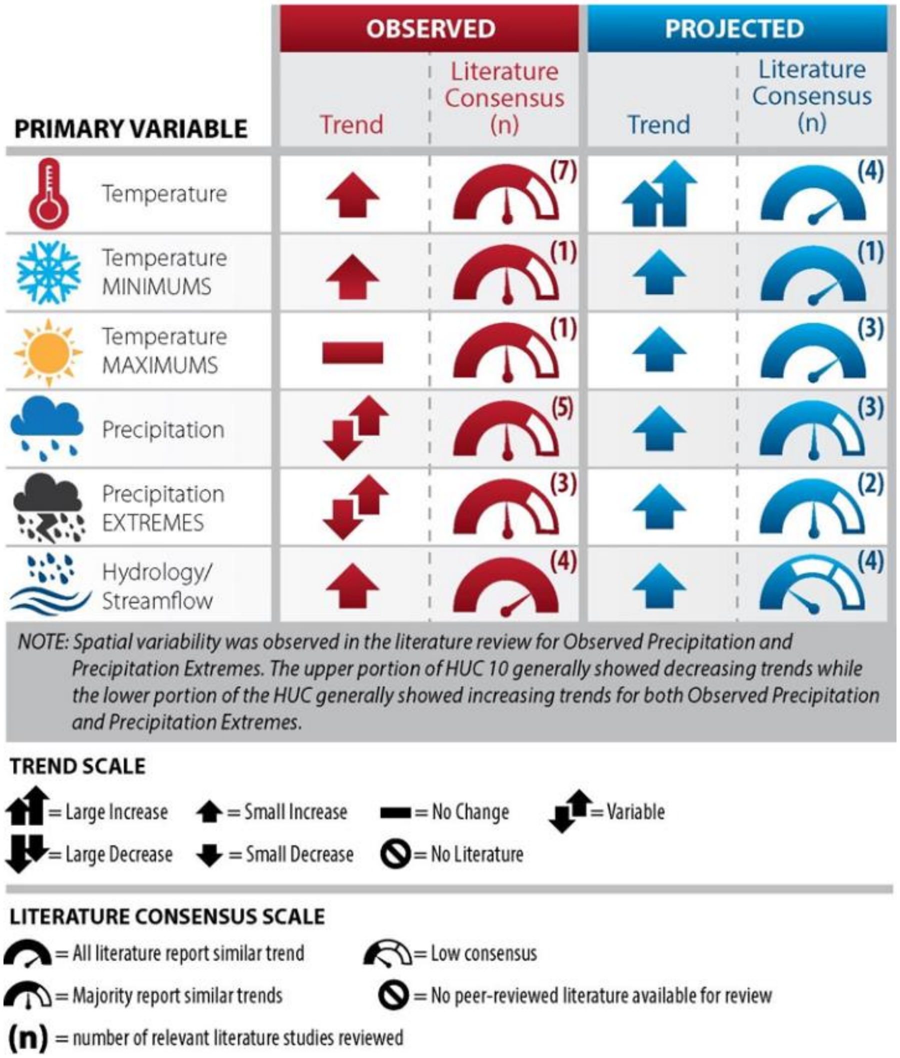
Uncertainty is inherent to projections of temperature and precipitation (USGCRP 2017). There is less confidence in GCM/ESM simulations of mean precipitation than there is in their simulations of mean temperature. The coarse spatial resolution of GCMs/ESMs mean that they are not always able to include those processes and physical features of the earth system which operate at smaller spatial scales and are important for the formation of precipitation (Kotamarthi et al. 2016). When applied, precipitation-runoff models introduce an additional layer of uncertainty. However, these methods represent the best available science to predict future hydrologic variables (e.g. precipitation, temperature, streamflow). It is best practice to use multiple GCMs when studying climate change impacts to understand how various model assumptions impact results (Gleckler et al. 2008).

2.3 OBSERVED AND PROJECTED TRENDS

2.3.1 Findings Summary

Literature review for overall observed trends in the Lower Missouri River Basin conclude that there have been observed increases in temperature which are projected to carry into the future. Precipitation trends from the reviewed references suggest upward trends but are not supported with statistical significance. Additionally, future streamflow models tend to favor an increase in streamflows, but there is variability in literature preventing full consensus. **Figure 3**, developed with the *USACE Water Resources Region 10: Missouri River* report summarizes climate literature utilized in the analysis of the entire Missouri River basin (USACE 2015).

Figure 3: Observed and Projected Trends in Hydrology - HUC-2 Region 10 (USACE 2015)



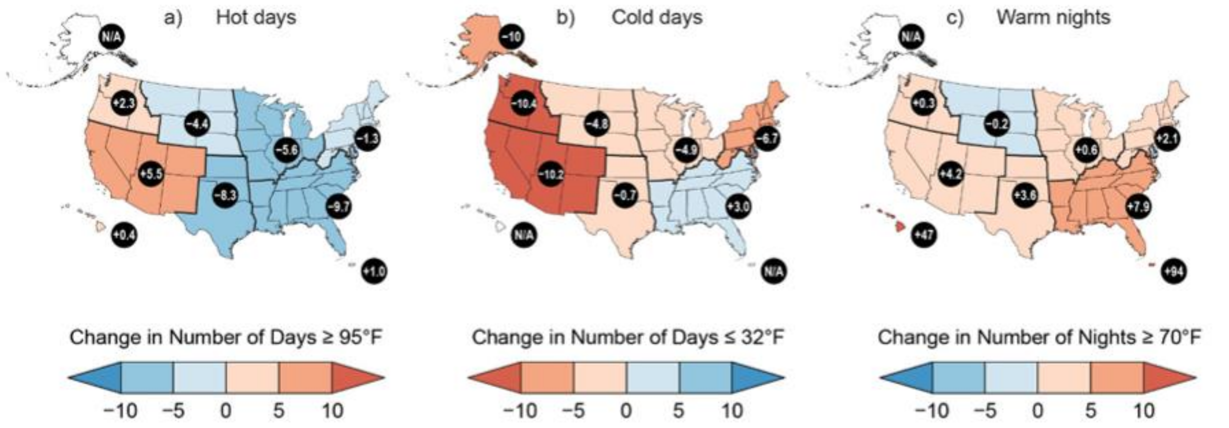
PRIMARY VARIABLE	OBSERVED Trend	OBSERVED Literature Consensus (n)	PROJECTED Trend	PROJECTED Literature Consensus (n)
Temperature	▲	(7)	▲▲	(4)
Temperature MINIMUMS	▲	(1)	▲	(1)
Temperature MAXIMUMS	▬	(1)	▲	(3)
Precipitation	⇅	(5)	▲	(3)
Precipitation EXTREMES	⇅	(3)	▲	(2)
Hydrology/ Streamflow	▲	(4)	▲	(4)

NOTE: Spatial variability was observed in the literature review for Observed Precipitation and Precipitation Extremes. The upper portion of HUC 10 generally showed decreasing trends while the lower portion of the HUC generally showed increasing trends for both Observed Precipitation and Precipitation Extremes.

2.3.2 Temperature

The Missouri River basin has experienced increases in average temperatures since the beginning of the 20th century, specifically warming in the winter and spring (NOAA 2022). These trends are most substantial regarding an upward shift in minimum temperatures (USACE 2015, Conant et al. 2018). There is also evidence of seasonal shifts, with spring occurring earlier in the year than in the past (Crimmins et al. 2023). Reported increases in historical temperature trends are most dramatic in the northern states of the Missouri River basin, and negligible in the southern region of the watershed (Larson & Schwein 2004). The Jefferson City area has experienced a decreased number of cold days (below 32°F) and increased number of warm nights (nights above 70°F) as shown in **Figure 4**. Although the number of hot days (above 95°F) have decreased, there is an overall warming trend, especially on a seasonal basis, for the area (Crimmins et al. 2023).

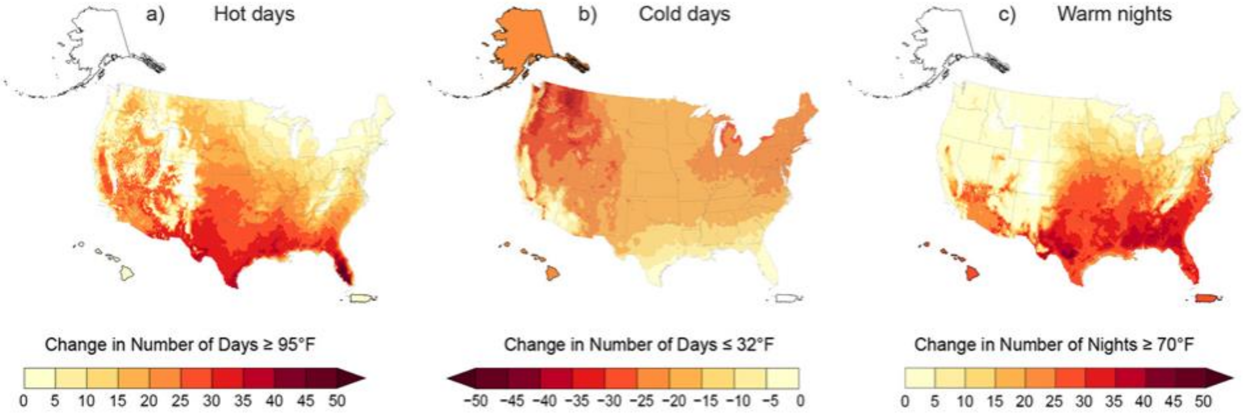
Figure 4: Observed Changes in Hot and Cold Extremes (Crimmins et al. 2023)



Hot days have increased in the West, hot nights have increased nearly everywhere, and cold days have decreased.

Trends in temperature are projected to increase within the Missouri River Basin and continental United States as a whole, with a likely increase in the frequency, severity, and duration of heat waves as well as a decrease in the number of cold days and increase of warm nights (Crimmins et al. 2023). This is directly influential to precipitation and, therefore, streamflow within the Lower Missouri River. Temperature projections for the United States are summarized in **Figure 5**.

Figure 5: Projected Changes to Hot and Cold Extremes at 2°C of Global Warming (Crimmins et al. 2023)

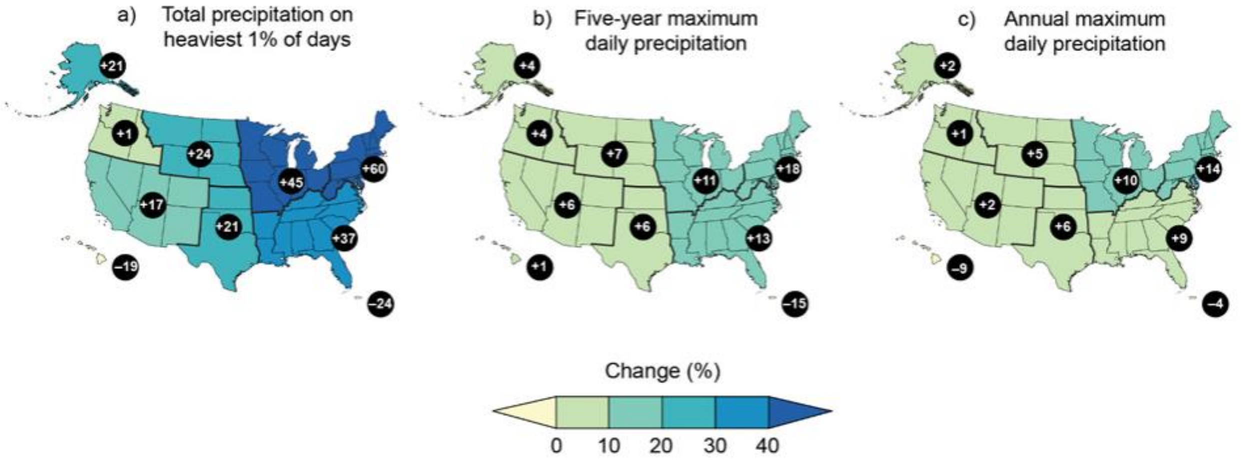


More hot days, even more warm nights, and fewer cold days are expected at a global warming level of 2°C.

2.3.3 Precipitation

Precipitation is the most influential factor to localized flooding of the Jefferson City study area. Large, widespread, and/or long duration storm events directly affect mainstem Missouri River flows through the Lower Missouri River Basin, as the local upstream watersheds are unregulated. Combinations of high Missouri River baseflow from the Upper Missouri River basin with the addition of notable rain events within the Lower Missouri River basin have resulted in historic floods at Jefferson City. Heavy precipitation events throughout the Midwest region have become more intense since 1958 as shown in **Figure 6** (Crimmins et al. 2023).

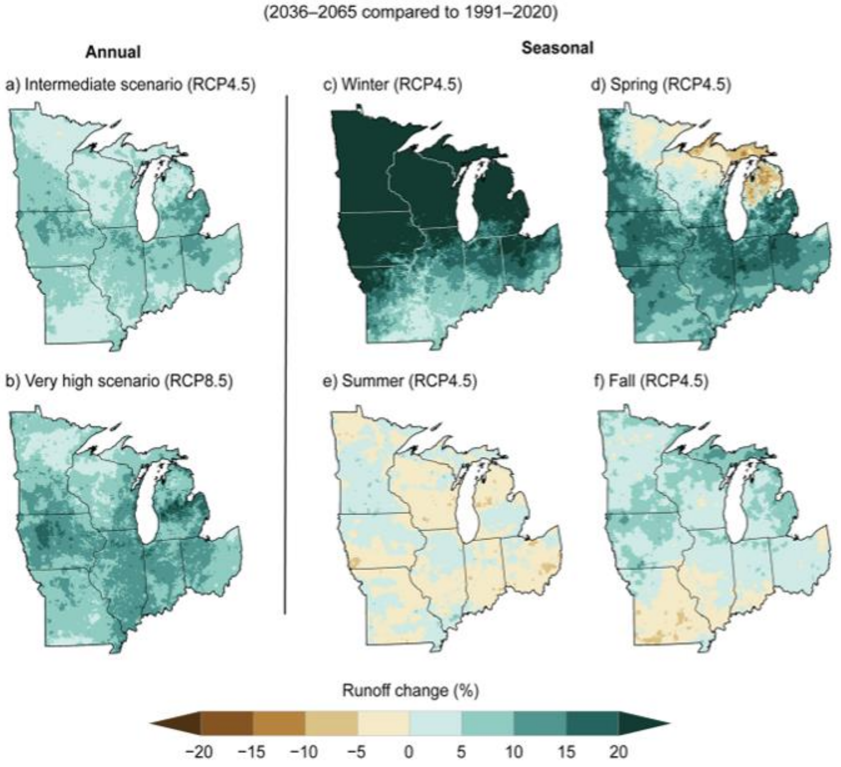
Figure 6: Observed Changes in the Frequency and Severity of Heavy Precipitation Events (Crimmins et al. 2023)



Heavy precipitation events are becoming more frequent and intense across much of the country.

Upward trends in projected cumulative runoff are generally reflective of increased winter and spring precipitation when considering the Variable Infiltration Capacity land-surface model, summarized in **Figure 7** (Crimmins et al. 2023).

Figure 7: Projected Changes in Cumulative Seasonal and Annual Runoff (Crimmins et al. 2023)

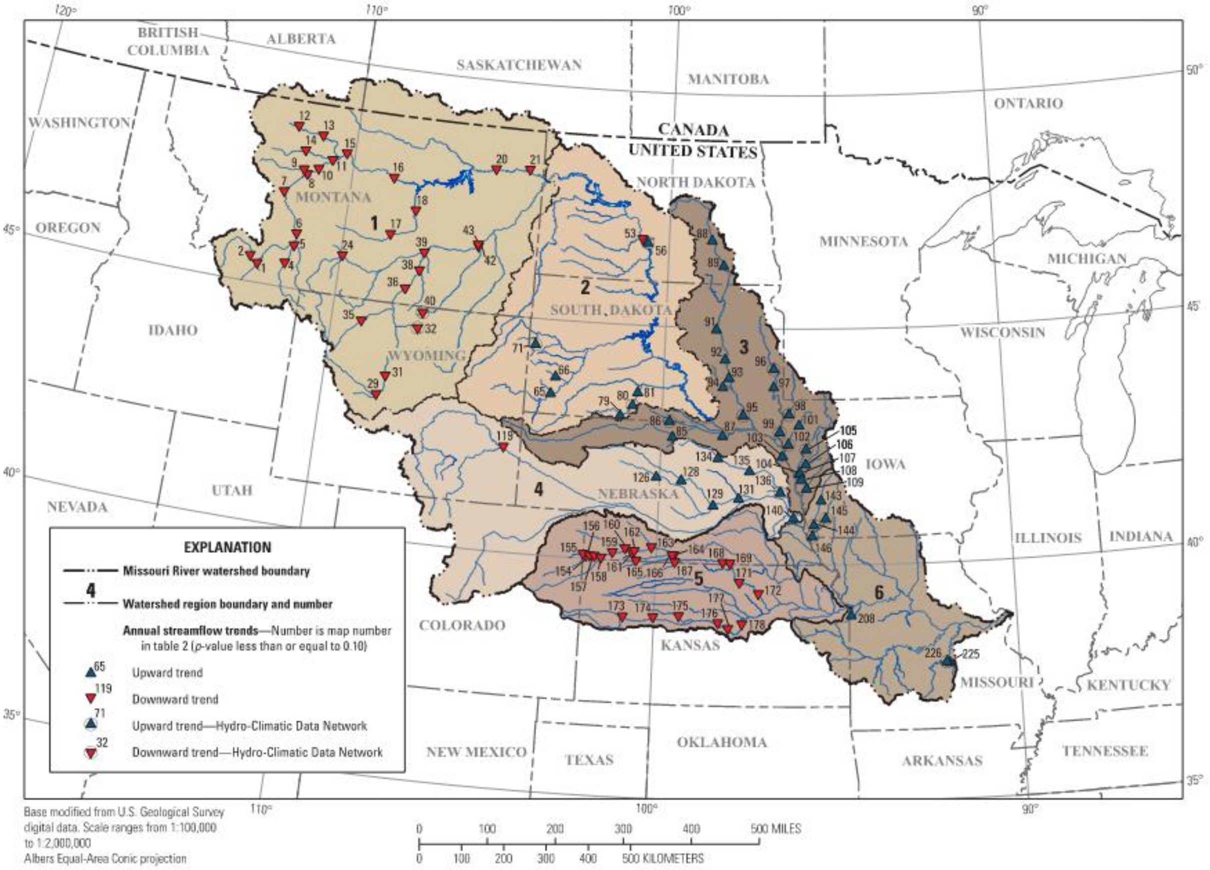


2.3.4 Streamflow

The Missouri River Basin has history of episodic trends, drought, and overabundance of surface water (Conant et al. 2018). This variability in streamflow has been evidenced over the last 1,200 years (Martin et al. 2019). The drought observed between 2000 and 2010 was one of the most severe in the past 1,200 years and was followed by substantial floods in 2011 and 2019 for much the Missouri River Basin. The 2019 flood was the most impactful at Jefferson City due to inundation duration, although peak flows were reflective of an 8% AEP occurrence at the Jefferson City gage. Flows at upstream gages in northern Missouri, Nebraska, and Iowa set records for the 2019 event.

Upward trends in Missouri River streamflow have been observed upstream of the Jefferson City gage and are likely attributed to climate change (Hoerling et al. 2013, Conant et al. 2018). A summary of stream gages with statistically significant trends are summarized in **Figure 8.**

Figure 8: USGS Stream gages in the Missouri River Basin with Statistically Significant Trends in Annual Peak Streamflow for Water Years 1960-2011 (Norton et al. 2014)



Future projections suggest variability in streamflow. Earlier snowmelt and increasingly wet springs are expected to increase daily maximum streamflow in the spring (Crimmins et al. 2023). This combination causes concern for timing of peak Missouri River flows, which historically floods when heavy, early spring storms correspond with snow melt from the Upper Basin. Hotter summers with maintained to decreased seasonal precipitation suggest a decrease in summer streamflows.

3 NONSTATIONARITY DETECTION AND TREND ANALYSIS

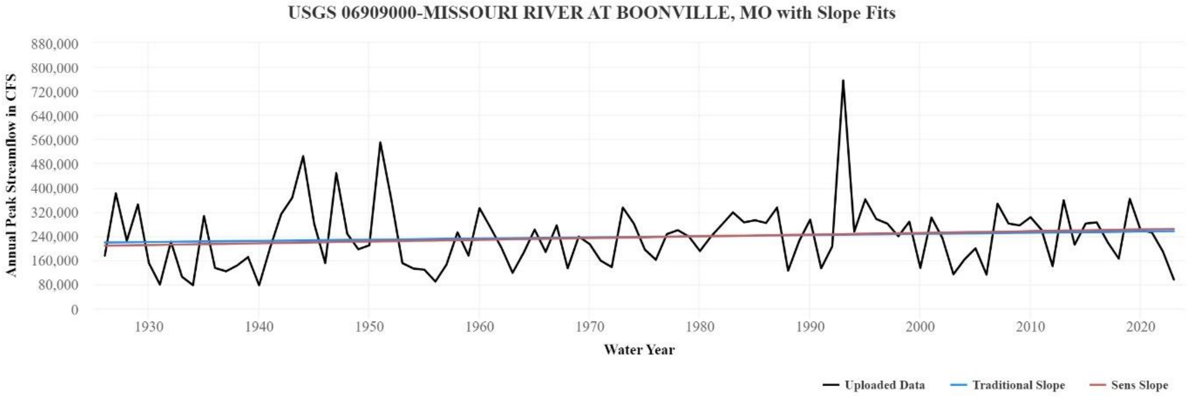
3.1 NONSTATIONARITIES – USGS DATA

Many traditional hydrologic analyses assume hydrologic timeseries are stationary (their statistical characteristics are unchanging) in time. The assumption can be tested using the techniques in the USACE Engineer Technical Letter (ETL) 1100-2-3, Guidance for Detection of Nonstationarities (2017). The USACE Time Series Toolbox (TST) is a web-based tool that performs the statistical tests described in the guidance. The hydrologic timeseries examined for this application is the annual instantaneous peak streamflow as recorded by USGS gages 06910450 and 06909000 on the Missouri River at Jefferson City and Boonville, respectively. The Jefferson City gage captures 507,500 square miles of drainage area (USGS 2024) and has a period of record from 2015 to 2023.The Boonville gage captures 500,700 square miles of drainage area (USGS 2024) and has a period of record from 1925 to 2023 (also the period of analysis). Due to the limit of flow data available at Jefferson City, the gage directly upstream at Boonville was utilized to conduct analysis of climate change factors.

For nonstationarity and trend analysis, this assessment analyzed observed annual peak flows. Although the mainstem Missouri River has regulated flows in South Dakota, these influences do not directly reflect to Lower Missouri River system flows and are averaged over enough river length to not result in false nonstationarity. The data set was trimmed to 1925 when a complete record of peak streamflows began to be maintained at Boonville.

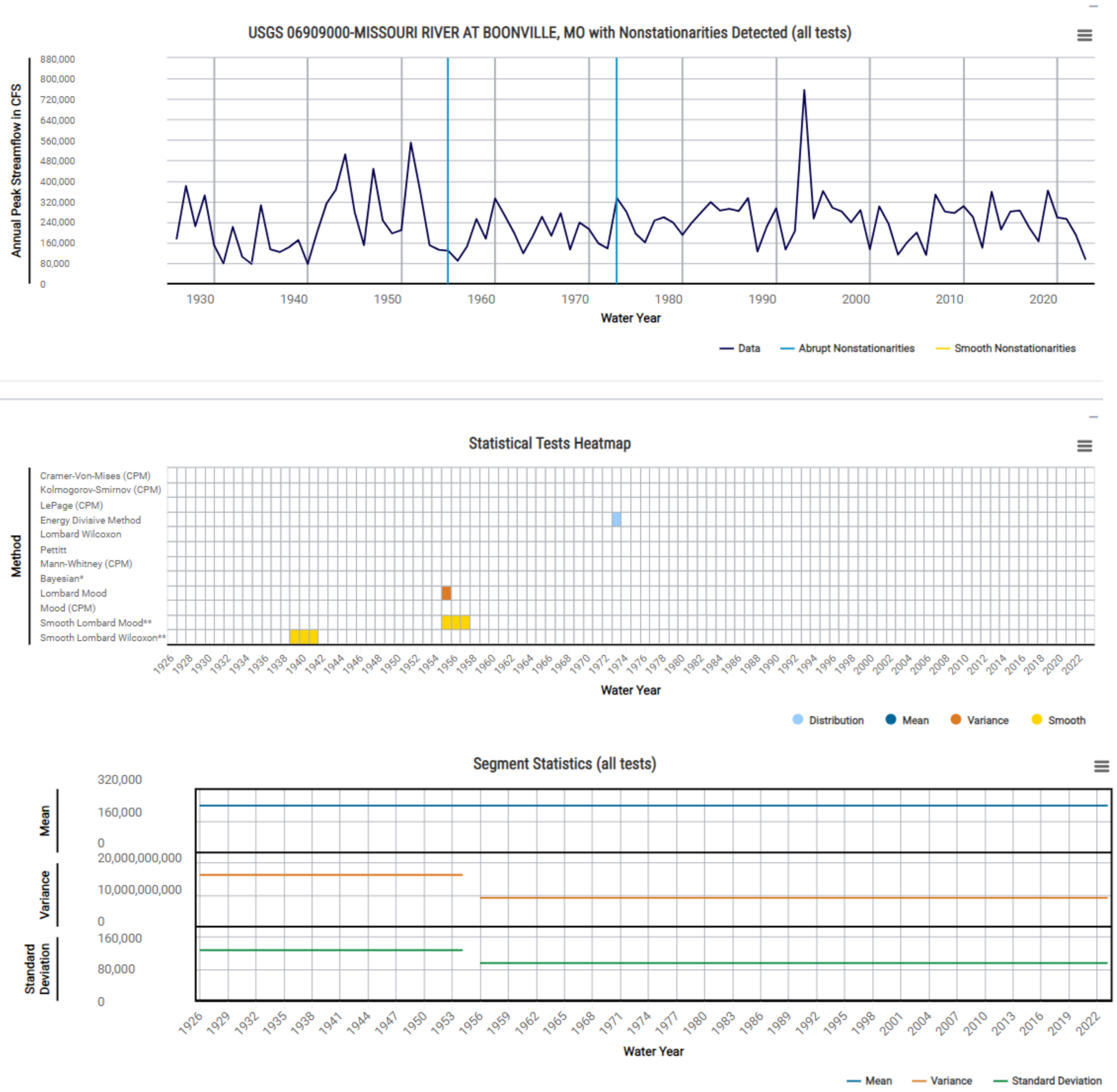
This assessment evaluated monotonic trends using the t-test, Mann-Kendall, and Spearman Rank Order tests. A p-value threshold of 0.05 (<0.05 is considered statistically significant) was applied to evaluate whether trends detected are statistically significant. The analysis indicated no statistically significant trend in the 1925 to 2023 period of record (see trendline in **Figure 9**).

Figure 9: Trend Analysis of Observed Annual Peak Streamflow at Boonville, MO. [t-Test, p-value = 0.31; Mann-Kendall, p-value = 0.093; and Spearman Rank-Order, p-value = 0.13]



As shown in **Figure 10**, the observed annual peak flow record at the Missouri River at Boonville, Missouri has evidence of a nonconclusive nonstationarity in 1955. A strong nonstationarity is one that demonstrates a degree of consensus, robustness, and a significant increase or decrease in the sample mean, variance, or both. The 1955 nonstationarity demonstrates some evidence of variance related to a smooth statistical change which results in a lesser standard deviation. This could be due to repetitive high flow conditions experienced in 1944, 1947, and 1951. The 1973 year identified a single test of nonstationarity due to change in distribution, but this is not supported by other tests.

Figure 10: Time Series Toolbox Output for Observed Annual Peak Streamflow for the Missouri River at Boonville, MO (1925 to 2023)



3.2 NONSTATIONARITIES – USGS DATA

The Missouri River Flow Frequency Study – Yankton, South Dakota to Hermann, Missouri, Appendix J: Qualitative Climate Change Analysis developed a No Regulation No Irrigation (NRNI) dataset for water years 1931-2019 (USACE 2023). The analysis resulted in robust change points detected in 1941 at Boonville and generally downstream of Omaha, likely due to recovery from a previous 12-year drought. Other indications of nonstationarities also appear to be in response to the river transitioning in or out of a drought condition.

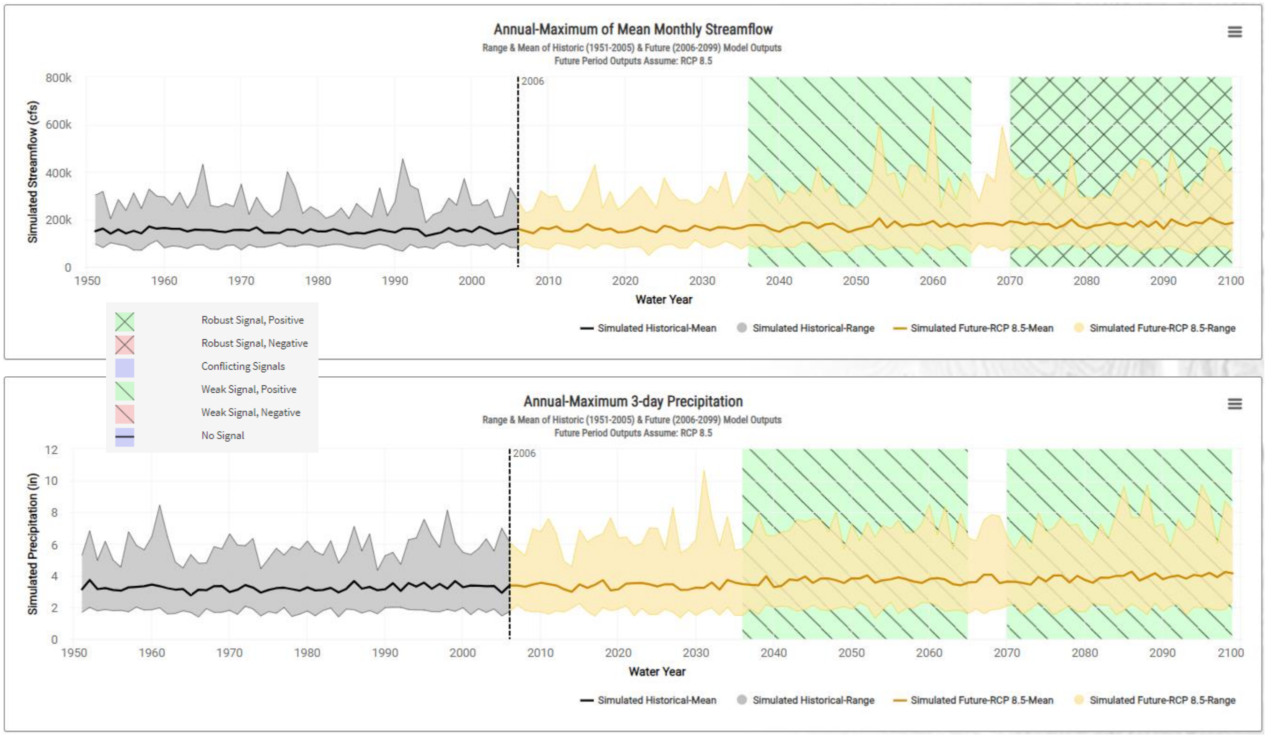
4 MONOTONIC TREND ANALYSIS

The USACE Climate Hydrology Assessment Tool (CHAT) displays various simulated, historic, and future, climate-influenced streamflow, temperature, and precipitation outputs derived from 32 GCMs. The CHAT uses Coupled Model Intercomparison Project Phase 5 (CMIP5) GCM meteorological data outputs that have been statistically downscaled using the Localized Constructed Analogs (LOCA) method. The CHAT produces projected results for 2006 to 2099 using two future scenarios: RCP 4.5 and RCP 8.5. The tool uses a reconstitution of historic greenhouse gas emissions to simulate output for the historic period of 1951 to 2005.

To analyze runoff, the tool uses LOCA-downscaled GCM outputs to force an unregulated, Variable Infiltration Capacity (VIC) hydrologic model. Areal runoff from VIC is then routed through a stream network using MizuRoute. Outputs represent the daily in-channel, routed streamflow for each stream segment—valid at the stream segment endpoint. Since the runoff is routed, the streamflow value associated with each stream segment is a representation of the cumulative flow, including all upstream runoff, as well as the local runoff contributions to that specific segment. Within the CHAT, the user can select streamflow output by stream segment. The user can also select precipitation/temperature output for a given 8-digit HUC watershed.

The Missouri River gage at Jefferson City is in the 4-digit HUC 1030 (Lower Missouri River) basin. The 8-digit HUC of interest specific to the study area is the Lower Missouri-Moreau (10300102) watershed. The Jefferson City gage is located along stream segment 10001095. The CHAT analyzes the annual maximum of mean monthly streamflow (unregulated) and the annual maximum 3-day precipitation to investigate if and how potential, future peak streamflow conditions will change. **Figure 11** shows the range of the modeled annual maximum of mean monthly streamflow and annual maximum 3-day precipitation output presented for the historic period (1951 to 2005) and the future period (2006 to 2099) under RCP 8.5. Figure 11 also includes an indication of whether this is agreement between GCMs in terms of the directionality of change and whether the signal of change emerges from the historic variability. Within the annual maximum mean monthly streamflow projections, there is weak evidence of positive change for the mid-century epoch and robust evidence of positive change for the end-of-century epoch. Within the annual maximum 3-day precipitation projections, there is weak evidence of positive change for both the mid-century and end-of-century epochs. The range of output is indicative of the uncertainty associated with projected, climate-influenced streamflow and precipitation.

Figure 11: Robustness Metrics and Range of Annual Maximum of Mean Monthly Streamflow Model Output and Annual Maximum 3-day Precipitation for the Lower Missouri River watershed (10300102)



Projections were also run for the RCP 4.5 condition, which resulted in weak signal for positive change in the annual maximum mean monthly streamflow project for the end-of-century epoch and no indicators for the mid-century epoch. The annual maximum 3-day precipitation for the RCP 4.5 condition also resulted in a weak positive signal for the end-of-century epoch and no signal for the mid-century epoch.

Both epochs for both RCP 4.5 and RCP 8.5 conditions resulted in robust signal for positive change in the annual mean 1-day temperature for both the mid-century and end-of-century epochs.

For the Lower Missouri-Moreau watershed (HUC 10300102), this assessment evaluated trends in mean model output using the t-Test, Mann-Kendall, and Spearman Rank-Order tests. For all three statistical tests, this assessment applied a 0.05 level of significance (p-values <0.05 are considered statistically significant). **Figure 12** and **Table 1** present the results of the three statistical tests and the slopes associated with identified, statistically significant trends. The mean of the 32 projections (per RCP) of simulated, annual maximum of mean monthly streamflow for the future period (2006 to 2099) shows a statistically significant, positive trend when using both RCP 4.5 and RCP 8.5 scenarios; although the historical trend does not reflect a statistically significant trend. The RCP 4.5 future trendline has a slope of 132.0 cfs a year, which equates to a 6,600 cfs change in the average of the 32 projections of annual mean streamflow over a 50-year period. The RCP 8.5 future trendline has a slope of 347.3 cfs a year, which equates to a 17,365 cfs change in the average of the 32 projections of annual mean streamflow over a 50-year period.

Figure 12: Trend Analysis of Average Model Output: Annual Maximum of Mean Monthly Streamflow for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

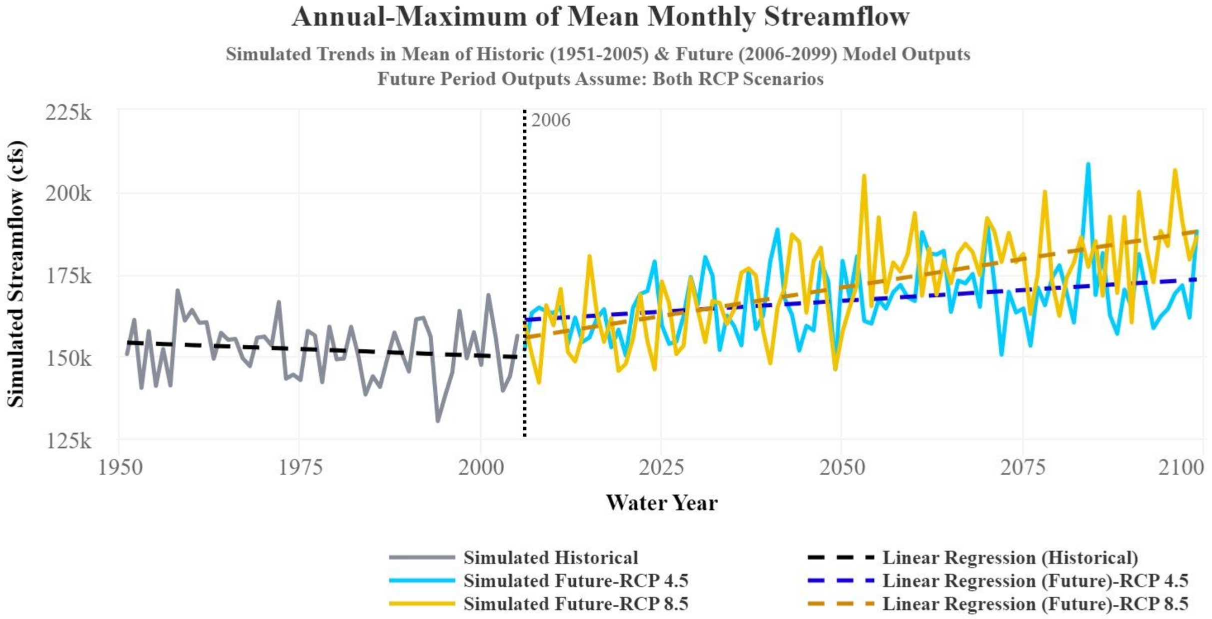


Table 1: Trend Analysis of Average Model Output: Annual Maximum of Mean Monthly Streamflow for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

Statistical Test	Historic (1951 – 2005)	Future (2006 – 2099) RCP 4.5	Future (2006 – 2099) RCP 8.5
t-Test	P-value = 0.281; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.001; Statistically Significant (>0.05); Slope is 132.0 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 347.3 and Direction is upward
Mann-Kendall	P-value = 0.303; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.00114; Statistically Significant (>0.05); Slope is 132.0 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 347.3 and Direction is upward
Spearman Rank Order	P-value = 0.325; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.001; Statistically Significant (>0.05); Slope is 132.0 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 347.3 and Direction is upward

Figure 13 and **Table 2** present the results of the three statistical tests and the slopes associated with statistically significant trends for the mean of the 32 projections (per RCP) of annual maximum 3-day precipitation. The mean of the simulated, annual maximum precipitation projections for the future period (2006 to 2099) shows a statistically significant, positive trend for the Lower Missouri River watershed under both emission scenarios. The CHAT computes a trendline slope of 0.0079 inches per year for the higher emission scenario, which would be a 0.395 inch increase in maximum 3-day precipitation over a 50-year period. The lower emission scenario has a trendline slope of 0.0029 inches per year, which would be a 0.145 inch increase in maximum 3-day precipitation over a 50-year period. There are no statistically significant trends in simulated, historic precipitation between 1951 and 2005.

Figure 13: Trend Analysis of Average Model Output: Annual Maximum 3-day Precipitation for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

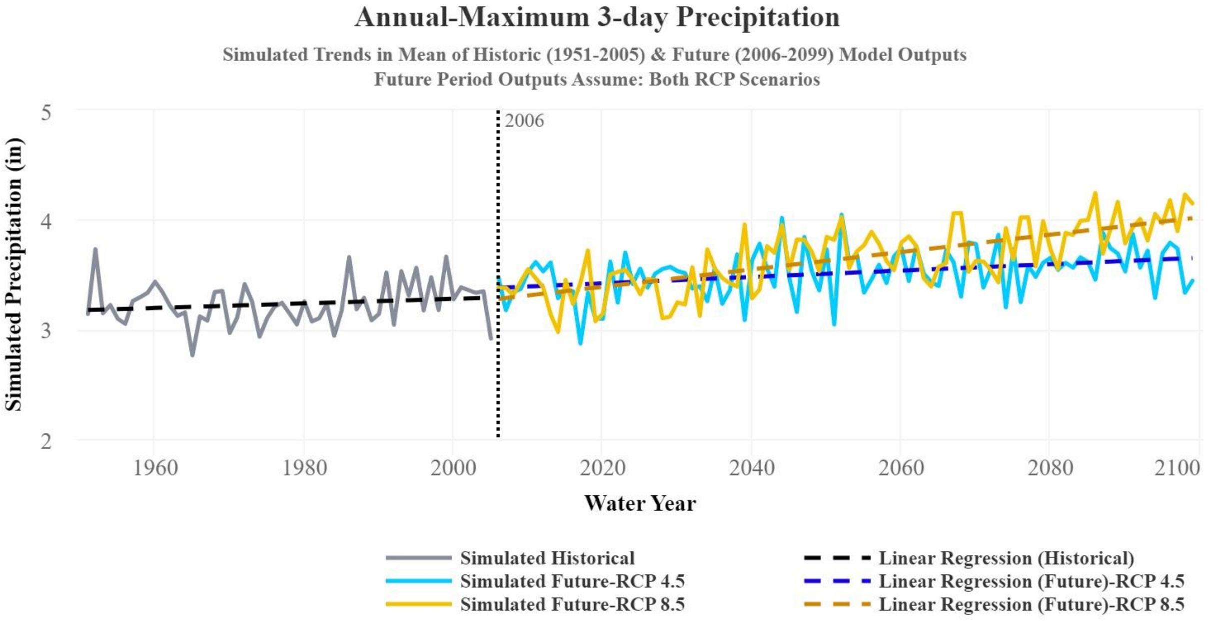


Table 2: Trend Analysis of Average Model Output: Annual Maximum 3-day Precipitation for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

Statistical Test	Historic (1951 – 2005)	Future (2006 – 2099) RCP 4.5	Future (2006 – 2099) RCP 8.5
t-Test	P-value = 0.209; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0029 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0079 and Direction is upward
Mann-Kendall	P-value = 0.184; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0029 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0079 and Direction is upward
Spearman Rank Order	P-value = 0.166; Not Statistically Significant (<0.05); Slope and Direction N/A (no trend)	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0029 and Direction is upward	P-value = <0.001; Statistically Significant (>0.05); Slope is 0.0079 and Direction is upward

The CHAT provides streamflow and precipitation outputs analyzed comparatively by describing simulated changes in monthly and annual streamflow and precipitation between a baseline epoch (1976 to 2005) and two future epochs: 2035 to 2064 (mid-century) and 2075 to 2099 (end of century). The tool presents epoch-based monthly and annual change in streamflow and precipitation using boxplot visualizations. The monthly boxplots provide insight into the seasonality of changes in streamflow and precipitation over time.

Figure 14 and **Figure 15** present changes in epoch mean of simulated monthly mean streamflow for stream segment 10001095 in the Lower Missouri – Moreau watershed (HUC 10300102). For the stream segment of the Missouri River analyzed, it appears that both high flow conditions in the spring and low flow conditions in the summer will likely continue to be more extreme. In general, flows throughout the winter and spring are anticipated to increase, and flows throughout the summer months are anticipated to decrease. When used to evaluate the change in the epoch mean of simulated annual mean streamflow, the CHAT calculated median change from the base Epoch (1976 to 2005) to the mid-century epoch (2035 to 2064) is 7.5 percent under the RCP 8.5 scenario. By the end-century epoch (2070 to 2099), the change relative to the base period is 12.8 percent under the RCP 8.5 scenario.

Figure 14: Change in Epoch Mean of Simulated Monthly Mean Streamflow for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

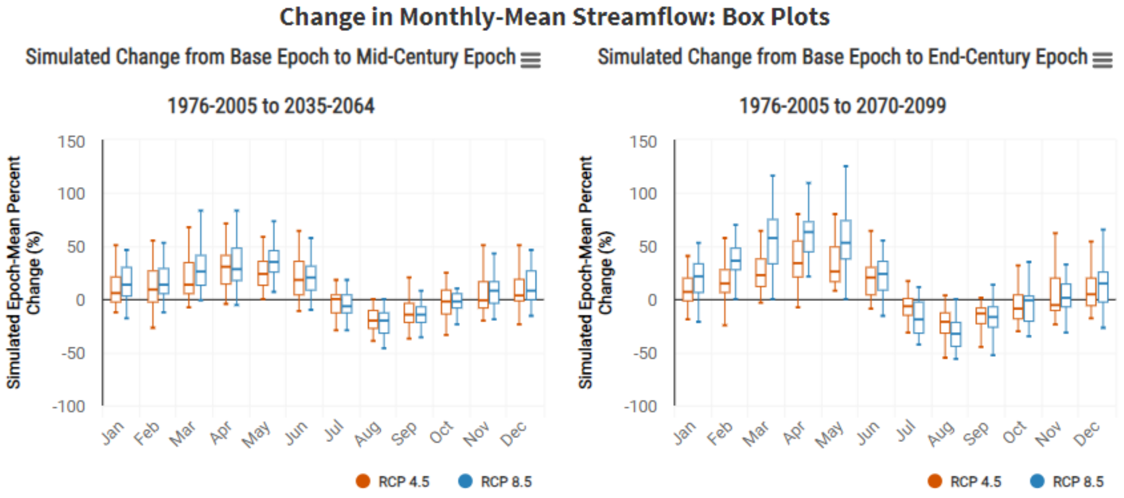


Figure 15: Change in Epoch Mean of Simulated Annual Mean Streamflow for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

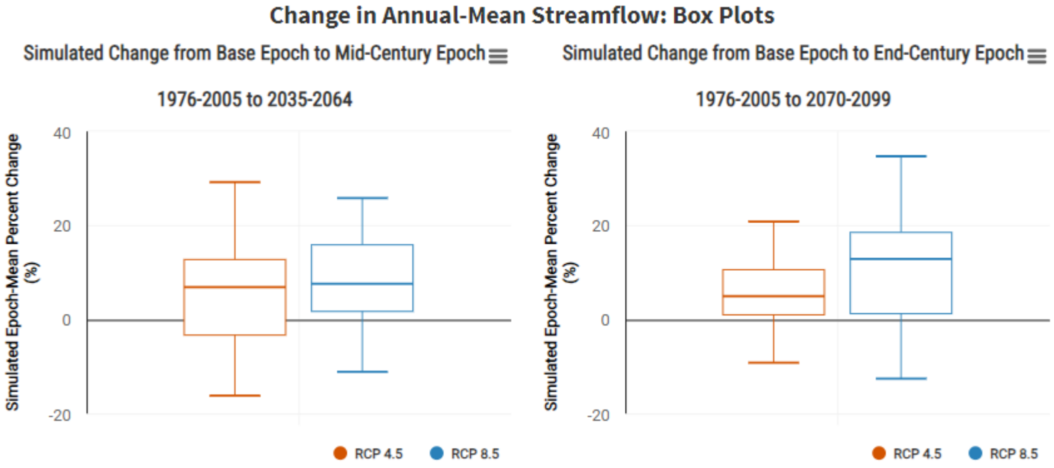


Figure 16 and **Figure 17** present changes in epoch mean of simulated monthly maximum 3-day precipitation for stream segment 10001095 in the Lower Missouri – Moreau watershed (HUC 10300102). Results for both the mid-century epoch (2035 to 2064) and the end-century epoch (2070 to 2099) indicate an increase an overall increase in monthly-maximum 3-day accumulated precipitation with especially notable increases in late winter and springtime precipitation. When used to evaluate the change in epoch mean of simulated annual maximum 3-day precipitation, the CHAT calculated median change from the base epoch (1976 to 2005) to the mid-century epoch (2035 to 2064) is 0.027 inches for RCP 4.5 and 0.386

inches for RCP 8.5. By the end-century epoch (2070 to 2099), the change relative to the base period is 0.317 inches for RCP 4.5 and 0.558 inches for RCP 8.5.

Figure 16: Change in Epoch Mean of Simulated Annual Maximum 3-day Precipitation for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095

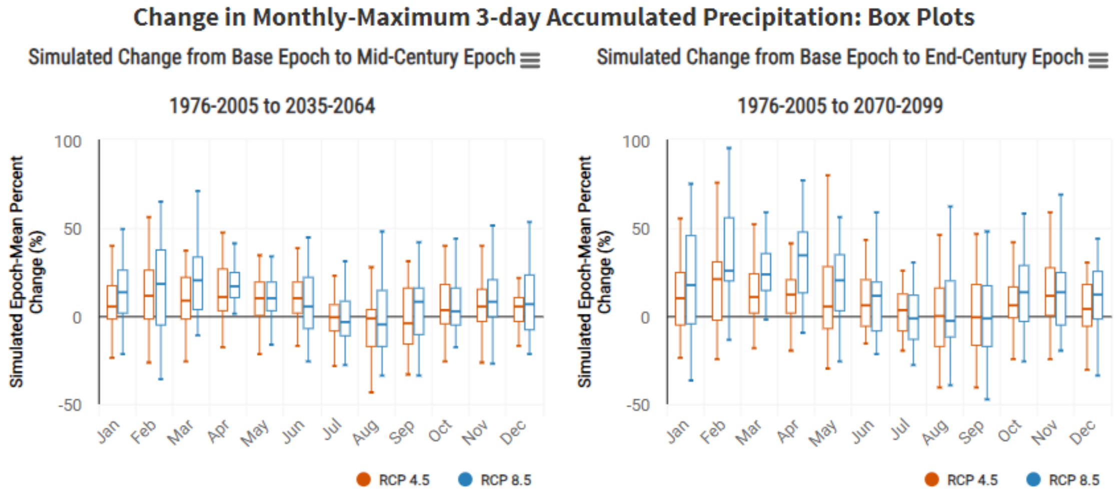
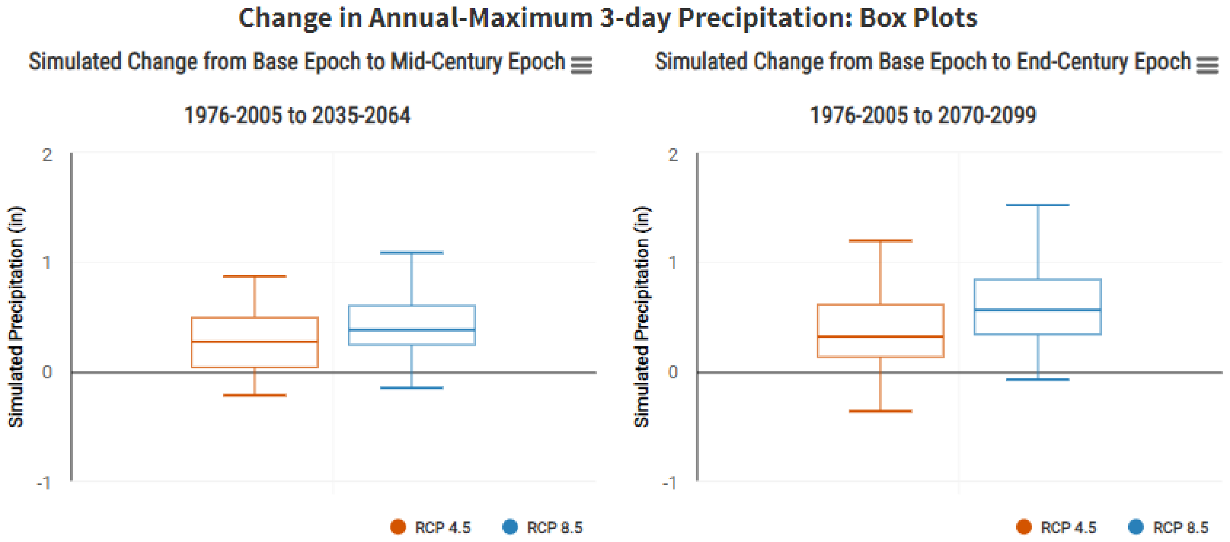


Figure 17: Change in Epoch Mean of Simulated Annual Maximum 3-day Precipitation for the Lower Missouri - Moreau watershed (HUC 10300102) stream segment 10001095



5 SCREENING LEVEL RELATIVE VULNERABILITY ASSESSMENT: FLOOD RISK REDUCTION

The USACE Climate Change Vulnerability Assessment (VA) Tool facilitates a screening level, comparative evaluation of climate change exposure to projects for a selected USACE business line for a 4-digit HUC watershed relative to the other 4-digit HUC watersheds within the Continental United States (CONUS). The VA Tool computes and aggregates a series of indicator variables into a vulnerability score using the Weighted-Order, Weighted-Average (WOWA) approach. The tool uses the CMIP5 GCM-based Bias

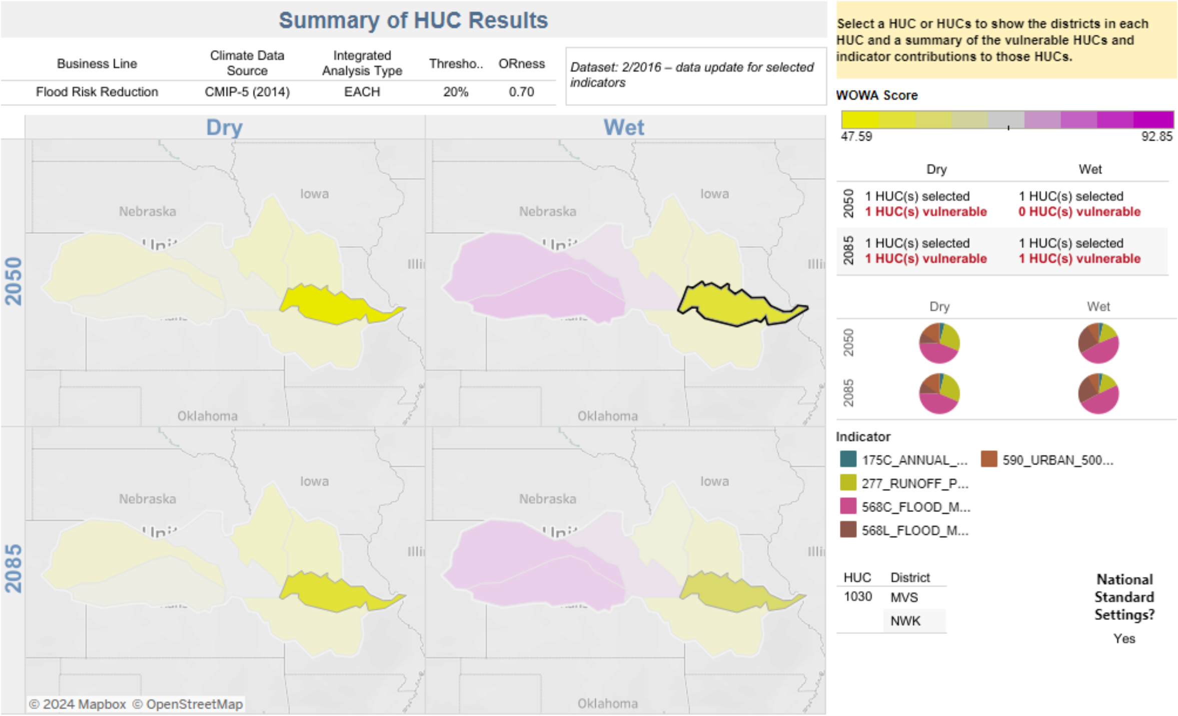
Corrected, Spatially Disaggregated (BCSD) VIC dataset (2014) to define projected hydrologic and meteorologic inputs to the tool's WOWA scores.

The VA Tool offers WOWA scores and indicator variable values for two subsets of simulations: wet (top 50 percent by cumulative runoff projections) and dry (bottom 50 percent by cumulative runoff projections). Relative vulnerability scores are available for two 30-year futures epochs (centered on 2050 and 2085). Watersheds with WOWA scores specific to a given business line that fall within the top 20 percent of WOWA scores for watersheds in CONUS are considered relatively vulnerable to climate change impacts. The projected outputs incorporated into VA scores contain considerable uncertainty. Some of this uncertainty is reflected by the differences in results for each of the subset-epoch combinations.

This assessment used the default, National Standards settings for the Flood Risk Reduction business line. Indicators used to compute the Flood Risk Reduction WOWA score include: long-term variability in hydrology, runoff elasticity (ratio of streamflow runoff to precipitation), local and cumulative flood magnification (indicator of how much high flows are projected to change over time within the HUC and in upstream HUC watersheds), and urban area within the 500-year floodplain.

As shown in **Figure 18** and **Table 3**, the dominant indicator variable contributing to the Flood Risk Reduction business line VA score for the Lower Missouri (HUC 1030) watershed is (568C) flood magnification for all epoch and subset combinations. The WOWA score changes by 4-6 percent between the 2050 and 2085 epochs for both the wet and dry subsets. The percentage by which the indicator variable contributes to the VA score changes between 5.5 percent and 9 percent over time for both wet and dry subsets.

Figure 18: Flood Risk Reduction Vulnerability Assessment Tool Output – Lower Missouri Watershed (HUC 1030)



Summary of HUC Results

Business Line	Climate Data Source	Integrated Analysis Type	Thresho..	ORness
Flood Risk Reduction	CMIP-5 (2014)	EACH	20%	0.70

Dataset: 2/2016 – data update for selected indicators

Select a HUC or HUCs to show the districts in each HUC and a summary of the vulnerable HUCs and indicator contributions to those HUCs.

	Dry	Wet
2050	1 HUC(s) selected 1 HUC(s) vulnerable	1 HUC(s) selected 0 HUC(s) vulnerable
2085	1 HUC(s) selected 1 HUC(s) vulnerable	1 HUC(s) selected 1 HUC(s) vulnerable

HUC	District
1030	MVS
	NWK

National Standard Settings?

Yes

Table 3: Vulnerability Assessment Tool Output - HUC 1030 Lower Missouri River Watershed - Flood Risk Reduction

Subset and Epoch	VA Score	% Change in VA Score (2050 to 2085)	Dominant Indicator	Dominant Indicator % Change (2050 to 2085) – Contribution to Overall WOWA Score	Dominant Indicator % Change (2050 to 2085) – Indicator Value
Wet - 2050	57.43	+6.09%	568C Flood Magnification	8.67%	8.67%
Wet - 2085	60.93	+6.09%	568C Flood Magnification	8.67%	8.67%
Dry - 2050	50.96	+4.31%	568C Flood Magnification	5.45%	5.45%
Dry - 2085	53.15	+4.31%	568C Flood Magnification	5.45%	5.45%

6 SUMMARY

The Lower Missouri Jefferson City L-142 FRM Study at Jefferson City will develop an array of measures and alternatives and evaluate them on their ability to reduce flood risk and flood impacts along the left-bank of the Missouri River at Jefferson City, Missouri. The climate change assessment conducted for this study assessed historic hydrometeorological data and projected future hydrometeorological data to gain insight on the projection of future risk at this site. The main climatic risk factor for the L-142 levee is increased Missouri River streamflows, especially during flood-prone seasons including spring and early summer.

Available literature suggests observed warming trends in the Lower Missouri River Basin are projected to carry into the future. Additionally, precipitation and streamflow models suggest upward trends, but with no significant developed consensus across sources. Generally, precipitation increases are most anticipated in the spring months and late winter.

Evaluations of future extreme precipitation and streamflow generated using the CHAT suggest future increases in both 3-day maximum precipitation and annual maximum mean monthly precipitation when RCP 8.5 is assumed, with the most robust evidence of increased monthly mean streamflow in the end-of-century (2070 – 2099) epoch. This is supported by the likely increases in spring precipitation and runoff. The VA Tool indicates that flood magnification drives the vulnerability score for the Lower Missouri River watershed (HUC 1030). Relative to the rest of the country, flood vulnerability in the Lower Missouri Basin is particularly impacted by climate change.

Table 4 indicates potential residual risks for flood risk management project features due to climate change. The table also includes a qualitative rating of how likely those residual risks are to materialize and undermine project features resulting in harm to the study area. Examples of building resilience into flood risk management project features includes designing top elevations of levees to protect against extreme events, providing designed overtopping at predetermined locations to reduce the risk of uncontrolled failures, and robust erosion protection designs.

Table 4: Residual Risk due to Climate Change

Project Feature	Trigger	Hazard	Harm	Qualitative Likelihood
Levees & Berms	Increased seasonal precipitation	Future flows may be larger than present Large flood volumes may occur more frequently	Levees could overtop more frequently or be loaded for longer durations, resulting in increased floodfighting and O&M costs.	Likely
Internal Drainage	Increased seasonal precipitation	Increased flows behind the leveed area Longer drawn down times along the Missouri River	Flow volume internal to the leveed area could increase, requiring additional pumps or an extended time to relief Longer river draw down times could result in longer internal drainage ponding conditions	Likely
Riprap Bank Stabilization	Increased seasonal precipitation	Future flows may be larger than present Large flood volumes may occur more frequently	Higher flows and velocities would result in increased O&M costs	Likely
Floodproofing measures	Increased seasonal precipitation	Future flows may be larger than present Large flood volumes may occur more frequently	Floodproofing measures could overtopped during more frequent storm events, leading to additional repair costs	Likely

All project features driving residual risk due to climate change have a likely qualitative likelihood. This likelihood rating is justified, as increases in precipitation were observed in every future projection trend test conducted, with variable robustness. As the Lower Missouri River basin is not regulated, increased precipitation is the main driver of flood events in this location. Increase in precipitation volumes due to severe or prolonged storm events would directly impact peak streamflows.

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