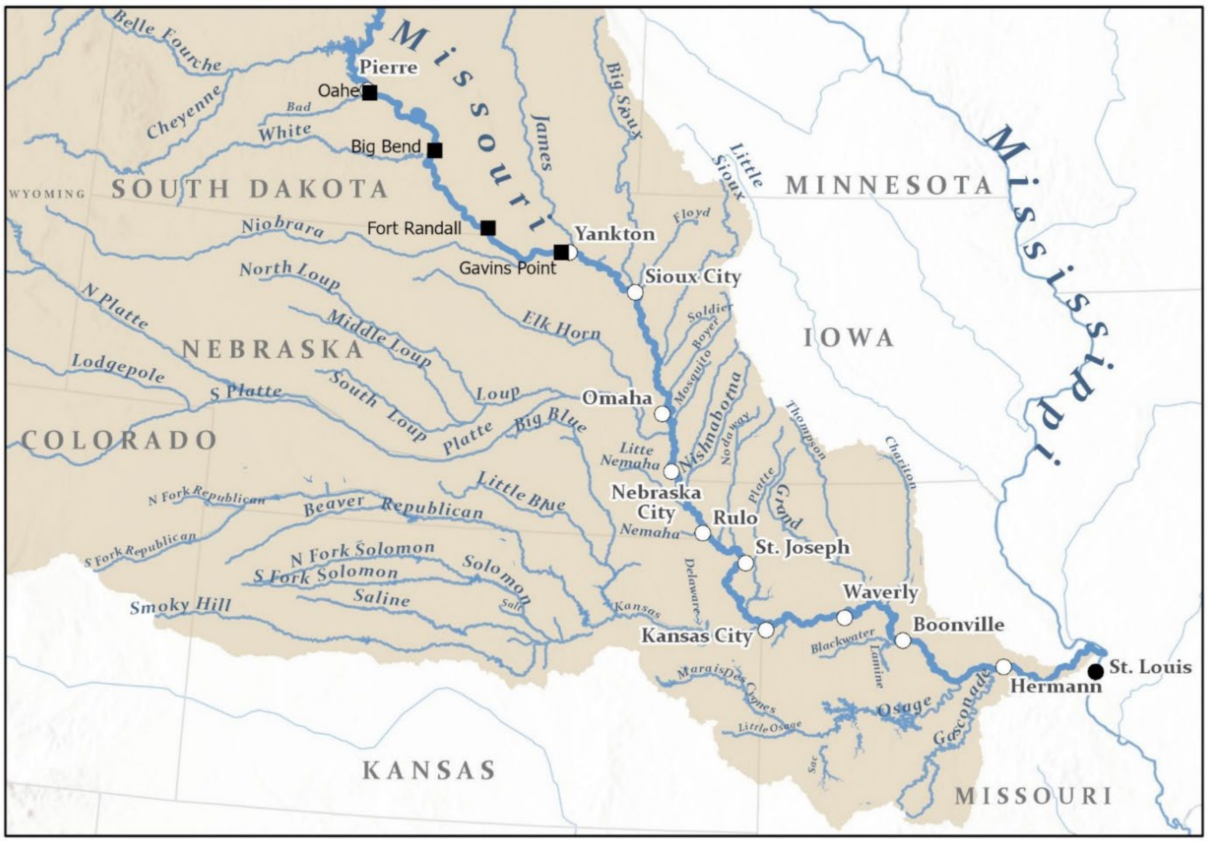
US Army Corps of Engineers ®

Missouri River Flow Frequency Study

Yankton, South Dakota to Hermann, Missouri

Appendix J: Qualitative Climate Change Analysis



U.S. Army Corps of Engineers
Northwestern Division
Omaha District, Kansas City District, and
Missouri River Basin Water Management

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1. Introduction

The main objective this climate assessment is to better understand future conditions along the mainstem Missouri River and determine potential resilience of future projects designs. The climate within the Missouri River Basin is analyzed using three inter-related variables: temperature, precipitation, and streamflow. Temperature and precipitation are the primary forcing variables of streamflow. Temperature influences the water holding capacity of the atmosphere and the phase of precipitation at the ground surface. Precipitation in cold weather will result in snow and ice accumulations on the ground surface. Precipitation in warm weather will result in liquid water accumulations at the ground surface that can infiltrate, runoff, or melt existing snow cover. In the Missouri River Basin snowmelt is considered the key driver of flooding. An analysis of precipitation and temperature data provides important context into streamflow trends within the basin. An increase in streamflow will affect future proposed flood mitigation measures along the Missouri River.

Future projects could involve all the authorized purposes of the U.S. Army Corps of Engineers on the Missouri River main stem. Authorized purposes include flood risk mitigation, navigation, irrigation, power, water supply, water quality control, recreation, and fish and wildlife. While the Missouri River has many authorized purposes, flood mitigation and navigation are the focus of the Missouri River Flow Frequency Study.

This appendix fulfills the requirements for qualitative climate assessments outlined in ECB 2018-14 (extended on 09-20-2020) *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects.* Phases I, II, and III required by the guidance are addressed. Phase I requires the identification of climate variables important to the region (stated above). Phase II includes a vulnerability analysis of business lines important to future projects in the future (stated above). The vulnerability analysis is documented in Section 7.0. Phase III is a risk assessment that provides information to decision-makers about how climate change should be considered in future projects. This analysis is provided near the end of the document.

The focus of this MRFF study is to update peak flow probabilities for several locations on the lower Missouri River. The current study was motivated by multiple recent flood events in the last 10 years. Note that the focus of the update is the main-stem Missouri River below Gavins Point Dam. Although recent floods had slightly different characteristics, the overall result is that increased floods, especially for the areas below Gavins Point Dam, have impacted billions of dollars in infrastructure and thousands of residents in several different states. The results of our analysis cannot be quantitatively included in the products and deliverables for the Lower Missouri River Flow Frequency study (MRFF), we make a concerted effort to incorporate relevant information to meet the overarching climate preparedness and resilience policy for USACE. It should be noted that the MRFF and our climate assessment focus on main-stem river locations.

2. Literature Review

2.1 Project Site and Background

The Missouri River Basin is an expansive and geographically diverse watershed (Figure 1). The Missouri River has a drainage area of 530,000 square miles and its mainstem is regulated by six mainstem dams above Yankton, South Dakota. Except for Fort Peck Dam, the other five projects were authorized and constructed as part of the Pick-Sloan Flood Control Act of 1944. The construction of the five main-stem projects spanned several decades starting in the late 1940s. Fort Peck, Garrison, and Oahe Dams in the most northern portion of the watershed have the largest storage volumes and manage runoff from mountain and plains snowpack but also rainfall. The lower dams—Big Bend, Randall, and Gavin's Point dams—manage plains snowpack and rainfall inflows plus releases from the upstream dams. Big Bend and Gavin's Point have very little flood storage. Fort Randall is a large hydropower producer and Gavins Point Dam acts as a reregulation dam. The six dams are operated as a system to maximize project benefits.

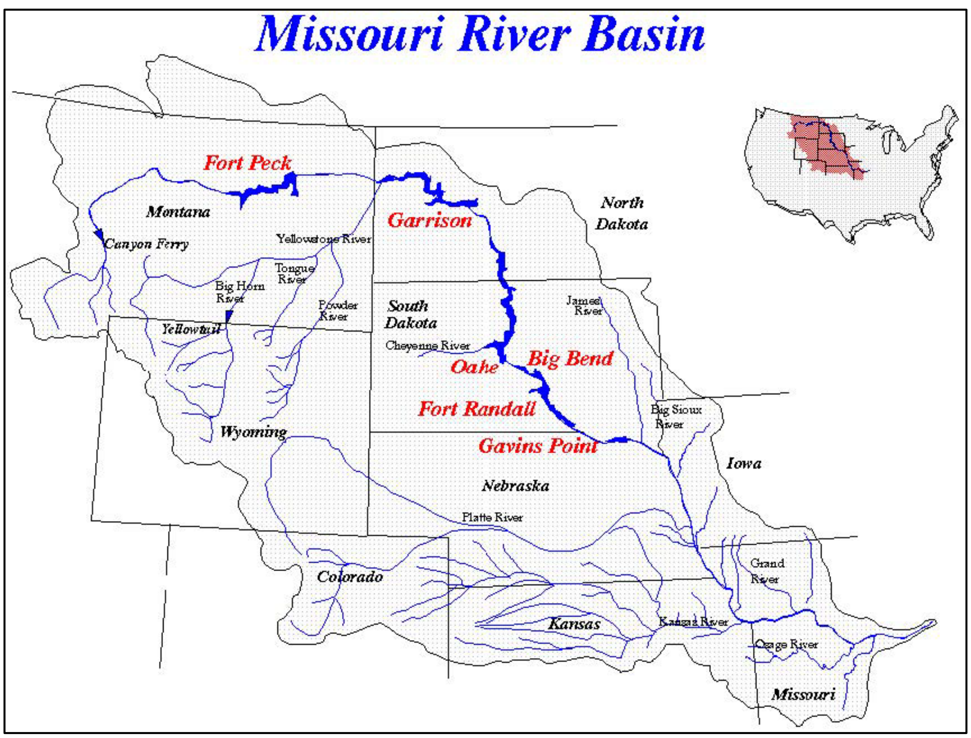

Figure 1. Missouri River Basin Map Showing the Location of USACE Projects

Mechanisms of flooding in the Missouri River basin include snowmelt and rainfall. The river has two large pulses of flow in March and May. The March pulse is due primarily to plains snowmelt and the May pulse is due to mountain snowmelt, northern plains snowpack and rain on snow. In addition to these snowmelt cycles, the mainstem is vulnerable to heavy rainfall within its large drainage area from spring through summer. The largest precipitation events typically occur in the upper basin. These are managed by the upper three dams with the largest flood storage—Fort Peck, Garrison, and Oahe. Seasons of importance include winter (snow accumulation), spring (snowmelt and rain on snow events), and summer (rainfall).

2.2 Main References

Our literature review is a general discussion of observed and projected trends for precipitation and temperature for the entire watershed with focus on the three seasons noted. However, we only summarize streamflow changes on the main-stem Missouri River. The main references of this literature review include:

- The Fourth National Climate Assessment (NCA) (Reidmiller et al. 2018). This source provides the most comprehensive discussion of projected changes in temperature and precipitation for regions within the Missouri River basin. The NCA divides regions by chapters in the report to help readers quickly find information related to their location. The NCA region used for this assessment was Northern Great Plains.
- Climate Science Special Report Fourth National Climate Assessment (NCA4) (USGCRP, 2017). This source provides the more technical information behind the Fourth NCA. It includes information from many of the scientific articles used in past climate assessments. It focuses is on the scale of the United States and less on the regional scale which is the focus of the NCA.
- The USACE Water Resources Region 10: Missouri River (USACE, 2015). The focus of this source is on the scale of the Missouri River Basin, the project site of this climate assessment.

2.3 Observed Trends

The climate literature relevant to the Missouri River basin is presented in continental-scale assessments (Vose et al. 2017, Easterling et al. 2017) and regionally focused reports (USACE 2015, Conant et al. 2018, Kloesel et al. 2018). Figure 2 presents a summary of the climate literature from the USACE Water Recourses Region 10: Missouri River (USACE, 2015). Overall, there is consensus temperature and streamflow are increasing. Precipitation trends are variable based on the literature included in the summary.

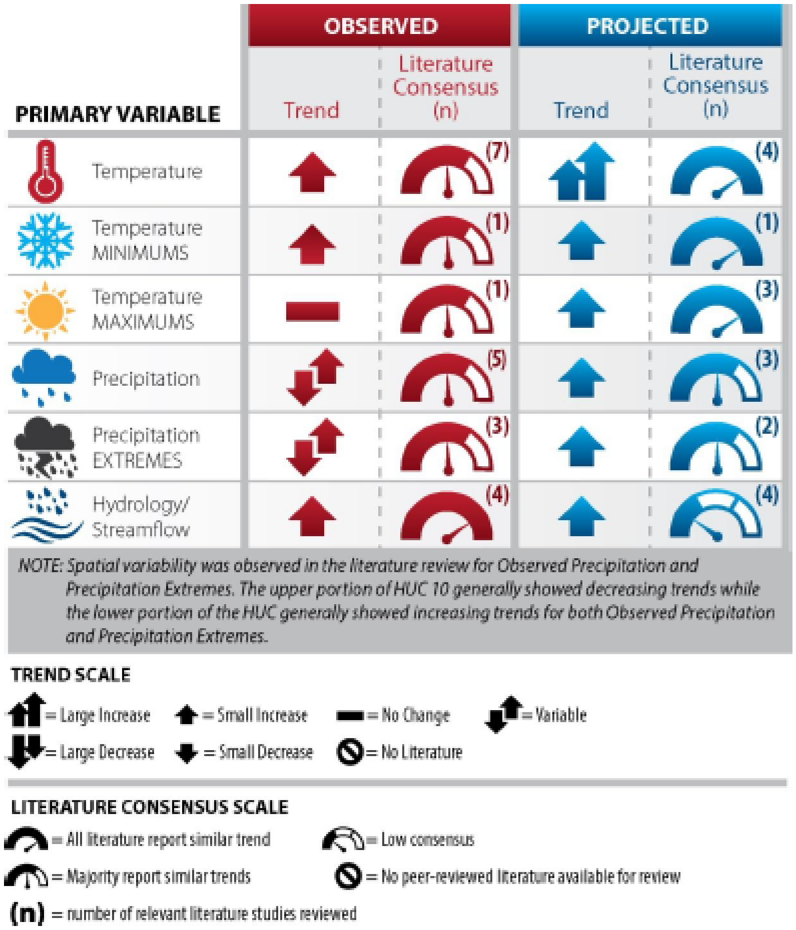

Figure 2. Summary of Climate Variables from USACE Region 10 Summary (USACE 2015)

2.3.1 Temperature

There is a consensus that temperatures have increased over the observed record (Vose et al. 2018). The most substantial warming trends in the Missouri River Basin are attributed to minimum temperatures (USACE 2015, Conant et al. 2018). In contrast, there is not a consensus with maximum temperatures since only a single reference is summarized. There is evidence that seasons are shifting, specifically that spring is occurring earlier in the year. State-by-state analyses of historical temperature trends reports negligible increases in the southern region of the watershed, while also highlighting increases in northern states (Larson & Schwein 2004). Notably, North Dakota has seen the largest increase in state-wide average temperatures relative to 1901-1960 baseline.

2.3.2 Precipitation

Observed trends in precipitation have a strong east-to-west decreasing gradient across the Missouri River Basin. The western region of the watershed is where the largest precipitation events and snow accumulations occur. Flooding on the mainstem Missouri River is related to large precipitation events in the upper basin, where frozen ground reduces infiltration and increases runoff. Much of the middle basin is semi-arid or arid, where less than 10% of basin precipitation reaches the Missouri River (Hoerling et al. 2013), Therefore, small changes in regional precipitation in the upper basin can lead to large changes in mainstem Missouri River streamflow. Based on the literature there is not a consensus on the trend direction for precipitation.

2.3.3 Streamflow

The Missouri River Basin also has a history of episodic trends, drought, and an overabundance of surface water (Conant et al. 2018). Tree-ring reconstructions of streamflow in the upper Missouri River Basin indicate considerable streamflow variability over the last 1200 years (Martin et al. 2019). Martin et al. (2020) reports the relatively recent "turn-of-the-century drought" which occurred between 2000 to 2010, is one of the most severe in the last 1200 years. Following this unpresented drought were substantial floods occurring in 2011 and 2019. Hoering et al. 2013 analyzed the meteorological drivers of the 2011 floods and attributed the event to a sequence of a cold-wet winter followed by late spring heavy-precipitation. Each of the events alone could have resulted in abnormally large runoff events, but they culminated in an extreme runoff year. Without being able to attribute basin runoff to a specific driver during the 2011 flood, it is difficult to directly link the variability to a known driver of climate change (e.g. atmospheric rivers, sea surface temperatures). In 2019, an extremely wet October through December following by large March precipitation event on areas of frozen soil resulted in several of the lower Missouri River streamgages to reach record stages. These record stages were observed for several weeks with some locations having over 270 days consecutive days above flood stage (HPRCC 2020).

There have been several studies of streamflow trends within the Missouri River Basin. Notron et al. 2014 provides a comprehensive trend analysis of observed peak streamflow records at 227 streamgages (Figure 3). The streamgage records were not corrected for any upstream impacts from human activities such as irrigation and reservoir regulation. They found streamflow had a decreasing trend upstream of Garrison Dam and in the western extents of the Kansas City District regulator domain. The drainage between Gavins Point Dam and Sioux City had showed increasing trend. Kibria et al. 2016 presents a regionally focused streamflow trend analysis in South Dakota. They found trend direction varied across South Dakota using flows from 18 rivers. For the mainstem Missouri River, they found decreasing streamflow trends in the northern half of the state and no trends in the southern half. Despite the regional differences in streamflow, the increasing trends in the Missouri River basin are suspected to be related to climate change (Hoerling et. al 2013, Conant et al. 2018).

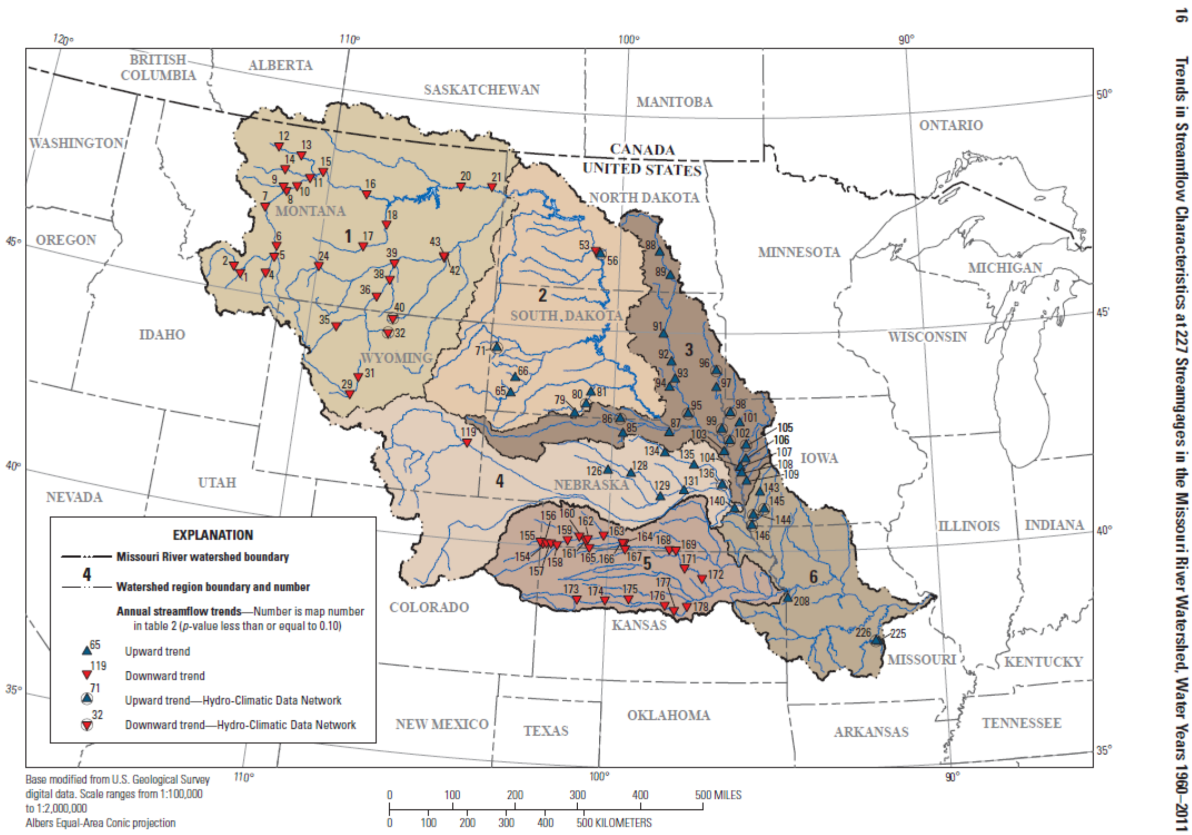

Figure 11. Streamgages in the Missouri River watershed with statistically significant trends in annual streamflow for water years 1960–2011.

Figure 3. USGS Streamgages in the Missouri River Basin with Statistically Significant Trends in Annual Peak Streamflow for Water Years 1960 – 2011 (Norton et al. 2014)

2.2 Projected Trends

2.2.1 Temperature

The trends in temperature are projected to increase across the basin, with the largest increases in the Lower Missouri River basin. While there is not a consensus on maximum temperature, the projected number of very hot days (e.g., temperatures above 90°F) in the lower Missouri River Basin will increase between 35-50 days in both wet and dry scenarios (Figure 4). Projected changes are shown for (top) the annual number of very hot days (days with maximum temperatures above 90°F, an indicator of crop stress and impacts on human health), (bottom) the annual number of cool days (days with minimum temperatures below

28°F, an indicator of damaging frost). Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). The number of days with temperatures below 28°F is projected to decrease across the entire basin, with the most significant reduction in the basin's upper extent (Vose et al. 2017, Contant et al. 2018).

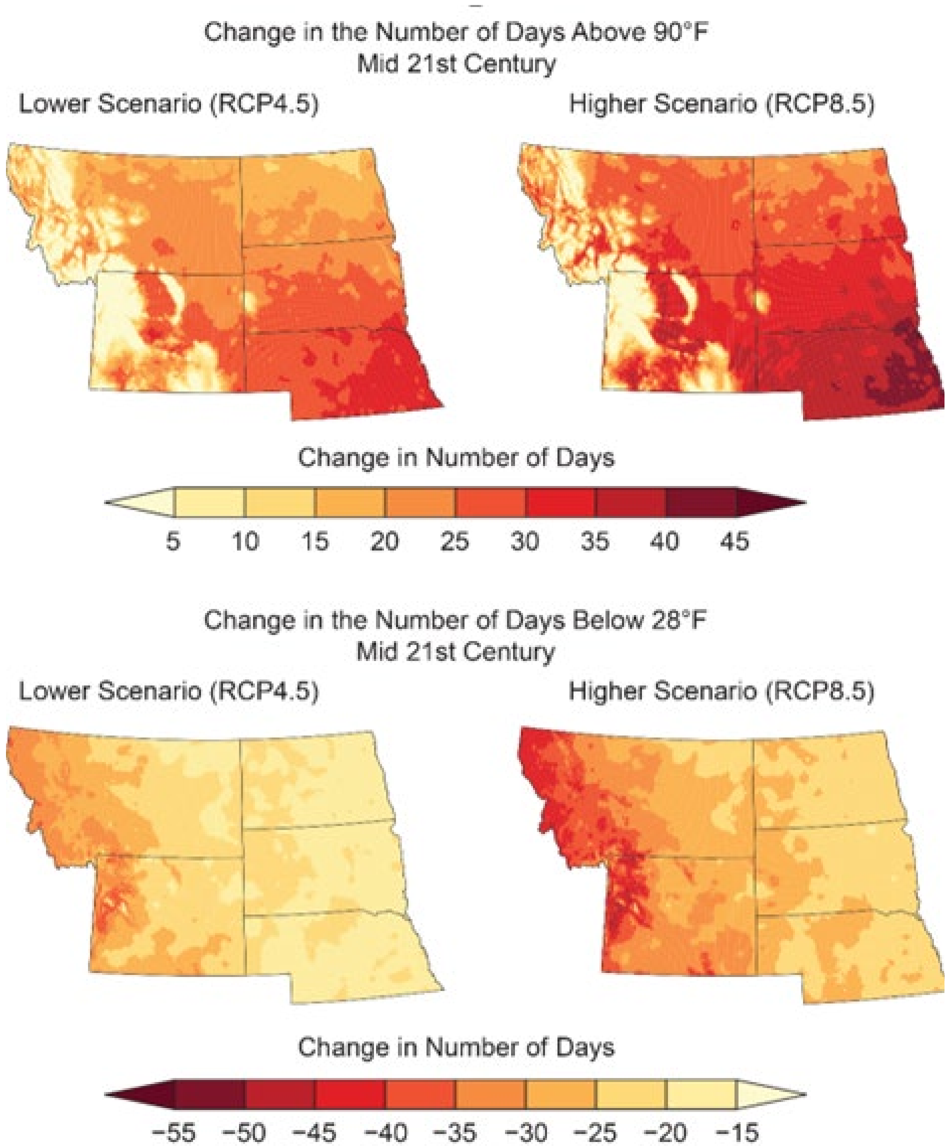

Figure 4. Projected Changes for Annual Number of Very Hot and Cool Days for the Middle of the 21st Century (Conant et al. 2018)

2.2.2 Precipitation

The number of days with precipitation greater than one inch (heavy precipitation events) is projected to increase in the montane western and eastern regions by the middle of the 21st century (Figure 5). Areas in white do not normally experience more than one inch of rainfall in a single day. Projections are shown as changes from the 1976–2005 average for the middle of the 21st century (2036–2065) for the lower and higher scenarios (RCP4.5 and RCP8.5). Despite the projections of increased frequency of heavy precipitation, the end of March Snow Water Equivalent (SWE) is expected to decline in the basin's montane western region (Figure 6). The historical and projected changes under a higher scenario in average snowpack are depicted. The central portion of the basin is projected to increase SWE by the middle of the 21st century, but the overall increase is small because the average accumulation is relatively low compared to the western portions of the basin.

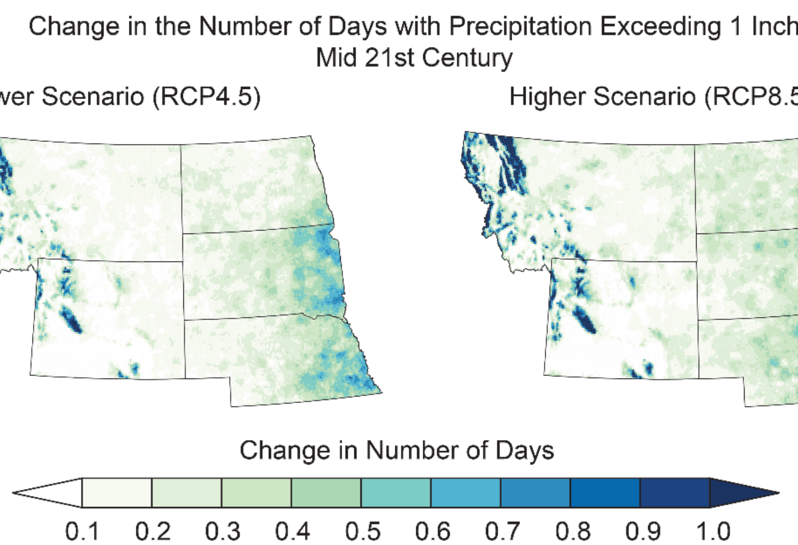

Figure 5. Projected Changes for Heavy Precipitation Events for the Middle of the 21st Century (Conant et al. 2018)

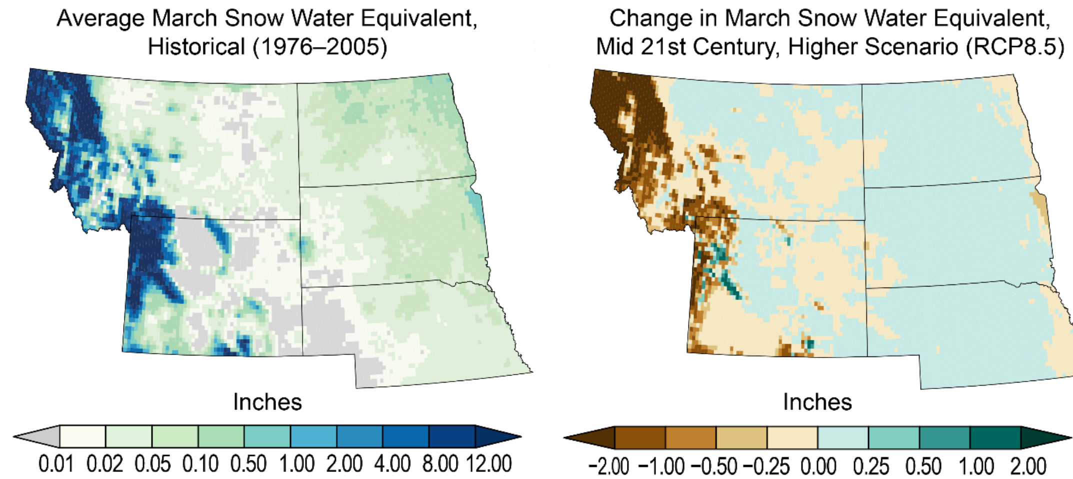

Figure 6. SWE Maps: Historical and Projected Changes (Conant et al. 2018)

2.2.3 Streamflow

Projected streamflow trends in the Missouri River basin are spatially variable (Figure 7) and there is a not consensus in scientific literature (Figure 2). In the western montane regions, streamflow projections are spatial inconsistent where large increases are adjacent to large decreases. For a large portion of the plains within the basin, streamflow is projected to remain constant. It should be noted, these areas are semi-arid and historically have not provided large contributions to mainstem Missouri River streamflow. In the south eastern portion of the basin, streamflow projections could increase by 0.10 cfs/mi^2 under RCP 8.5.

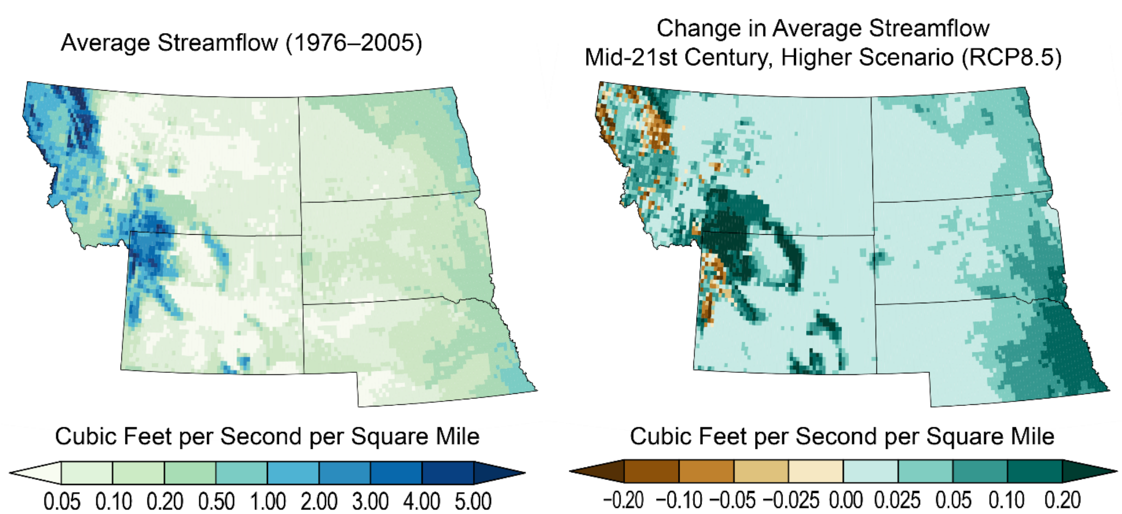

Figure 7. Annual Average Streamflow: Historical and Projected Changes (Conant et al. 2018)

3. Analysis Tools

The methods used for our qualitative climate change assessment were consistent with the standardized tools created by the USACE Climate Preparedness and Resilience Community of Practice. Specifically, these tools include the Climate Hydrology Assessment Tool (CHAT), the Nonstationarity Detection Tool (NSD), and the Vulnerability Assessment (VA) Tool. These tools are used within the three phases of the overall climate assessment required by ECB 12018-14. Phase I of the assessment requires initial scoping and identifying climate factors that are important to the region. Phase I also includes a decision of whether a quantitative assessment is needed. For the MRFF, the decision was to move forward with the qualitative assessment and consider future needs for a quantitative climate change study outside of the MRFF study. Phase II of the qualitative assessment includes a vulnerability analysis. This requires using the aforementioned tools to determine existing and future vulnerabilities in the watershed. Finally, Phase III is the risk assessment that should be included in the report documentation. Depending on the study type (e.g., planning, operational, design, etc.) the results of the qualitative assessment should be discussed in the report documentation. This provides information to decision-makers about how climate change was considered within the framework of the overall study.

The NSD evaluates nonstationarities or change points within observed annual instantaneous records at USGS gage stations. This tool uses several statistical tests to identify approximate dates when the changes mean, variance, or overall distribution occurred (Appendix A, Table 17). An identified change point can be identified as strong or robust based on the number and type of tests that identify the same change point. A strong change is when two or more of the tests of the same statistical property (i.e. mean, variance, or distribution) identify the same points. A robust change point is when two or more different statistical properties are statistically significant. Engineering Technical Letter (ETL) 1100-2-3 *(USACE, 2019)* documents all the tests contained within the NSD*.* A summary of the monotonic trend tests is available in Table 18 in Appendix A.

The CHAT provides trend information related to trends in the historical peak flows and projected annual maximum monthly flow-based on Global Climate Models (GCM). Trends from observed instantaneous peak streamflow at USGS gages are determined using a least-squares linear regression model. Trends in projected annual maximum monthly streamflow from downscaled GCMs a Bias Correction and Spatial Disaggregation method (BCSD; Wood et al., 2004). The Variable Infiltration Capacity model is used to project annual monthly maximum streamflow estimates for HUC 4 watershed.

The final step in the Phase II Vulnerability Assessment for qualitative analysis requires using the VA tool to assess HUC 4 watersheds impacts on USACE business lines. The VA tool results are used for a screening-level assessment of vulnerabilities to multiple USACE business lines at the HUC-4 watershed level. The basis for the metrics included in the vulnerability assessment are the CMIP5 projections of temperature, precipitation, and streamflow. The VA tool evaluates the vulnerability of USACE business lines using a Weighted Order Weighed Average (WOWA) aggregates the contributions of specific indicators into a representative metric. A business line is considered vulnerable when it's relative contribution to the overall WOWA metric exceeds a user-specified threshold tolerance. In this analysis, we used the national standard default tolerance settings. The default parameters are also provided on the VA tool outputs provided in Section 7.0.

4. Data

A qualitative climate assessment requires analysis of USGS streamflow records and downscaled GCM streamflow projections. These data are readily available in the NSD and CHAT tools. The NSD tool performs statistical changepoint and nonparametric monotonic trend tests of observed instantaneous annual peak streamflow data served by the USGS. The CHAT builds the nonparametric monotonic trend analysis from NSD by performing a linear least-squares regression of instantaneous annual peak streamflow data. The CHAT also analyzes downscaled GCM projections of annual maximum monthly streamflow in HUC-4 watersheds. Trends in projected annual maximum monthly streamflow can be analyzed by performing a least-squares regression of the mean projected annual maximum streamflow.

There are 14 USGS gages on the mainstem Missouri River available for analysis in the NSD and CHAT tools (Table 1). The location of the mainstem Missouri River gages extends from above Fort Peck Dam to below Gavins Point Dam. The streamflow data available for analysis in the NSD and CHAT are not corrected for regulation of the storage reservoirs and agricultural irrigation depletions. While some information can be gleaned from the regulated flows in the USGS records, the detection of nonstationarity and trends due to climate change is more effectively accomplished using unregulated streamflows that have irrigation depletions removed.

Table 1. Missouri River Mainstem USGS Gages and Period of Record Analyzed in the NSD Tool

USGS Gage Number	Station Name	Drainage Area (square miles)	Start Year	End Year
06115200	Missouri River near Landusky, MT	40987	1929	2019
06132000	Missouri River below Fort Peck Dam, MT	57556	1931	2019
06177000	Missouri River near Wolf Point, MT	82290	1930	2019
06185500	Missouri River near Culbertson, MT	91557	1960	2019
06342500	Missouri River at Bismarck, ND	186400	1930	2019
06486000	Missouri River at Sioux City, IA	318559	1977	2014

USGS Gage Number	Station Name	Drainage Area (square miles)	Start Year	End Year
06610000	Missouri River at Omaha, NE	326759	1929	2019
06807000	Missouri River at Nebraska City, NE	413959	1930	2019
06813500	Missouri River at Rulo, NE	418859	1950	2014
06818000	Missouri River at St. Joseph, MO	420100	1930	2019
06893000	Missouri River at Kansas City, MO	484100	1930	2019
06895500	Missouri River at Waverly, MO	485900	1978	2014
06909000	Missouri River at Boonville, MO	500700	1930	2019
06934500	Missouri River at Hermann, MO	522500	1955	2019

To overcome the limitations of mainstem Missouri River USGS streamflow data, a No Regulation No Irrigation (NRNI) dataset was created by the Missouri River Basin Water Management staff at Northwestern Division for 19 main-stem locations for water years 1931-2019 (Table 2). The NRNI dataset was created to represent naturalized flow conditions without any reservoir regulation and irrigation depletions. The effects of reservoir regulation are removed using a conservation of mass assumption and mass balance. The volume of irrigation depletions is estimated using historical records provided by the Bureau of Reclamation. Depletions for multiple basin development conditions are estimated by the US Bureau of Reclamation (USBR) using their Regional Depletions model (USBR 2012). This model estimates agricultural withdrawals and return flows based on ag census data, meteorological data, types of conveyance systems, etc. In areas of high groundwater usage, additional analyses are performed to remove groundwater effects on surface water. USBR reservoir effects (water stored in a reservoir and lost to evaporation) are estimated from data retrieved from USBR's Hydromet Data System. Water supply withdrawals are estimated using per capita demand assumptions and fit to a monthly temporal pattern. Several trans-basin diversions are also included in the USBR depletions with data coming from a variety of sources. Final USBR depletions are calculated on a HUC8 scale and a monthly time step. This data is disaggregated to a daily time step so it can be utilized in reservoir and river models and estimate NRNI flows. Currently, only main-stem Missouri River locations have NRNI data available; therefore, our analysis is limited to these 19 locations.

Table 2. NRNI Flow Locations Metadata Table

NRNI Station	CWMS Name	Latitude (decimal degrees)	Longitude (decimal degrees)
Fred Robinson Bridge	RBMT	47.631	-108.688
Fort Peck Dam	FTPK DAM	48.000	-106.417
Wolf Point	WPMT	48.112	-105.533
Culbertson	CLMT	48.124	-104.473
Garrison Dam	GARR DAM	47.495	-101.417
Bismarck	BIS	46.814	-100.821
Oahe Dam	OAHE DAM	44.450	-100.402
Big Bend Dam	BEND DAM	44.038	-99.447
Fort Randall Dam	FTRA DAM	43.068	-98.549
Gavins Point Dam	GAPT DAM	42.848	-97.482
Sioux City	SUX	42.486	-96.414
Omaha	OMA	41.426	-95.922
Nebraska City	NCNE	40.682	-95.847
Rulo	RUNE	40.054	-95.422
St Joseph	STJ	39.753	-94.857
Kansas City	MKC	39.112	-94.588
Waverly	WVMO	39.215	-93.515
Boonville	BNMO	38.980	-92.745
Hermann	HEMO	38.710	-91.439

The NRNI maximum daily values were used with the CHAT and NSD functions to create the output required by ECB 2018-14. Peak streamflow records suitable for change point and trend analyses were create by applying an annual maxima block filter to n-day center moving averages. The n-day durations used in this analysis are based on a centered moving average of 7-day, 15-day, 31-day, 91-day, and 121-day. These durations provide straightforward date assignment of the computed average flow value since there is an even number of days before and after each timestep. Durations less than 7-day were not used because of the increased uncertainty with precise peak flow routing associated with removing regulation and irrigation depletions. The NRNI daily average values were used with the CHAT and NSD functions to create the output required by ECB 2018-14.

There are several sources of uncertainty in the NRNI data that could impact the climate signal within the data. First, the agricultural depletions across the time series are monthly estimates. Second, the aquifer in the Missouri River Basin is not spatially uniform and changes can lead to a transient signal in the NRNI data depending on regional depletions. Third, the available USGS streamflow records vary since the number of operational gages in the basin increased over time. Finally, land-use changes in the basin are not explicitly accounted for in the NRNI data which could impact the runoff volume and timing. As the proportion of the basin used for agricultural purposes increases, the infiltration and runoff characteristics of the basin could change. The impacts of these uncertainties could result in false change points or trends. For example, monthly depletions provide a presentative volume from the historical period. However, the error between the uniform depletion value and actual daily depletion could vary throughout the monthly timeframe. Therefore, the error in depletion estimates for the n-day time window being used for the centered moving average could also vary between water years. This could result in change points that are an artifact of temporal resolution differences between streamflow and depletion data.

In addition to streamflow, we performed trend analyses on precipitation and temperature data from ground-based climate stations from the Global Historical Climatology Network database (GHCND). The precipitation and temperature trend analyses were completed statistical functions directly from the R computing library (R Core Team, 2020). The functions used in this analysis were extracted from the NSD toolkit scripts and documentation. A verification of the scripted results against the approved USACE Time Series Toolbox is provided in Appendix F. The primary motivation for developing R computer scripts for this analysis was to accommodate for the large number of gages and n-day durations combinations considered in this analysis.

While these locations do not represent trends for the entire Missouri River, they provide insight into regional trends of precipitation and temperature. The GHCND stations included in this study were identified by Northerwestern Division and Omaha District (NWO) water managers and the trend analysis intended to provide insight how this climate assessment can be used in the MRFF study. Appendix E has a summary of the GHCND and periods of records used for trend analysis. A location map of the USGS gages, NRNI flow locations, and GHCND stations is shown in (Figure 8).

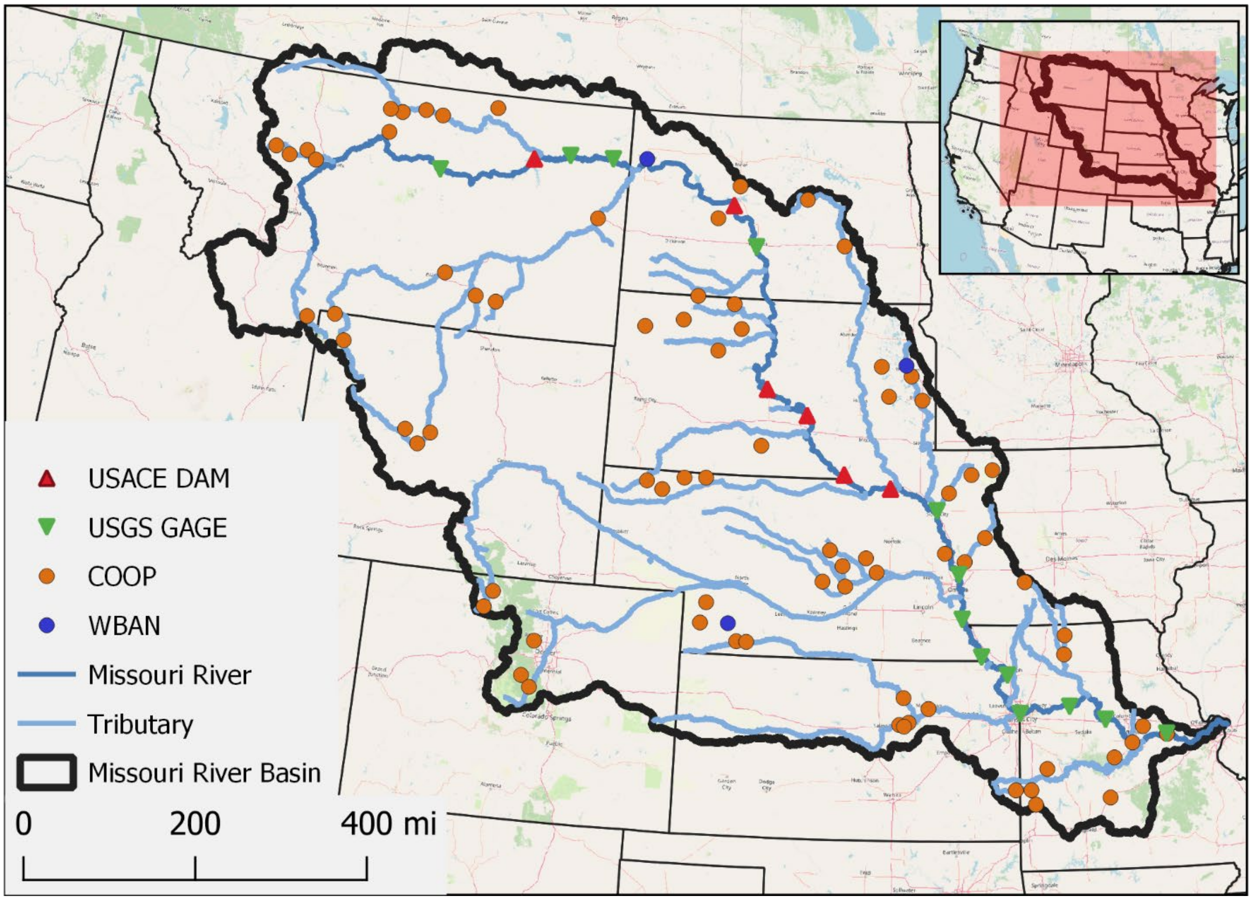

Figure 8. Missouri River Basin – Mainstem Flow and Global Historical Climatology Network (GHCN) Analysis Locations

The NRNI and GHCND data trends are provided by the analysis zones provided in (Figure 9). The boundaries of each zone were identified in the Missouri River Basin Priorities geodatabase. For analysis zones with USACE dams, the zones reflect the upstream drainage area. For areas below Gavins Point Dam, the analysis zones represent different priority areas from the CWMS model. The Lower Missouri are divided into two boundaries based upon district office regulation boundaries.

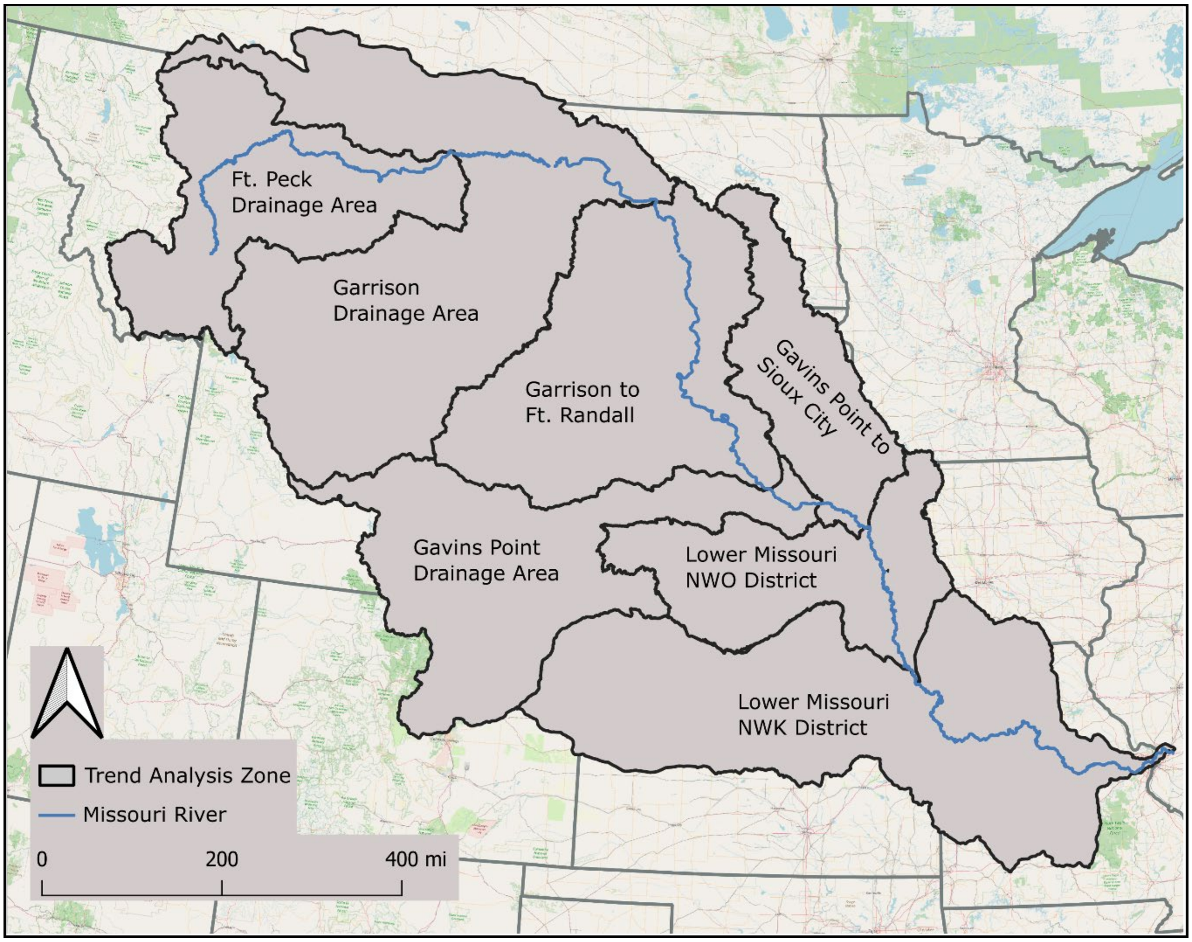

Figure 9. NRNI Streamflow, Temperature, and Precipitation Trend Analysis Zones

5. Nonstationarity Analyses of Streamflow

The focus of our analysis is on changes to natural streamflow characteristics, which may be a result of climate shifts in the watershed. Therefore, we base most of the analysis and discussion on the NRNI data results. The results from the CPR tools are also reported for completeness in our analysis, but the discussion is limited since the Missouri River Basin is highly regulated and anthropogenically influenced river system. Significance of the statistical tests are assessed at the 95% confidence level (p-value < 0.05). In the context of a nonstationarity analysis, a p-value is a measure of the probability that a change point could have occurred by random chance.

The assumption of stationarity (statistical characteristics of hydrological time series are constant through time) has been a pillar for water resources development (Milly et al., 2008). This assumption has enabled the use of well-accepted statistical methods in water resources planning and design that rely primarily on the observed record. Climate change has the potential to undermine this assumption. Recent issuance of USACE civil works policy guidance includes methodologies for the detection of nonstationarities in streamflow in support of USACE project planning, design, construction, operations, and maintenance (ECB 2016-25, USACE, 2016; ETL 1100-2-3, USACE, 2017). Changes in hydrological processes can be abrupt or gradual. There are statistical techniques to detect abrupt and slow changes in mean, variance, and distribution of time series data. A detailed description of these techniques is included in Appendix A.

5.1 Nonstationarities-USGS Data

Only 14 of the 19 streamflow locations we are discussing in this document were available within the NSD based on the USGS station gage data. The instantaneous peak streamflow from the USGS is used in the NSD tool at each location. Some periods were adjusted in the tool interface to avoid issues related to missing values. In all cases, the length of continuous record exceeded the minimum length (e.g. 30 years) required for change point detection tests. In general, the period included in the NSD tool was maximized for the longest period of continuous data and is summarized in Table 1. The nonstationarity type (i.e. mean, variance, distribution) and default parameters used in our analysis are available with the detailed NSD tool output shown in Appendix A.

Several nonstionarities occur within the USGS station gage data (Table 3) which may be a result of dam construction, land use and climate change. It is difficult to separate these causes simply by evaluating the gage data. Therefore, the focus of the nonstationarity analysis is presented in the next section using the NRNI flow data.

Table 3. Missouri River Mainstem USGS Gages – Change Point Detection Results Using Peak Annual Streamflow Data Available in NSD

USGS Gage Number	NRNI Name	Change Points (Approximate Year, Number of Tests)						
06115200	Fred Robinson Bridge	1981,1	1982,3	1983,1	1999,1			
06132000	Fort Peck Dam	1956,1	1957,5	1960,1	1980,1	1981,3	1986,2	2009,1
06177000	Wolf Point	1955,3	1977,1	1978,1	1979,1	1987,5	1997,2	
06185500	Culbertson	1982,3	1987,2	1990,1	1999,1	2000,2	2004,1	
06342500	Bismarck	1951,4	1952,4	1960,1	1990,1	1998,4	2000,1	
06486000	Sioux							
06610000	Omaha	1951,3	1952,3	1953,1	1960,2	1961,1		
06807000	Nebraska City	1951,1	1952,4	1961,1				
06813500	Rulo							
06818000	St. Joseph	1941,2	1945,2	1952,2				
06893000	Kansas City	1940,1	1951,3	1953,1				
06895500	Waverly							
06909000	Boonville, MO	1940,3	1955,1	1974,1				
06934500	Hermann, MO	1986,1						

5.2 Nonstationarities-NRNI Data

A statistical nonstationarity change point analysis of NRNI annual maximum streamflow for n-day durations ranging from 7 to 121 days is presented for the period 1930 to 2019. These durations are representing a range of hydrologic responses, including rain-driven peaks and longer duration peaks associated with snowmelt. The number of detections were summarized for each statistical type (mean, variance, and distribution, for each NRNI flow location as an indicator of the relative strength of the change points within each flow location. Robust change points (e.g. identified by two or more statistical properties) are presented when they occurred (USACE 2019). Statistical significance of the results is assessed at the 95% confidence level. The change point analysis was completed using the R computing language and verification of the scripted results against the USACE Time Series Toolbox is presented in Appendix F.

A general trend we found for the NRNI data is the number of robust change points detected is positively correlated with the n-day duration. In addition, more NRNI flow locations were identified to have robust change points for longer duration time series (Table 4). Across the Missouri River Basin, there were several change points that fell within a two-year window and are summarized in Table 5. Key results include:

- The 7-day duration resulted in change points in the flow locations downstream of Omaha (Figure 10).
- A 1941 change point persisted across all the n-day durations. This trend is most apparent in the Lower Missouri River trend analysis zones (Figure 9).
- The 91-day duration resulted in the most change point years, where a fraction of the NRNI flow locations were had change points in 1941, 1946, 1961, 1984, and 1999 (Figure 11).
- The 121-day duration time series had 84.2% (16 of 19) flow locations with a 1941 change point. Possible explanations for the change points identified in Table 5 are provided in Table 6 and Figure 12.

Table 4. Percentage of NRNI Flow Locations with Robust Change Point Detected for Each n-day Duration

Duration	Percent of NRNI Sites
7-day	37
15-day	47
31-day	63
61-day	79
91-day	100
121-day	100

Table 5. Percentage of NRNI Flow Locations with Similar Robust Change Points for Each n-day Duration Time Series

Change Point (Approximate)	7-day % NRNI Locations	15-day % NRNI Locations	31-day % NRNI Locations	61-day % NRNI Locations	91-day	121-day
1941	36.8%	47.4%	63.2%	63.2%	84.2%	89.5%
1946					10.5%	10.5%
1961				15.8%	10.5%	
1984		5.3%		5.3%	5.3%	15.8%
1999	10.5%				10.5%	26.3%
2007	5.3%					

Table 6. Possible Explanations for Strong Change Point Detections of NRNI Data

Change Point (approximate)	Possible Explanation
1941	Last year of low runoff during a 12-year drought (1930-1941). Next 3 years are above median runoff.
1946	Only year between 1942 and 1953 with a runoff near a lower quartile runoff year. Only 2 other years in that span are below the median runoff.
1960	Last year of low runoff during an 8-year drought (1954-1960).
1984	Potentially start of a drought. 1985 is less than a lower quartile runoff year, but 1986 is greater than an upper decile runoff year. 1987 is considered the start of a 6-year drought from 1987-1992.
1999	Runoff in 1999 is greater than an upper quartile year and then an 8-year drought begins (2000-2007).
2007	Last year of low runoff during an 8-year drought (2000-2007)

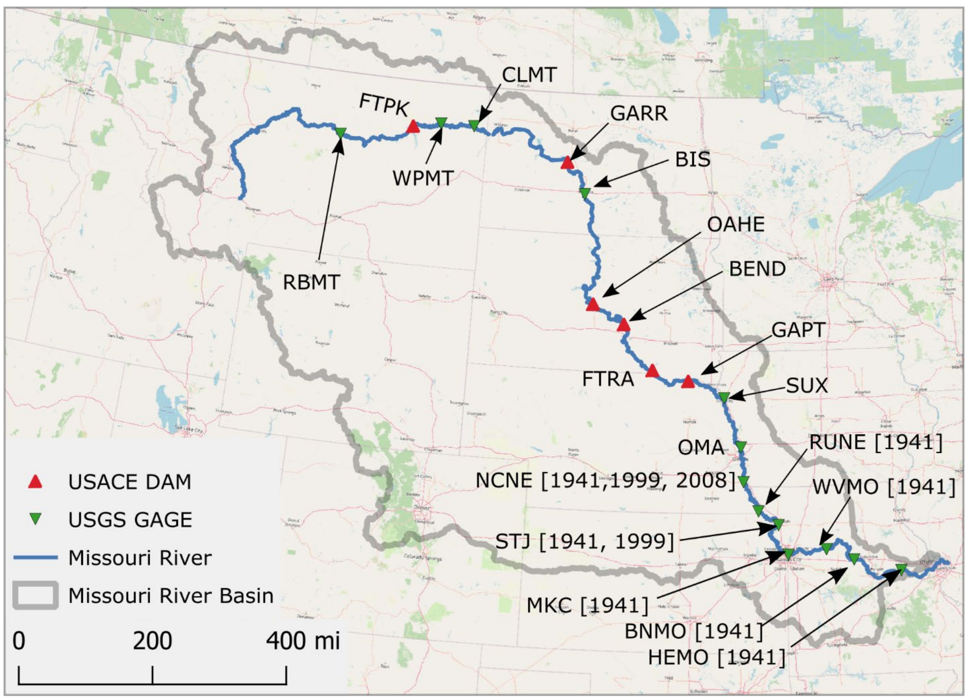

Figure 10. Location and Timing of Robust Change Points Detected in the 7-Day NRNI Time Series

Note: Each site references the CWMS name; change points are indicated in square brackets.

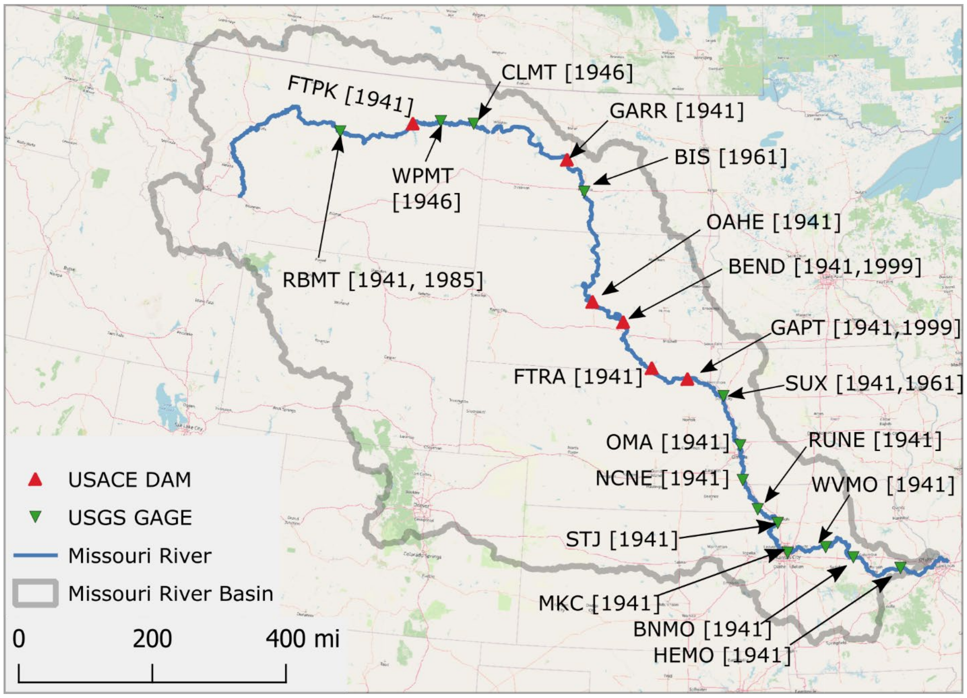

Figure 11. Location and Timing of Robust Change Points Detected in the 91-Day NRNI Time Series

Note: Each site references the CWMS name; change points are indicated in square brackets.

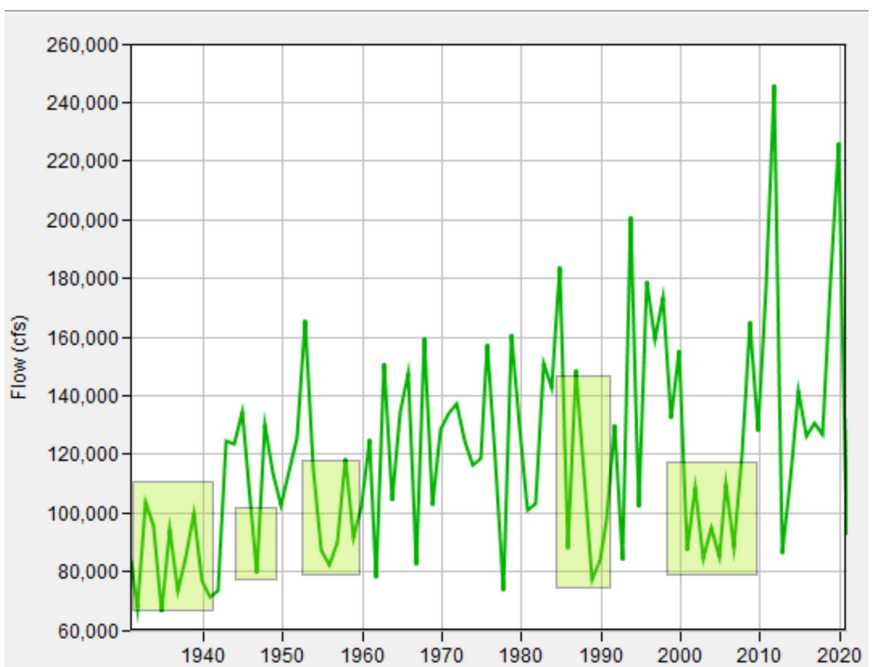

Figure 12. 91-Day Volume Duration Annual Maximum NRNI Time Series at Rulo, NE

Note: Annotated regions show interpretation of the change points in Table 6.

6. Monotonic Trend Analysis

A monotonic trend analysis of the USGS peak annual streamflow and NRNI was also performed for our assessment. The trend analysis for USGS peak annual streamflow data were completed using the routines encoded in the CHAT. The trend analysis for the NRNI data was performed in R (R Core Team, 2020) using the same functions described in USACE (2017). The analysis routines used for NRNI data are compared with the outputs of the CHAT and NSD tools in Appendix F.

An important distinction between the trend analysis of USGS peak streamflow and the NRNI data the NRNI data were sampled from an average daily flow record. The trend analysis using USGS data is all performed within the CHAT using annual peak instantaneous flow values. In contrast, the trend analysis for the NRNI data is based on daily flow values. While the magnitude of NRNI peak streamflow events is less than the corresponding USGS instantaneous streamflow record, the NRNI data represents an unregulated-flow condition with irrigation effects removed and is more appropriate to assess climatic drivers. The trend line in the CHAT uses linear regression fit while the trend values for the NRNI were calculated using nonparametric methods. For purposes of this analysis, the non-parametric values are discussed in the results.

6.1 USGS Annual Peak Instantaneous Streamflow (1975-2016)

Due to the substantial development of large storage projects following the 1950s and 1960s in the Missouri River Basin, the USGS streamflow trend analysis period was restricted to water years 1975-2016 (Table 7). Most of the large infrastructure and irrigation diversion projects were completed by 1975 and is consistent with many of the change points identified in Section 5. Based on the CHAT results and a 95% confidence level, there were no statistically significant trends in the USGS peak flow values. In general, there is a negative trend in peak instantaneous flow values in the watershed above Oahe Dam, while below Gavins Point Dam there were primarily positive trend directions. While some differences in the trend direction did occur, it is difficult to make any meaningful conclusion from the results because the USGS streamflow data includes irrigation and regulation. The detailed results from the CHAT for each location are shown in Appendix C.

Table 7. Mainstem Missouri River USGS Streamgage Monotonic Trend Results

Location	Trend Direction	p-value
Fred Robinson Bridge	Negative	0.24
Fort Peck	Negative	0.37
Wolf Point	Negative	0.85
Culbertson	Negative	0.66
Garrison	n/a	n/a
Bismarck	Negative	0.81
Oahe	n/a	n/a
Big Bend	n/a	n/a
Fort Randall	n/a	n/a
Gavins Point	n/a	n/a
Sioux City	Positive	0.42
Omaha	Positive	0.39
Nebraska City	Positive	0.56
Rulo	Positive	0.32
St. Joseph	Positive	0.82
Kansas City	Negative	0.61
Waverly	Positive	0.77
Boonville	Negative	0.96
Hermann	Negative	0.66

Note: A value of n/a is provided for all USACE dam locations

6.2 Mean Projected Annual Maximum Monthly Streamflow (HUC 4)

In our study we did not evaluate the mean projected annual maximum monthly streamflow for every HUC 4 within the Missouri River Basin (Figure 13). The key HUC 4 basins (which contain the USGS gages summarized in the previous section) we analyzed using the CHAT are listed in (Table 8). These HUC basins were selected to represent the various hydrologic forcing mechanisms within the Missouri River Basin, which include mountain snowmelt (HUC 1004), plains snowmelt with rainfall (HUC 1013), rainfall with some snowmelt contribution (HUC 1023), and rainfall (HUC 1024 and 1030). While this naming convention can be confusing, the 'mean projected' term simply refers to how the ensemble of hydrologic projections from various global climate models (GCM) and representative concentration pathway (RCP) combinations are summarized. The time series produced by the CHAT is annual maximum monthly streamflow.

The results of the trend analysis for future hydrologic projections were very consistent for all subbasins. There is statistically significant positive (increasing) annual maximum streamflow for all HUC 4 subbasins (Table 8). One key consideration with the results from the CHAT is that the hydrologic projections do not include reservoir regulation. The primary message from the CHAT results is the annual peak monthly flow values are likely to increase throughout the 21st century. The detailed outputs for the mean projected annual maximum monthly streamflows from the CHAT for each HUC 4 are shown in Appendix D.

Table 8. Mainstem HUC 4 watershed Trends Using Monthly Maximum GCM Streamflow Data in the CHAT

HUC 4 Number	HUC 4 Name	Trend Direction	p-value
1004	Missouri-Musselshell	Positive	<0.0001
1013	Missouri-Oahe	Positive	<0.0001
1023	Missouri-Little Sioux	Positive	<0.0001
1024	Missouri-Nishnabotna	Positive	<0.0001
1030	Lower Missouri	Positive	<0.0001

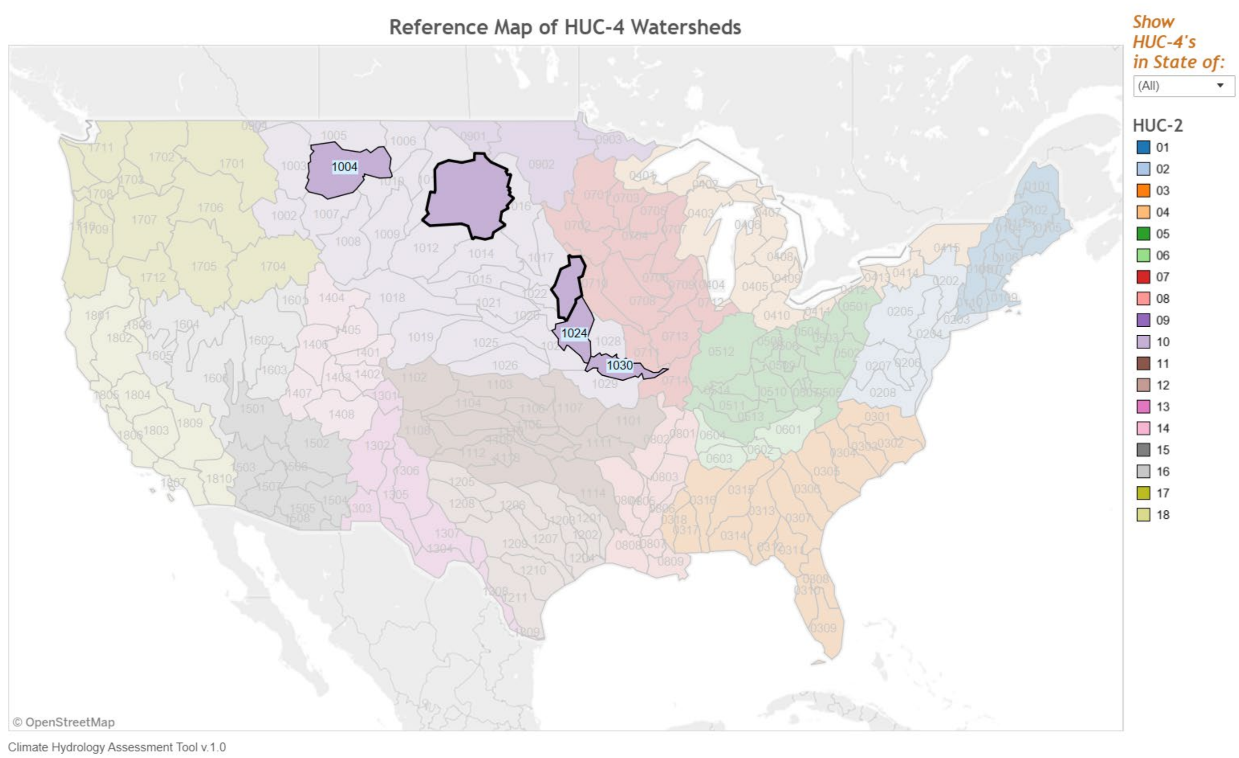

Figure 13. Selected HUC-4 Boundaries for CHAT Analysis

6.3 NRNI Peak Flow and Seasonal Volume Trends

Monotonic trend analyses of NRNI peak flow and seasonal volume for the mainstem Missouri River flow locations are presented in the section. The trend analyses were performed on the entire 1930-2019 NRNI streamflow dataset. The significance of the trends was determined using the Mann-Kendall test at 95% confidence level. The direction and magnitude of the trends were determined using the sign (negative or positive) and value of the Sens Slope statistic. The monotonic trends of the NRNI data were developed using the R computing library (R Core Team, 2020). A verification of the R scripts against the USACE Time Series Toolbox is provided in Appendix F.

For the NRNI streamflow dataset, trends in n-day annual maximum peak streamflow are presented for 1930-2019 (Figure 14, Table 9). Statistically significant positive trends exist for all n-day durations from the NRNI locations below Omaha. Omaha has statistically significant positive trends for durations longer than 15 days. For durations longer than 31 days, all NRNI flow locations below Gavins point have statistically significant positive trends.

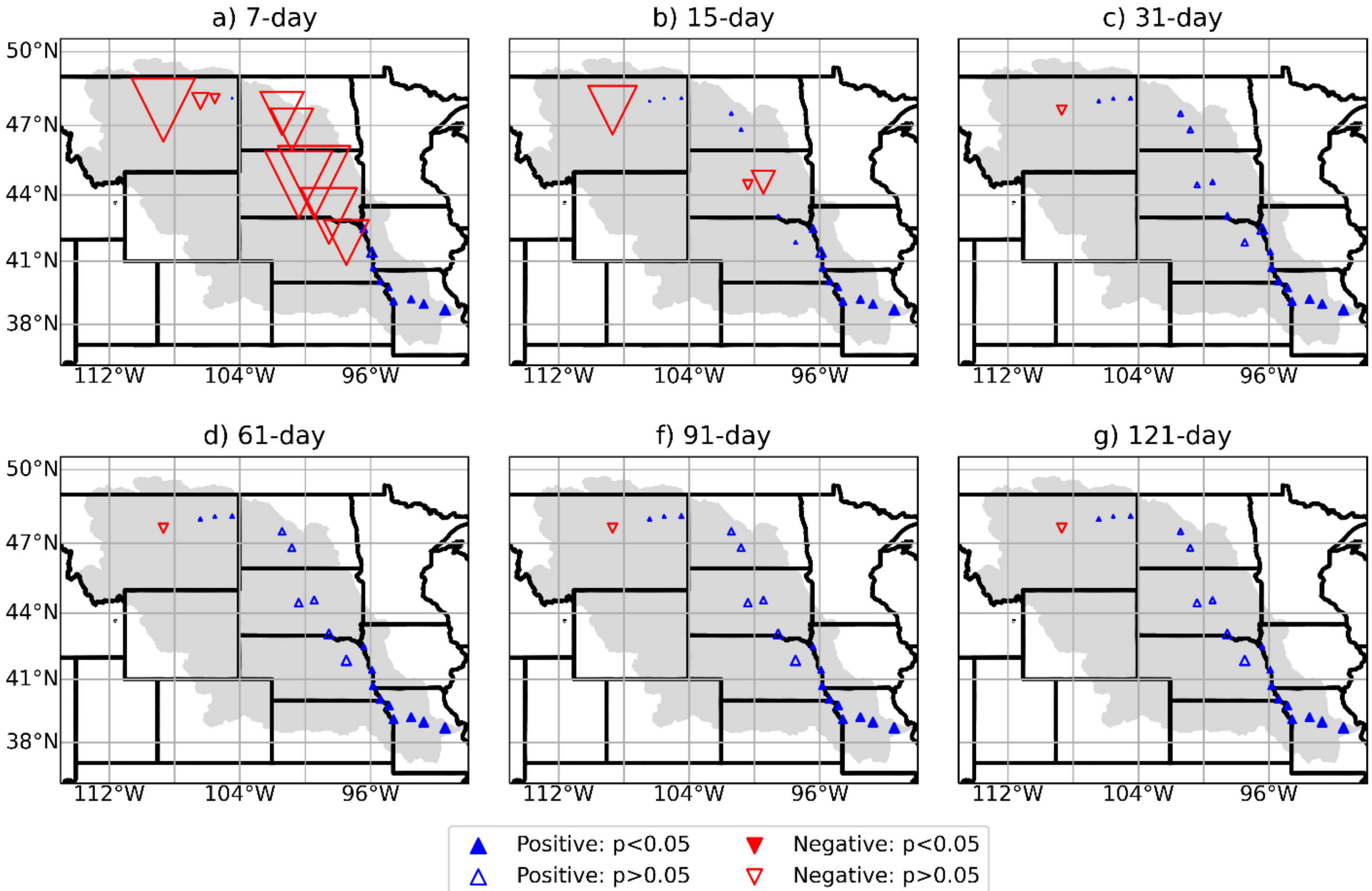

Figure 14. NRNI Peak Streamflow Trends for n-day Durations

Note: The size of the markers represents the relative magnitude of the resulting Sens slope

Table 9. NRNI Peak Streamflow Trend Magnitude and Direction for n-day Durations

n-day duration	7	15	31	61	91	121
	Sens Slope	Sens Slope	Sens Slope	Sens Slope	Sens Slope	Sens Slope
Station	%/Decade^{-1}	%/Decade^{-1}	%/Decade^{-1}	%/Decade^{-1}	%/Decade^{-1}	%/Decade^{-1}
Fred Robinson Bridge	-3.02	-2.97	-2.52	-2.33	-1.63	-1.31
Fort Peck	-0.12	0.11	0.54	0.55	0.63	0.66
Wolf Point	-0.04	0.07	0.34	0.27	0.38	0.30
Culbertson	0.02	0.21	0.59	0.54	0.74	0.55
Garrison	-0.33	0.22	0.71	0.82	0.90	0.49
Bismarck	-0.32	0.24	0.80	0.87	0.90	0.64
Oahe	-0.69	-0.03	0.66	1.01	1.05	0.84
Big Bend	-0.80	-0.14	0.53	0.85	0.82	0.60
Fort Randall	-0.46	0.14	0.90	1.30	1.35	1.20
Gavins Point	-0.29	0.18	1.03	1.42	1.55	1.40
Sioux City	**0.82**	**1.08**	**2.08**	**2.49**	**2.82**	**2.48**
Omaha	**1.68**	**1.89**	**3.01**	**3.71**	**3.89**	**3.75**
Nebraska City	**2.85**	**3.13**	**3.87**	**3.97**	**3.98**	**3.84**
Rulo	**3.15**	**3.11**	**3.75**	**4.25**	**4.40**	**4.28**
St Joseph	**3.38**	**3.34**	**4.00**	**4.32**	**4.57**	**4.40**
Kansas City	**4.00**	**4.09**	**4.12**	**4.44**	**4.75**	**4.64**
Waverly	**4.29**	**4.26**	**4.45**	**4.76**	**5.11**	**5.01**
Boonville	**5.41**	**4.85**	**4.55**	**5.03**	**5.34**	**5.54**
Hermann	**6.35**	**5.92**	**5.18**	**4.89**	**5.25**	**5.34**

Note: The magnitudes of the trends represent the change as a percentage of the average annual maximum n-day durations. Bold numbers in the table indicate a statistically significant trend at 95% confidence level. The sign (negative or positive) of the Sens Slope implies the direction of the trend.

The directions of the trends the n-day duration NRNI peaks streamflow data follow a general pattern of decreasing (i.e. Sens Slope <0) to increasing (i.e. Sens Slope >0) in the downstream direction. Once the tests indicate an increasing trend, the trend direction remains positive for the remaining downstream NRNI locations. There is an exception to this generality where there is a sequence of positive-negative-negative-positive in the 15-day timeseries for the NRNI flow locations bounded by Bismarck and Fort Randall. This specific sequence in the 15-day duration time series is not statistically significant which could potentially be caused by uncertainties in the development of the NRNI data for this reach.

NRNI volume trends are calculated for Annual (October to September), winter (January to March), and spring (April – July) seasons (Figure 15). Overall, seasonal volume trends are positive and increase in magnitude in the downstream direction, except for a negative trend at Fred Robinson Bridge in the spring season (Table 10). The positive volume trends are statistically significant at 95% confidence at all NRNI flow locations for the winter season. The summer season has fewer NRNI flow locations with statistically significant trends downstream of Gavins Point. The NRNI flow locations downstream of Big Bend also have statistically significant positive trends in annual volume.

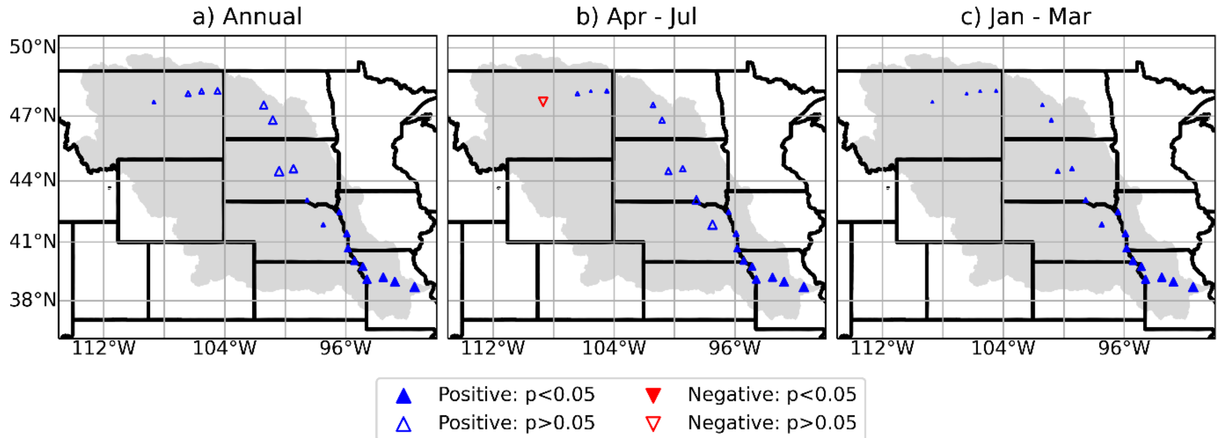

Figure 15. NRNI Seasonal Volume Trends

Note: The size of the markers represents the relative magnitude of the resulting Sens slope

Table 10. NRNI Seasonal Volume Trend Magnitude and Direction

	Annual	Apr - Jul	Jan - Mar
	Sens Slope	Sens Slope	Sens Slope
Station	kaf/year	kaf/year	kaf/year
Fred Robinson Bridge	5	-5	**4**
Fort Peck	16	4	**4**
Wolf Point	14	1	**4**
Culbertson	21	4	**5**
Garrison	34	7	**8**
Bismarck	38	9	**11**
Oahe	47	12	**16**
Big Bend	37	9	**14**
Fort Randall	**58**	19	**19**
Gavins Point	**68**	22	**21**
Sioux City	**113**	**43**	**26**
Omaha	**171**	**70**	**34**
Nebraska City	**212**	**91**	**44**
Rulo	**242**	**109**	**50**
St Joseph	**266**	**114**	**54**
Kansas City	**300**	**134**	**57**
Waverly	**324**	**147**	**62**
Boonville	**370**	**183**	**66**
Hermann	**411**	**204**	**82**

Note: Bold numbers in the table indicate a statistically significant trend at 95% confidence level. The sign (negative or positive) of the Sens Slope implies the direction of the trend.

6.4 GHCND Climate Trends

Monotonic trend analyses of temperature and precipitation are presented in this section. The trends are reported within a trend analysis zone if they produce a statistically significant trend at 95% confidence. The analysis presented here is outside the scope of a qualitative climate assessment, but is presented as an auxiliary data source that could help the larger MRFF study. Table 11 presents the statistically significant trend for each climate variable. The trends for maximum temperature, minimum temperature, and annual precipitation are also plotted in Figure 16, 17Figure 17. GHCND Minimum Temperature Trends and 18, respectively.

Table 11. GHCND Stations Trend Analyses of Precipitation, Maximum Temperature, and Minimum Temperature

Trend Analysis Zone	GHCND ID	Precipitation (mm/year)	Maximum Temp. (°C/year)	Minimum Temp. (°C/year)	Closest Tributary
Ft. Peck Drainage Area	USC00240364		0.11	0.11	SUN R
Ft. Peck Drainage Area	USC00242857		-0.04	0.03	SUN R
Garrison Drainage Area	USC00241297			0.02	ROSEBUD CR
Garrison Drainage Area	USC00243929			0.03	MILK R
Garrison Drainage Area	USC00325638			0.04	MISSOURI R
Garrison Drainage Area	USC00489905	-0.02		0.03	YELLOWSTONE R
Garrison Drainage Area	USW00094014			-0.04	MISSOURI R
Garrison Ft. Randall	USC00320766		0.08	0.06	MISSOURI R
Garrison Ft. Randall	USC00390701			0.03	GRAND R
Garrison Ft. Randall	USC00392429	0.05			MOREAU R
Garrison Ft. Randall	USC00394864			0.04	CEDAR CR
Garrison Ft. Randall	USC00397062			0.10	MOREAU R
Garrison Ft. Randall	USC00398307			0.07	MOREAU R
Garrison Ft. Randall	USC00399442		-0.09	-0.03	WHITE R
Gavins Point Drainage Area	USC00050454		-0.04	0.02	S PLATTE R
Gavins Point Drainage Area	USC00050848			-0.02	S PLATTE R
Gavins Point Drainage Area	USC00051528		-0.05		S PLATTE R
Gavins Point Drainage Area	USC00058756	0.02			N PLATTE R
Gavins Point Drainage Area	USC00253355		-0.08		NIOBRARA R
Gavins Point to Sioux City	USC00322949			0.08	JAMES R
Gavins Point to Sioux City	USC00391076	0.05	-0.05		BIG SIOUX R
Gavins Point to Sioux City	USC00392302			0.03	JAMES R
Lower Missouri	USC00132171	0.04			BOYER R
Lower Missouri	USC00134894	0.06			BOYER R

Trend Analysis Zone	GHCND ID	Precipitation (mm/year)	Maximum Temp. (°C/year)	Minimum Temp. (°C/year)	Closest Tributary
Lower Missouri	USC00136800	0.05			FLOYD R
Lower Missouri	USC00137844	0.05		0.04	FLOYD R
Lower Missouri	USC00252770	0.05			CEDAR CR
Lower Missouri	USC00253425		-0.08	-0.04	CEDAR CR
Lower Missouri	USC00254985	0.06	-0.04		MIDDLE LOUP R
NWK District	USC00140010		0.06	0.05	SMOKEY HILL R
NWK District	USC00141559		-0.05		REPUBLICAN R
NWK District	USC00142835		-0.06		MARMATON R
NWK District	USC00144972	0.06			KANSAS R
NWK District	USC00230204	0.06	-0.04		OSAGE R
NWK District	USC00232503			0.04	OSAGE R
NWK District	USC00233079	0.06			MISSOURI R
NWK District	USC00234271			0.03	MISSOURI R
NWK District	USC00234705	0.08			MARMATON R
NWK District	USC00234825			0.03	OSAGE R
NWK District	USC00235987	0.07	-0.05		MARMATON R
NWK District	USC00236866		-0.07		WELDON R
NWK District	USC00255090	0.03	-0.04		S PLATTE R
NWK District	USC00255310		-0.04	-0.04	REPUBLICAN R
NWK District	USW00024020			-0.03	REPUBLICAN R

Note: The values within the table are Sens Slope values and the direction of the trend is shown by the sign of the value (positive or negative). Only sig. trends (p-value < 0.05) are reported.

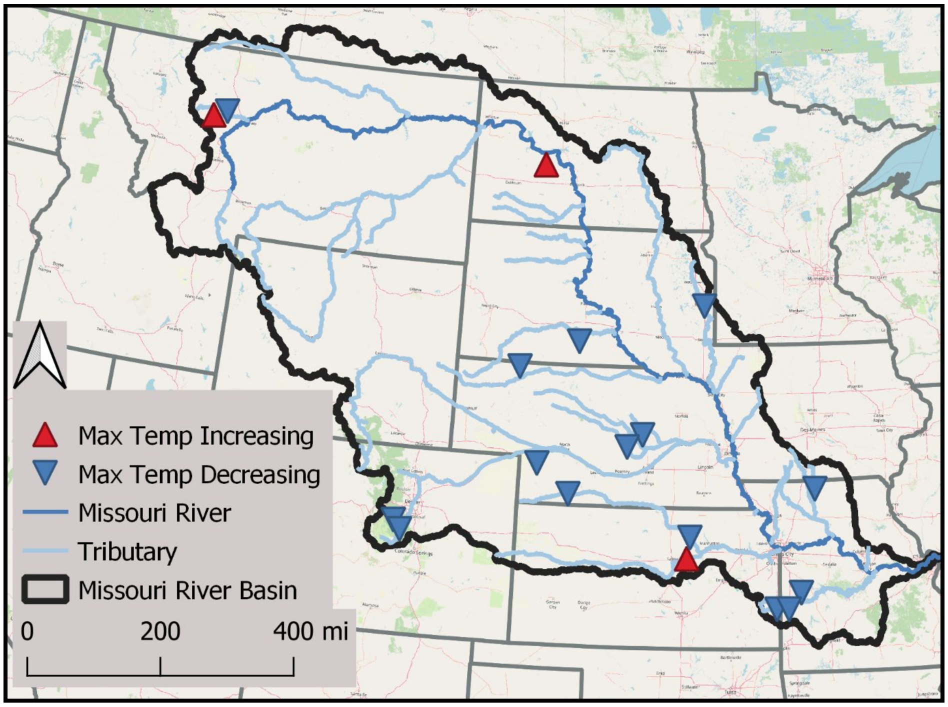

Figure 16. GHCND Maximum Temperature Trends

Note: The map symbols indicate trend direction.

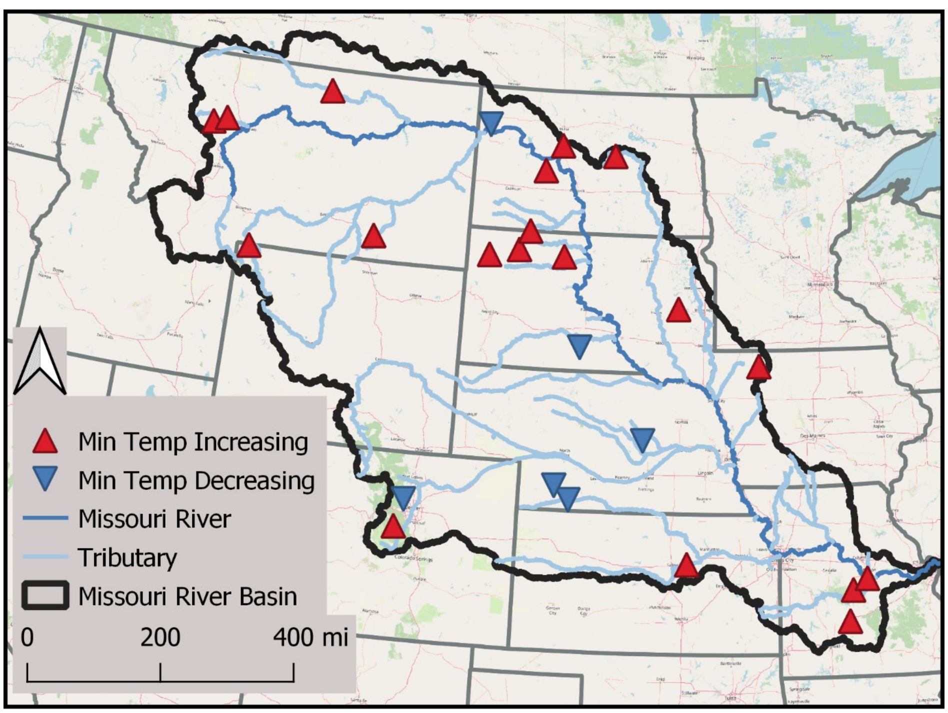

Figure 17. GHCND Minimum Temperature Trends

Note: The map symbols indicate trend direction.

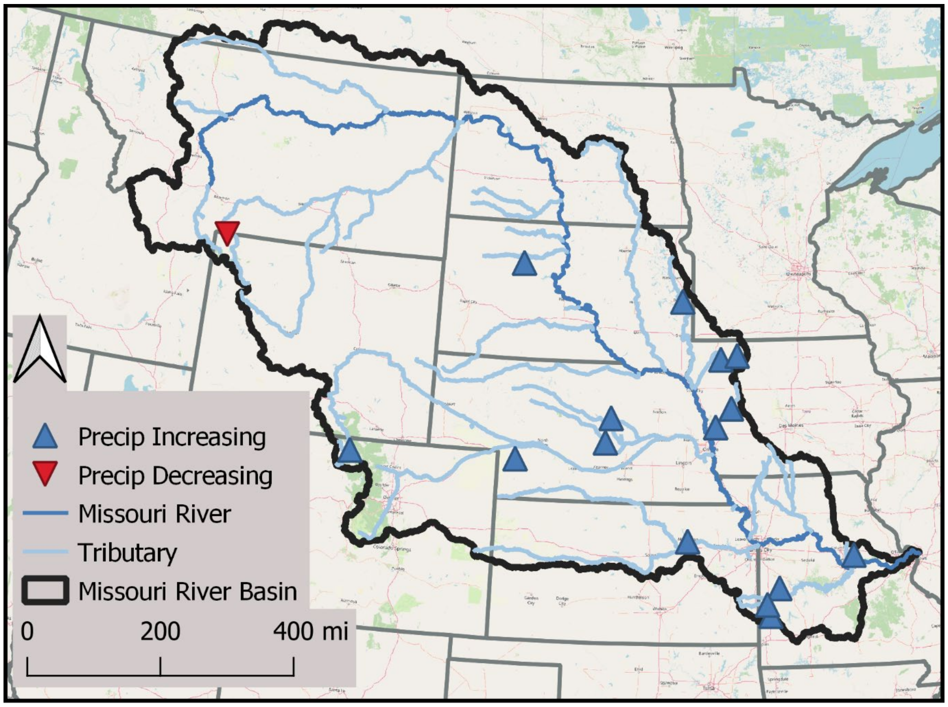

Figure 18. GHCND Annual Precipitation Trends

Note: The map symbols indicate trend direction.

The GHCND trend analysis indicate temperature and precipitation are changing across the basin. Minimum temperatures have a warming trend across the basin, with most of the trends in the upper basin. Maximum temperatures indicate some decreases across the basin, but are most common in the lower basin. Precipitation is increasing in the lower part of the basin. Collectively, these trends indicate hydroclimate drivers are changes in in the Missouri River Basin. These decreasing trends could be related to cropland intensification. Mueller et al. (2016) suggests that increased cropland results in create evapotranspiration on hotter days which reduced maximum temperatures through latent heat flux and increased precipitation.

7. Vulnerability Analysis (HUC 4)

A vulnerability assessment for HUC-2 region 10 was completed for the flood risk reduction, navigation, emergency management, hydropower, recreation, water supply, and ecosystem restoration. When a HUC is designated as vulnerable by the USACE tool, it means that the HUC ranks within the top 20% most vulnerable HUCs of those considered in the portfolio. Just because a HUC is not identified as vulnerable in the tool does not mean that it is not vulnerable, it means instead that it is not among the most vulnerable of those considered.

The number of vulnerable watersheds, dominant indicator, and the most vulnerable trend analysis zone for the dry and wet scenarios are provided in Table 13 and Table 13, respectively. All the USACE business lines are considered vulnerable in both the dry and wet scenarios, with flood risk reduction, recreation, and ecosystem restoration producing the largest proportion of vulnerable watersheds. Between the wet and dry scenarios the trend analysis zone the contains the most vulnerable watersheds exist within the Lower Missouri (NWK District) boundary. The VA HUC summary plots are provided in Appendix G.

Table 12. Missouri River Basin VA Analysis Summary for the Dry Scenario

		Dry			
		2050		2085	
Business Line	**Dominant Indicator (Scenario)**	**Number Vulnerable Watersheds**	**Most Severe Trend Analysis Zone**	**Number Vulnerable Watersheds**	**Most Severe Trend Analysis Zone**
Flood Risk Reduction	568C	8	Lower Missouri NWK	7	Lower Missouri NWK
Navigation	570C	8	Lower Missouri NWK	5	Lower Missouri NWK
Emergency Management	700C	4	Lower Missouri NWK	2	Lower Missouri NWK
Hydropower	221C	2	Lower Missouri NWK	2	Lower Missouri NWK
Recreation	570L	15	Lower Missouri NWK	5	Lower Missouri NWK
Water Supply	277	4	Lower Missouri NWK	4	Lower Missouri NWK
Ecosystem Restoration	8	16	Lower Missouri NWK	14	Lower Missouri NWK

Table 13. Missouri River Basin VA Analysis Summary for the Wet Scenario

		Wet			
		2050		2085	
Business Line	Dominant Indicator	Number Vulnerable Watersheds	Most Vulnerable Trend Analysis Zone	Number Vulnerable Watersheds	Most Severe Trend Analysis Zone
Flood Risk Reduction	568C	12	Lower Missouri NWK	13	Lower Missouri NWK
Navigation	568C	9	Lower Missouri NWK	10	Lower Missouri NWK
Emergency Management	568C	4	Lower Missouri NWK	4	Lower Missouri NWK
Hydropower	221C	3	Garrison to Ft Randall	3	Garrison to Ft Randall
Recreation	570L	13	Lower Missouri NWK	11	Lower Missouri NWK
Water Supply	156	9	Lower Missouri NWK	12	Lower Missouri NWK
Ecosystem Restoration	8	15	Lower Missouri NWK	15	Lower Missouri NWK

The relative WOWA contribution of all the indictors for flood risk reduction and navigation are tabulated in Table 14 and Table 15, respectively. For the flood risk reduction business line, the top three indictors are 568C, 568L, and 277. The indictor 568 flood magnification factor describes a change in flood runoff relative to the observed record. When 568 in a dominant indicator for a business line vulnerability, there is a risk of increased bed scour and energy spills at hydropower plants. The letter "c" corresponds to cumulative runoff and is controlled by flooding from upstream locations, while "l" describes a local contribution from the HUC watershed. The indicator 227 is an elastic metric that compares the changes in runoff to changes in precipitation. The comparison between precipitation and runoff implies the two metrics are interrelated. For the navigation business lines the top three indicators are 570C, 568C, and 570L. The indicator 570 low flow describes the potential for low runoff. When local (l) or cumulative (c) indicator contributes to the overall WOWA score, the demands of navigation or recreation will be impacted by more frequent periods of low flow.

The indicator which had largest change in contribution from the WOWA score for flood risk reduction was from 277-Runoff precipitation and annual covariance for the dry and wet scenarios, respectively (Table 14). The indicators with the largest contribution change for navigation were drought severity and sediment for the dry and wet scenarios, respectively (Table 15). Both of these indicators had a positive change between the 2050 epoch and 2085 epoch resulting in a larger contribution to the overall vulnerability.

Table 14. Flood Risk Reduction Vulnerability Analysis Results

	Scenario	Dry Scenario			Wet Scenario		
	Epoch	2050	2085		2050	2085	
District	Indicator Short Name	% WOWA Score	% WOWA Score	Change in indicator Contribution	% WOWA Score	% WOWA Score	Change in indicator Contribution
	175C_ANNUAL_COV	7.0	6.8	-0.2	6.1	5.7	-0.4
	277_RUNOFF_PRECIP	19.1	17.6	-1.5	13.1	12.9	-0.2
NWO	568C_FLOOD_MAGNIFICATION	46.4	46.9	0.5	50.7	51.7	1.0
	568L_FLOOD_MAGNIFICATION	20.7	22.6	0.9	26.5	26.5	0.0
	590_URBAN_500YRFLOODPLAIN	6.8	6.2	-0.6	3.2	3.2	0.0
	175C_ANNUAL_COV	27.1	24.8	-2.3	12	10.3	-1.7
	277_RUNOFF_PRECIP	30.0	32.6	2.6	11.6	11.6	0.0
NWK	568C_FLOOD_MAGNIFICATION	27.4	27.7	0.3	49.9	50.1	0.2
	568L_FLOOD_MAGNIFICATION	9.6	9.2	-0.4	23.8	25.2	1.4
	590_URBAN_500YRFLOODPLAIN	5.9	5.8	-0.1	2.8	2.7	-0.1

Table 15. Navigation Vulnerability Analysis Results

	Scenario	Dry Scenario			Wet Scenario		
	Epoch	2050	2085		2050	2085	
District	Indicator Short Name	% WOWA Score	% WOWA Score	Change in indicator Contribution	% WOWA Score	% WOWA Score	Change in indicator Contribution
NWO	95_DROUGHT_SEVERITY	<2	<2		<2	<2	
	156_SEDIMENT	6.2	5.8	-0.4	13.1	16.4	3.3
	192_URBAN_SUBURBAN	<2	<2		<2	<2	
	221C_MONTHLY_COV	3.6	3.5	-0.1	3.4	3.1	-0.2
	277_RUNOFF_PRECIP	12.3	11.7	-0.6	12.1	11.1	-1.0
	441_500YRFLOODPLAIN_AREA	<2	<2		<2	<2	
	568C_FLOOD_MAGNIFICATION	19.7	22.2	2.5	29.6	31.2	1.6
	570C_90PERC_EXCEEDANCE	22.9	22.5	-0.4	18.2	16.0	-2.2
	570L_90PERC_EXCEEDANCE	16.6	15.5	-0.9	13.5	11.5	-2.0
	700C_LOW_FLOW_REDUCTION	16.5	15.5	-1.0	8.2	7.3	-0.9
NWK	95_DROUGHT_SEVERITY	1.4	6.0	4.6	1.0	4.1	3.1
	156_SEDIMENT	5.3	3.7	-1.6	10.2	11.3	1.1
	192_URBAN_SUBURBAN	<1	<1	0.0	<1	<1	
	221C_MONTHLY_COV	3.6	3.3	-0.3	3.4	2.8	-0.6
	277_RUNOFF_PRECIP	22.3	22.4	0.1	17.8	17.3	-0.5
	441_500YRFLOODPLAIN_AREA	<1	<1	0.0	1.0	<1	
	568C_FLOOD_MAGNIFICATION	14.9	15.8	0.2	32.0	31.5	-0.5
	570C_90PERC_EXCEEDANCE	20.7	20.5	-0.2	15.2	14.0	-1.2
	570L_90PERC_EXCEEDANCE	10.0	8.4	-1.6	6.8	6.6	-0.2
	700C_LOW_FLOW_REDUCTION	19.8	18.3	-1.5	11.8	11.0	-0.8

The remainder of this section will present VA tool outputs for the flood risk reduction business line. These maps provide a spatial context of the vulnerabilities and how they are projected to change over time. Figure 19 provides a summary of the VA tool output for the flood risk reduction business line in the NWO area of the Missouri River Basin. The dry-2050 scenario has three vulnerable watersheds located in the lower extent of the basin. The dry-2085 scenario is similar to the dry-2050, but has a total of two vulnerable watersheds. The wet-2050 and wet-2085 scenarios have nine vulnerable watersheds, with most of them located in the lower extent of the basin. Notably, both wet scenarios predict a vulnerability in the upper extent of the basin near Ft. Peck Dam.

Figure 20 summarizes the VA tool output the NWK portions of the Missouri River Basin. The dry-2050 and dry-2085 scenarios each have five vulnerable watersheds. The wet-2050 and wet-2085 have three and four vulnerabile watersheds, respectively. Most of them located in the western extent of the NWK area. Notably, both Republican and Smokey Hill Rivers are considered most vulnerable for epochs of the wet scenario.

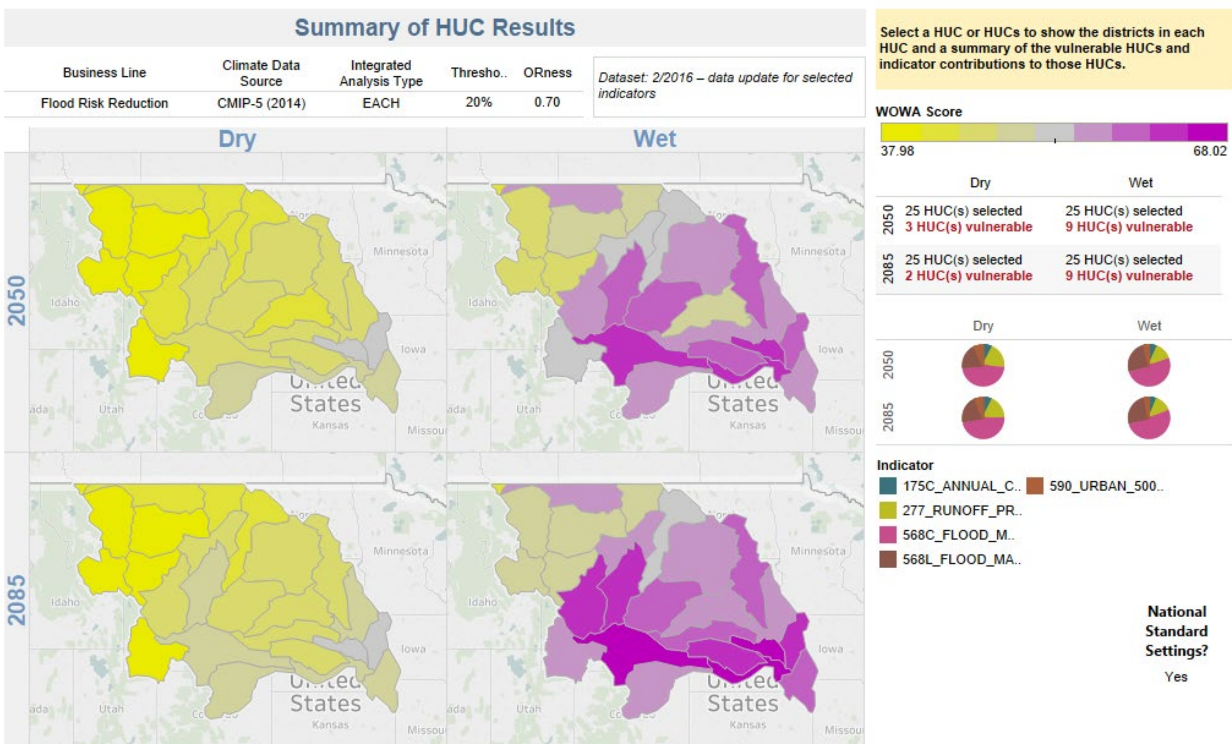

Figure 19. NWO VA Tool Summary for the Flood Risk Reduction Business Line

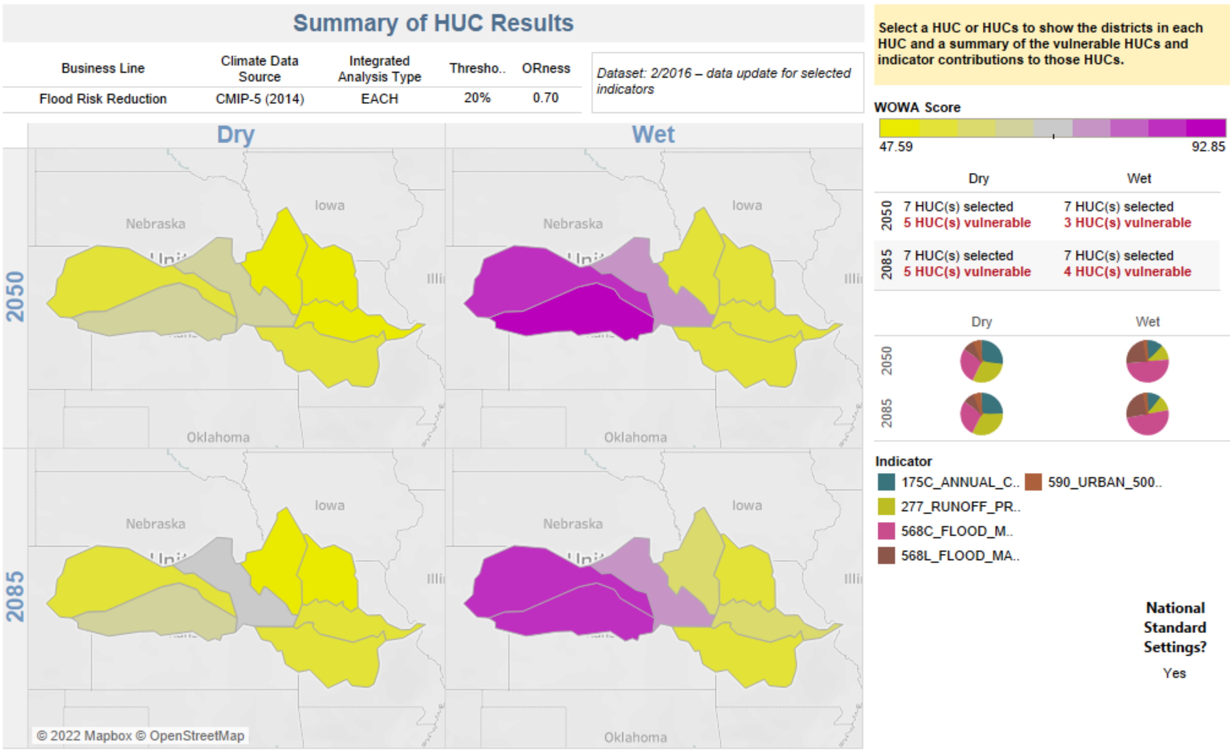

Figure 20. NWK VA Tool Summary for the Flood Risk Reduction Business Line

The dominant indicator for the dry and wet scenarios over time are presented in Figure 21 through Figure 24. In general, most of the HUC 4 watersheds in the NWO portion of the Missouri River Basin have a dominant indicator of the cumulative 568-Flood Magnification factor (Figure 21 and 22). The flood magnification factor indicates an increased risk of flooding that might result in energy spills at hydropower plants. Two watersheds in the dry-2050 and dry-2085 have a dominant indictor of 590 Urban 500-year floodplain. This indicator means the 500-year floodplain has a significant amount of urbanized area.

The NWK portion of the Missouri River Basin for the dry scenario (Figure 23) has three dominant indicators which are 277-Runoff precipitation, 568-Flood Magnification factor, and 175-Annual covariance. The runoff precipitation represents deviations of the mean monthly runoff compared with deviations mean precipitation. This indicator is dominant for the Gasconade-Osage HUC for both epochs. The annual covariance indicator long-term variably in hydrology. For the 2050 epoch, annual covariance is the dominant indicator for the Kansas, Republican, and Smoky Hill Rivers. The 2085 epoch only shows annual covariance as the dominant indicator for the Smoky Hill and Republican Rivers. The wet scenario (Figure 24) has a single dominant indicator for both epochs, which is flood magnification.

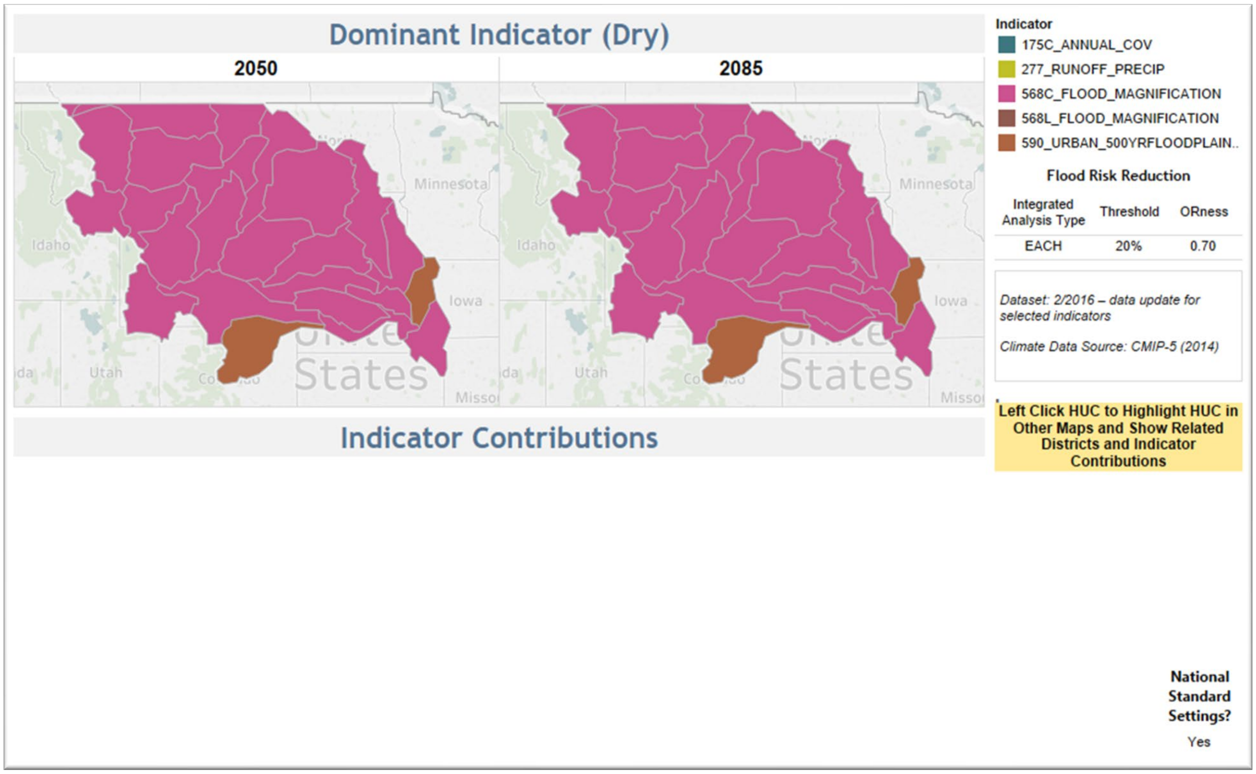

Figure 21. NWO VA Tool Dominant Indicator for the Dry Scenario

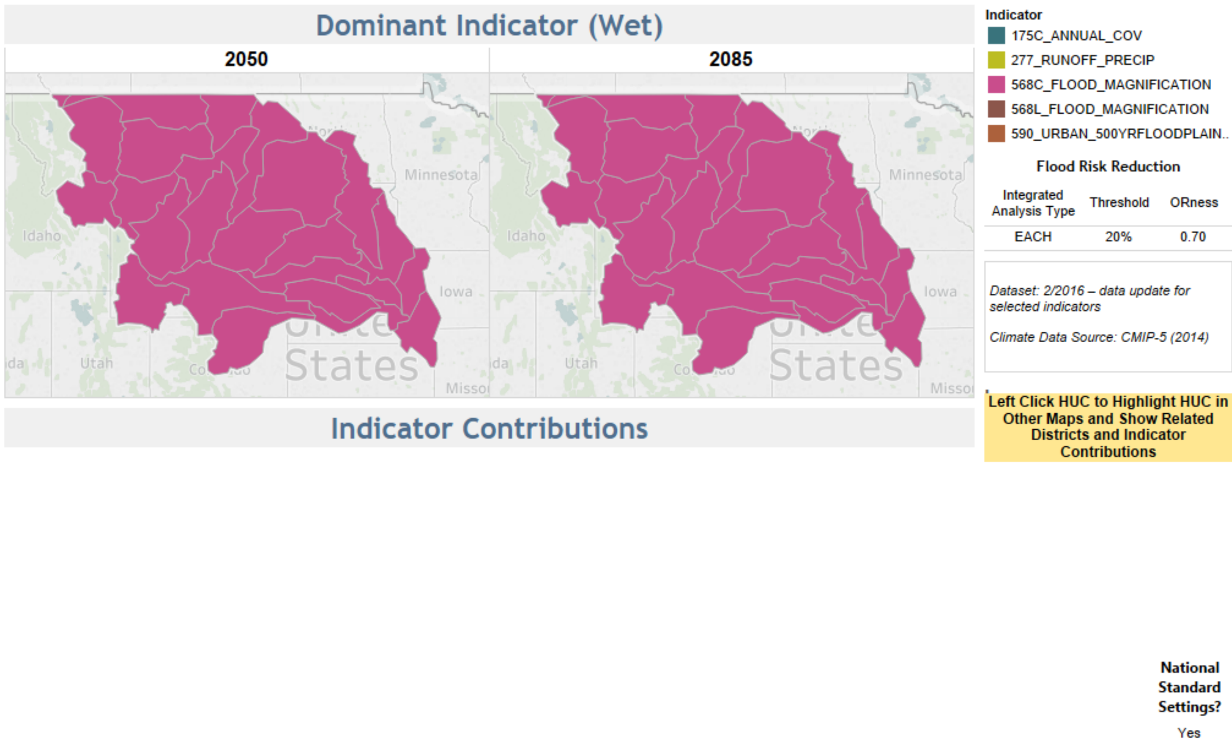

Figure 22. NWO VA Tool Dominant Indicator for the Wet Scenario

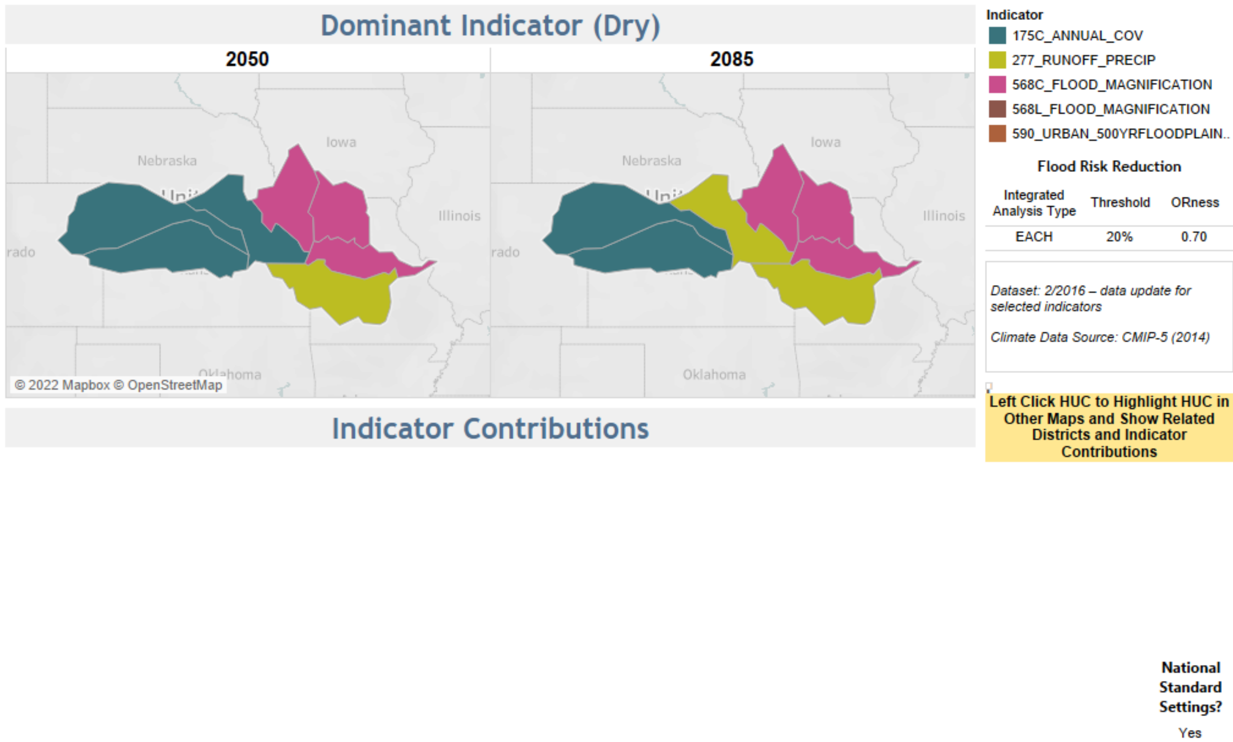

Figure 23. NWK VA Tool Dominant Indicator for the Dry Scenario

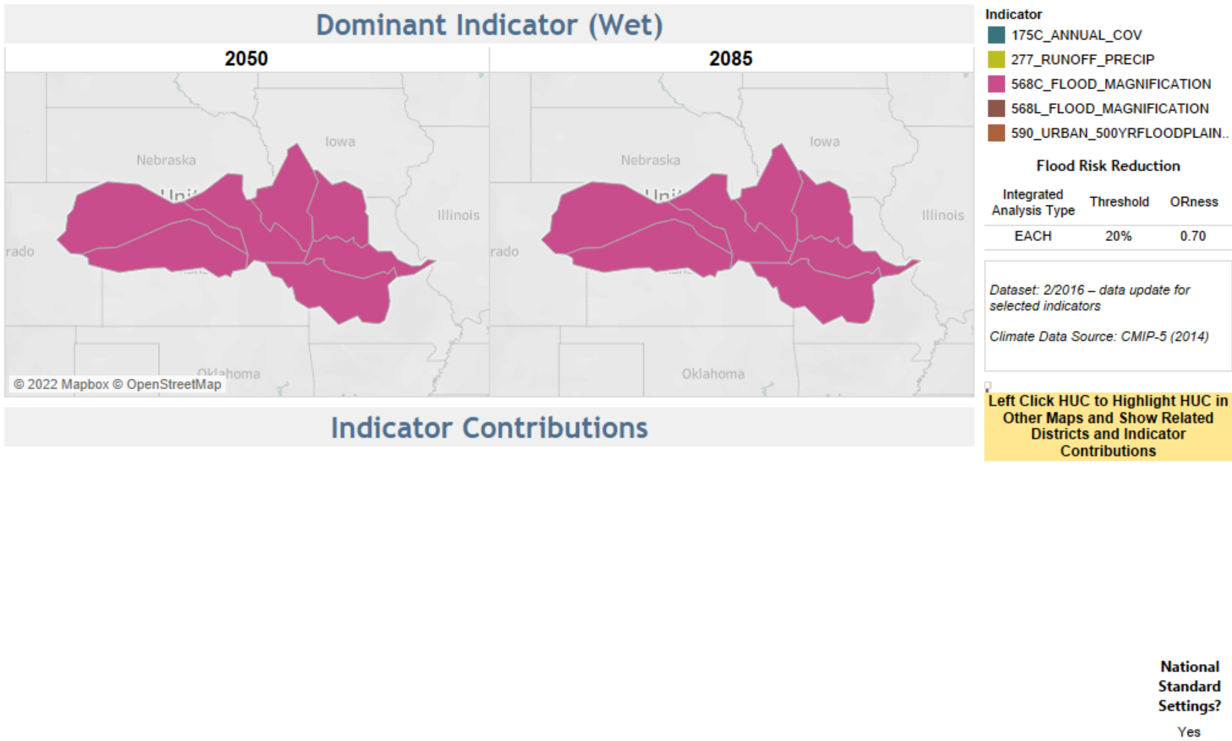

Figure 24. NWK VA Tool Dominant Indicator for the Wet Scenario

For the dry-250 and dry-2085 scenario, the largest increases in flood risk reduction WOWA scores are in the southern portion of the NWO portion of the Missouri River Basin (Figure 25). Notably, WOWA scores decreased in 6 subbasins between the 2050 and 2085 scenarios. In contrast, the NWK portion of the basin has increased WOWA scores and no HUC with decreased values (Figure 26). The results for both portions of the Missouri River Basin suggests vulnerability will increase through time, especially for the southernmost drainages in the basin.

The change in flood risk reduction WOWA scores for the NWO portion of the basin between the wet-2050 and wet-2085 scenarios is presented in Figure 27. WOWA scores increased from the wet-2050 scenario between 0 to 11.5% for most of the HUC 4 basins. In contrast to the dry scenario, the NWK portions of the basin do have decreased areas of decreased WOWA scores between epochs (Figure 28). The largest decrease in WOWA for flood risk reduction is in the Smoky Hill River Basin.

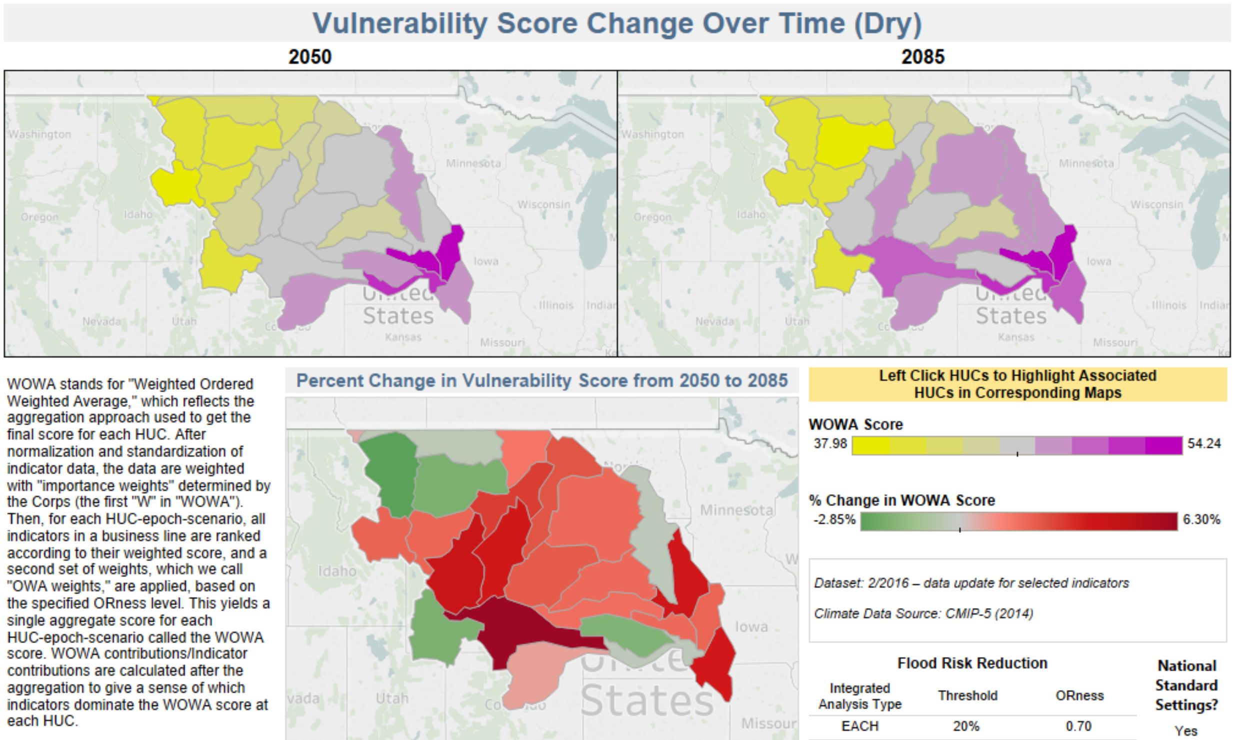

Figure 25. NWO VA Tool Flood Risk Reduction Vulnerability Score Over Time for the Dry Scenario

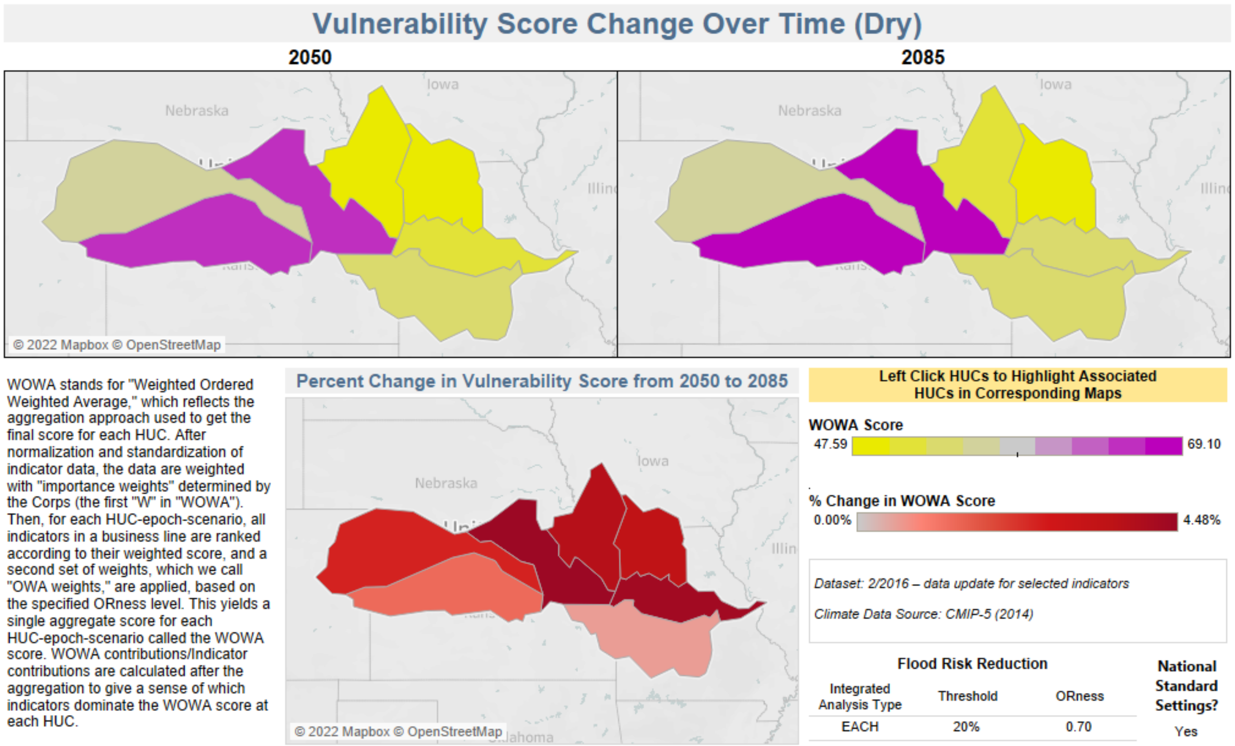

Figure 26. NWK VA Tool Flood Risk Reduction Vulnerability Score Over Time for the Dry Scenario

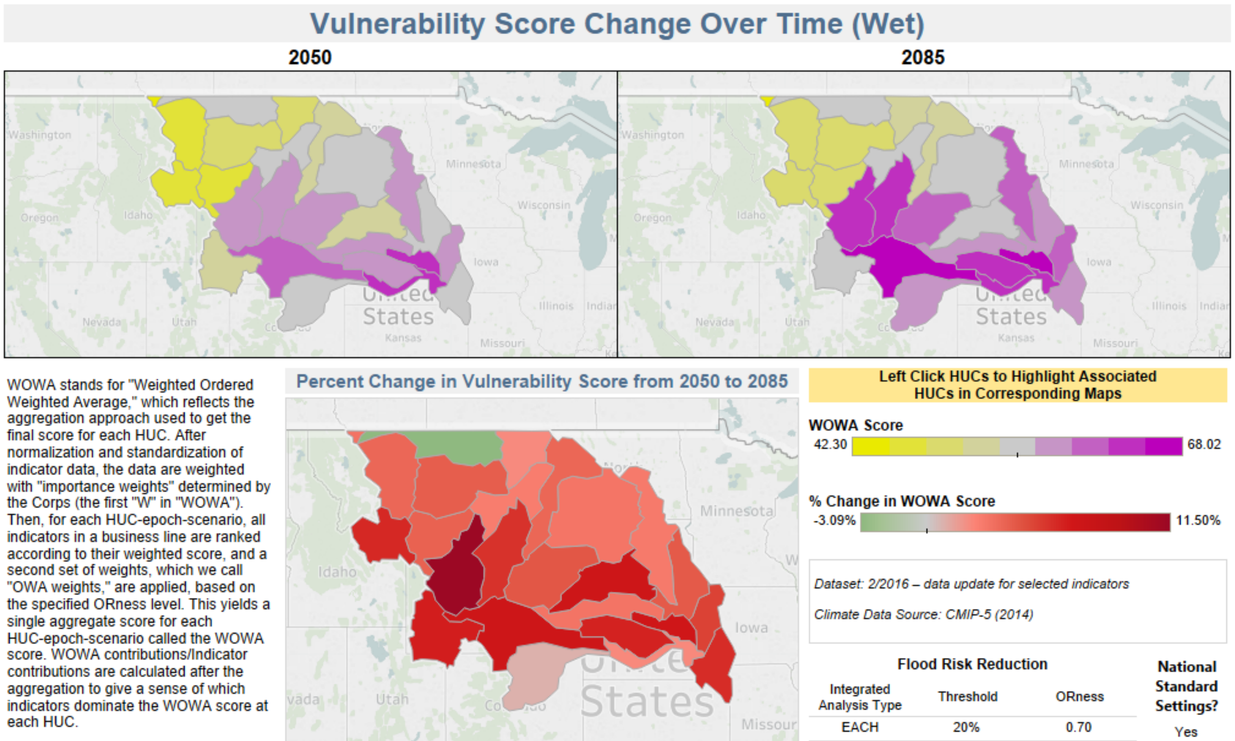

Figure 27. NWO VA Tool Flood Risk Reduction Vulnerability Score Over Time for the Wet Scenario

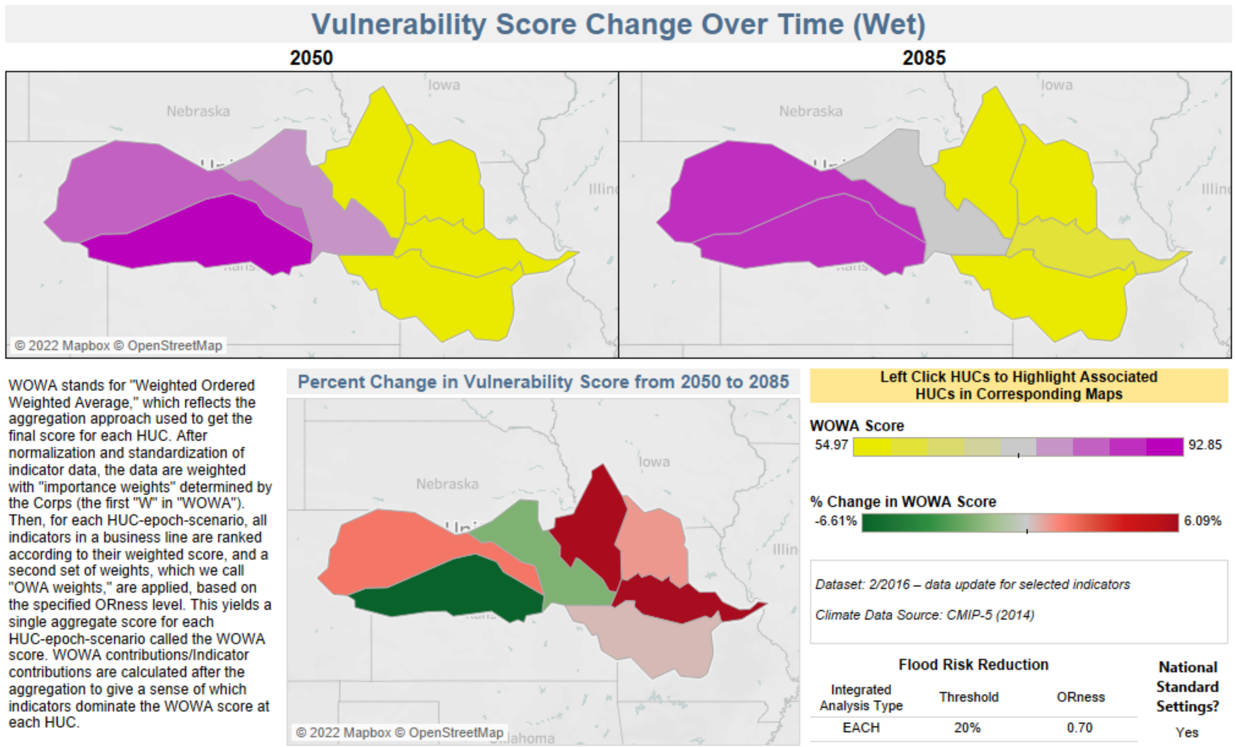

Figure 28. NWK VA Tool Flood Risk Reduction Vulnerability Score Over Time for the Wet Scenario

8. Summary

The Missouri River basin climate's qualitative assessment is based on scientific literature, streamflow trends, analysis of 96 downscaled GCM model predictions through 2100, and a vulnerability assessment of the flood risk reduction business line. Streamflow data were analyzed for statistical change points and monotonic trends using 19 NRNI flow locations on the mainstem Missouri River. Projected trends in streamflow were based on zonal statistics of five HUC-4 watersheds that contain USACE dams. The vulnerabilities of the flood risk reduction USACE business lines were analyzed using the VA tool.

Scientific literature relevant to the Missouri River Basin climate is presented in continental-scale assessments (Vose et al. 2017, Easterling et al. 2017) to regionally focused reports (USACE 2015, Conant et al. 2018, Kloesel et al. 2018). Temperatures have increased over the 100-year observed recorded and are projected to continue to increase through the end of the 21st century. The warming trend is projected to increase the largest in minimum temperature, which will lead to less SWE accumulations in the montane western regions of the basin. Increases in average and maximum temperatures are projected to be the largest in the southern part of the basin. Higher temperature will result in more evapotranspiration.

Precipitation is projected to increase across the basin, with the largest increases in the winter and spring months. There is a strong consensus that streamflow has increased over the observed record, but future projections have a low consensus with variable directions. All the NRNI flow locations had a statically significant change point in at least one of the n-day duration time series analyzed. The number of NRNI flow locations with change points increased with longer duration sampling. The most common change point across all the NRNI flow locations was identified around 1941. Other common change points occurred around 1946, 1961, 1984, 1999, and 2007. The statistical tests for changes to the mean and distribution of the data were the most common types of change points detected. These change points could indicate the mean NRNI peak streamflow have increased throughout the period of record or could be related to transient signals within the NRNI data. A monotonic trend analysis of the NRNI peak streamflow found NRNI flow locations below Omaha had an increasing trend for all n-day duration time series. Longer n-day duration timeseries resulted in increasing trends downstream of Sioux City. NRNI flow locations above Sioux City commonly had a decreasing trend, but none were found to be statistically significant. Seasonal volume trends resulted in all NRNI flow locations having an increasing trend in winter, with fewer upstream NRNI locations in the spring and annual time series. The combination of statistically significant change points and increasing monotonic trends in NRNI flow locations below Gavins Point potentially indicates climate has influenced streamflow in that portion of the Missouri River Basin.

The Missouri River Basin climate has observed and projected trends that indicate a vulnerability for the flood risk reduction USACE business line. The flood risk reduction business line has vulnerable watersheds in both future climates (i.e. dry, wet) and scenarios (i.e. 2050, 2085). The most common dominant indicator for flood risk vulnerability is related to a cumulative flood magnification. In the Missouri River Basin, this means there is a potential for flooding or property damage in the future. For the watersheds that contain USACE dams, flood magnification indicates a potential for energy spills during the winter and spring seasons. An indicator relating to the urbanized acreage within the 500-year flood plan was dominant for two southern watersheds in the dry-2050 and dry-2085 scenarios. Over time, the number of number of vulnerabilities increase in both dry and wet scenarios. The dry scenario has the largest increases in vulnerability in the southern region of the basin. The wet scenario resulted in increased vulnerability across the entire river basin. Based on this assessment, it is likely climate change has already impacted streamflow in the Missouri River basin. Continued changes in peak streamflow are expected as precipitation extremes are expected to be transient through the end of the 21st century. Table 16 is a genialized risk matrix for projects that will use the MRFF results.

Table 16. Residual Climate Risks – Lower Missouri River Flood Frequency Study

Feature or Measure	Trigger	Hazard	Harm	Qualitative Likelihood
Levee Raise	Increased precipitation (Livneh et al. 2016)	Future flood volumes may be larger than present; Large floods may occur more frequently	Flood waters may remain on the levee for longer durations and more frequently. Likelihood of damage increases.	Likely
Spillway Modification	Increased precipitation (Livneh et al. 2016)	Future flood volumes may be larger than present; Large floods may occur more frequently	Flood water may be routed through spillways more frequently. Likelihood of damage increases.	Likely
Ecosystem Restoration	Longer periods of low flow from extended drought periods (Martin et al. 2020)	Drought may become more persistent than present. Multi-year droughts will occur more frequently.	General drying will harm riparian habitat adjacent to the water body.	Likely

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Appendix A: NSD Statistical Tests and Tool Output

Table 17. Summary of Mean, Variance, and Distribution Change Point Tests Identified in USACE (2019)

Test Type	Test Name	Test Description
Mean	Lombard Wilcoxon	Nonparametric test that nests the Wilcoxon score function within the Lombard test statistic to detect both smooth and abrupt shifts in mean by time.
Mean	Pettitt	Nonparametric test that identifies changepoints in the mean by testing whether two samples come from the same population.
Mean	Mann-Whitney	Nonparametric test on mean shift, that tests if a randomly selected value from one sample is greater than or less than a randomly selected value from the comparison sample (seen as the nonparametric counterpart to the t-test).
Mean	Bayesian CPD	Parametric (Gaussian) test that uses product partitions to identify change points within a sequence using MCMC sampling by assuming a sequence can be broken into partitions with a constant mean, where changes in the mean between partitions are change points.
Variance	Mood	A nonparametric case of a Pearson’s Chi-test that evaluates change points based on volatility in medians between defined samples.
Variance	Lombard Mood	Nests the Mood score function within the Lombard test statistic to detect both smooth and abrupt shifts in variance by time.
Distribution	Cramer von Mises	Nonparametric goodness-of-fit test that compares two empirical distributions by evaluating a test statistic of distributional distance.
Distribution	Kolmogorov-Smirnov	Nonparametric test that compares two empirical distributions by evaluating a test statistic of distributional distance.
Distribution	LePage	Nonparametric test which simultaneously tests the equality of both the location and scale parameters, where inequality in one suggests distributional shift.
Distribution	Energy Divisive	Nonparametric test based on hierarchical clustering, where change points are iteratively identified and can be diagrammed as a binary tree. The statistical significance is examined by means of a permutation test that combines bisection and multivariate divergence measures.

Table 18. Summary of Monotonic Trend Statistical Tests Identified in USACE (2019)

Test Name	Test type	CoP Tool	Description
Mann-Kendall	Nonparametric	NSD	Detects trends based on sequences of disordinate pairs
Spearman Rank Order Test	Nonparametric	NSD	A nonparametric measure of the strength and direction of association that exists between two variables measured on at least an ordinal scale.
Least-squares linear regression Slope	Parametric	CHAT	The slope of the regression line makes the vertical distance from the data points to the mean regression line as small as possible.
Sens Slope	Nonparametric	NSD	The slope of the regression line makes the vertical distance from the data points to the median regression line as small as possible.

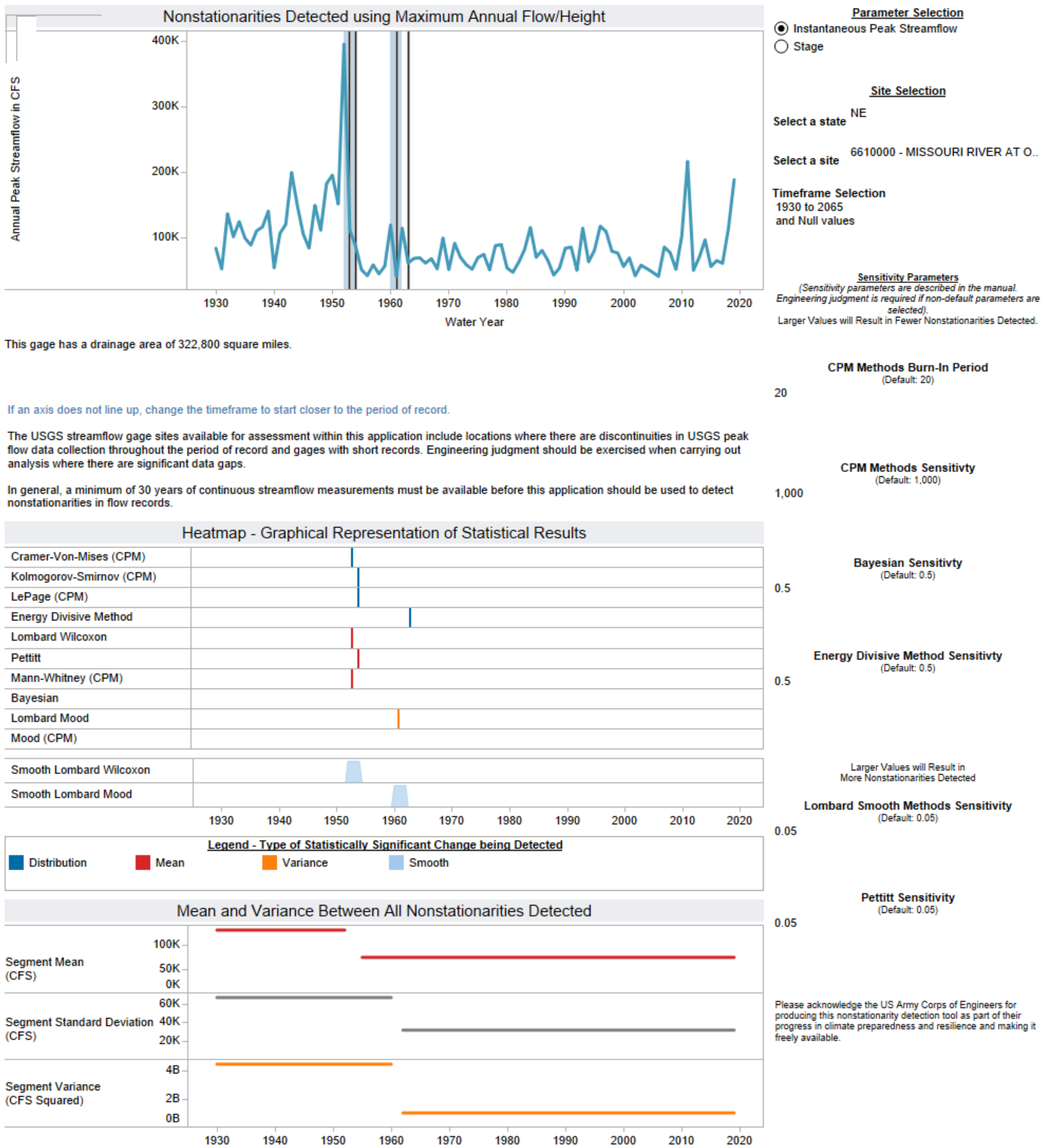


Figure 29. NSD Output for USGS Gauge 06610000 Missouri River at Omaha, NE

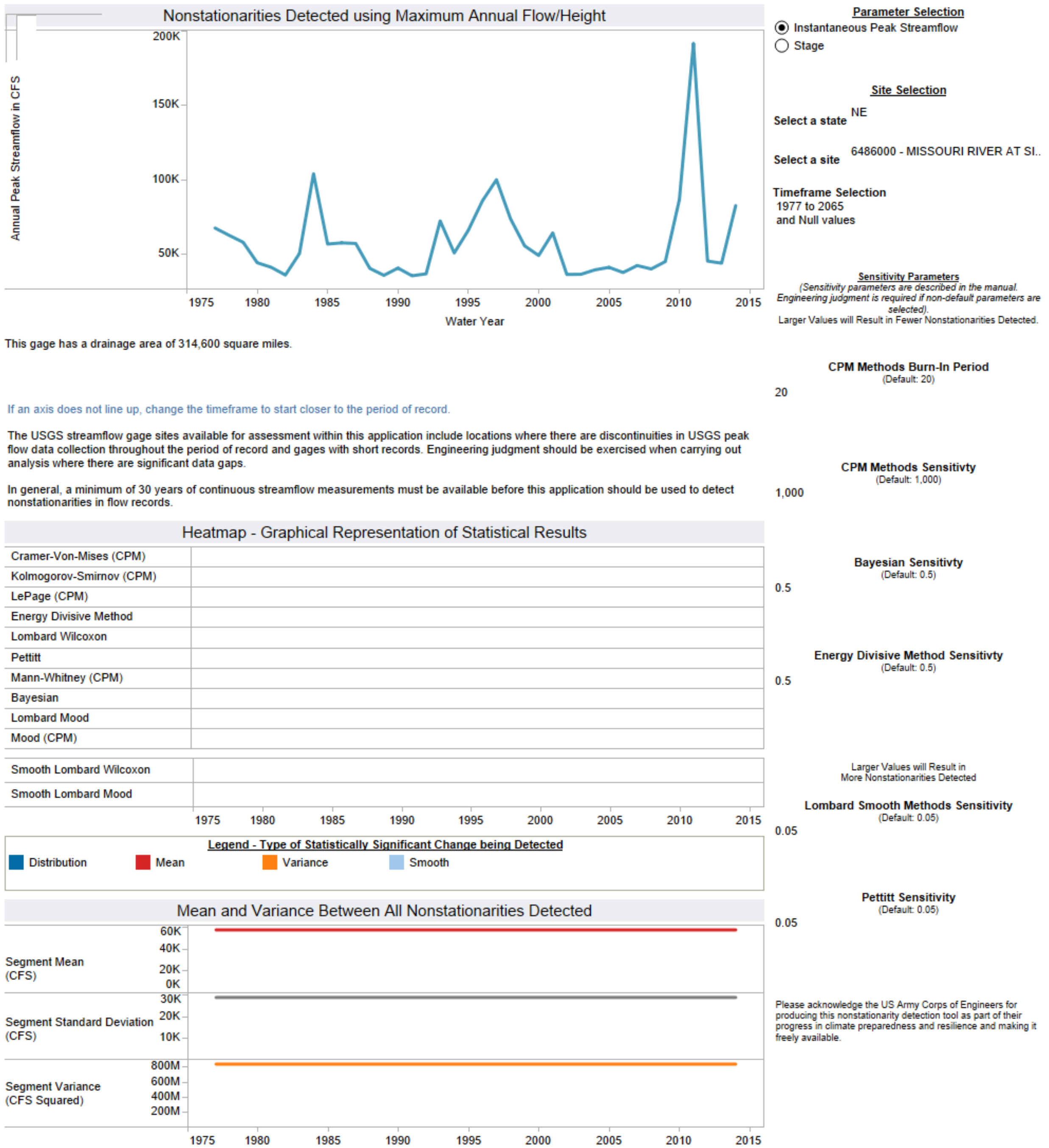


Figure 30. NSD Output for USGS Gauge 06486000 Missouri River at Sioux City, IA

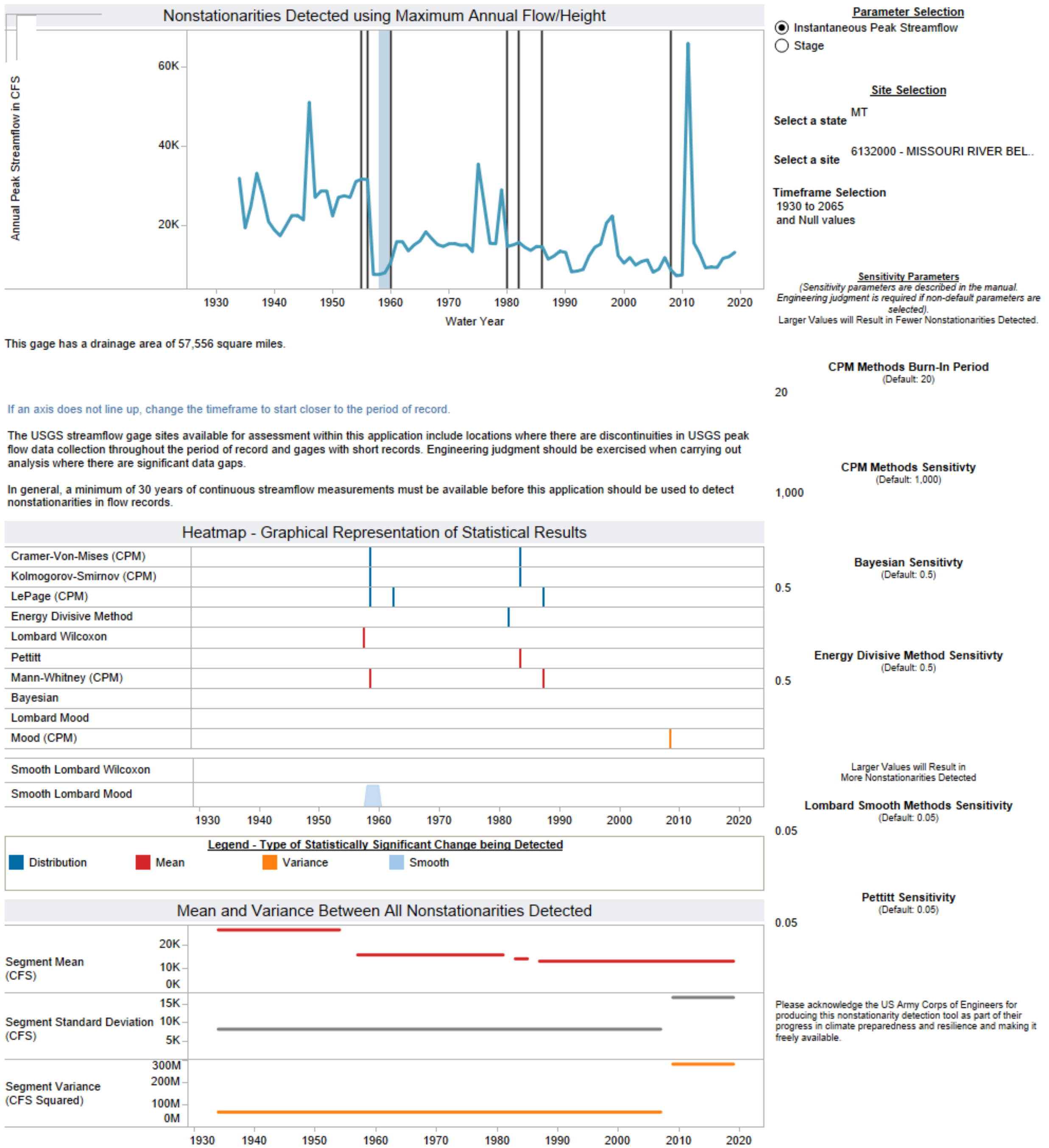


Figure 31. NSD Output for USGS Gauge 06132000 Missouri River below Fort Peck Dam, MT

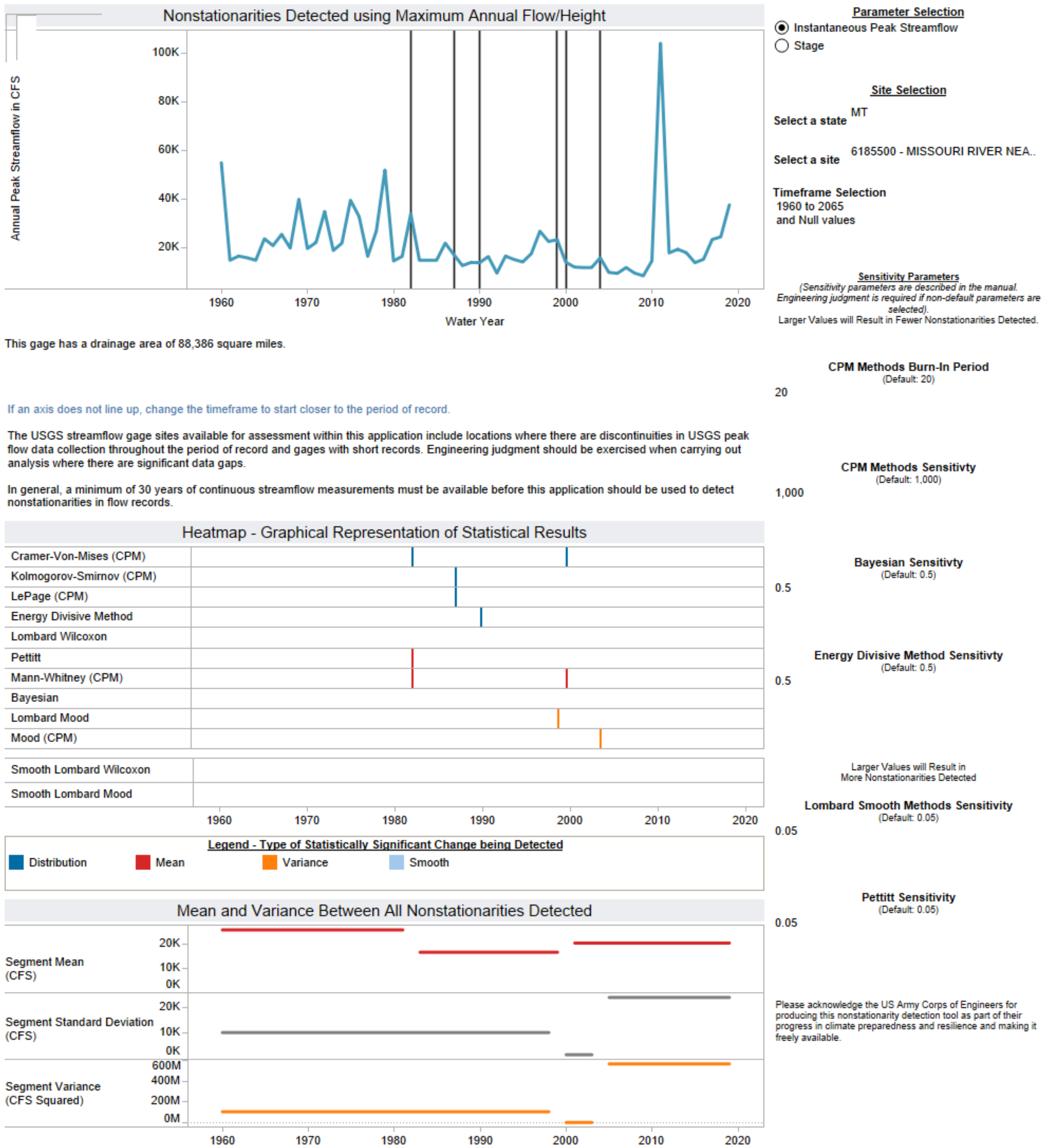


Figure 32. NSD Output for USGS Gauge 06185500 Missouri River near Culbertson, MT

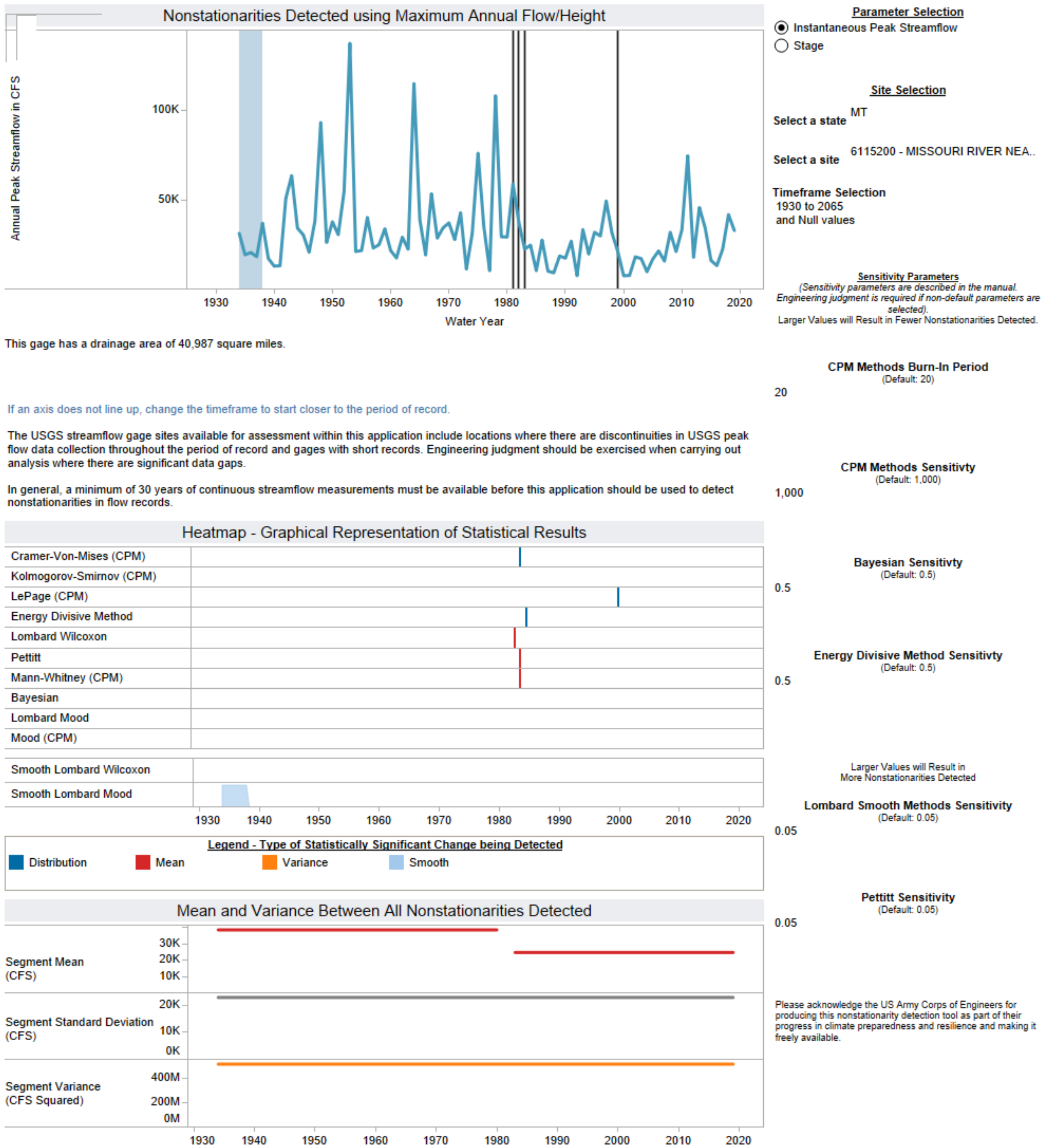


Figure 33. NSD Output for USGS Gauge 06115200 Missouri River near Landusky, MT

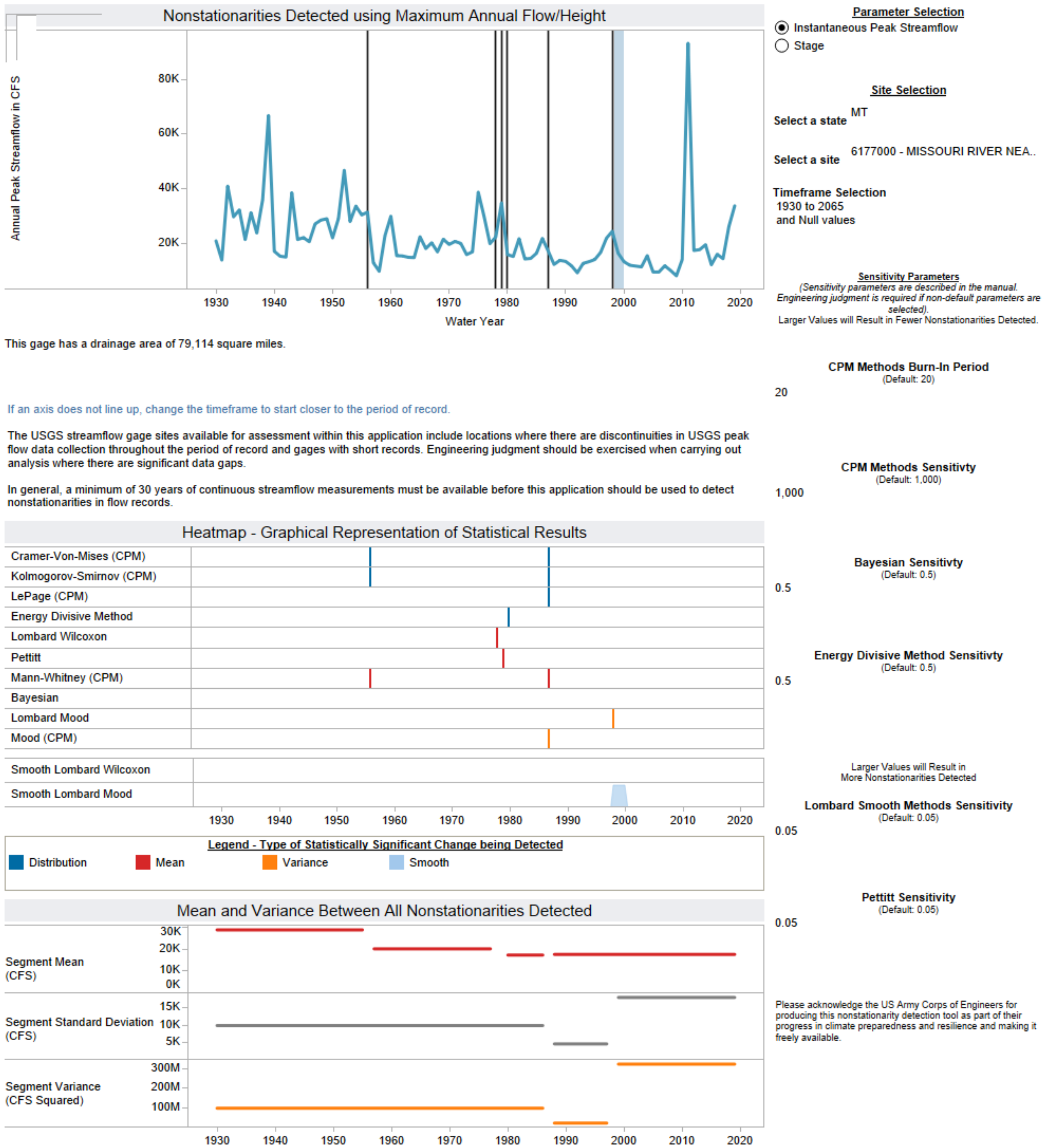


Figure 34. NSD Output for USGS Gauge 06177000 Missouri River near Wolf Point, MT

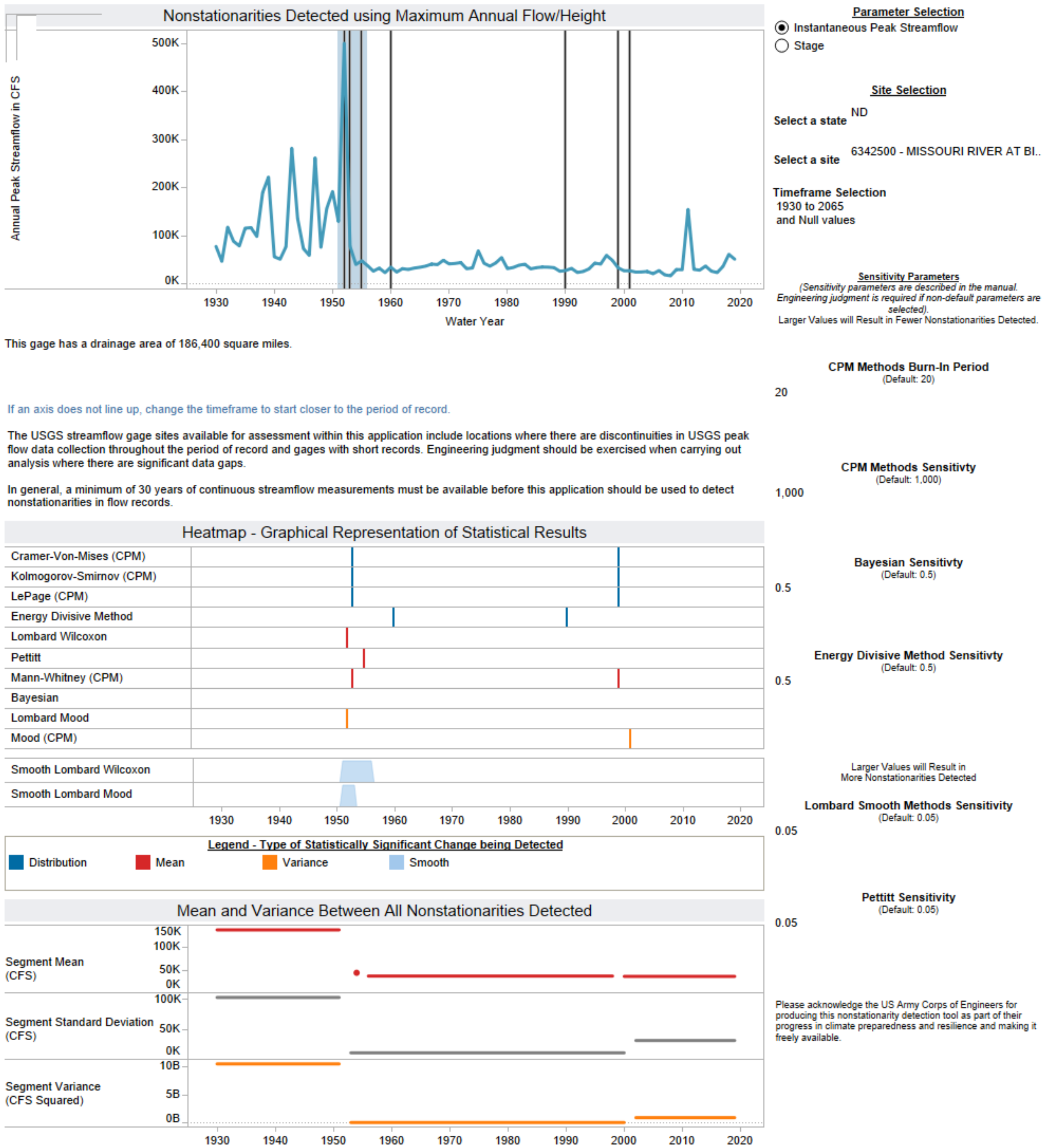


Figure 35. NSD Output for USGS Gauge 06342500 Missouri River at Bismarck, ND

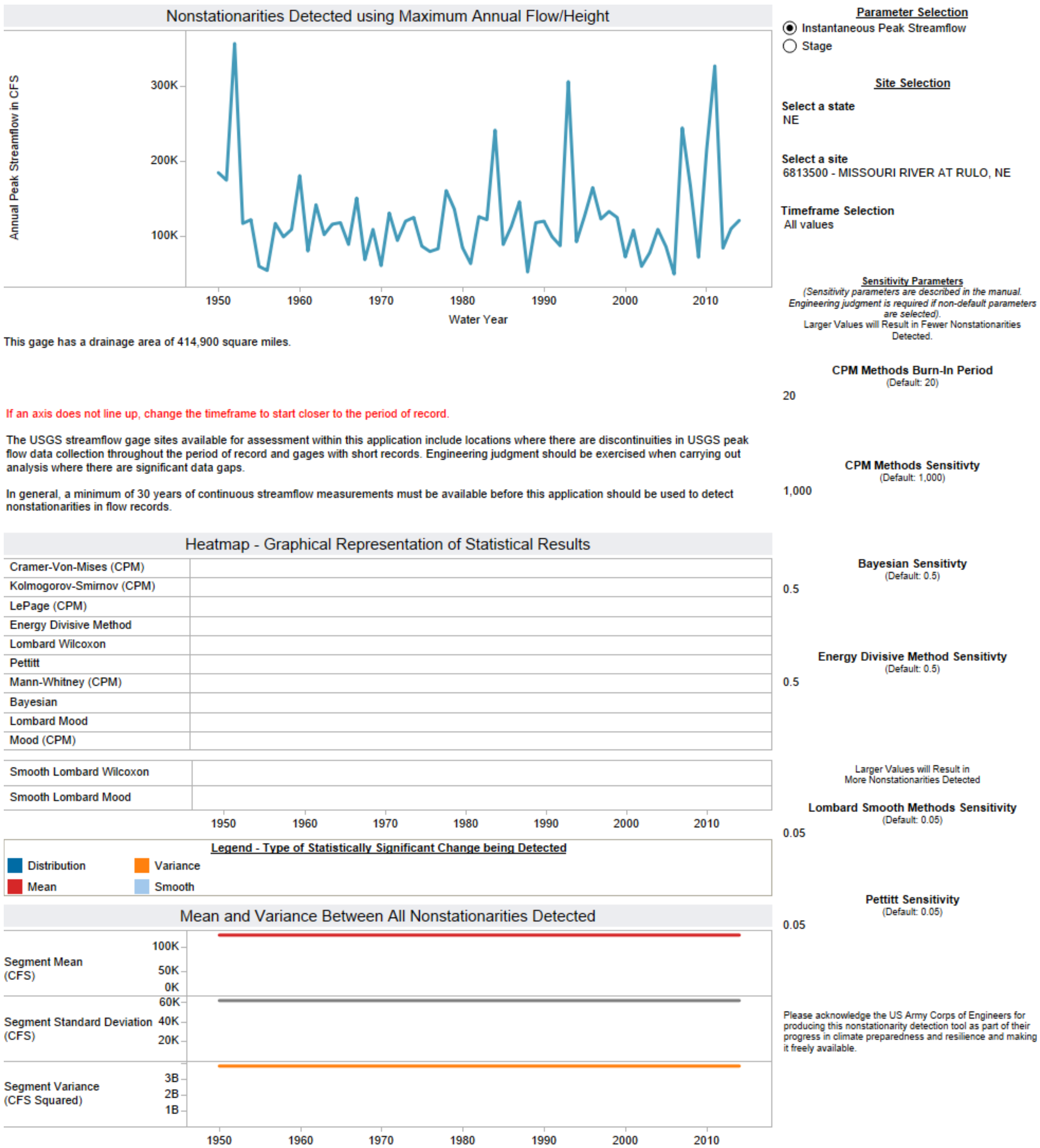


Figure 36. NSD Output for USGS Gauge 06813500 Missouri River at Rulo, NE

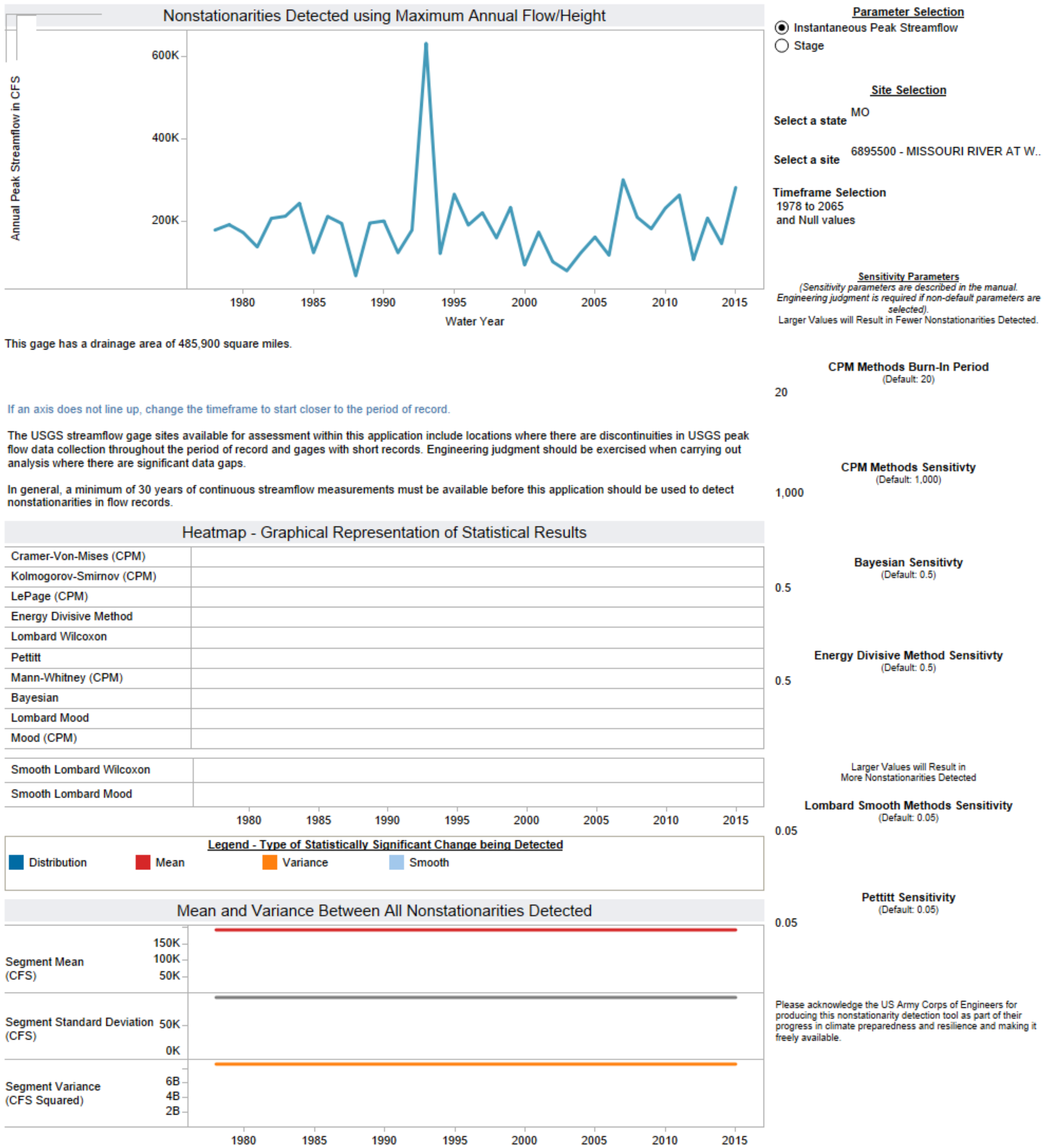


Figure 37. NSD Output for USGS Gauge 06895500 Missouri River at Waverly, MO

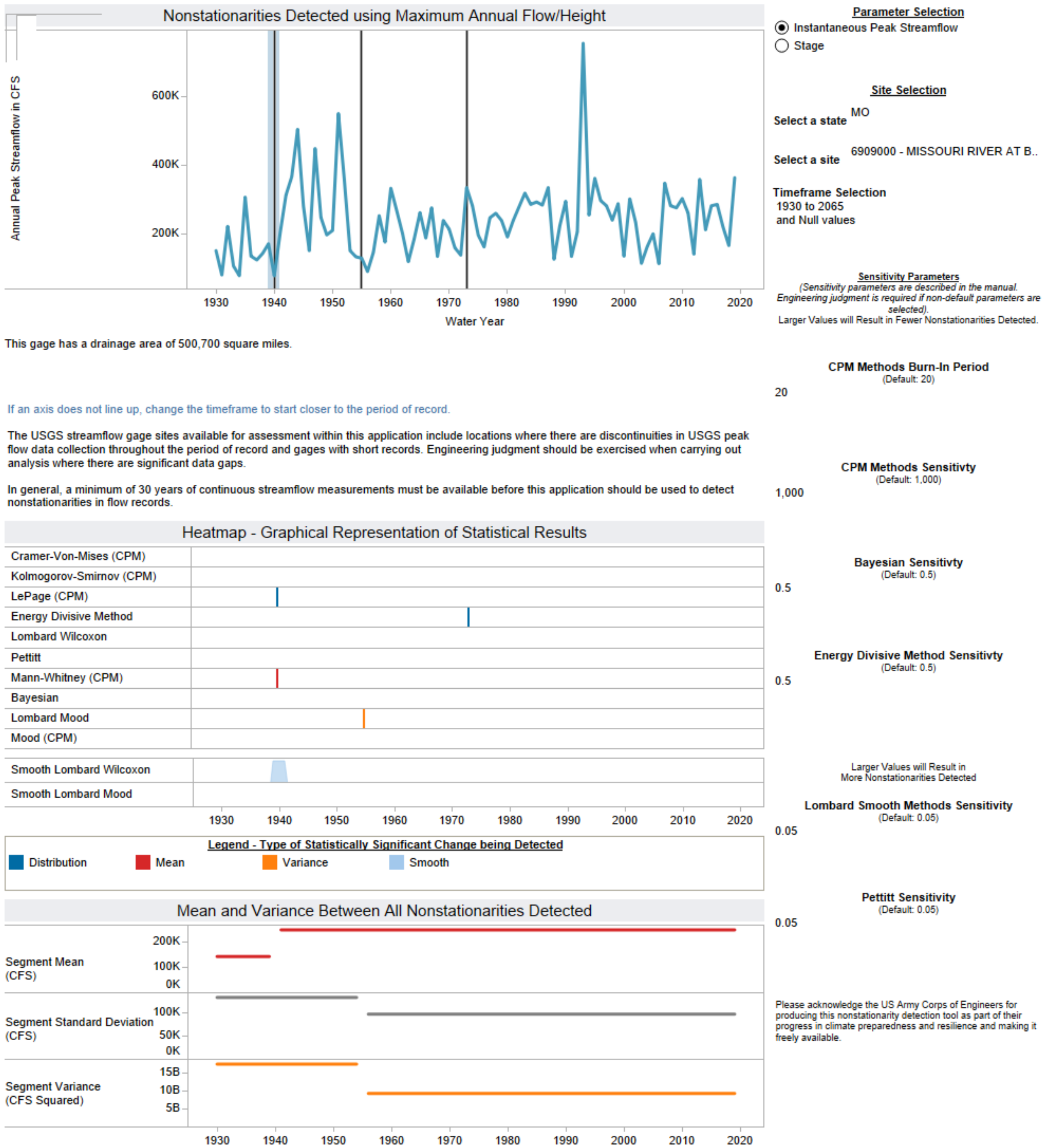


Figure 38. NSD Output for USGS Gauge 06909000 Missouri River at Boonville, MO

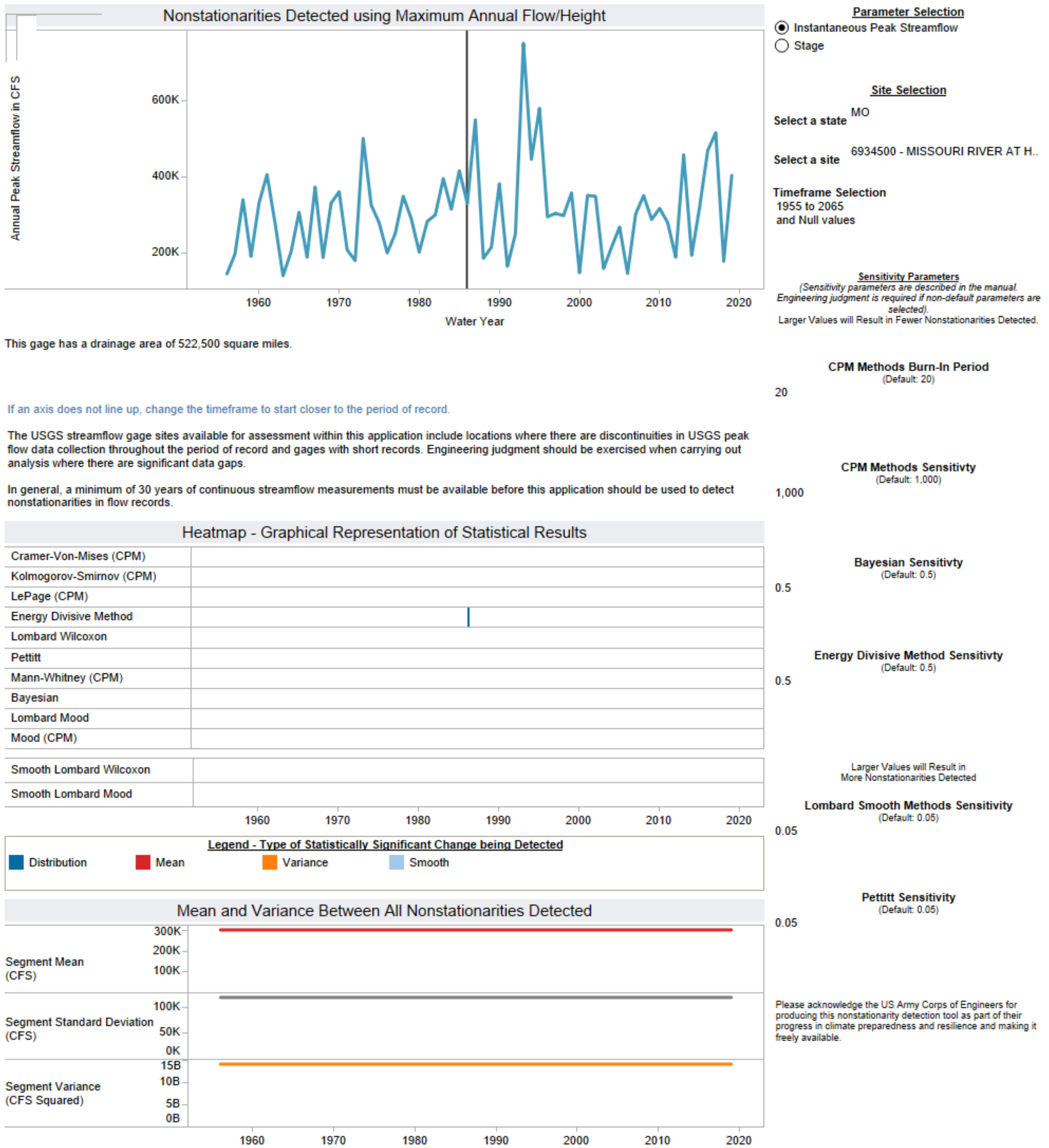


Figure 39. NSD Output for USGS Gauge 06934500 Missouri River at Hermann, MO

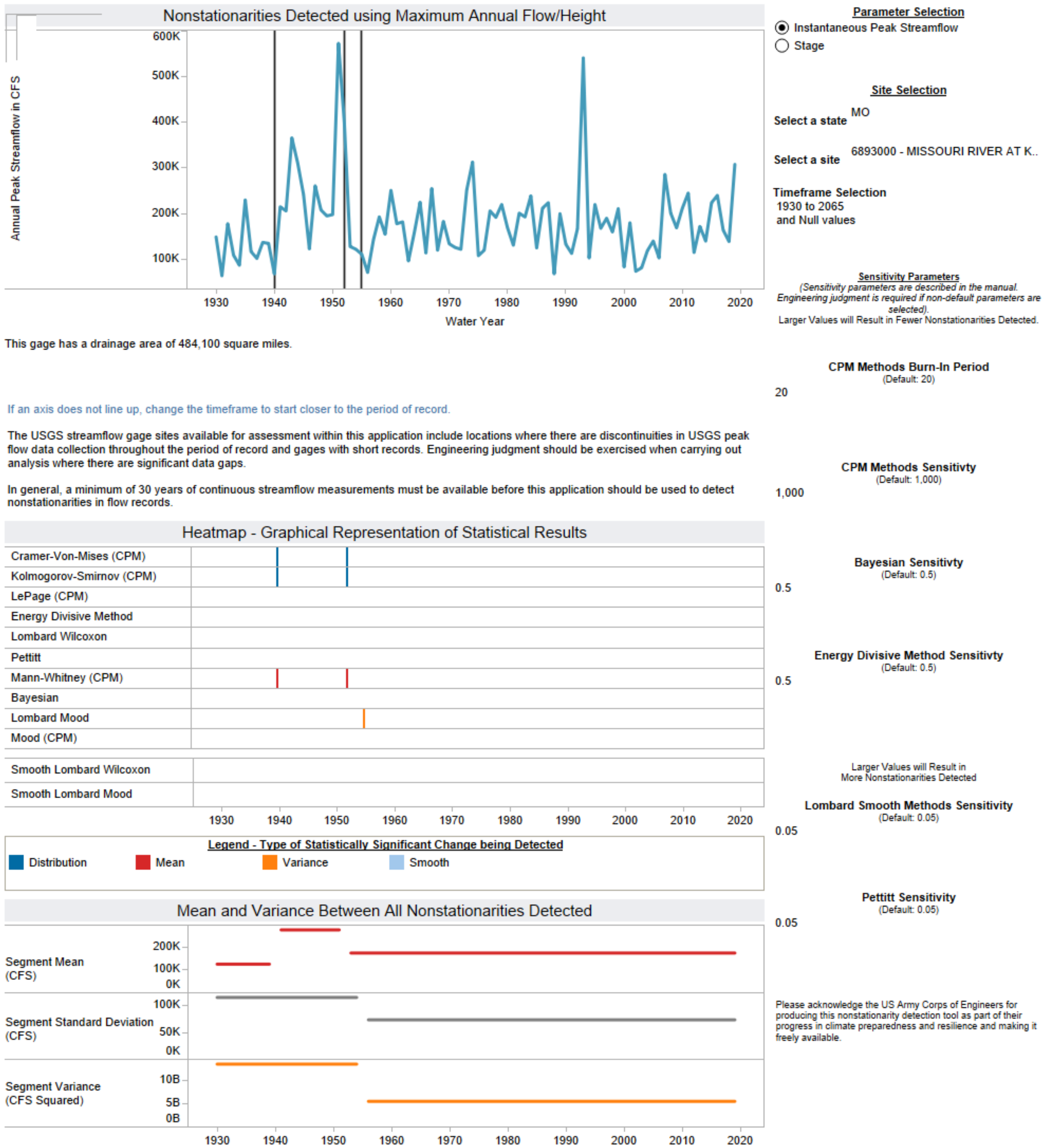


Figure 40. NSD Output for USGS Gauge 06893000 Missouri River at Kansas City, MO

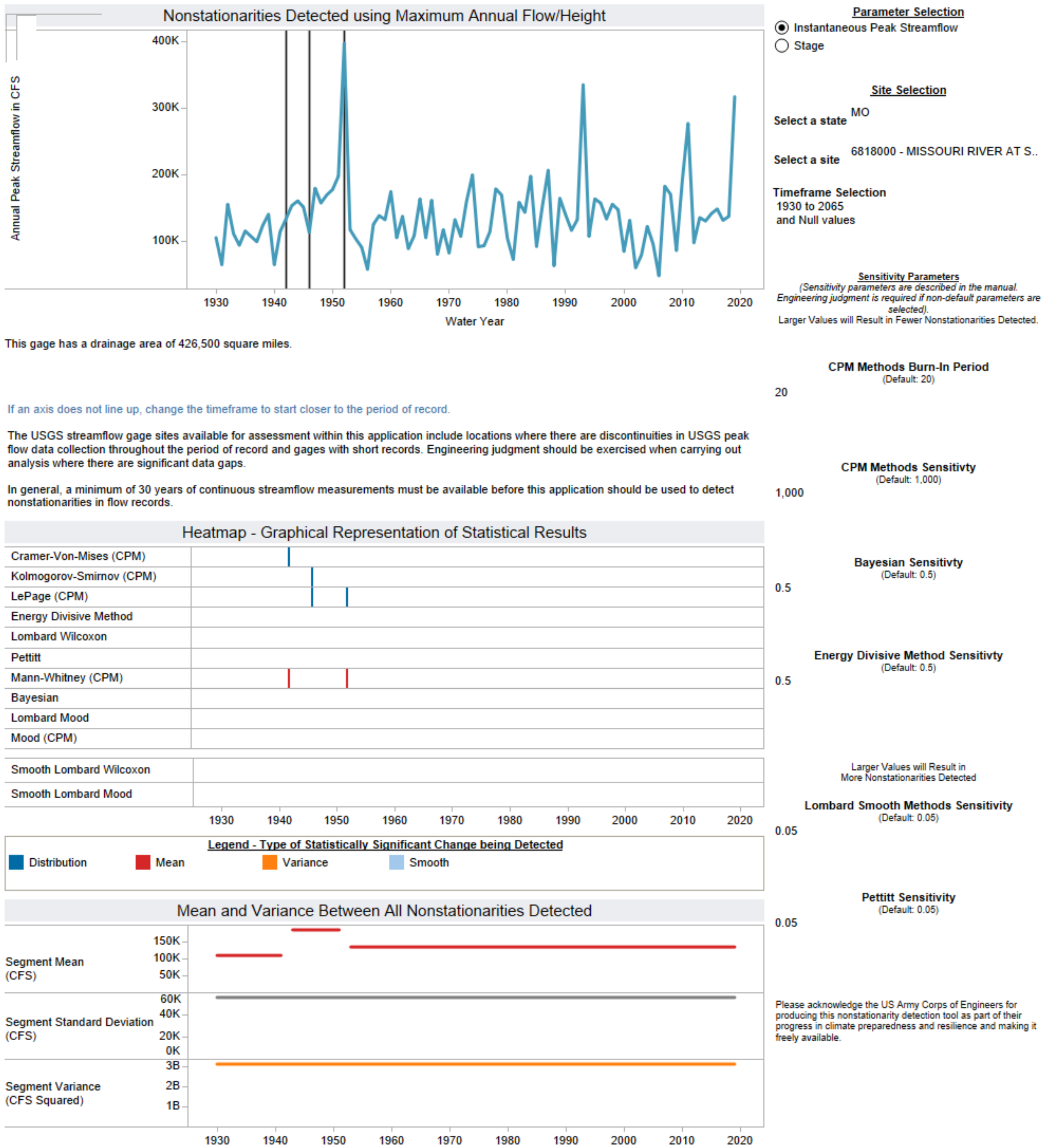


Figure 41. NSD Output for USGS Gauge 06818000 Missouri River at St. Joseph, MO

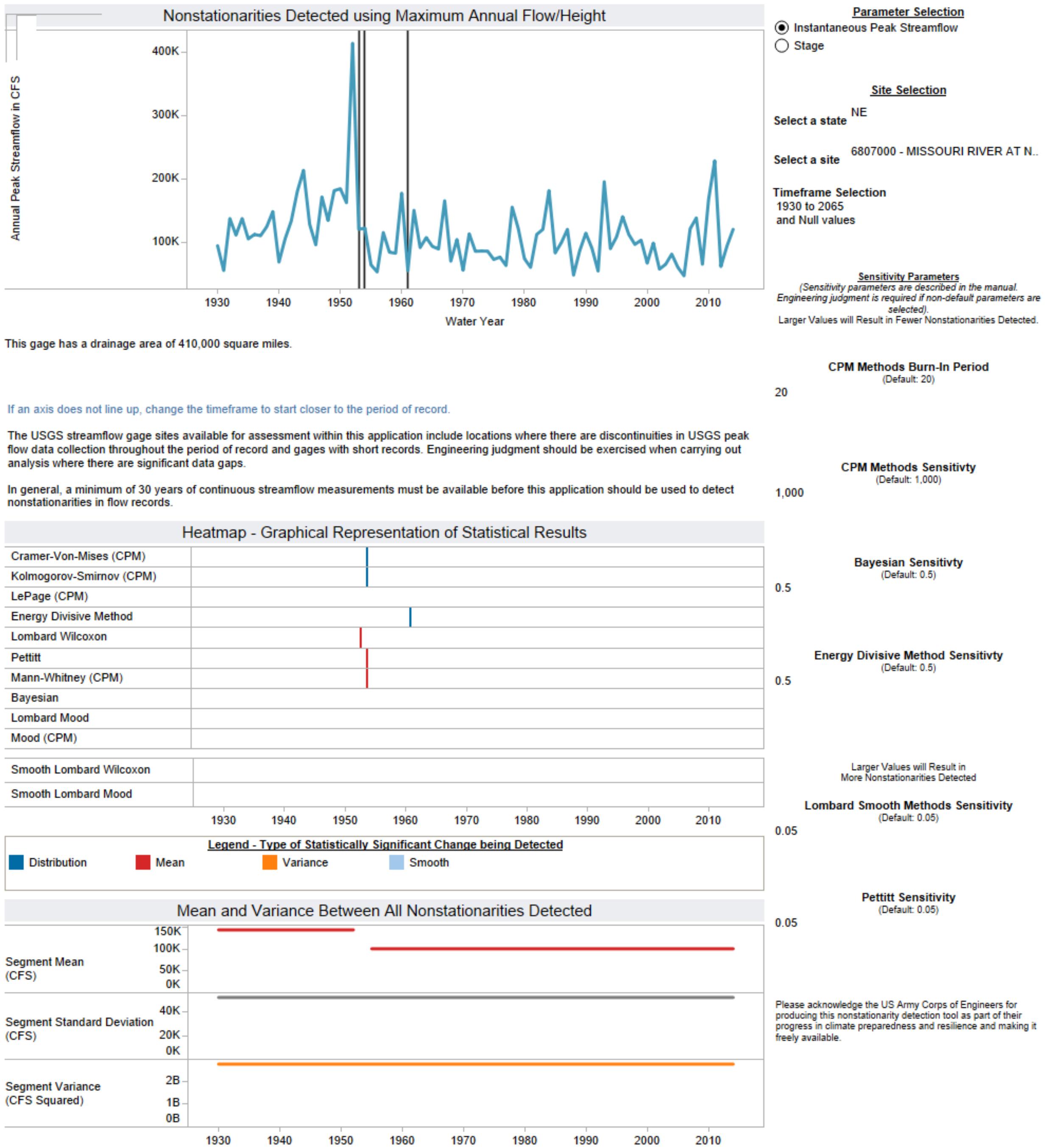


Figure 42. NSD Output for USGS Gauge 6807000 Missouri River at Nebraska City, NE

Appendix B: NRNI Nonstationarity Analysis

The following sections describe the nonstationarity detection points found in the NRNI data. The sections are presented from upstream to downstream.

1. Ft. Peck Drainage Area

The Ft. Peck Drainage area contains two NRNI flow locations (Table 19). The corresponding n-day NRNI streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 19. The resulting time series for Fred Robinson Bridge and Fort Peck are presented in Figure 43 and 44, respectively.

Table 19. Ft. Peck drainage area NRNI flow locations

NRNI Name	CWMS Name	Flow Location Type
Fred Robinson Bridge	RBMT	USGS GAGE
Fort Peck	FTPK DAM	USACE DAM

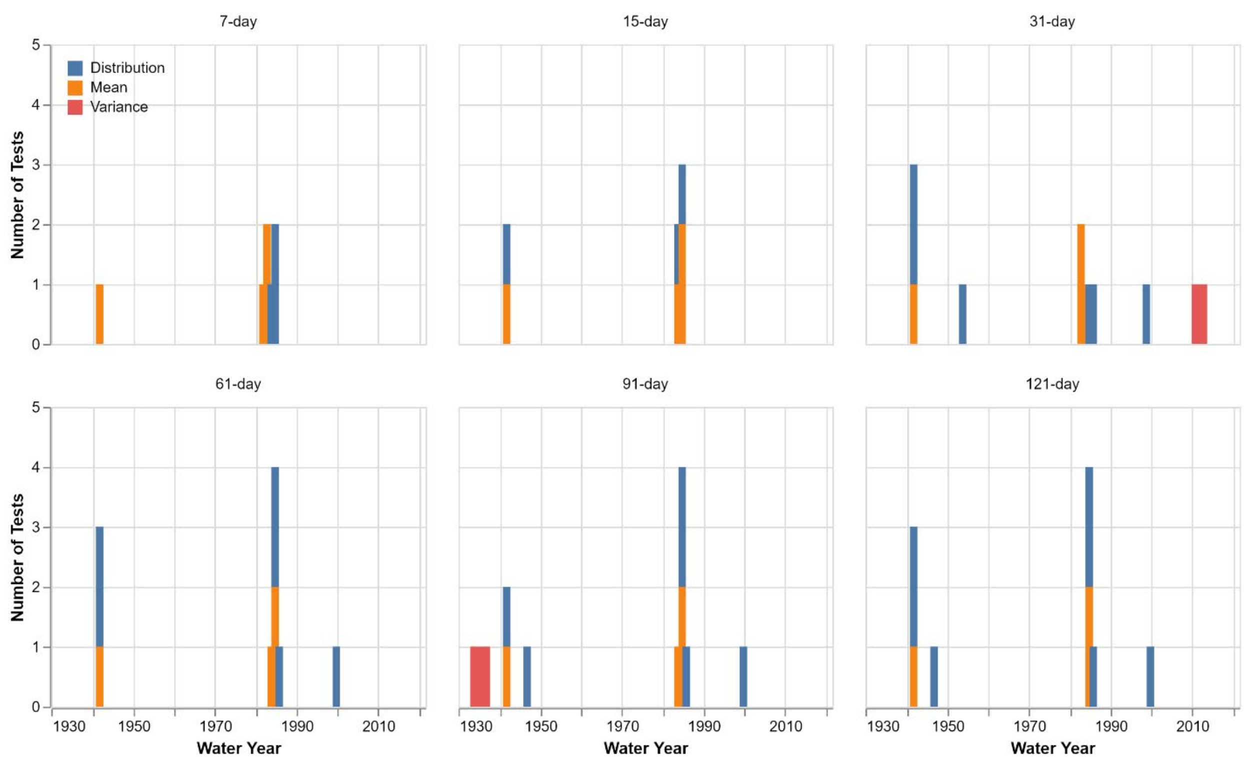


Figure 43. Fred Robinsons Bridge Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

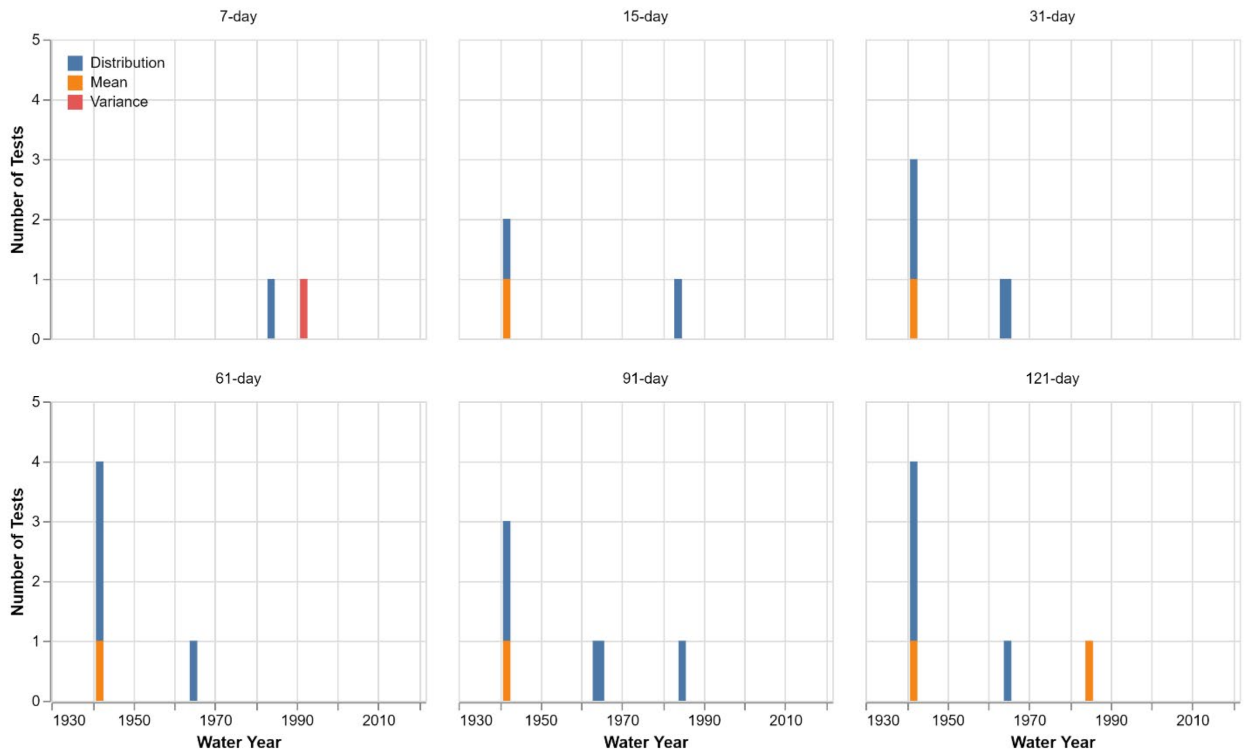


Figure 44. Ft. Peck Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

A robust (i.e. identified by more than one test type) change point time series for the Ft. Peck drainage area is shown in Figure 45. Robust change points were identified in n-day durations greater than 7 days for water years 1941 and 1985.

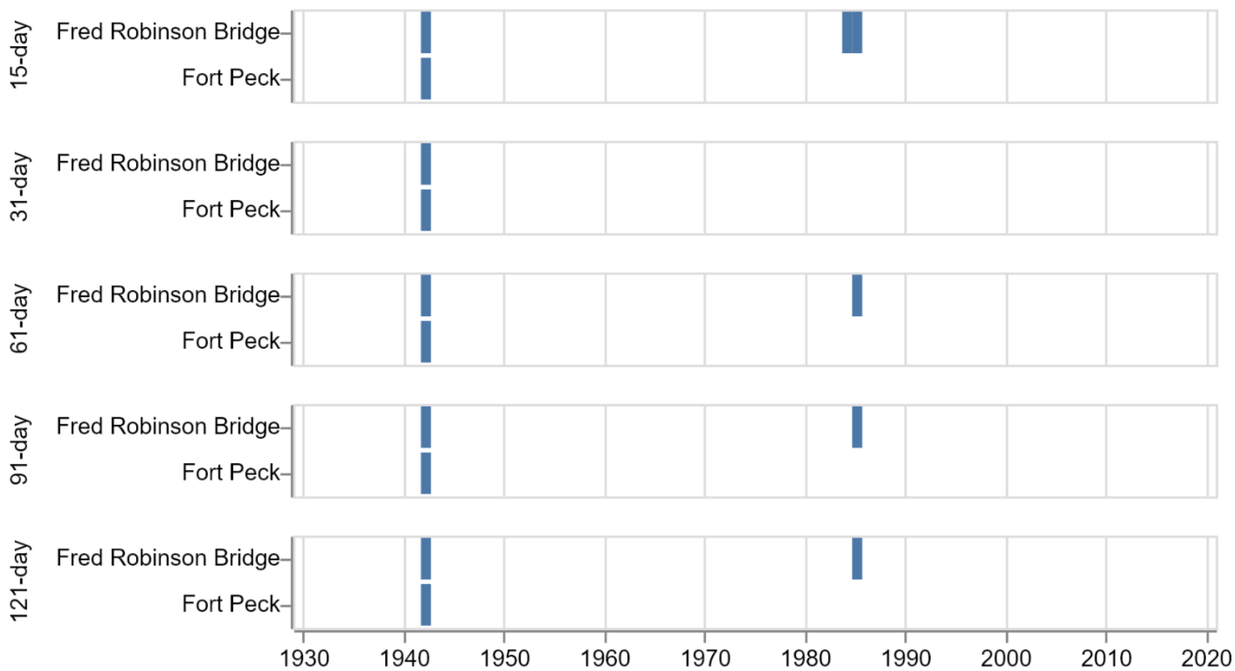


Figure 45. Ft. Peck Drainage Area Robust Change Point Timeseries

2. Garrison Drainage Area

The Garrison drainage area contains two USGS gages and 1 NRNI Flow location (Table 20). The corresponding n-day NRNI streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 17. The resulting time series for Wolf Point, Culbertson, and Garrison are presented in Figure 46, and Figure 47, respectively.

Table 20. Garrison Drainage Area NRNI Flow Locations

NRNI Name	CWMS Name	Flow Location Type
Wolf Point	WPMT	USGS GAGE
Culbertson	CLMT	USGS GAGE
Garrison	GARR DAM	USACE DAM

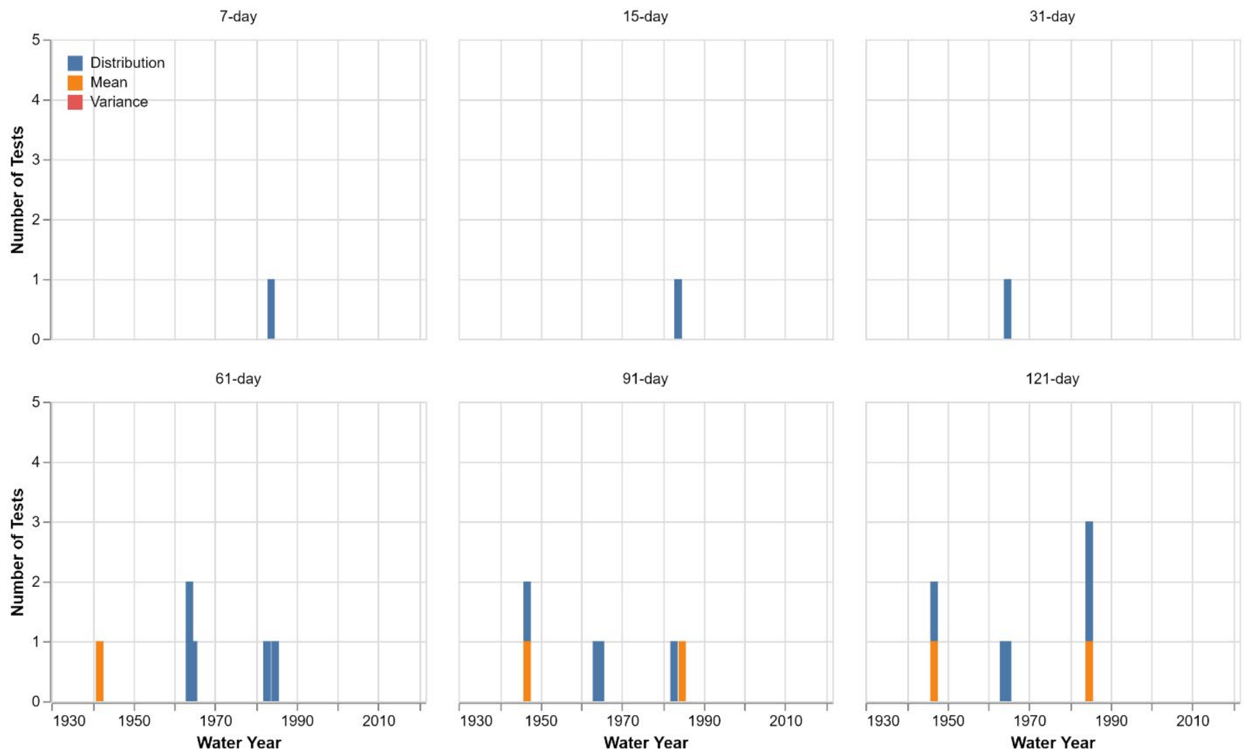


Figure 46. Wolf Point Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

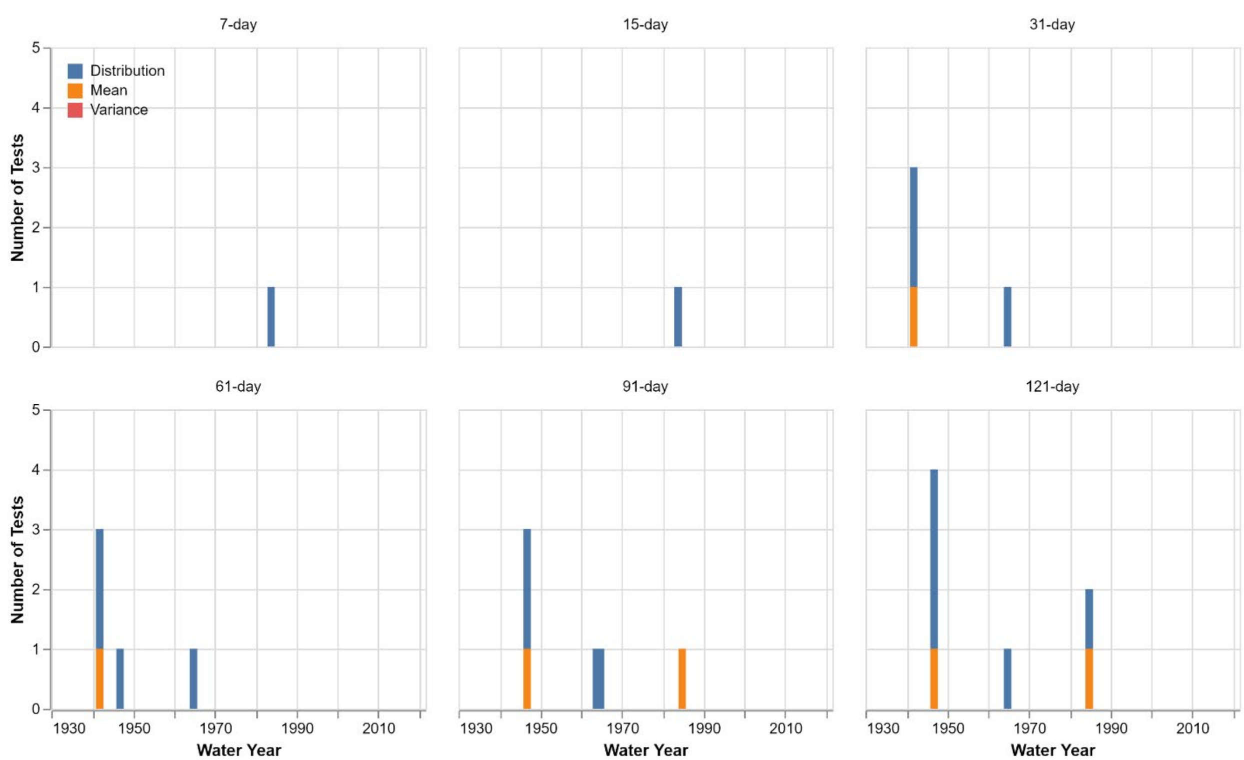


Figure 1. Culbertson Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

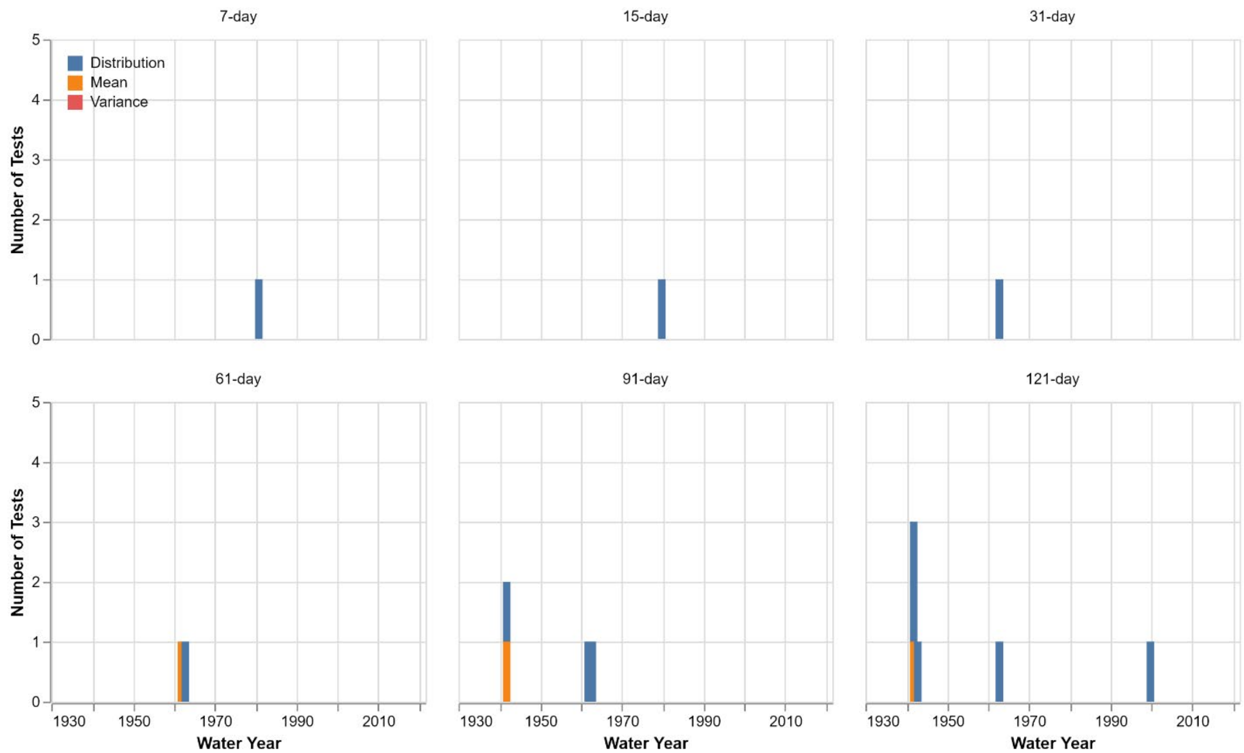


Figure 2. Garrison Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

The robust change points for each n-day duration are shown in Figure 49. Robust change points were identified within the trend analysis zone in the water years 1941, 1946, and 1981. The 1941 change point occurs in the 31-day, 61-day, 91-day, and 121-day NRNI peak streamflow records, but the signal shifts downstream for durations longer than 61-days. The 1946 change point was identified in the 91-day and 121-day time series.

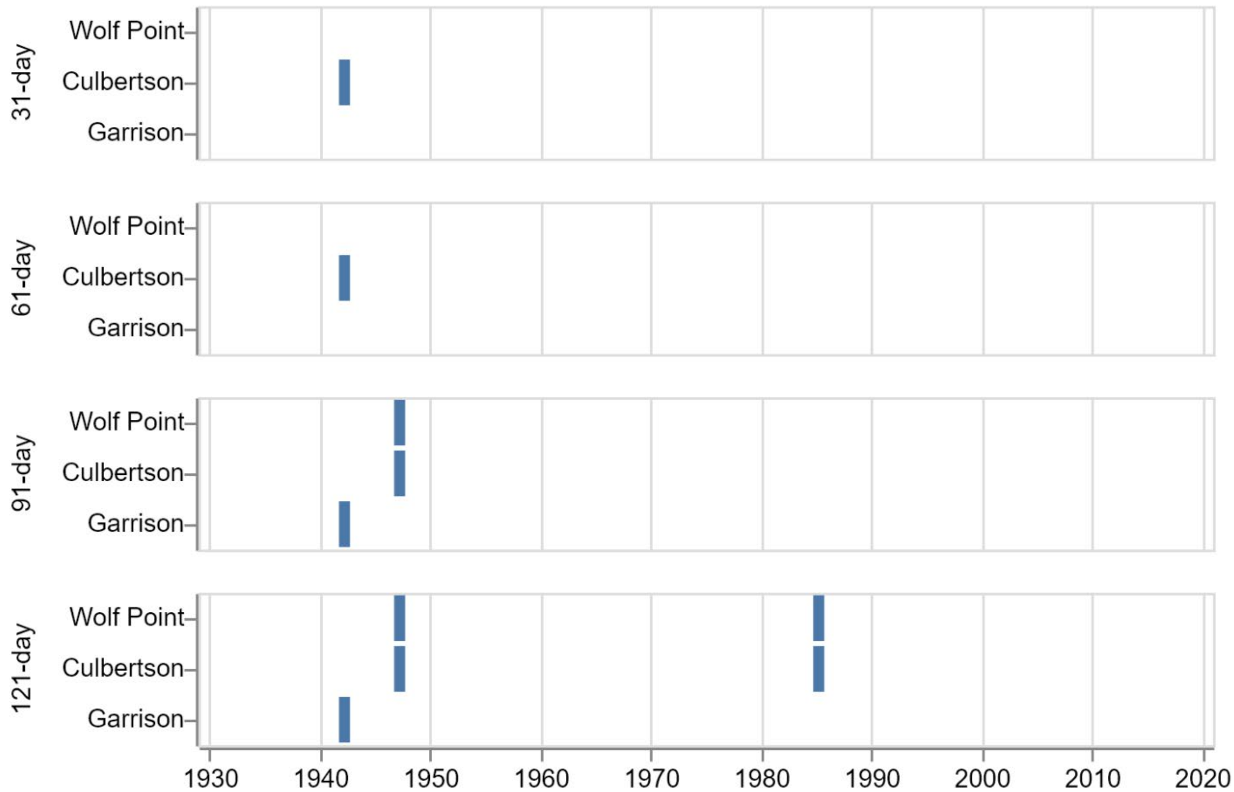


Figure 49. Garrison Drainage Area Robust Change Points for NRNI n-day Flow Durations

Note: A robust change point is defined when two or more tests from different statistical properties identify the same change point.

3. Garrison to Ft. Randall

There are 4 NRNI flow locations in the Garrison to Fort Randall trend analysis zone (Table 21). The corresponding n-day annual maximum NRNI streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 21. The resulting time series for each NRNI flow location, from upstream to downstream, are presented in Figures 50, 51, 52, and 53, respectively.

Table 21. Garrison to Oahe NRNI Flow Locations

NRNI Name	CWMS Name	Flow Location Type
Bismarck	BIS	USGS GAGE
Oahe	OAHE DAM	USACE DAM
Big Bend	BEND DAM	USACE DAM
Fort Randall	FTRA DAM	USACE DAM

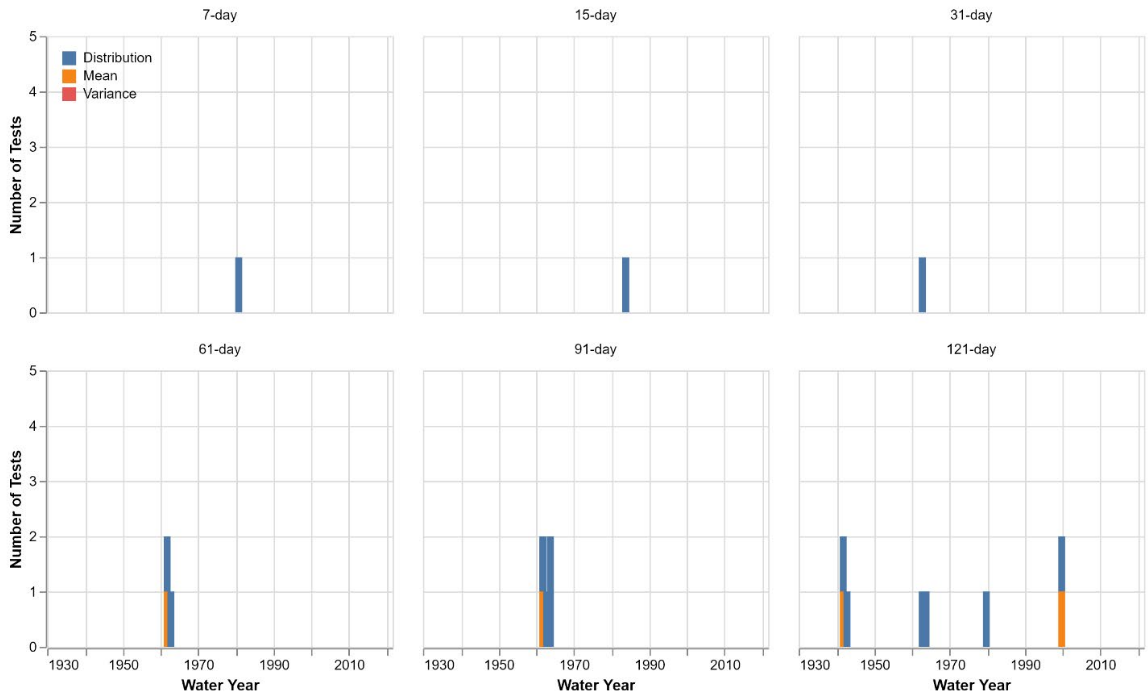


Figure 50. Bismarck Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

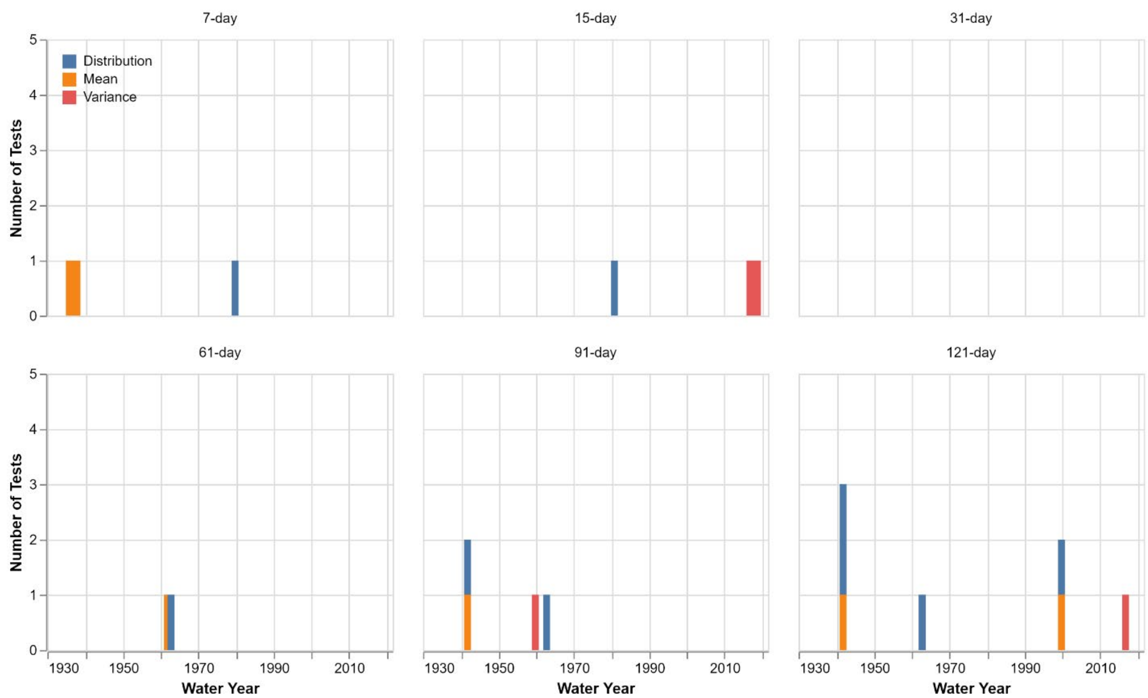


Figure 51. Oahe Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

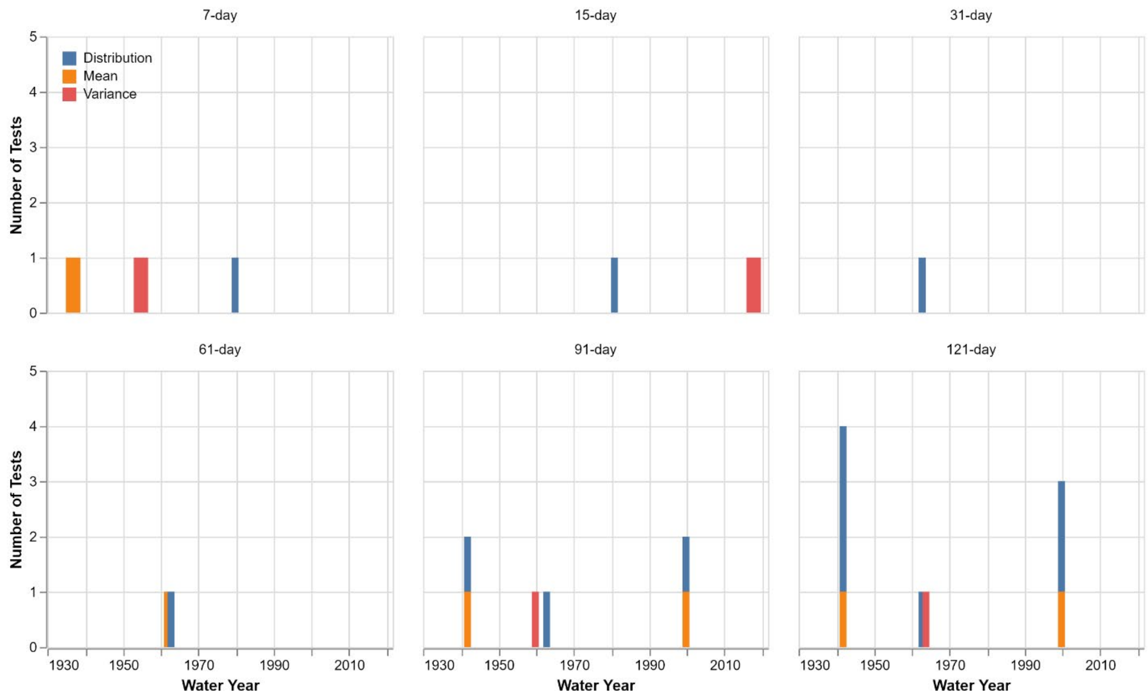


Figure 52. Big Bend Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

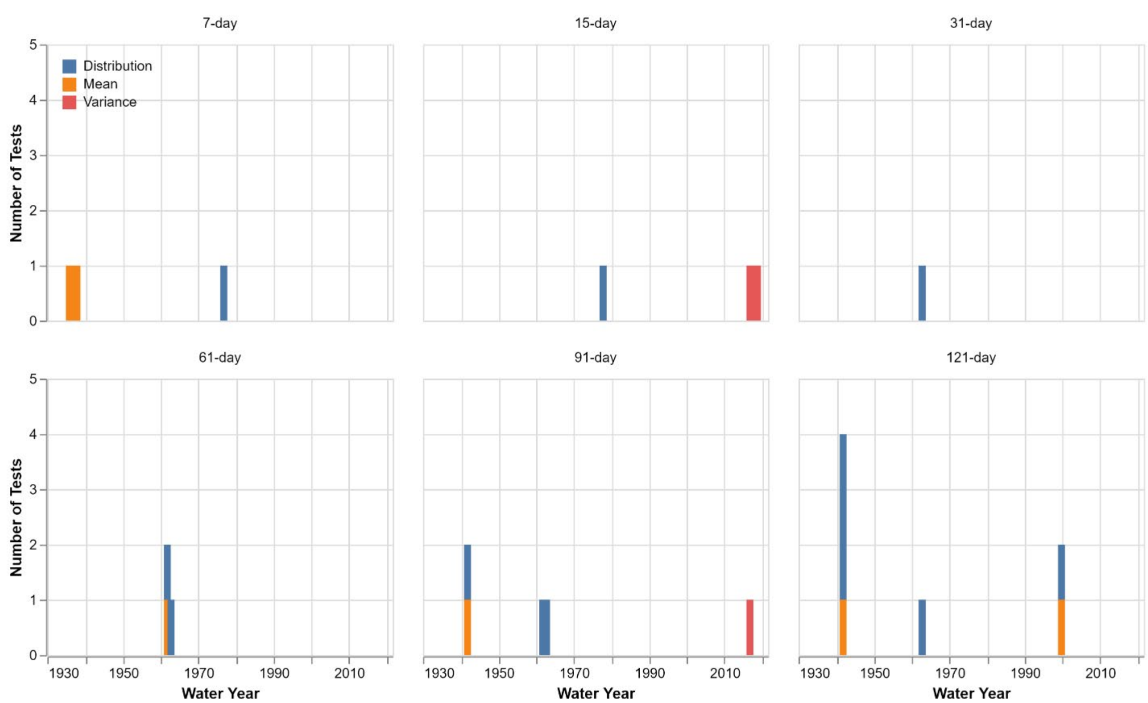


Figure 53. Ft. Randall Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

The robust change point time series for the Garrison to Oahe trend analysis zone is presented in Figure 54. The 61-day time series identified a robust change point around 1961 for Bismarck and Ft. Randall. The 91-day time series had change points identified in 1941 (n=3), 1961 (n=1), and 1999 (n=1). The 121-day time series had robust change points in 1941 and 1999 for all the NRNI flow locations in the trend analysis zone.

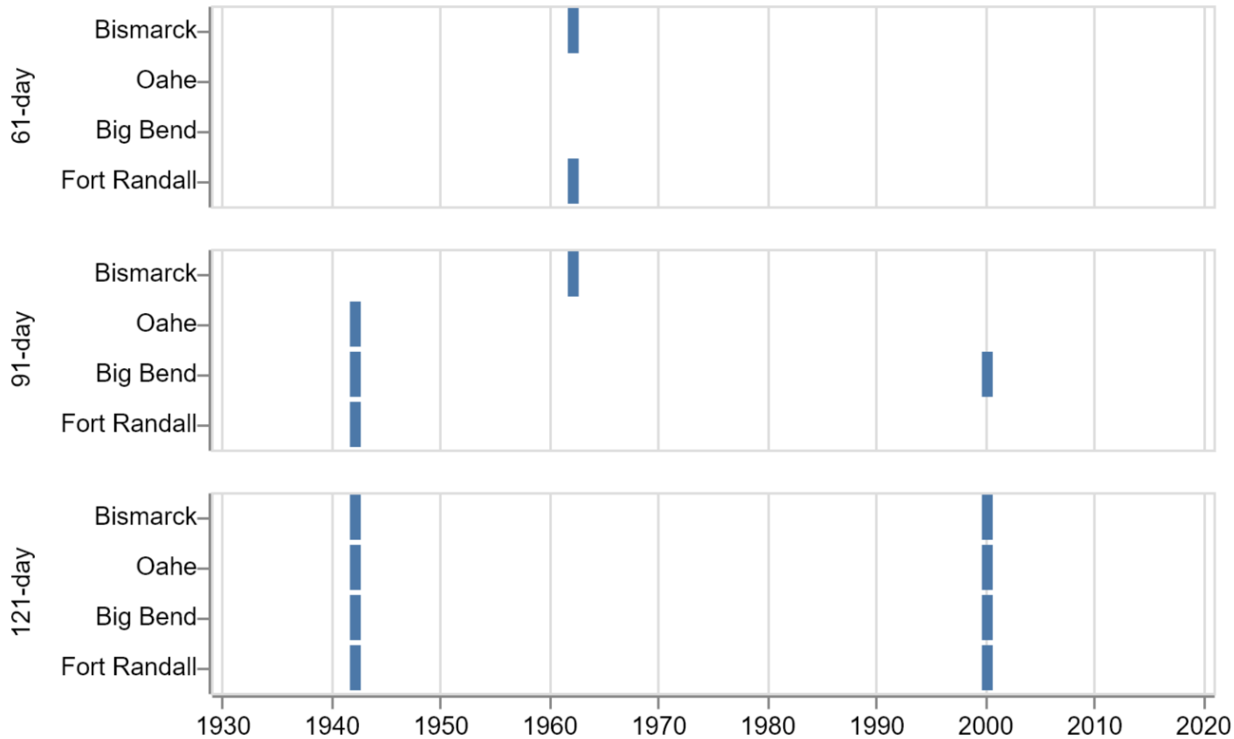


Figure 54. Garrison to Ft. Randall Trend Zone Robust Change Point Timeseries

4. Gavins Point Drainage Area

There is one NRNI flow location in the Gavins Point drainage area trend analysis zone (Table 22). The corresponding n-day annual maximum NRNI streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 22. The resulting time series for Gavins Point is presented in Figures 55.

Table 3. Gavins Point Drainage Area NRNI Locations

NRNI Name	CWMS Name	Flow Location Type
Gavins Point	GAPT DAM	USACE DAM

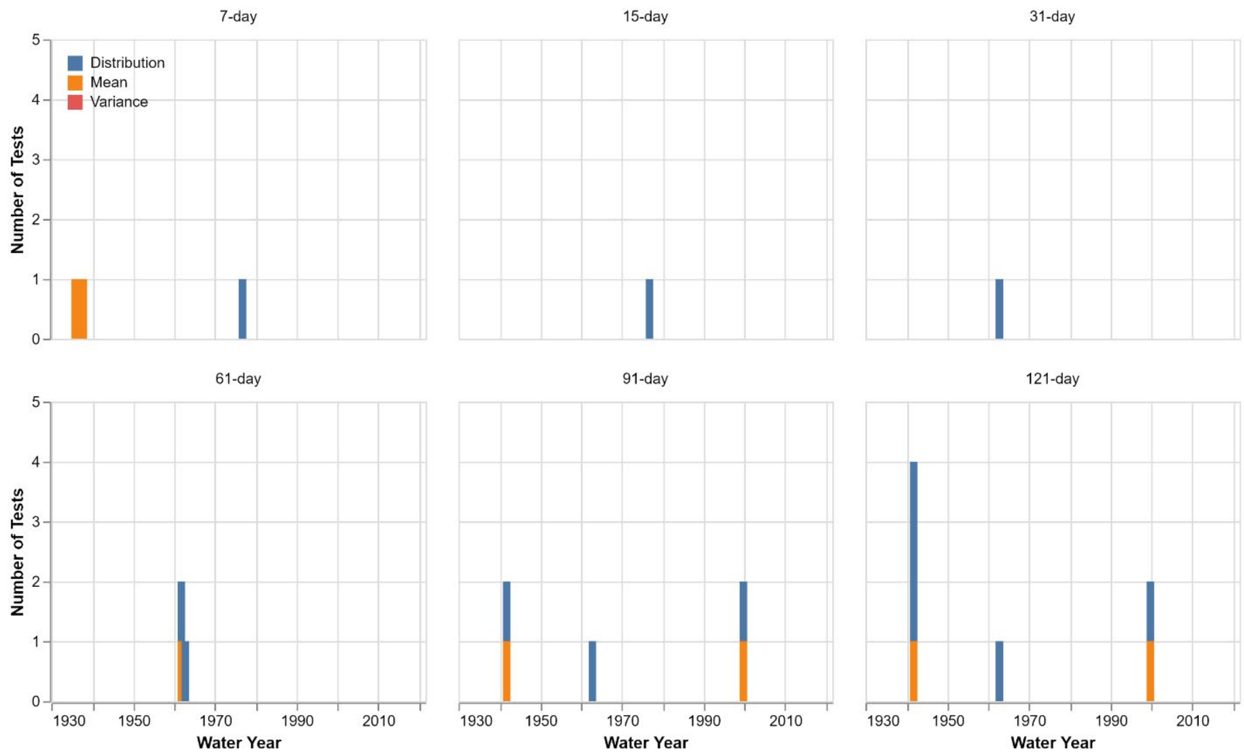


Figure 55. Gavins Point Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

Robust change points were identified in 1942, 1962, and 2000 in the n-duration greater than 31 days (Figure 56). The 91-day and 121-day durations both identified the 1942 and 2000 change points.

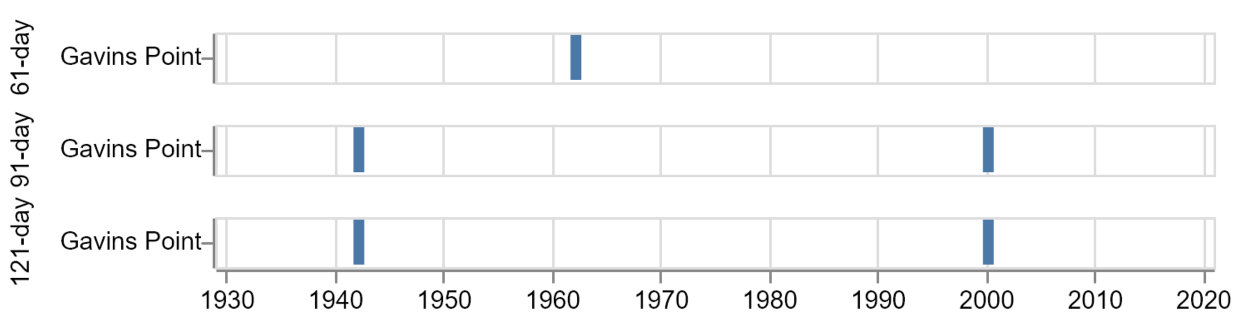


Figure 56. Gavins Point Drainage Area Robust Change Point Time Series

5. Gavins Point to Sioux City

There is one NRNI flow location in the Gavins Point to Sioux City trend analysis zone (Table 23). The corresponding n-day annual maximum NRNI streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 23. The resulting time series for Sioux City is presented in Figure 57.

Table 23. Gavins Point to Sioux City NRNI locations

NRNI Name	CWMS Name	Flow Location Type
Sioux City	SUX	USGS GAGE

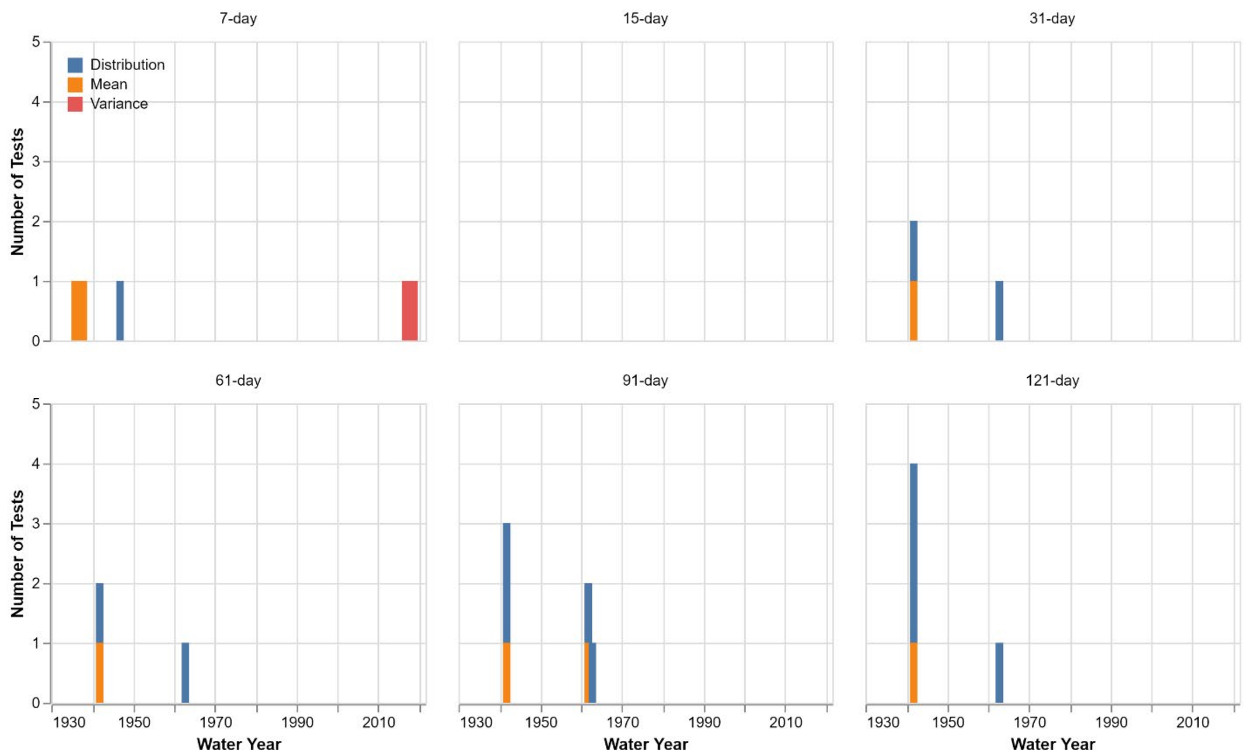


Figure 57. Sioux City Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

The robust change points for the Gavins Point to Sioux City are shown in Figure 58. A change point in 1941 was identified in 1941 for n-day durations longer than 15 days. A change point in 1961 was also identified in the 91-day time series.

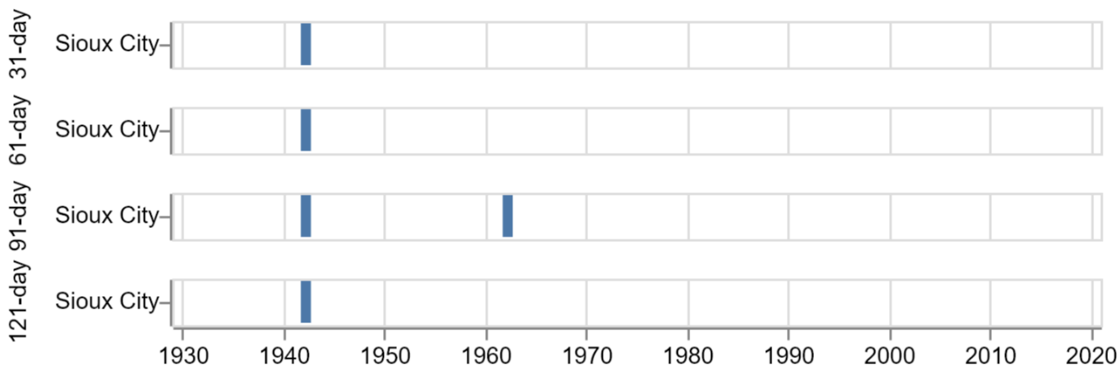


Figure 58. Gavins Point to Sioux City Robust Change Point Time Series

6. Lower Missouri – NWO District

The Lower Missouri trend analysis zone contains three NRNI flow locations (Table 24). The corresponding n-day annual maximum streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 24. The resulting time series for Omaha, Nebraska City, and Rulo are presented in Figures 59, 60, and 61, respectively.

Table 24. Lower Missouri (NWO District) NRNI Flow Locations

NRNI Name	CWMS Name	Flow Location Type
Omaha	OMA	USGS GAGE
Nebraska City	NCNE	USGS GAGE
Rulo	RUNE	USGS GAGE

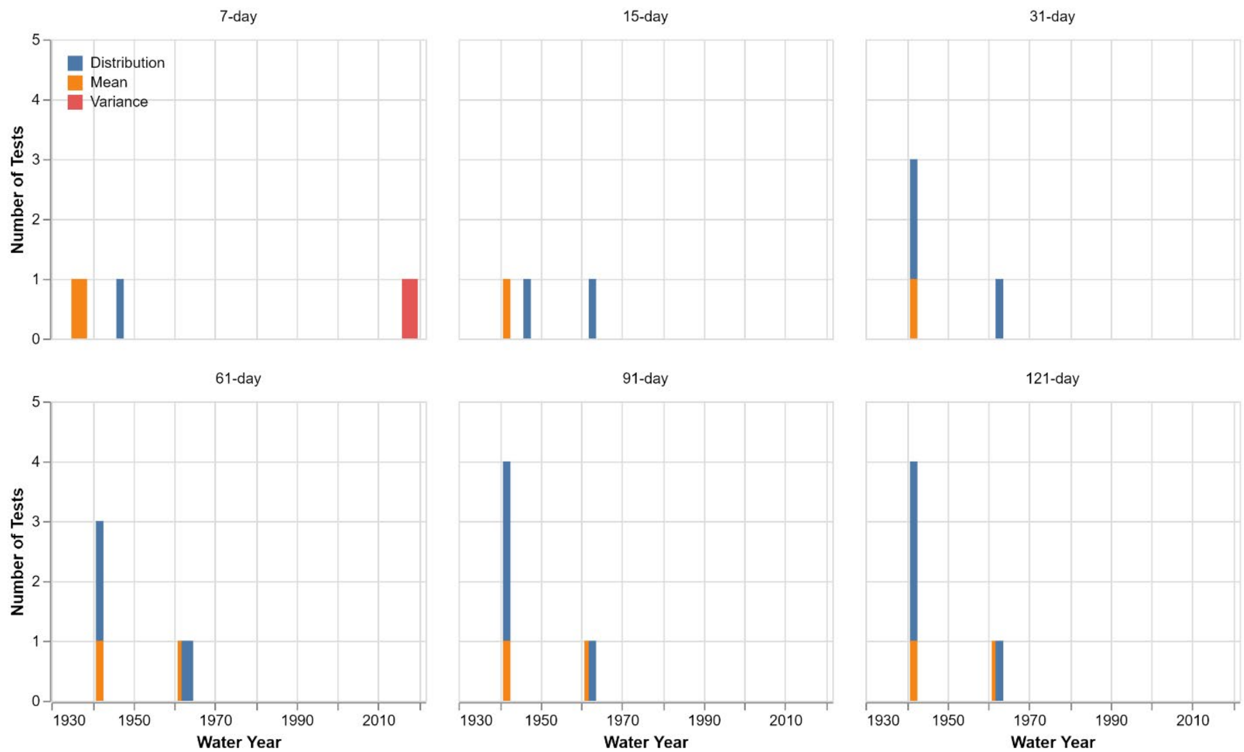


Figure 59. Omaha Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

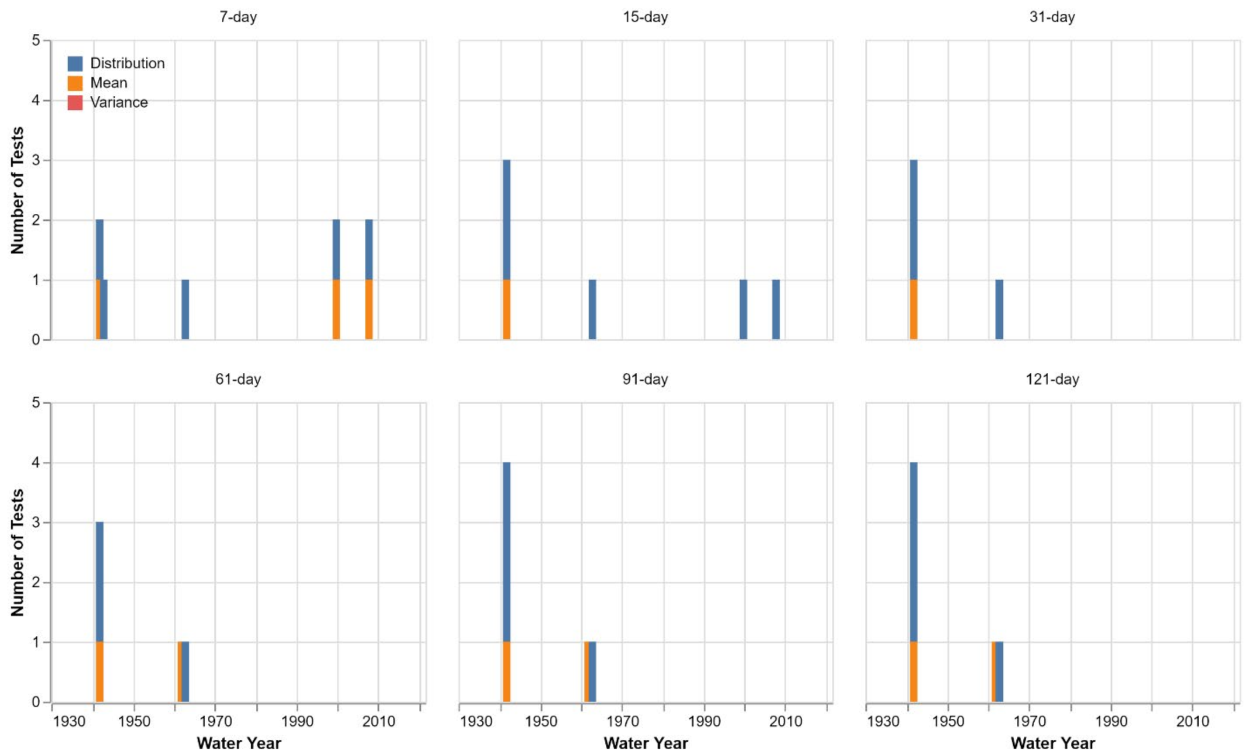


Figure 60. Nebraska City Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

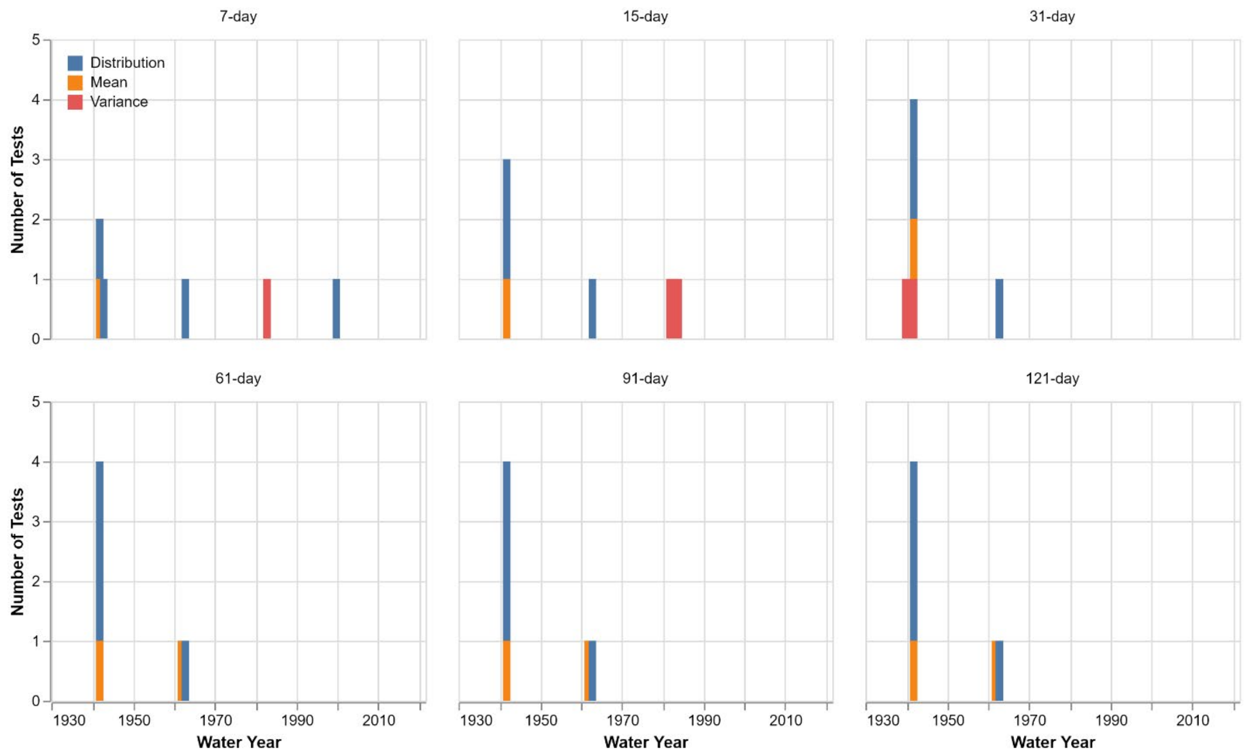


Figure 61. Rulo Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

The robust change points for the Lower Missouri trend analysis zone are shown in Figure 62. A robust change point in 1941 was identified in all the n-day duration at Nebraska City and Rulo. Omaha had 1941 change point identified for n-day durations greater than 15 days. Two additional robust change points were identified at Nebraska City in 1999 and 2007 in the 7-day time series.

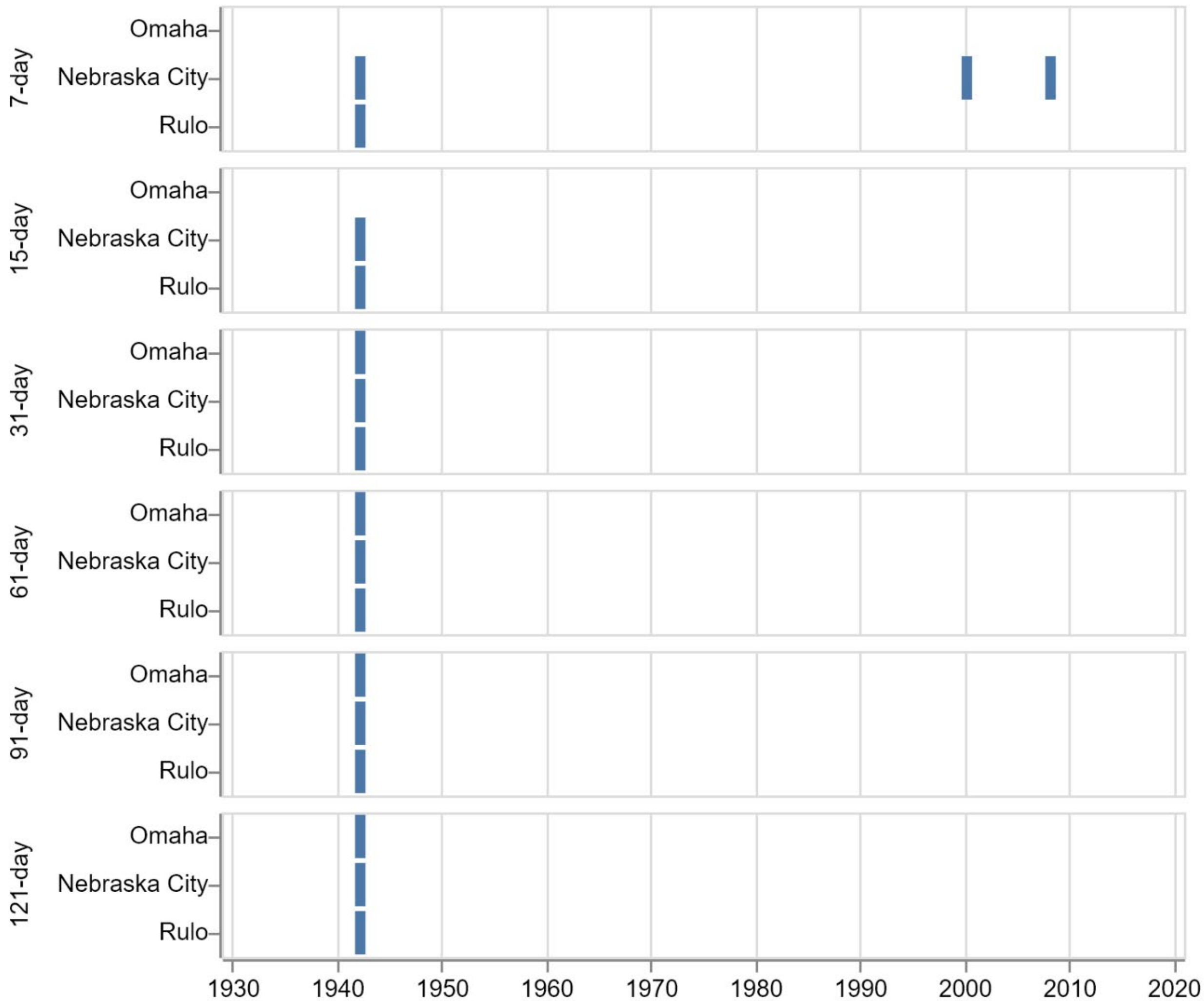


Figure 62. Lower Missouri Trend Analysis Zone Robust Change Point Time Series

7. Lower Missouri NWK District

The NWK District trend analysis zone contains five NRNI flow locations (Figure 63). The corresponding n-day annual maximum streamflow records were analyzed for statistically significant change points using the statistical tests described in Table 25. The resulting change point time series for each NRNI location are presented in upstream to downstream order from Figure 64 to 67.

Table 25. Lower Missouri (NWK District) NRNI Flow Locations

NRNI Name	CWMS Name	Flow Location Type
St Joseph	STJ	USGS GAGE
Kansas City	MKC	USGS GAGE
Waverly	WVMO	USGS GAGE
Boonville	BNMO	USGS GAGE
Hermann	HEMO	USGS GAGE

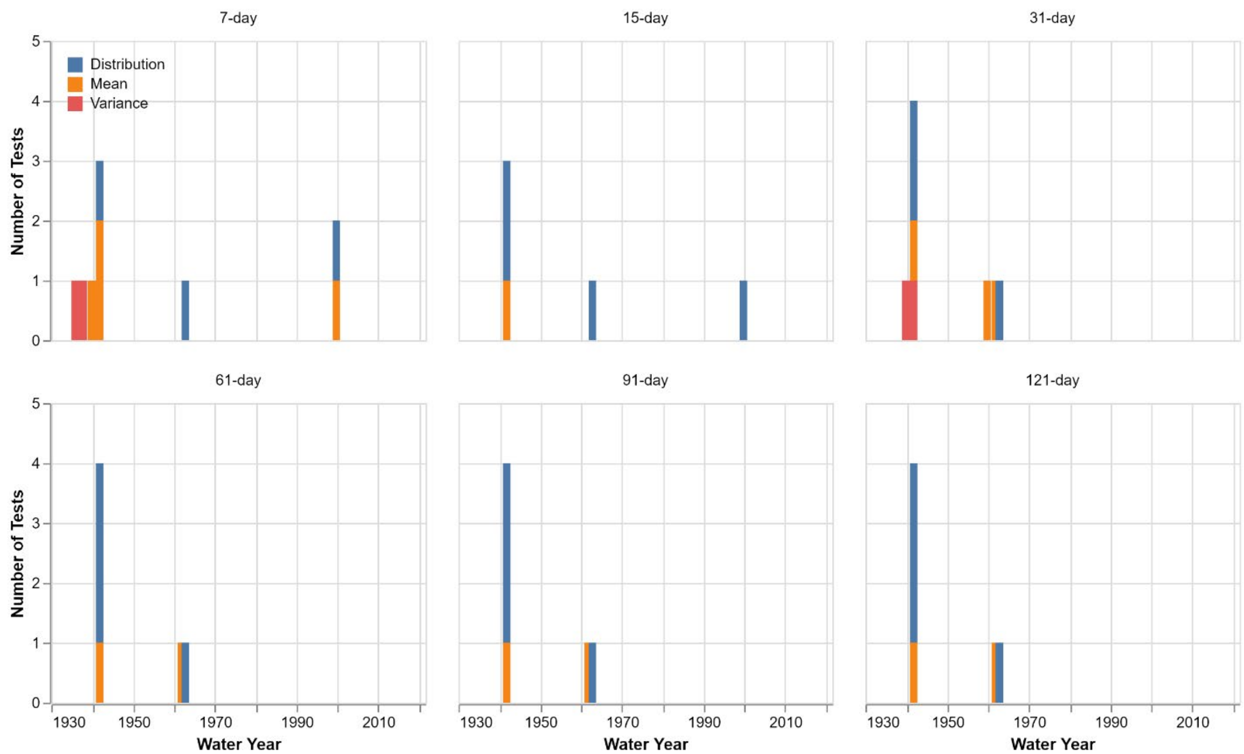


Figure 63. St. Joseph Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

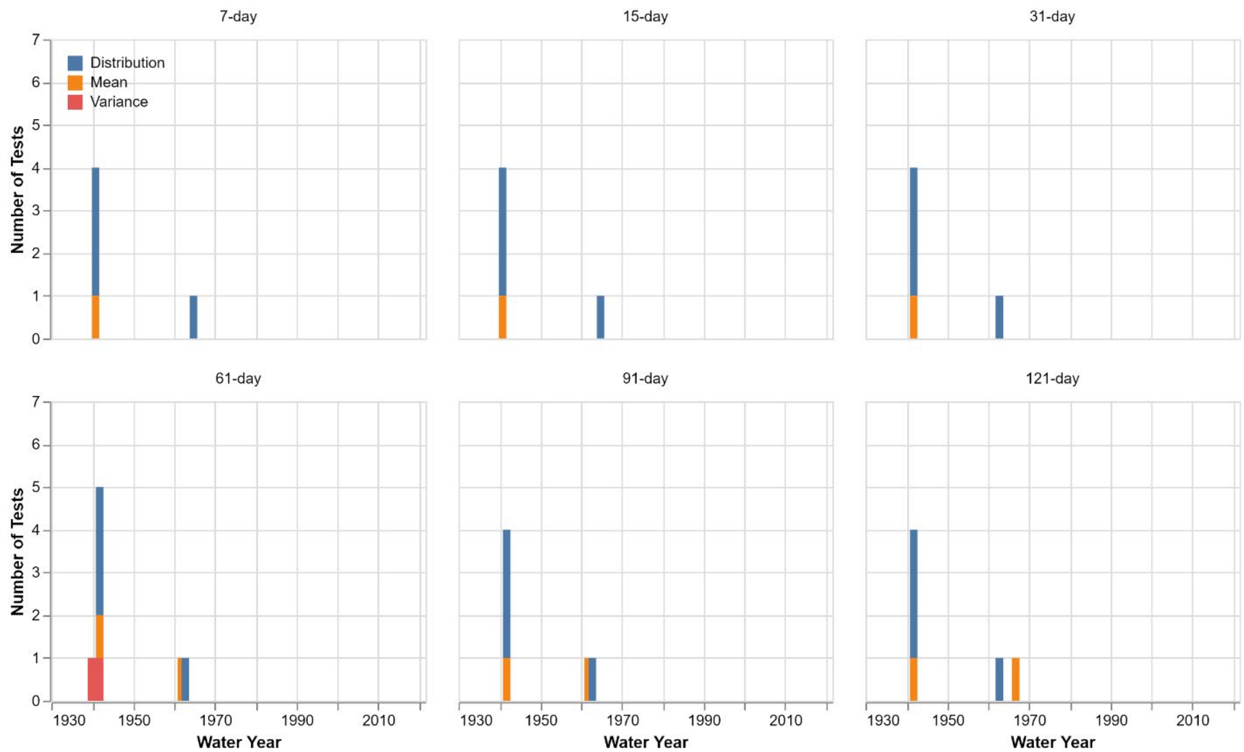


Figure 64. Kansas City Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

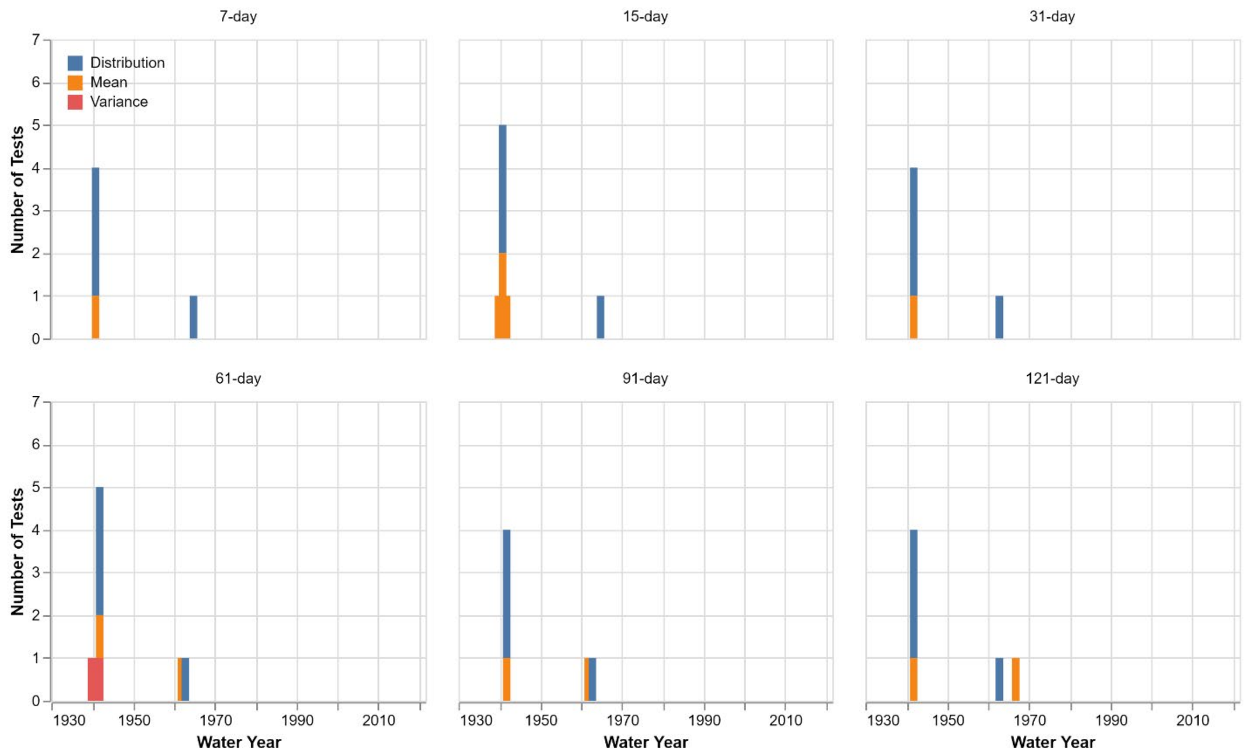


Figure 65. Waverly Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

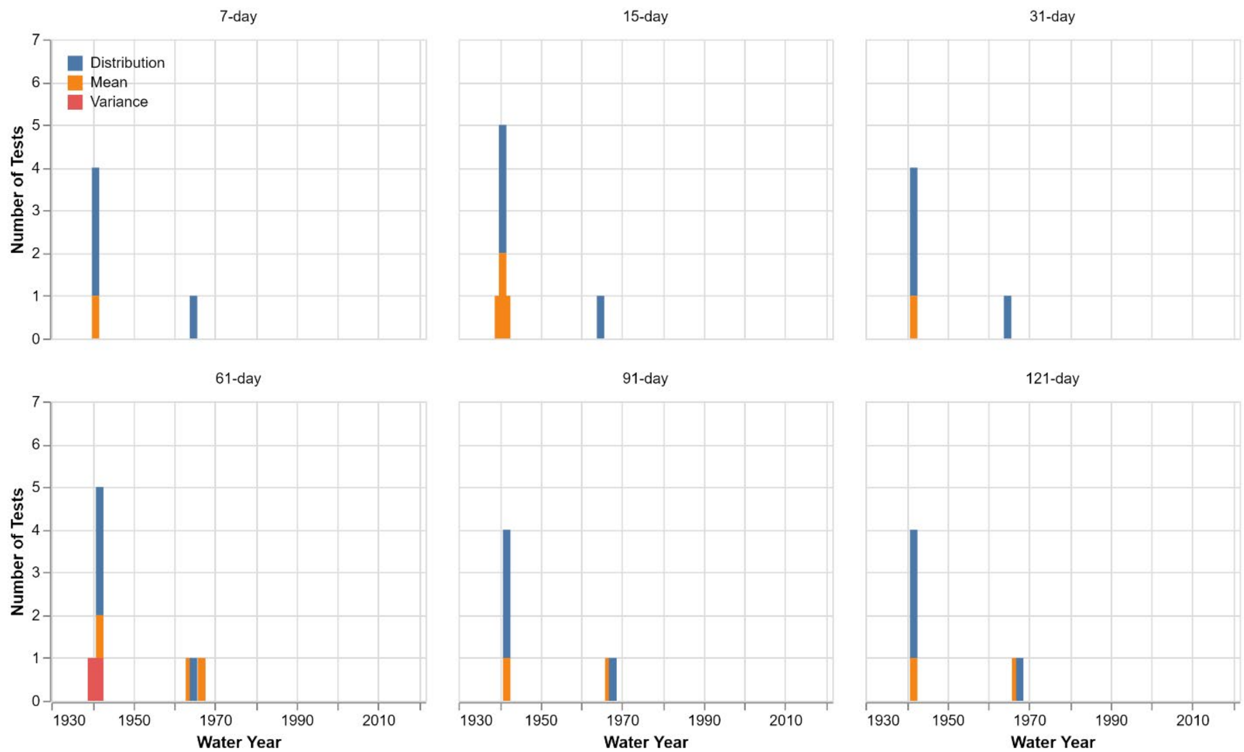


Figure 66. Boonville Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

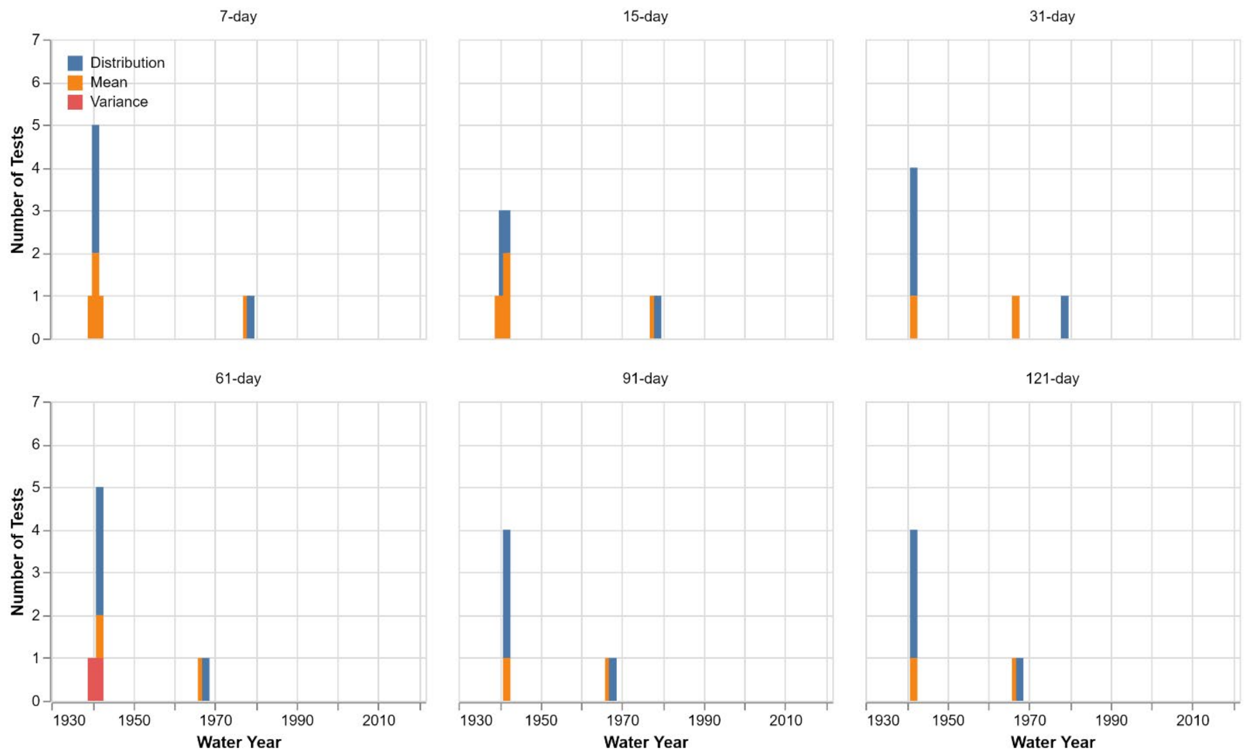


Figure 67. Hermann Nonstationary Change Detection Points for n-day Durations Ranging Between 7 and 121 days

The robust change points for the NWK District trend analysis zone is presented in Figure 68. Change points were detected across all the n-day durations at each NRNI flow location around 1941. An additional robust change detection also occurred at St. Joseph around 2000.

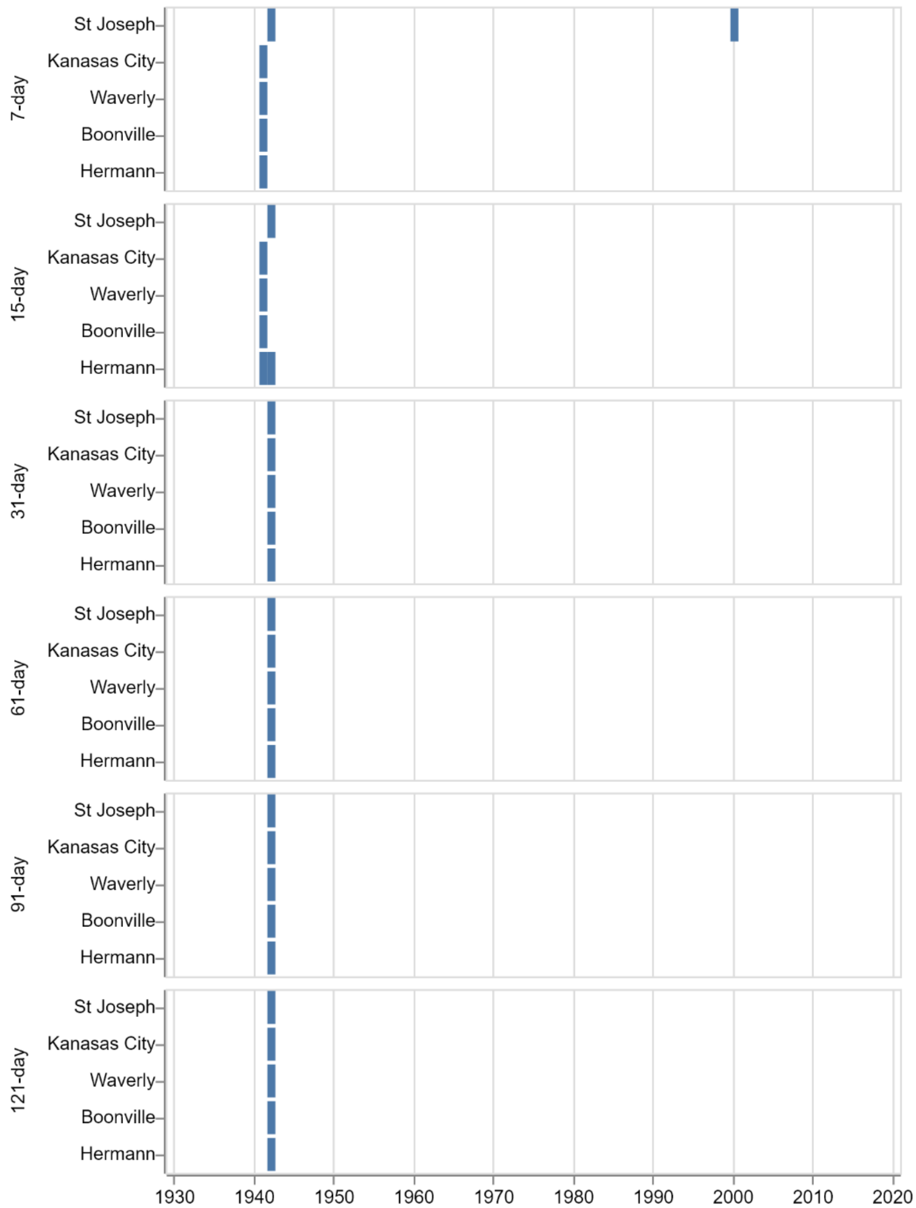


Figure 68. NWK District Trend Analysis Zone Robust Change Point Time Series

8. Missouri River Basin Summary

The types of statistical tests used to identify robust change points are shown in Figure 69. Change point tests relating to mean and distributional properties were the most frequent for identifying robust points. Variance based statistical tests were only identified in the Big Bend Drainage Area and NWK District trend analysis zones.

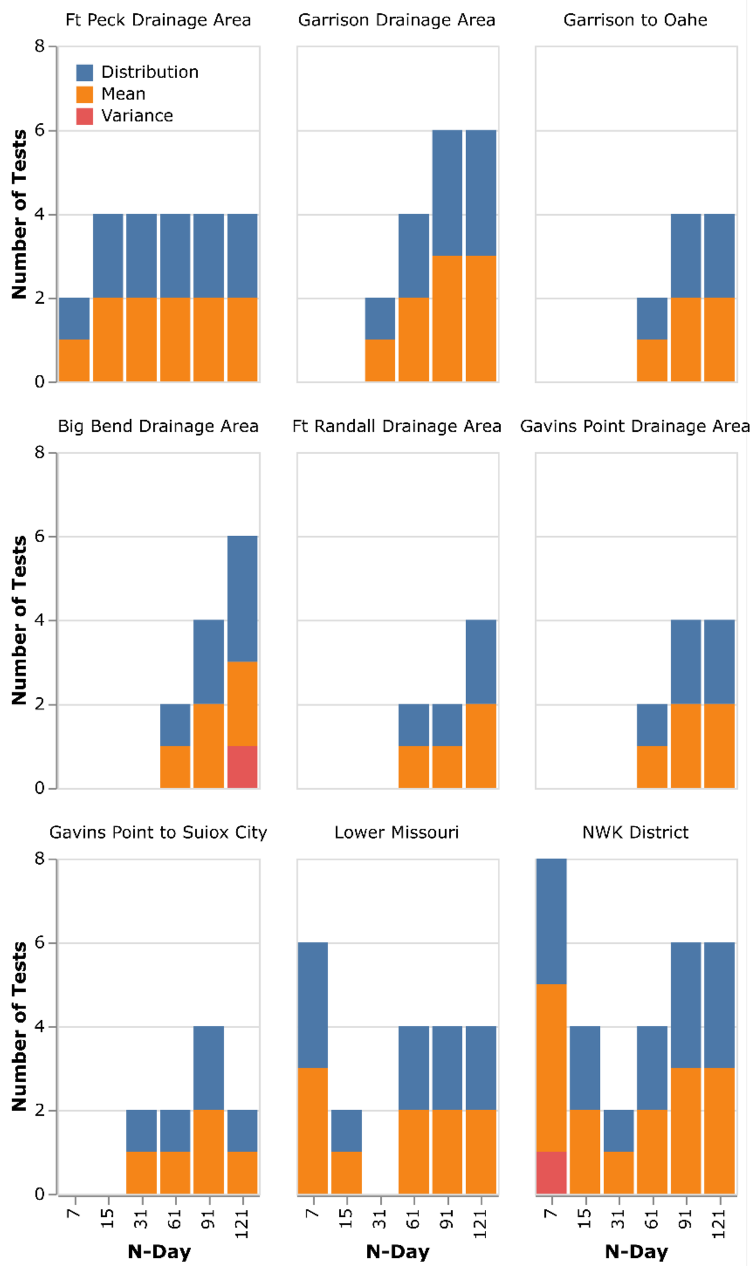


Figure 69. Trend Analysis Zone Robust Change Point Statistical Test Types

Appendix C: Annual Instantaneous Peak Streamflow Trends

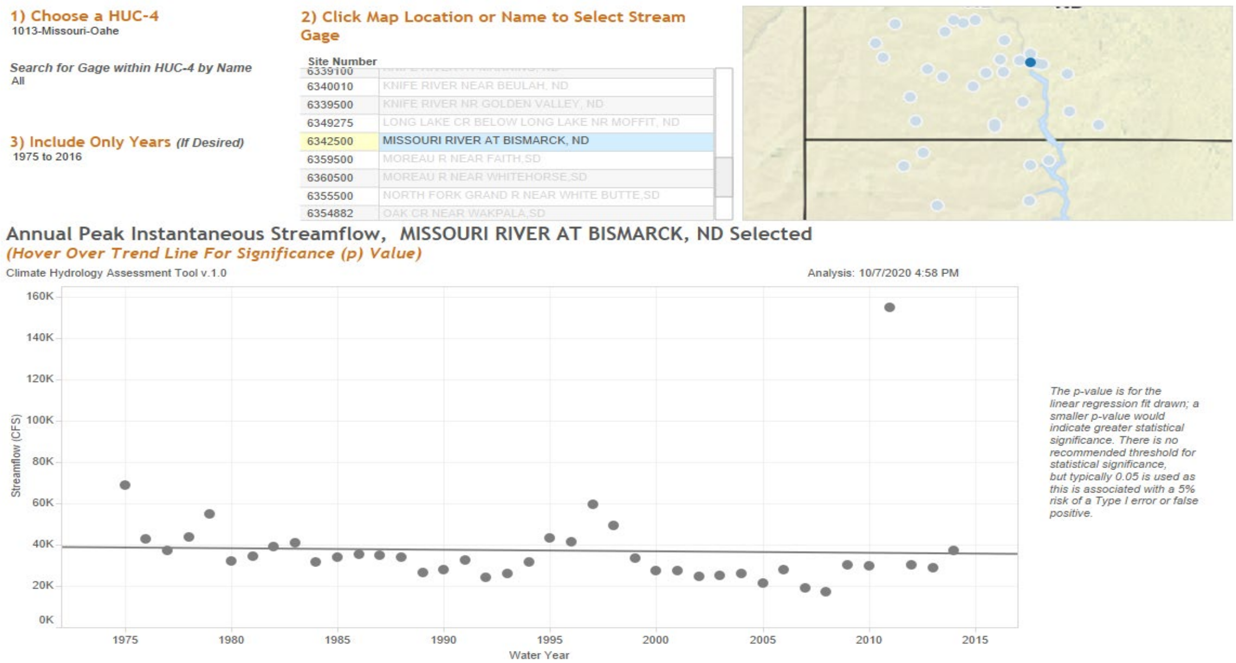


Figure 70.

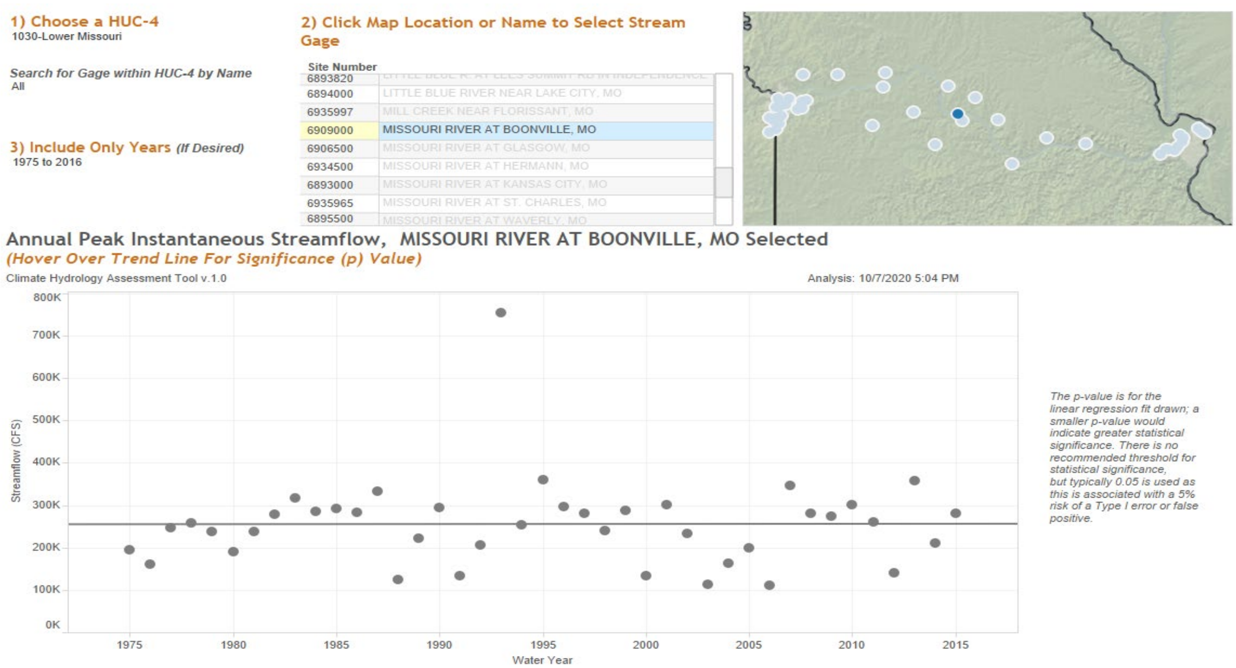
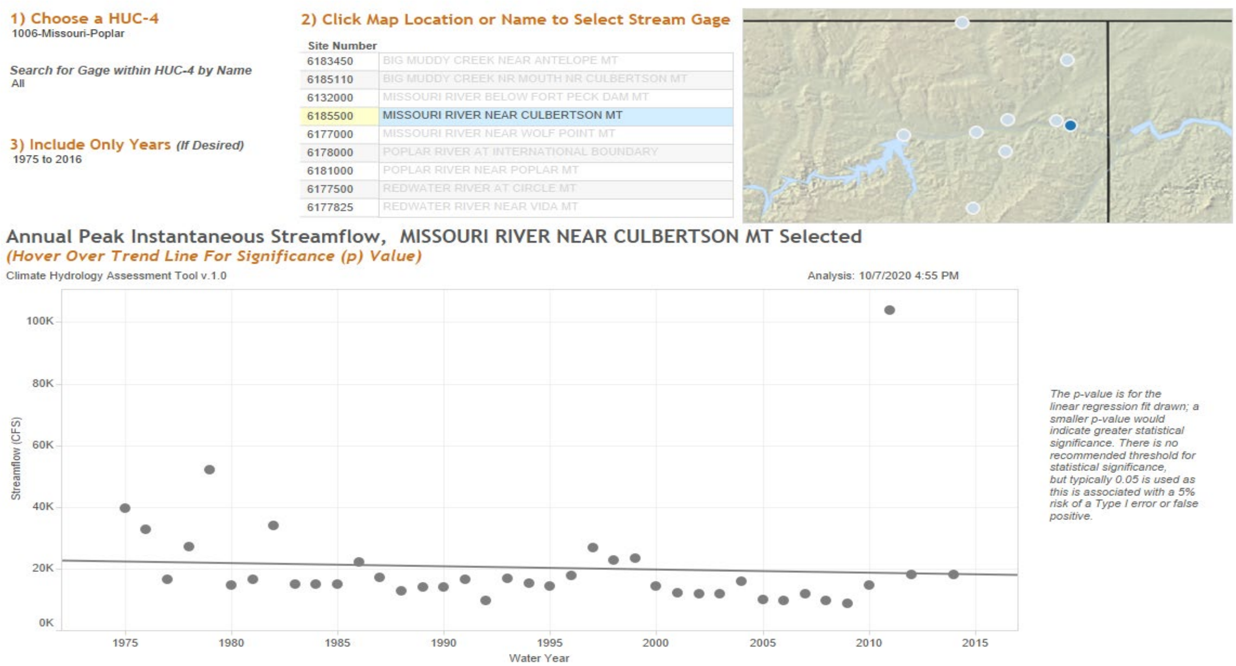


Figure 71.



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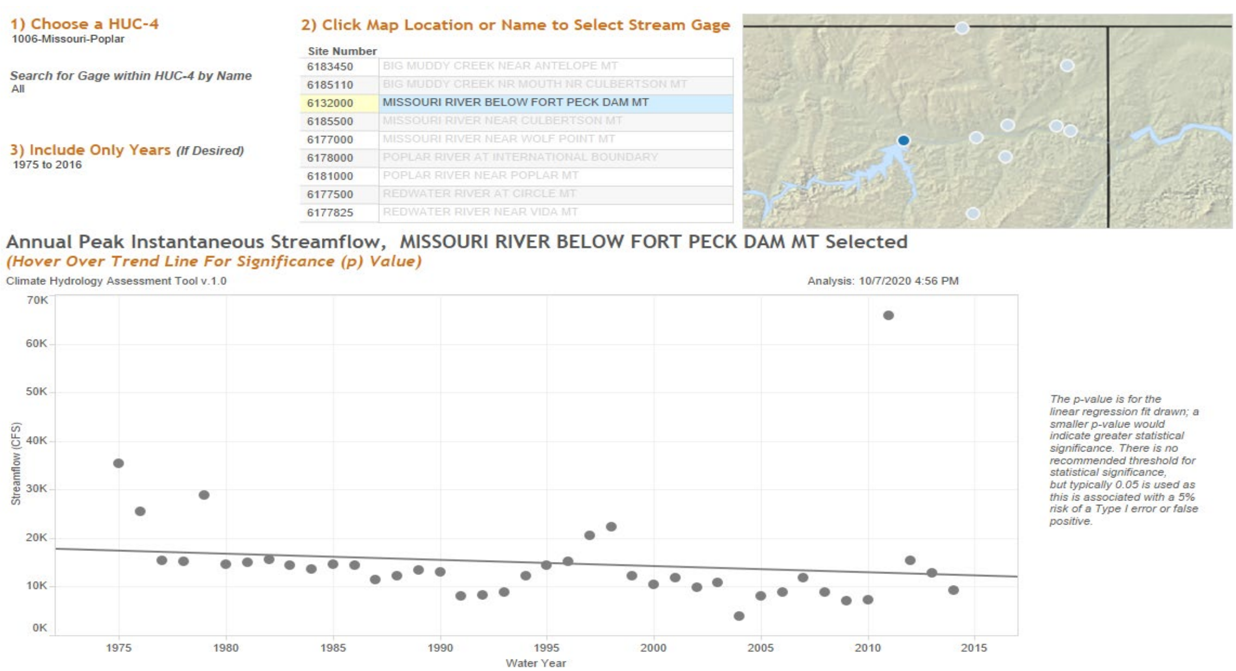

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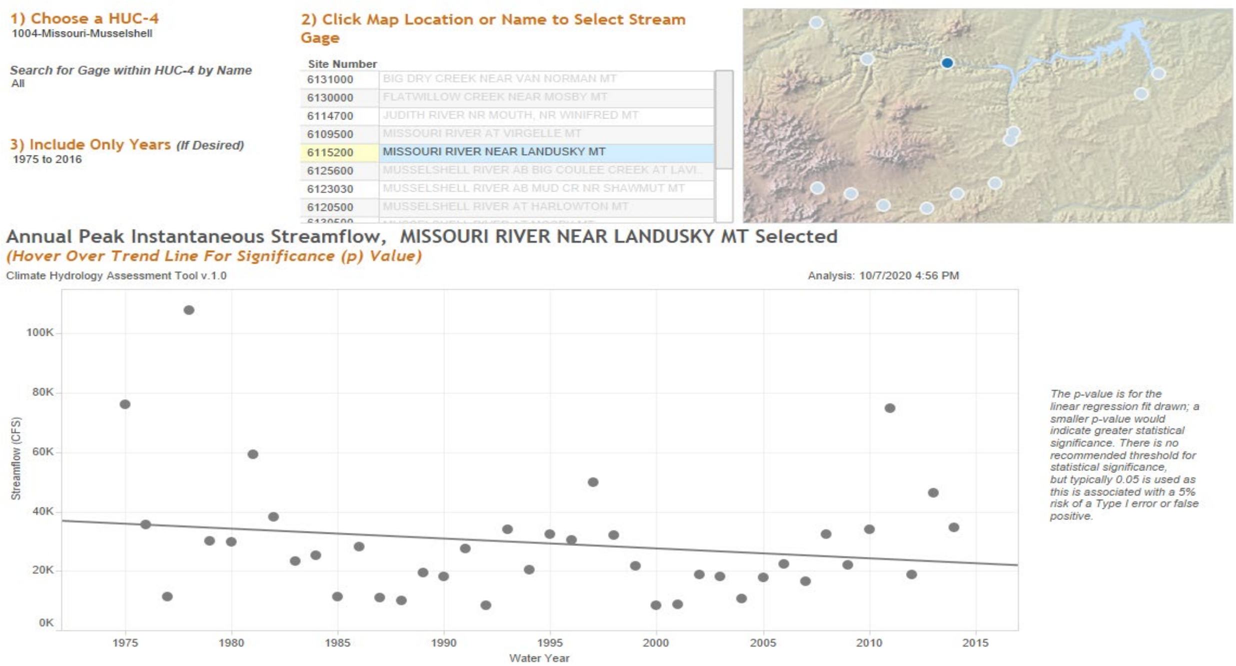

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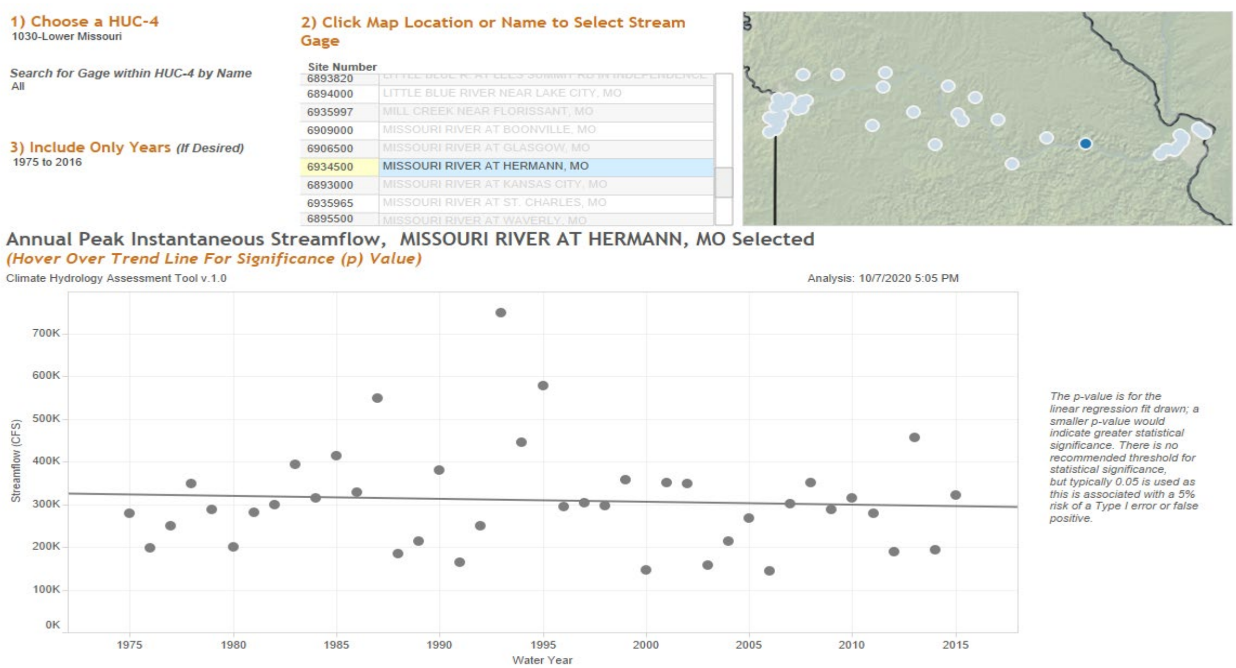

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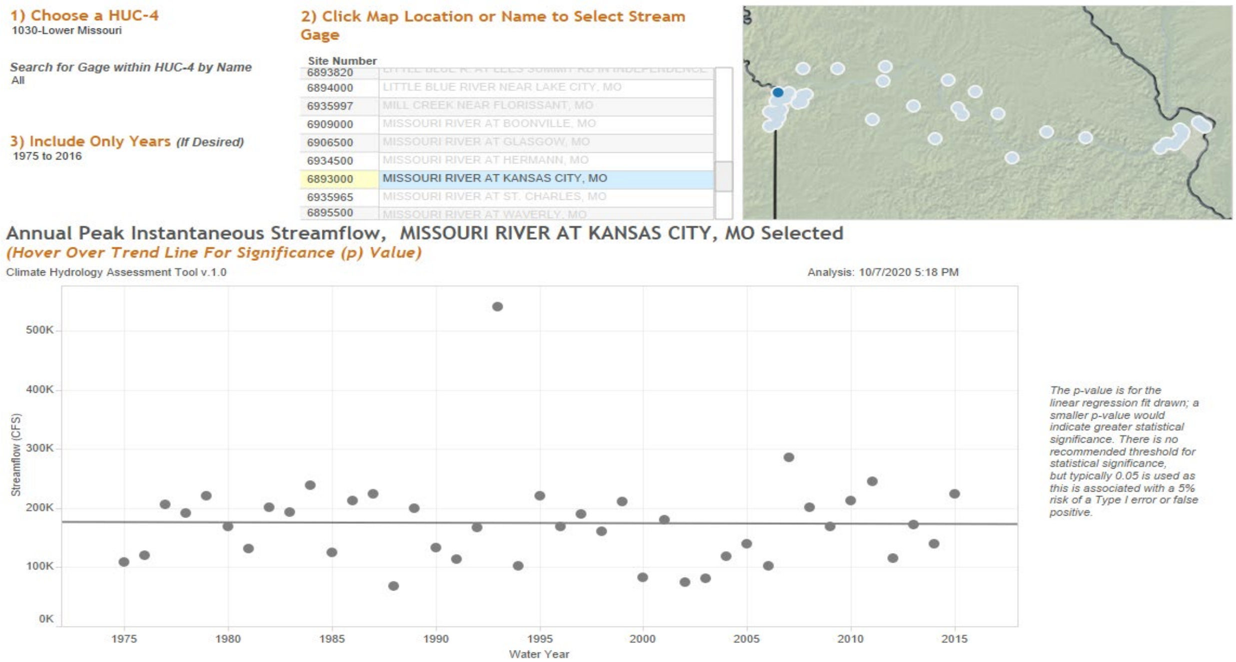
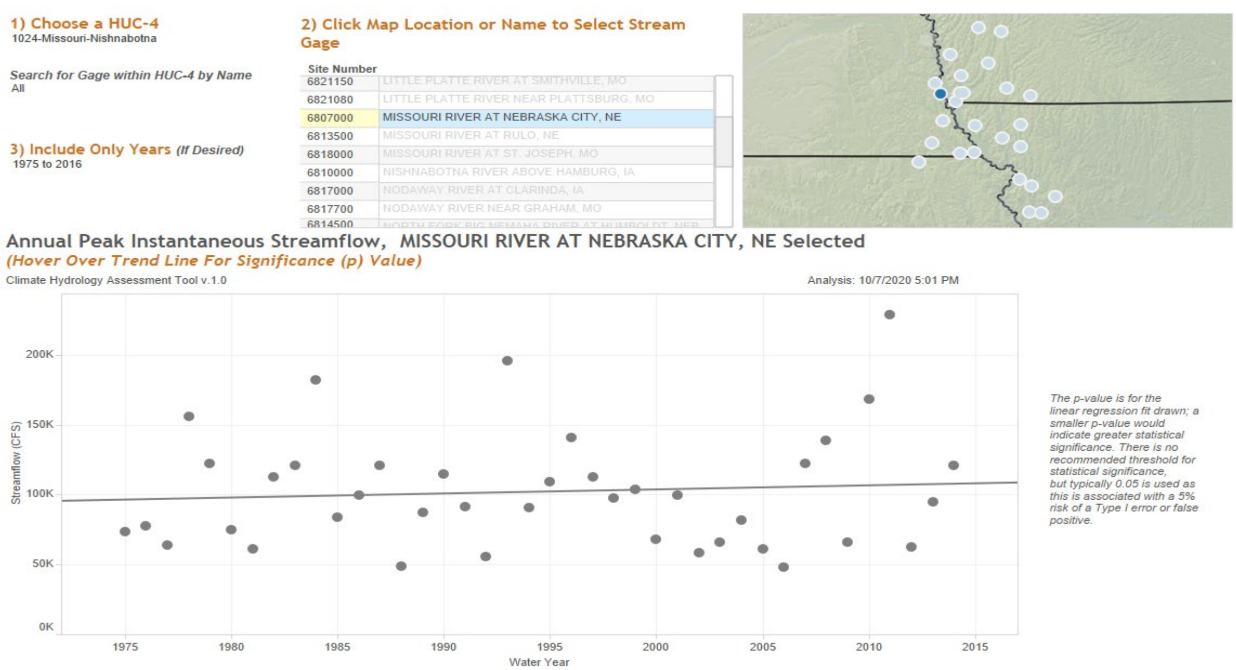


Figure 76.



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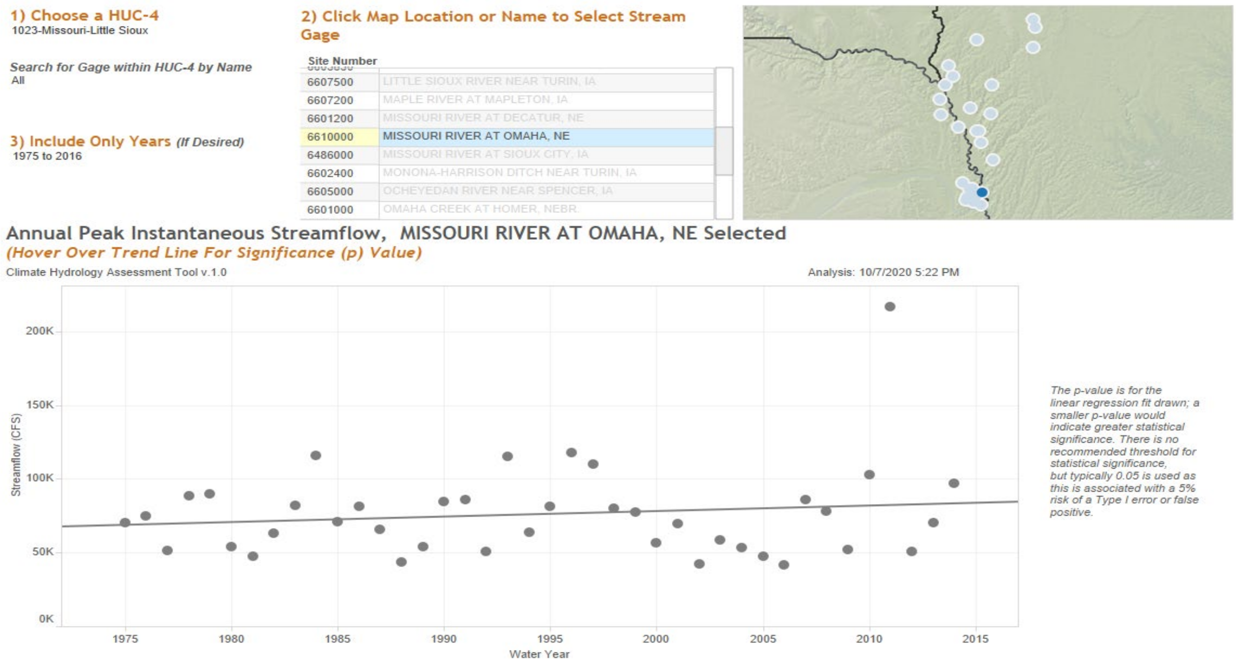

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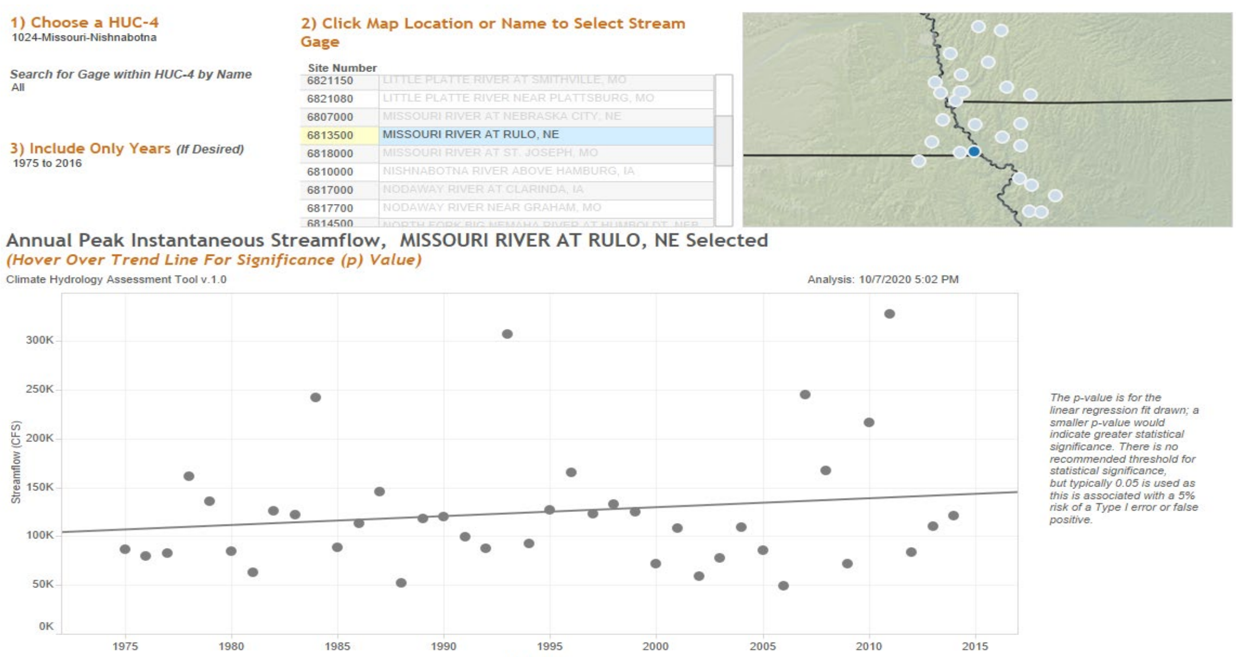

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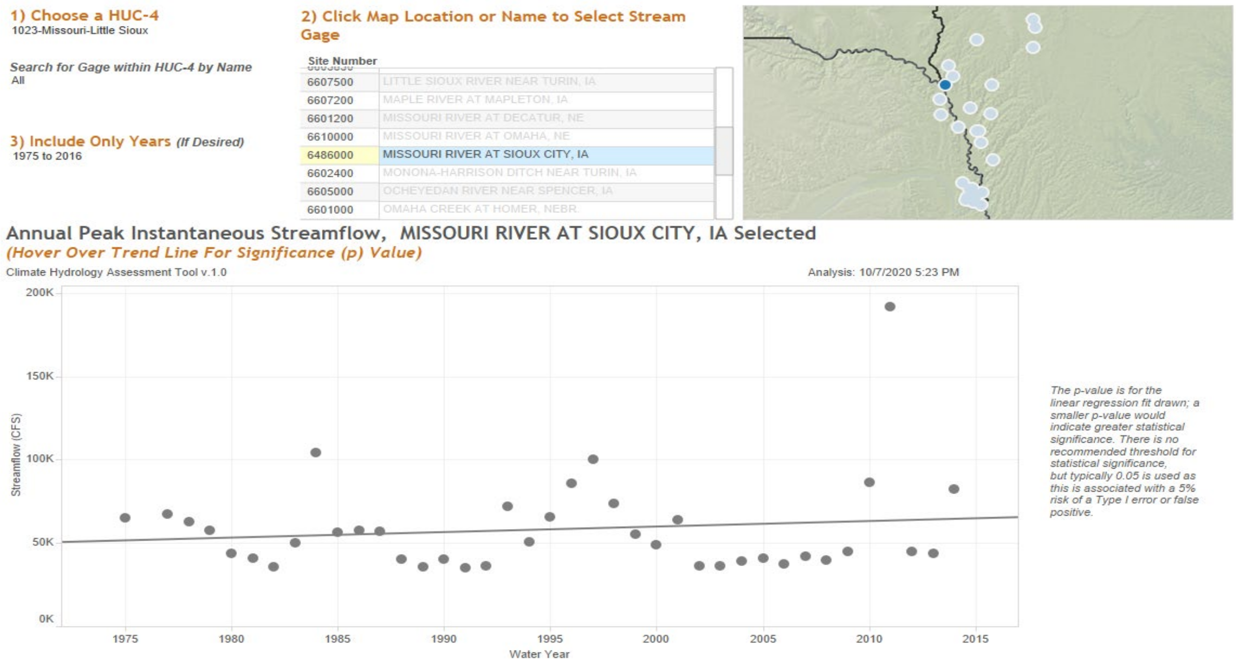

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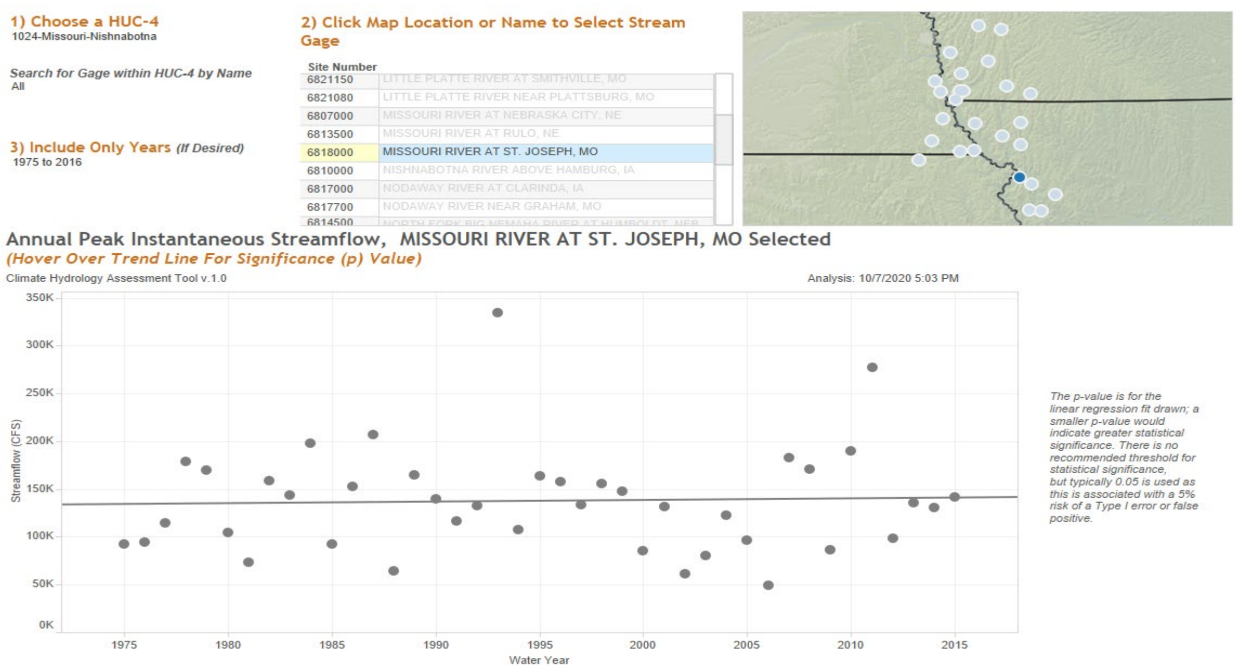

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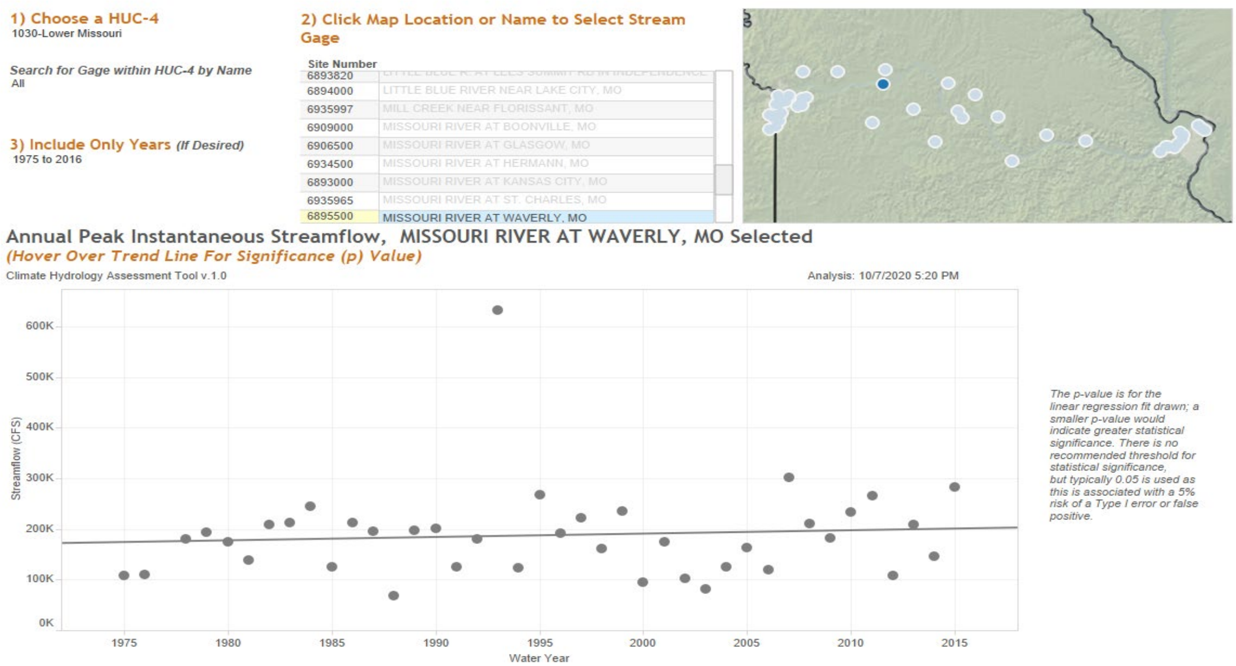

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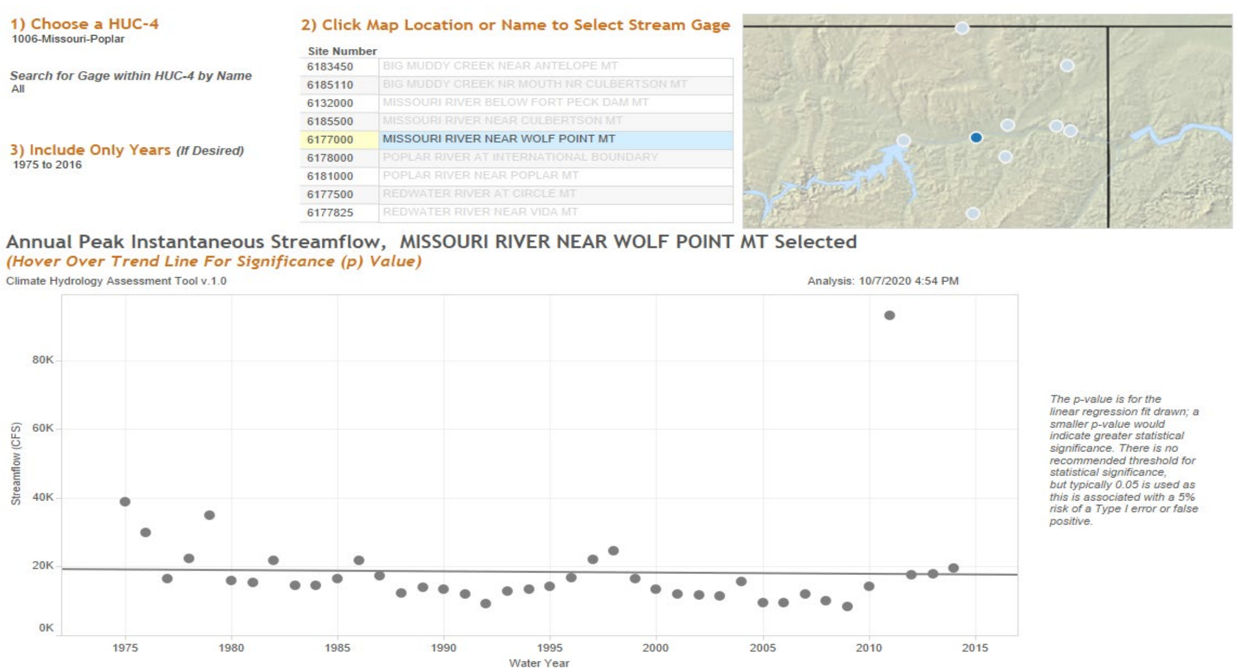

Figure 83.

Appendix D: Mean Projected Annual Maximum Monthly Flow

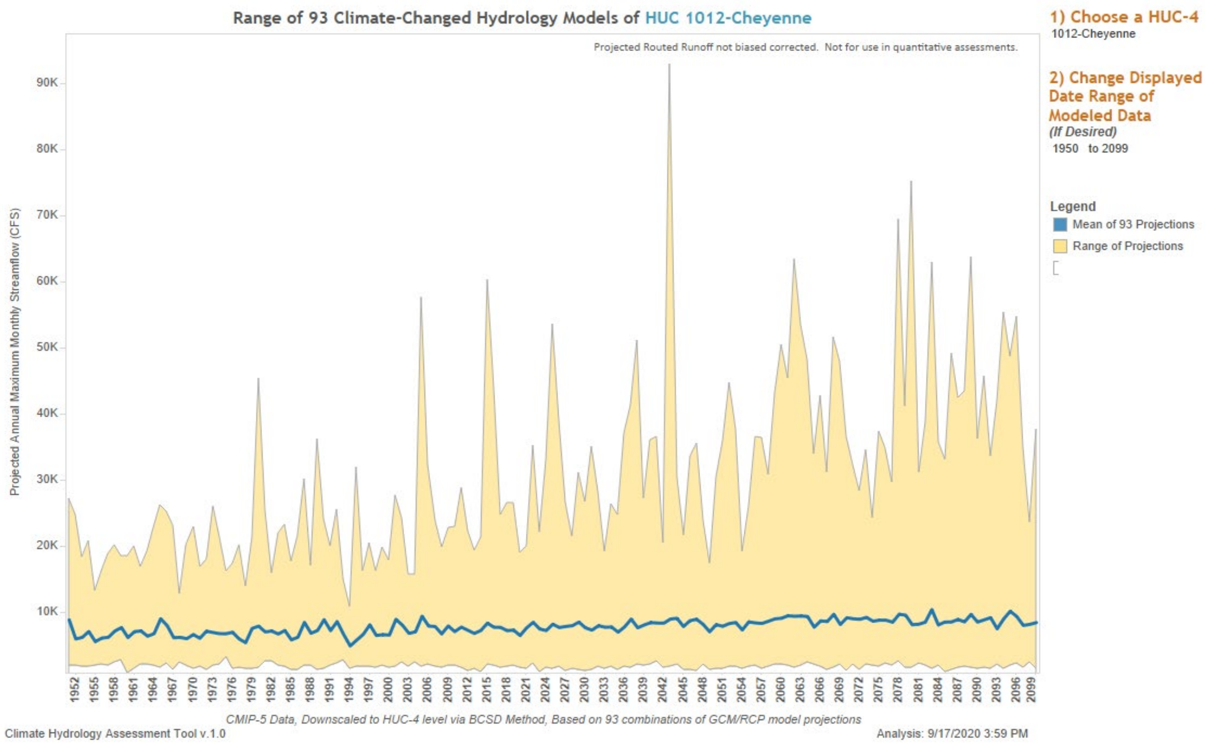

Figure 84. Mean Projected Annual Maximum Monthly Flow for HUC 1012 Cheyenne

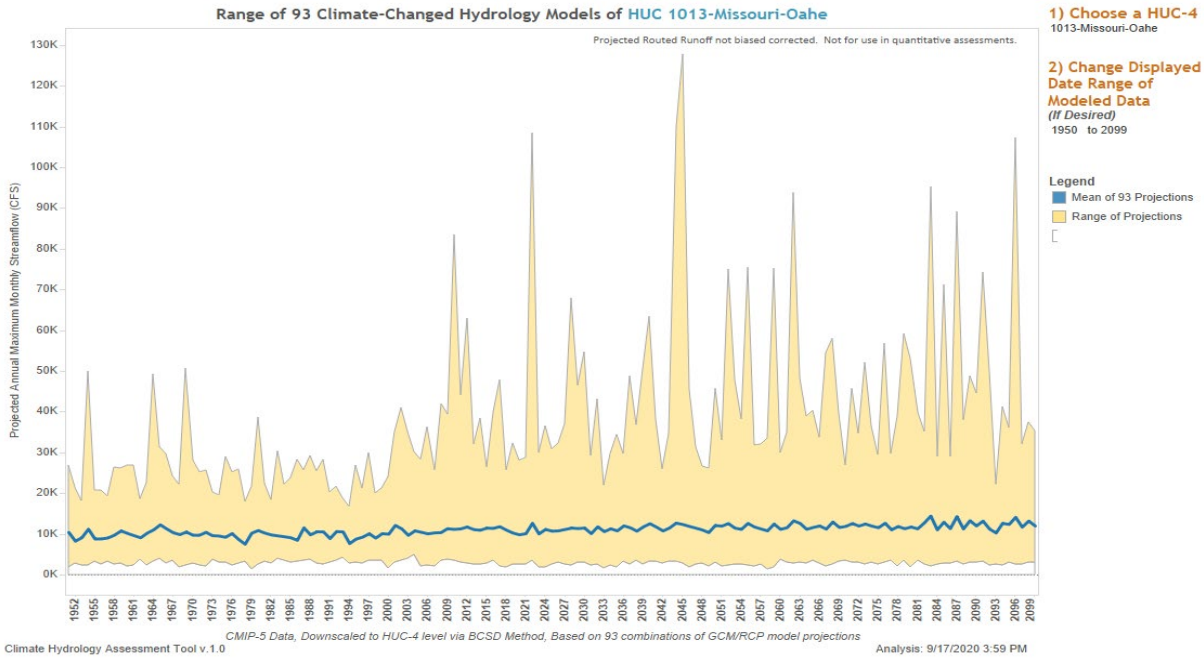

Figure 85. Mean Projected Annual Maximum Monthly Flow for HUC 1013 Missouri-Oahe

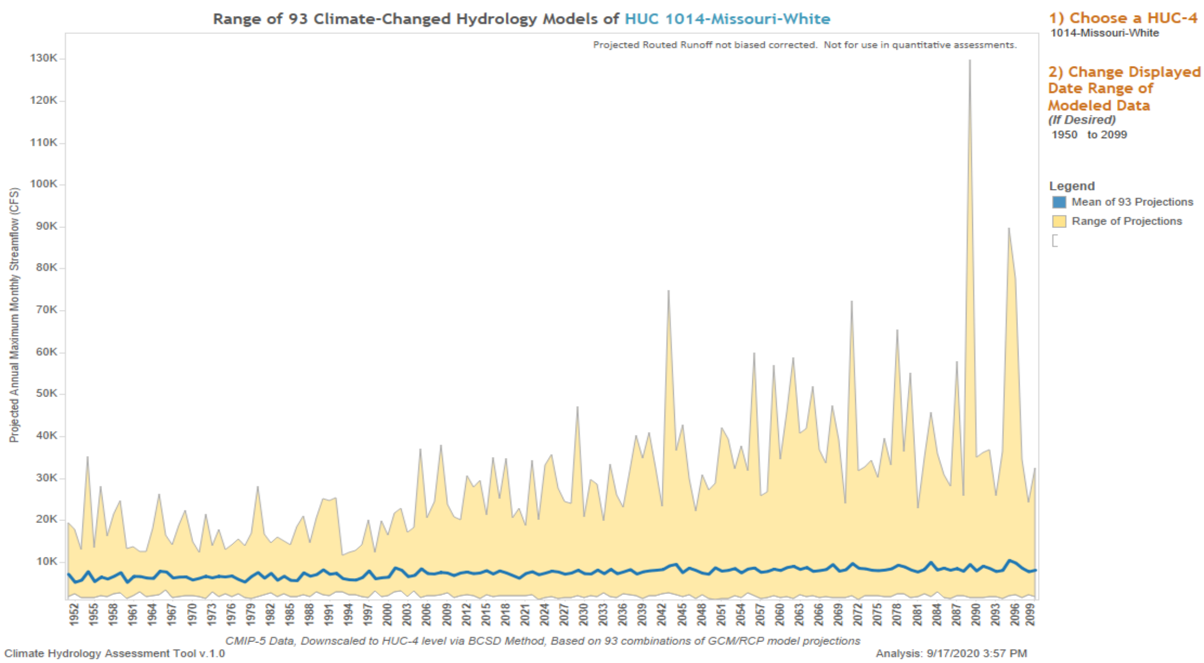

Figure 86. Mean Projected Annual Maximum Monthly Flow for HUC 1014 Missouri-White

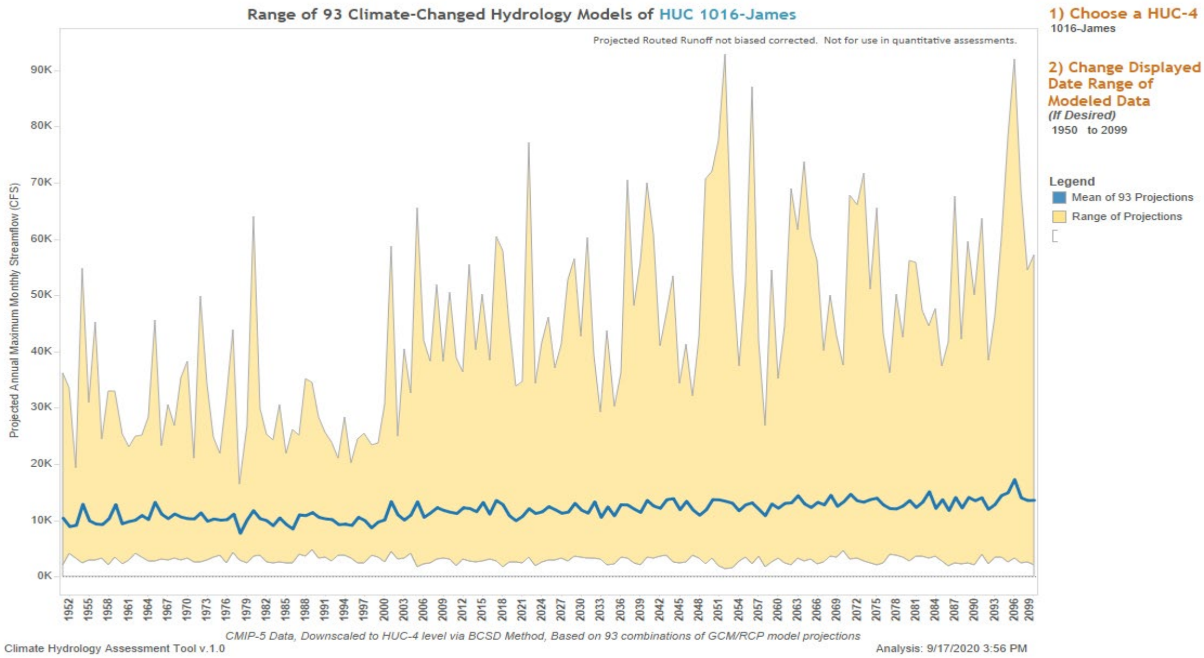

Figure 3. Mean Projected Annual Maximum Monthly Flow for HUC 1016 James

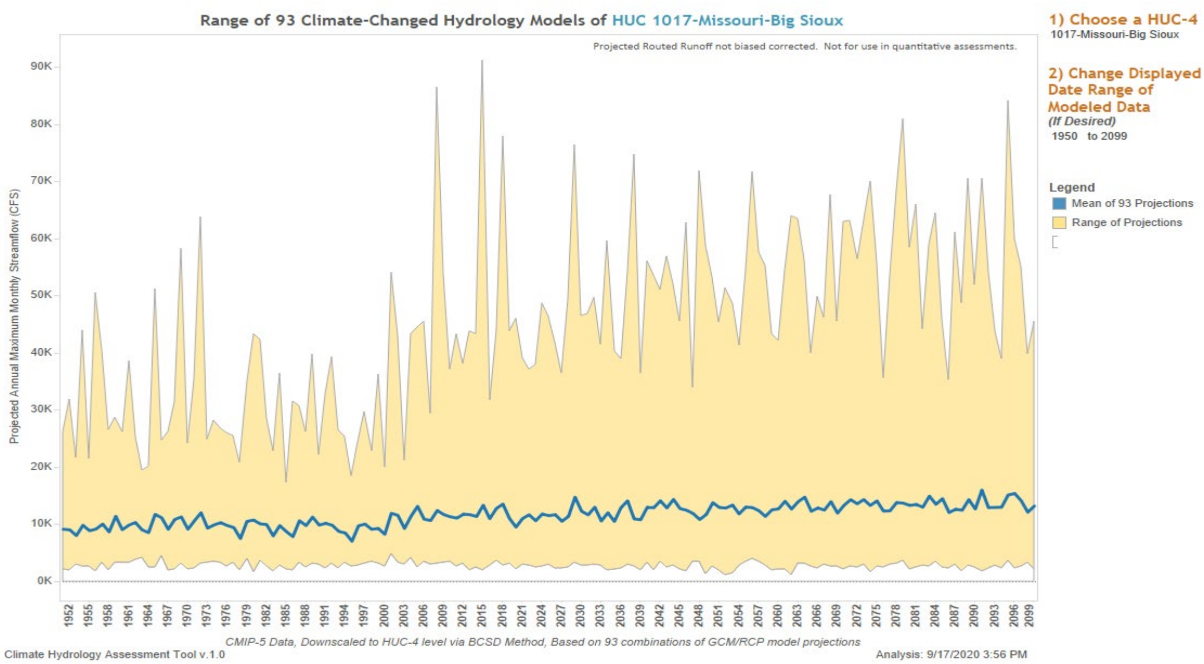

Figure 4. Mean Projected Annual Maximum Monthly Flow for HUC 1017 Missouri-Big Sioux

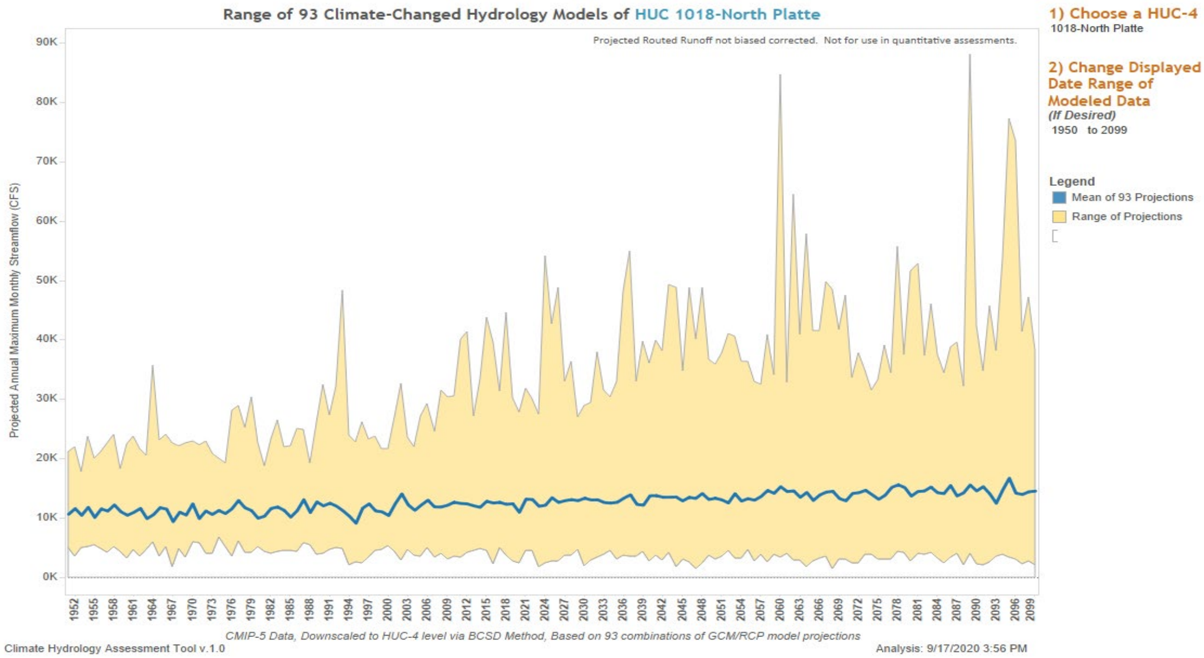

Figure 5. Mean Projected Annual Maximum Monthly Flow for HUC 1018 North Platte

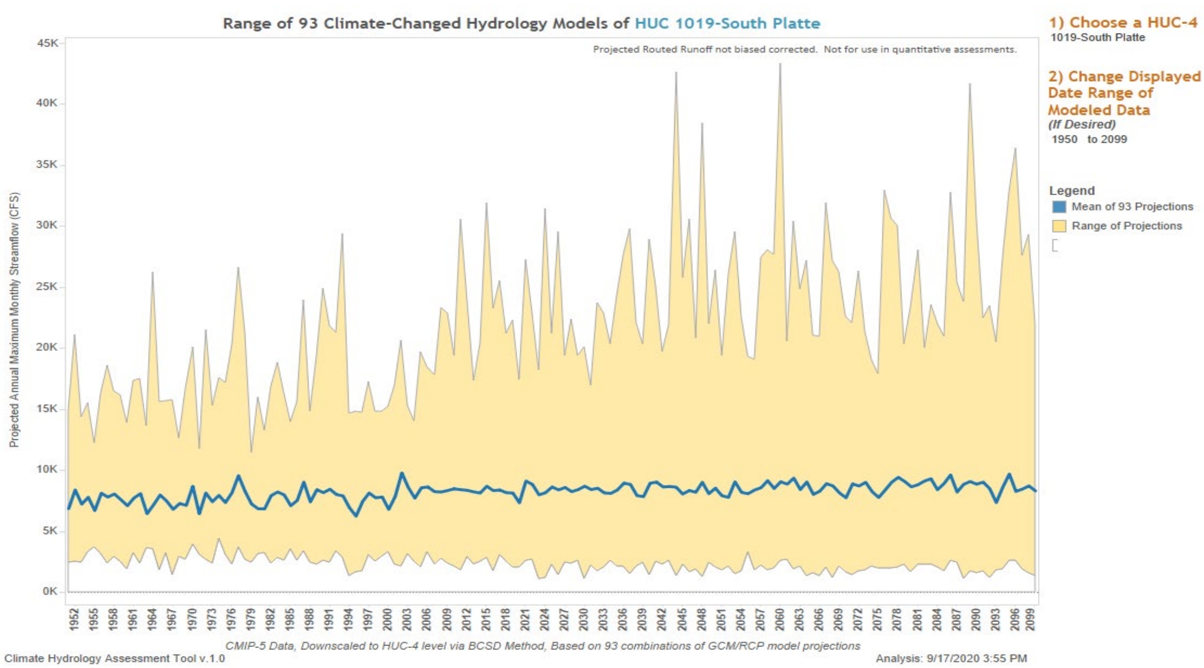

Figure 6 Mean Projected Annual Maximum Monthly Flow for HUC 1019 South Platte

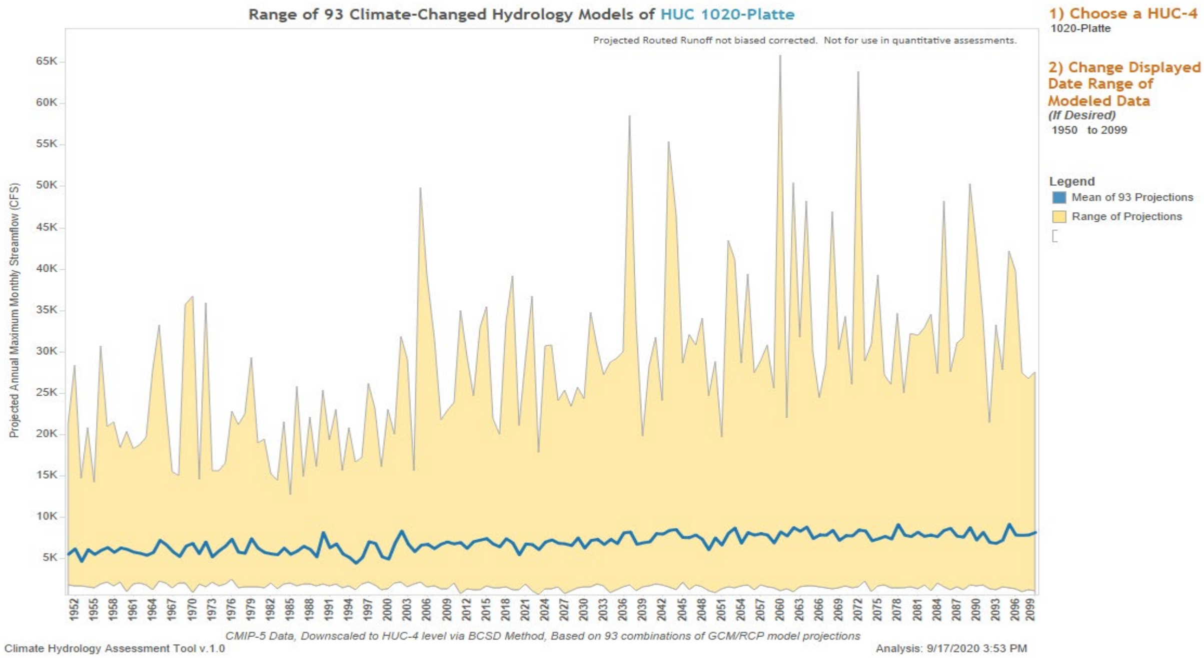

Figure 7. Mean Projected Annual Maximum Monthly Flow for HUC 1020 Platte

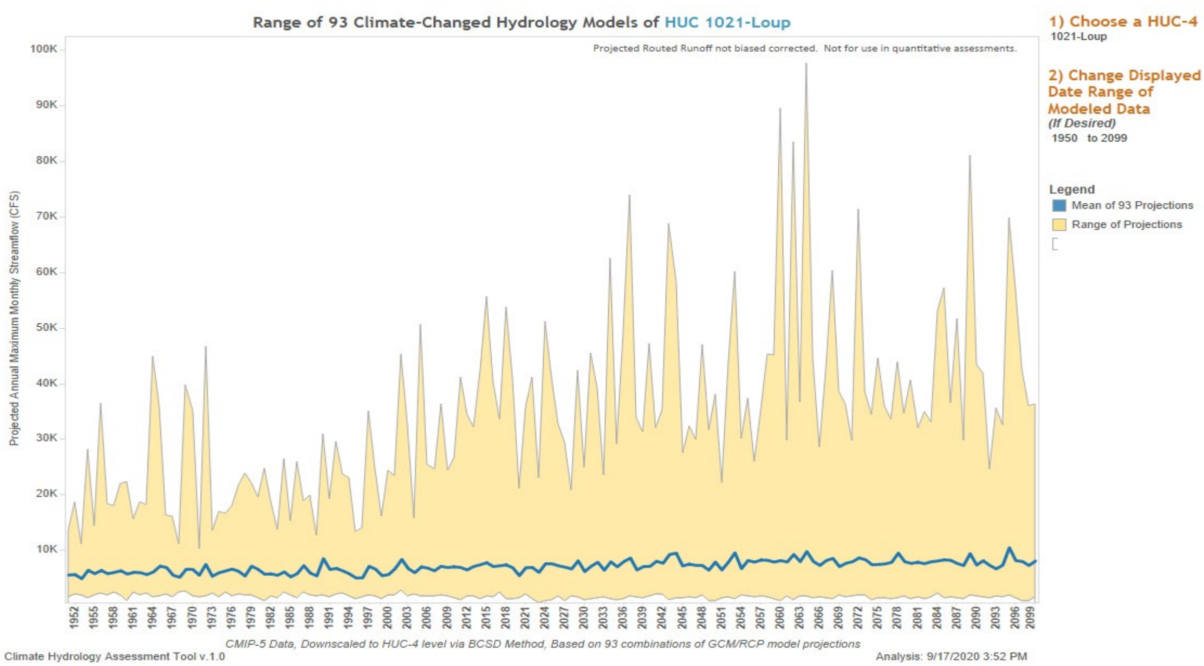

Figure 8. Mean Projected Annual Maximum Monthly Flow for HUC 1021 Loup

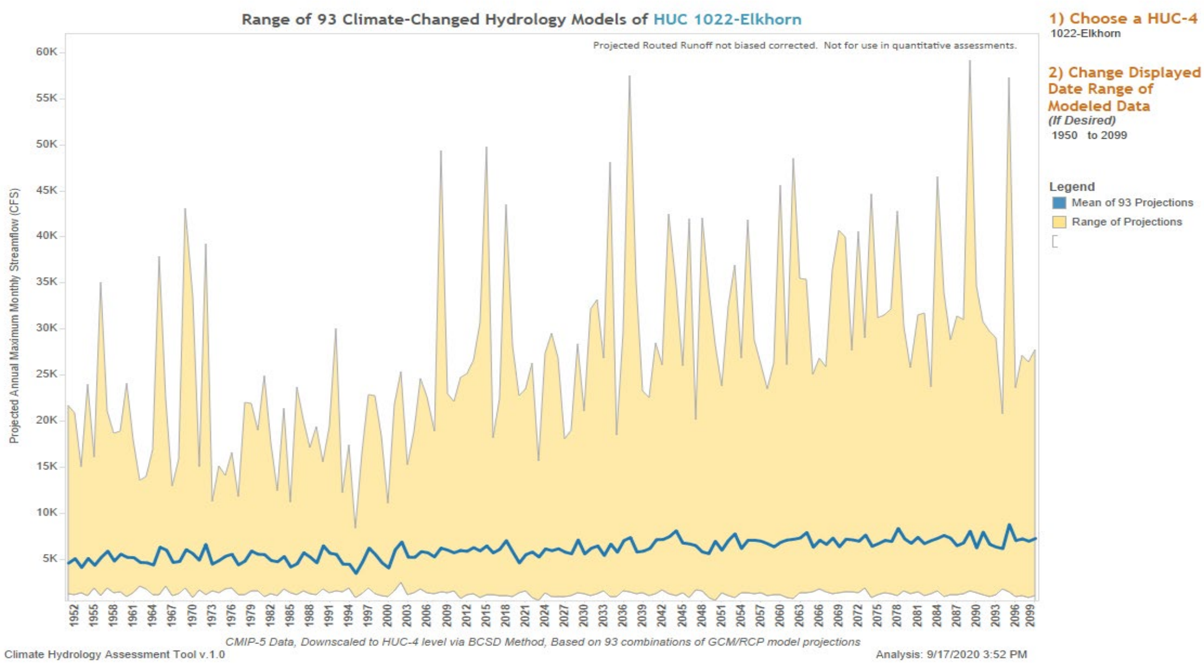

Figure 9. Mean Projected Annual Maximum Monthly Flow for HUC 1022 Elkhorn

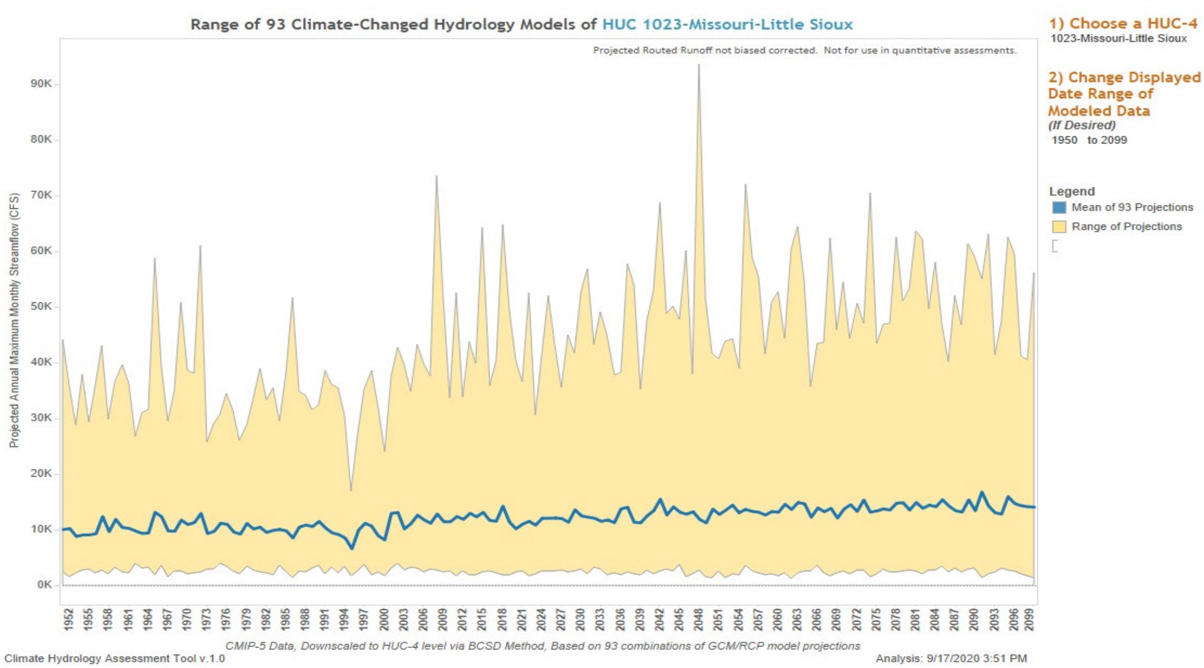

Figure 10. Mean Projected Annual Maximum Monthly Flow for HUC 1023 Missouri-Little Sioux

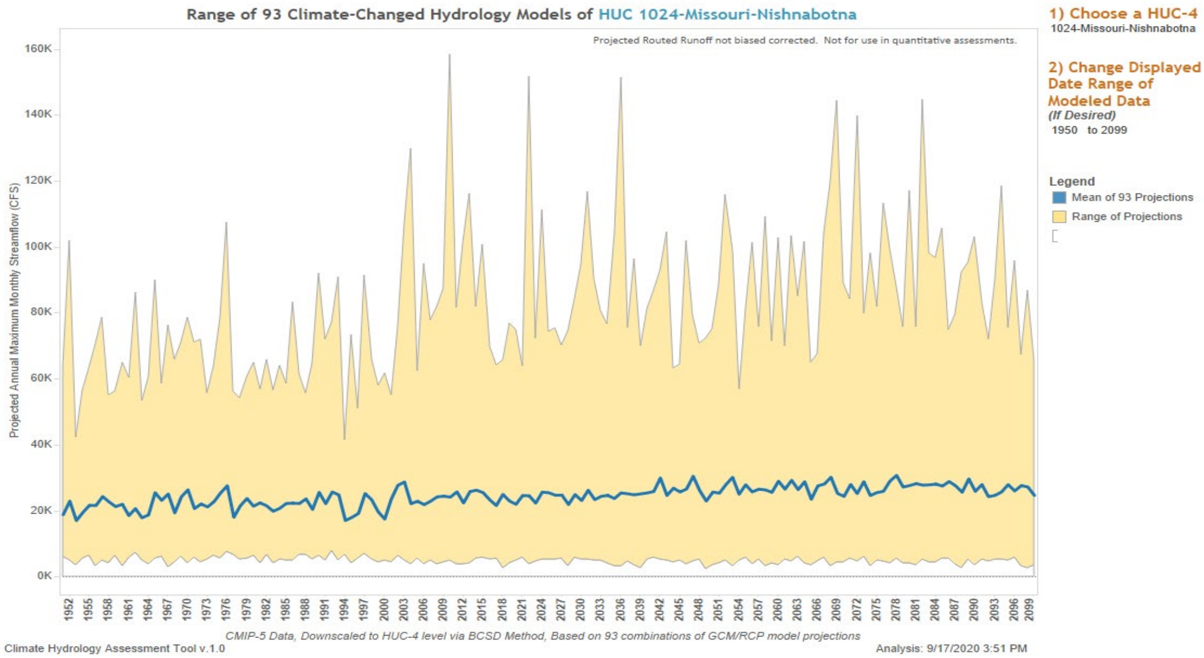

Figure 11. Mean Projected Annual Maximum Monthly Flow for HUC 1024 Missouri-Little Sioux

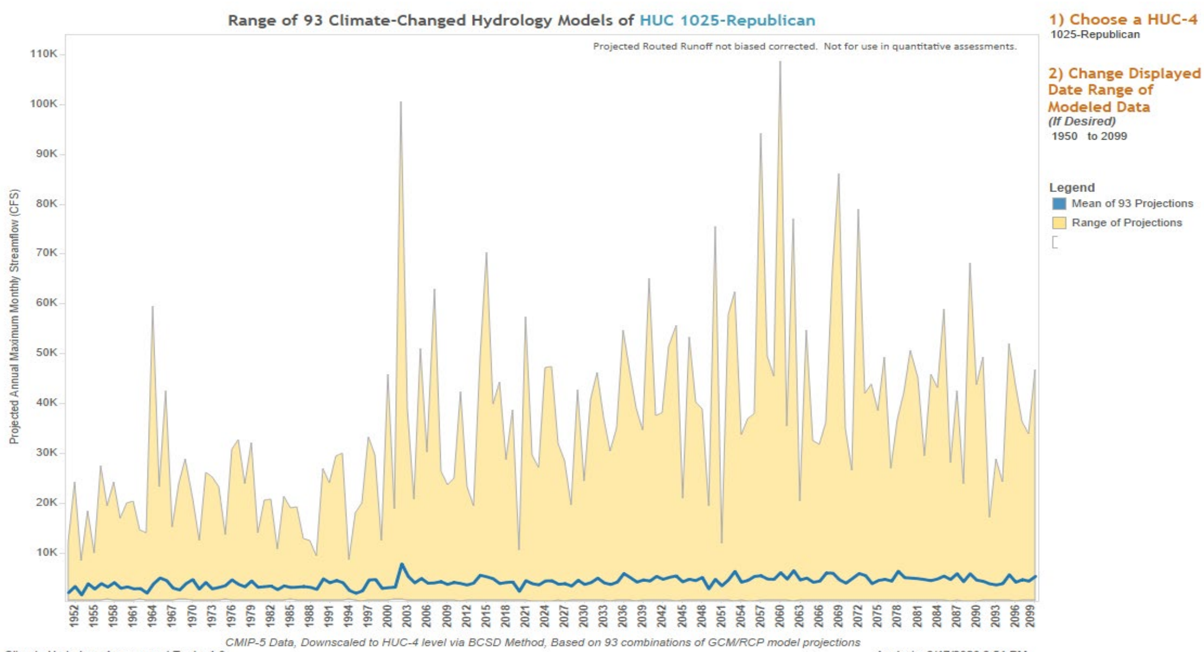

Figure 12. Mean Projected Annual Maximum Monthly Flow for HUC 1025 Republican

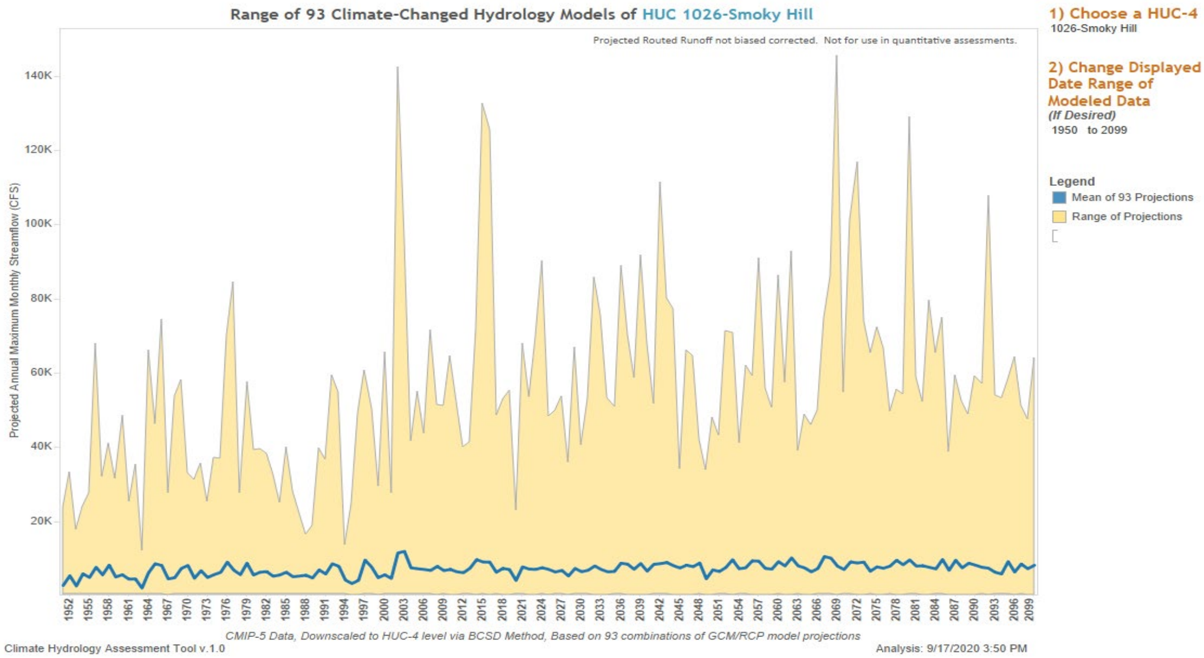

Figure 13. Mean Projected Annual Maximum Monthly Flow for HUC 1026 Smoky Hill

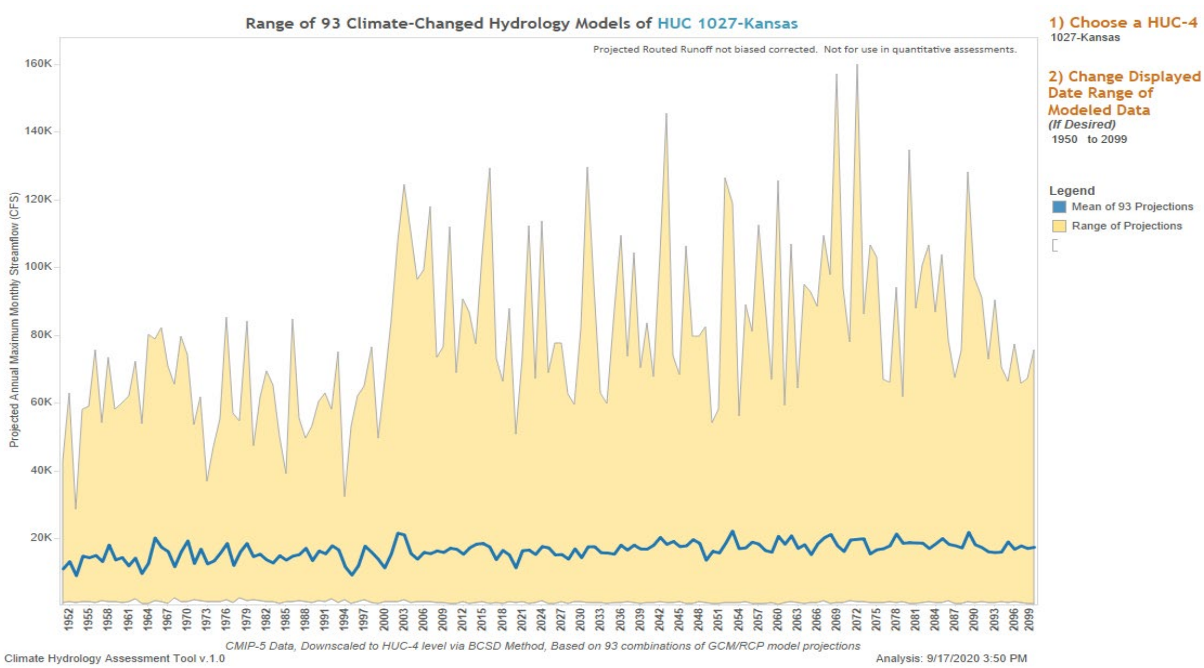

Figure 14. Mean Projected Annual Maximum Monthly Flow for HUC 1027 Kansas

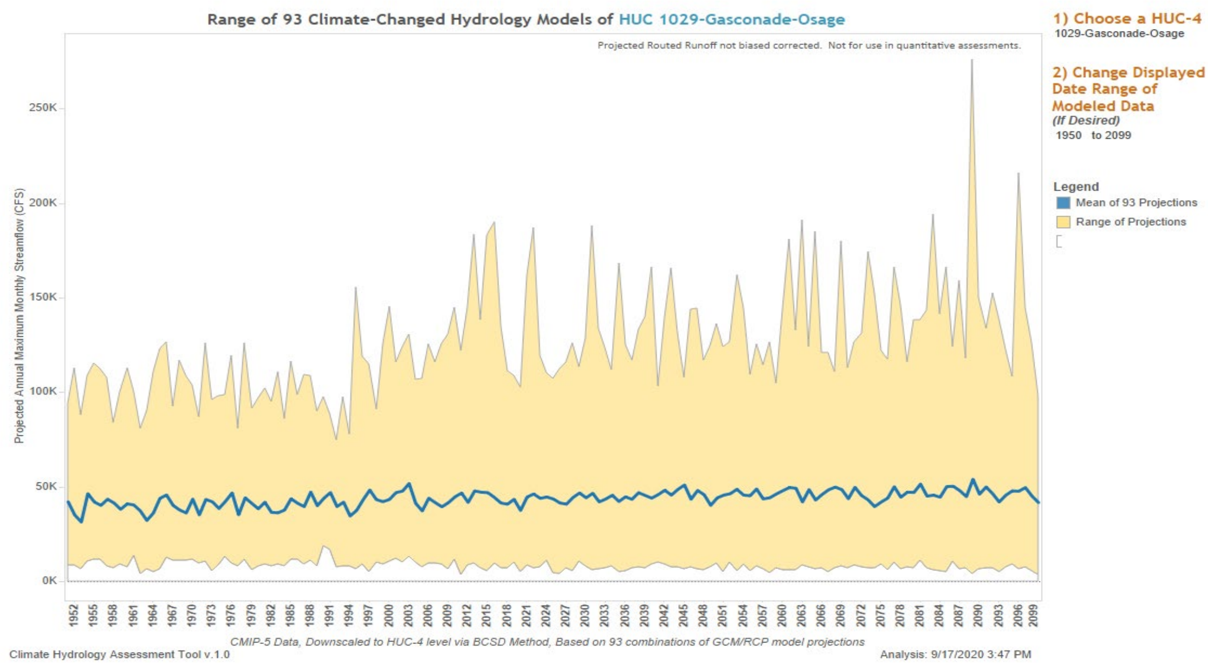

Figure 15. Mean Projected Annual Maximum Monthly Flow for HUC 1029 Gasconade-Osage

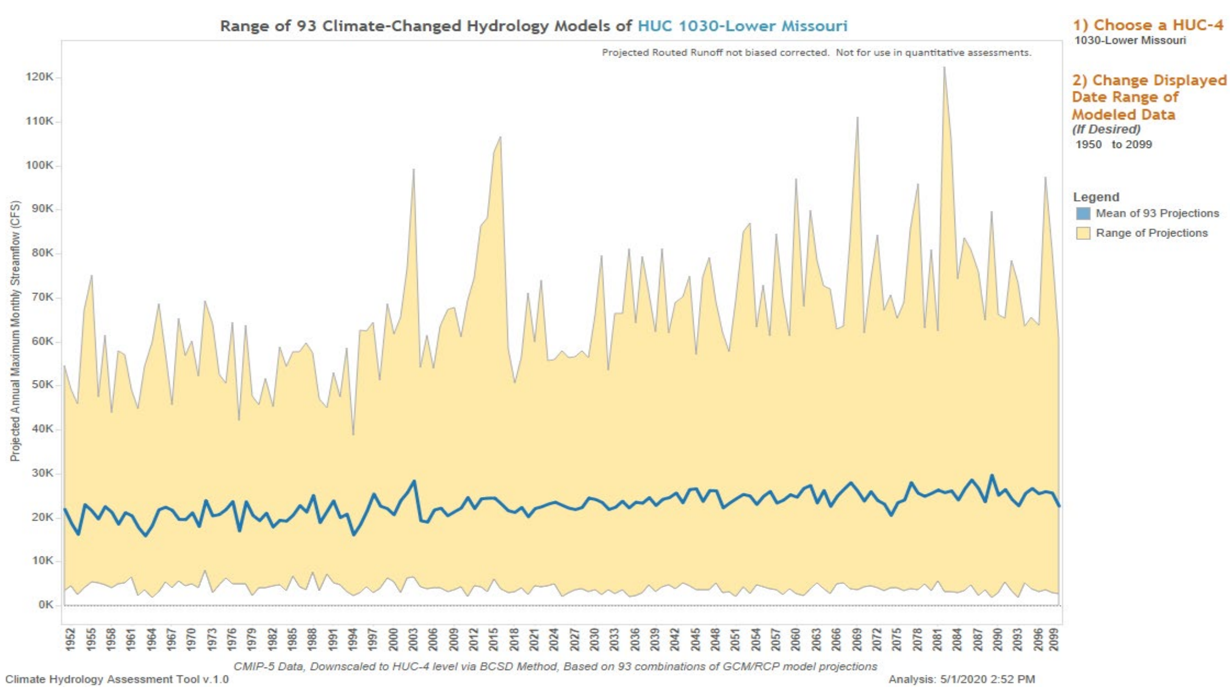

Figure 16. Mean Projected Annual Maximum Monthly Flow for HUC 1030 Lower Missouri

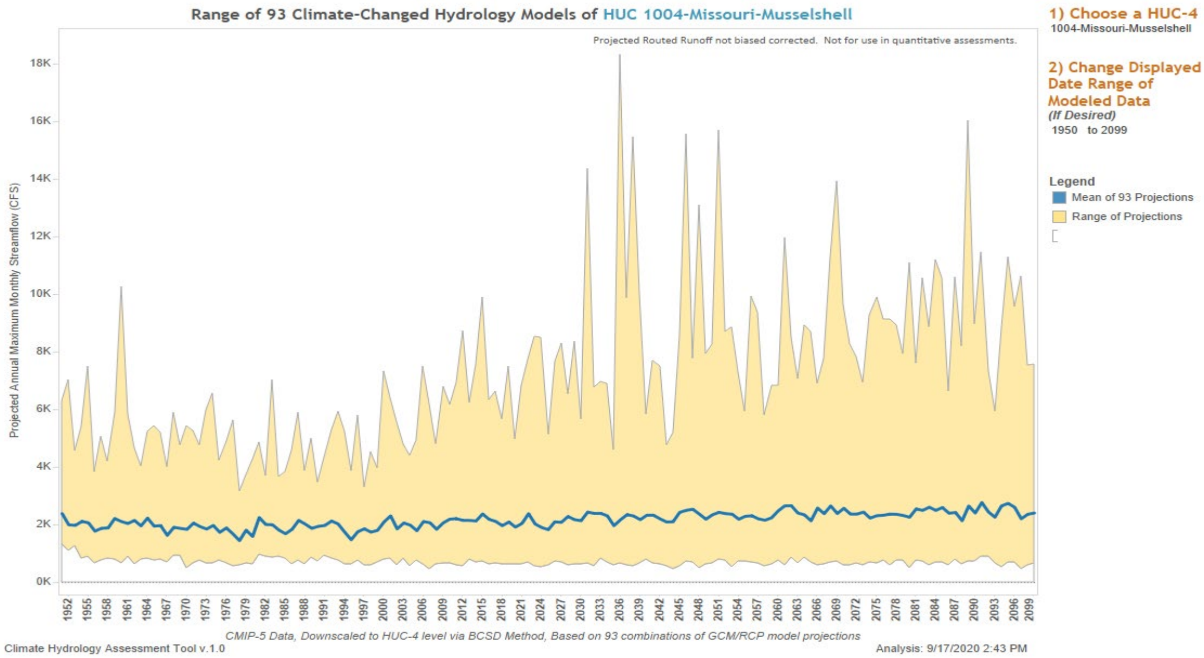

Figure 17. Mean Projected Annual Maximum Monthly Flow for HUC 1004 Missouri-Musselshell

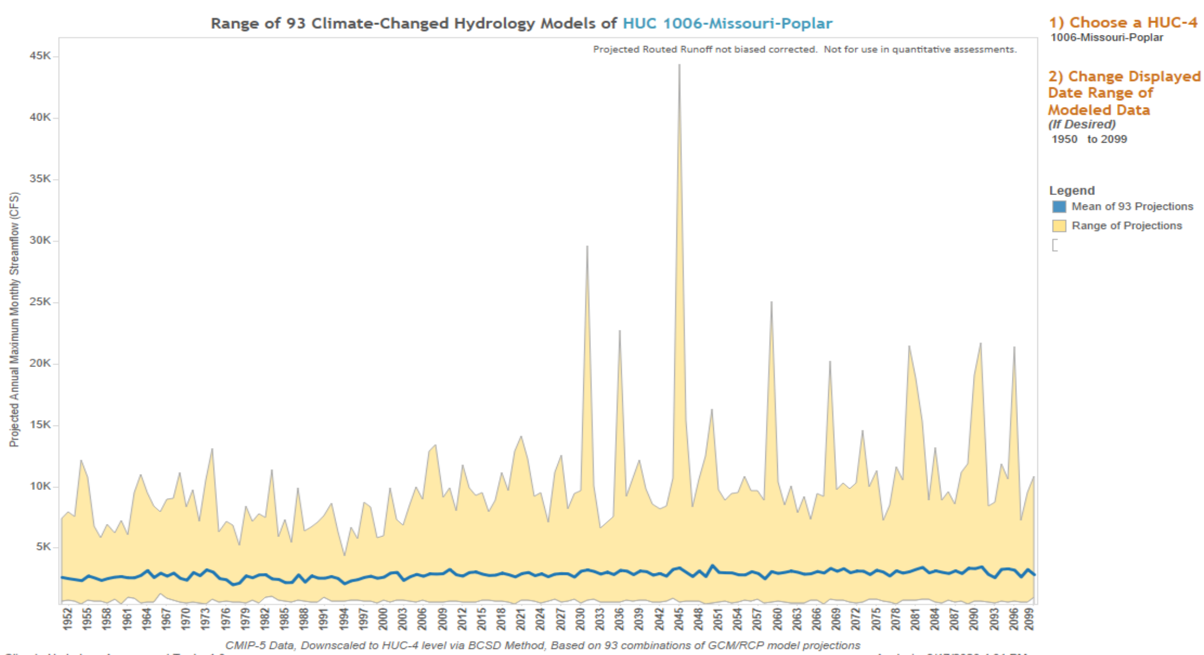

Figure 18. Mean Projected Annual Maximum Monthly Flow for HUC 1006 Missouri-Poplar

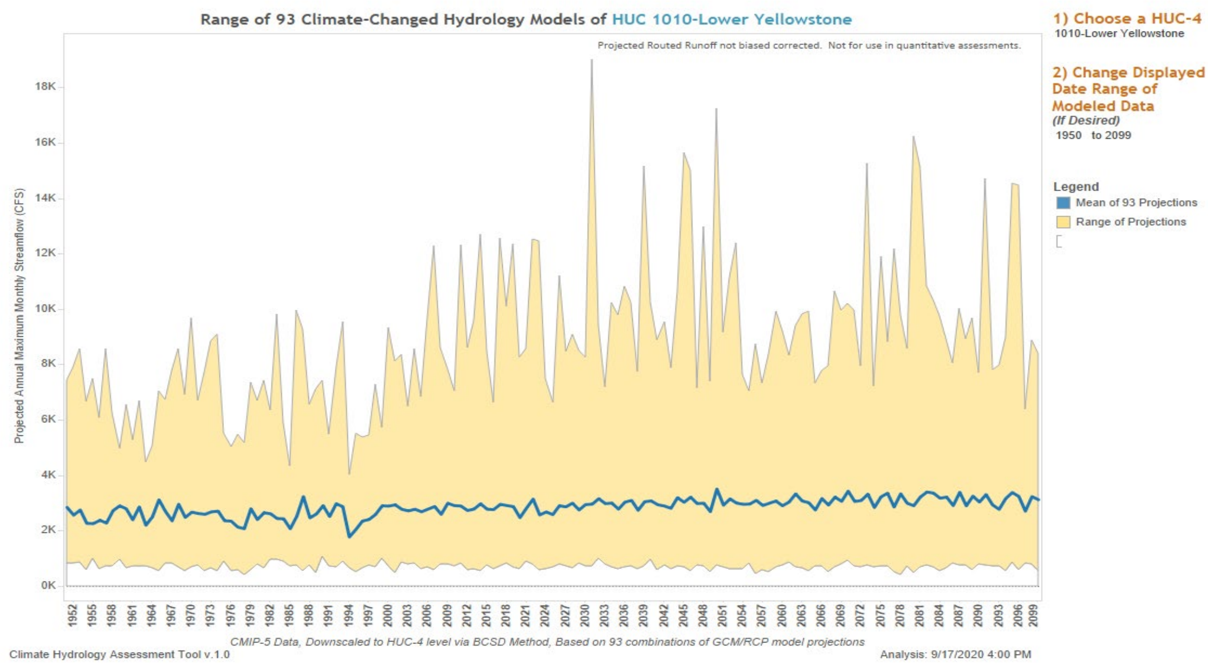

Figure 19. Mean Projected Annual Maximum Monthly Flow for HUC 1006 Lower-Yellowstone

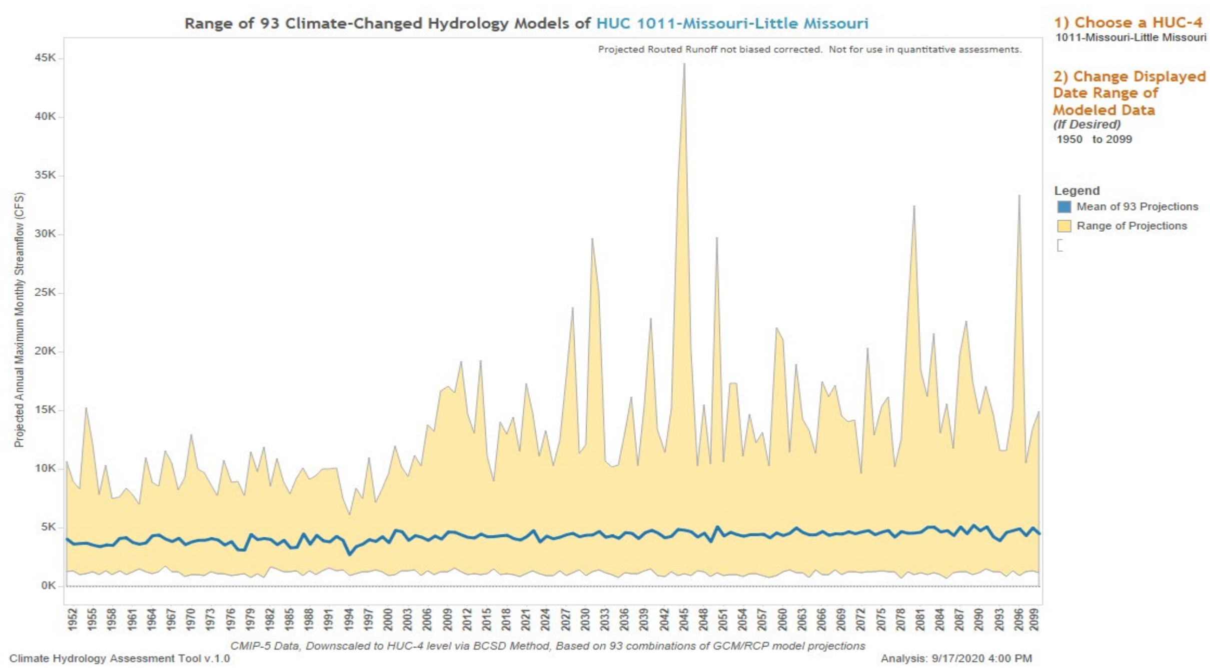

Figure 20. Mean Projected Annual Maximum Monthly Flow for HUC 1011 Missouri-Little Missouri

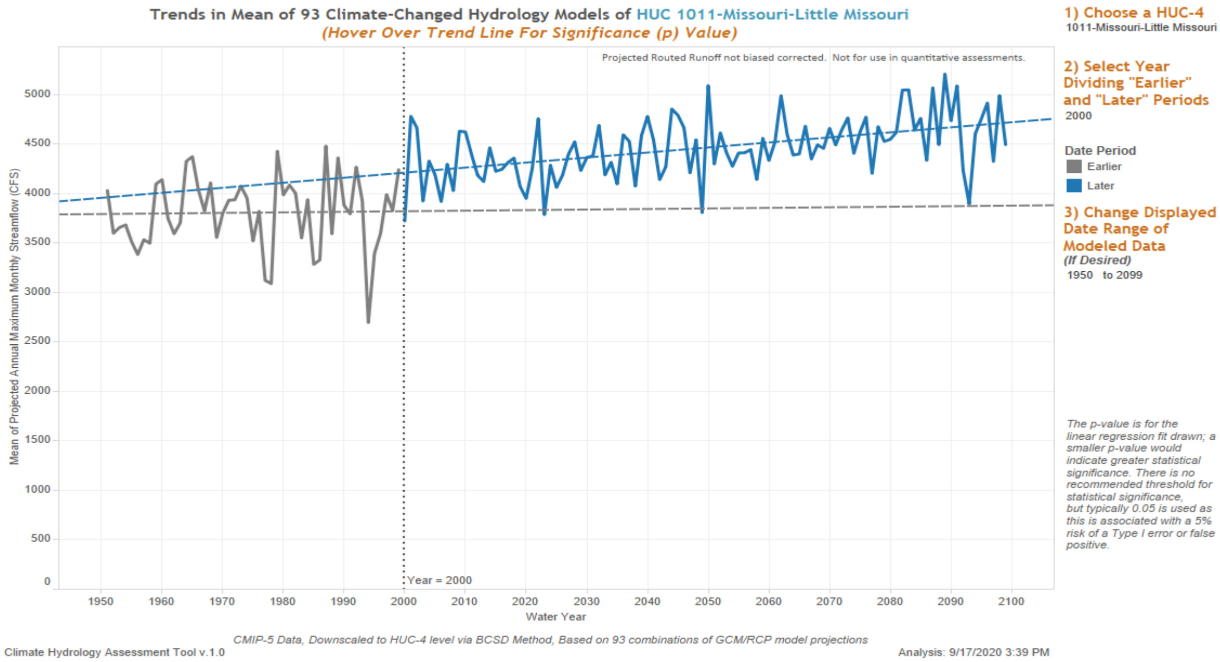

Figure 21. Linear Regression Of Mean Projected Annual Maximum Monthly Flow for HUC 1011 Missouri-Little Missouri

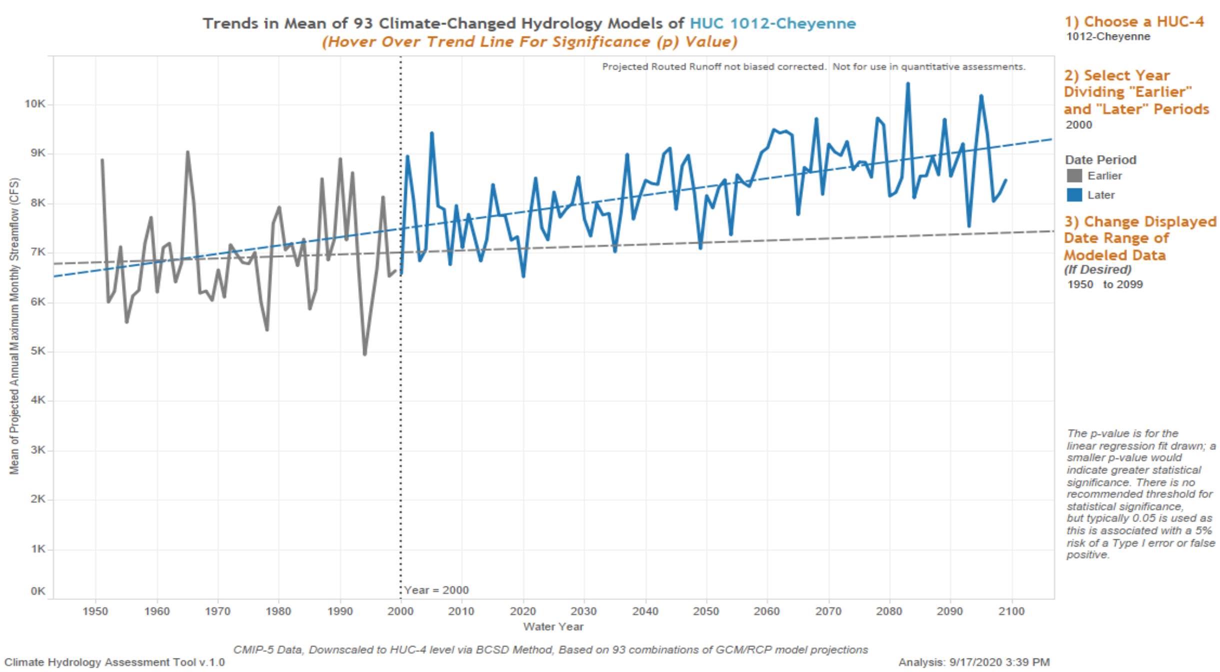

Figure 22. Linear Regression Of Mean Projected Annual Maximum Monthly Flow for HUC 1012 Cheyenne

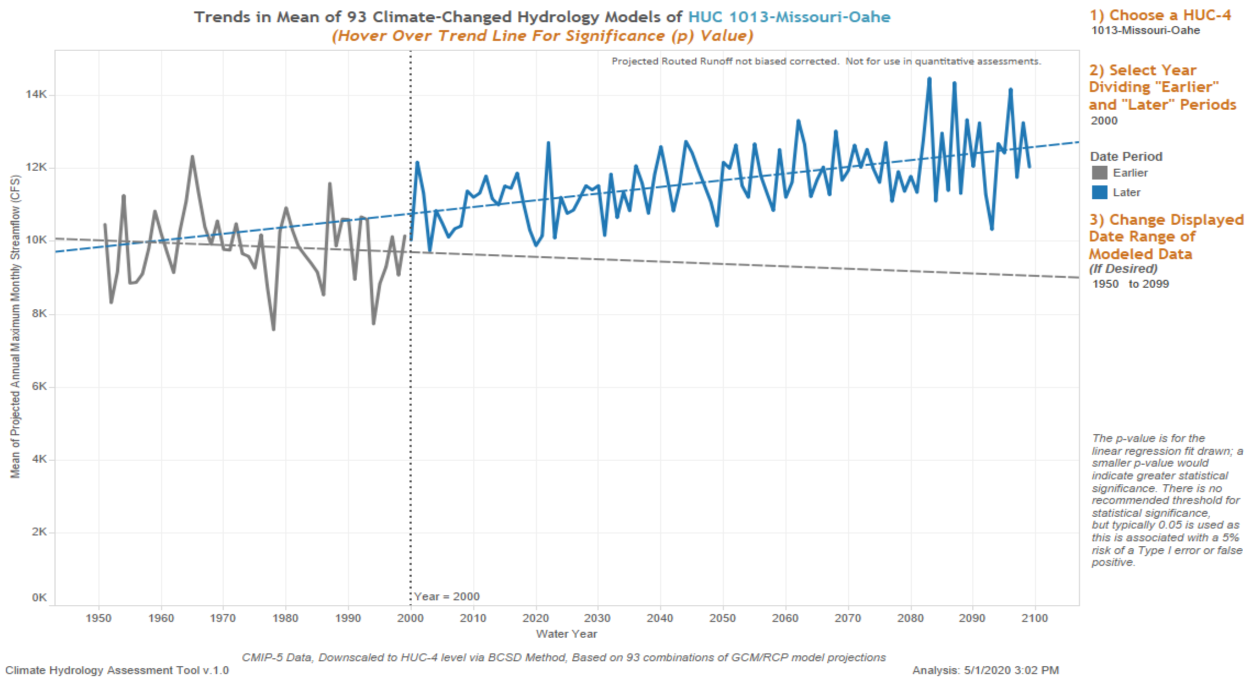

Figure 23. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1013 Missouri-Oahe

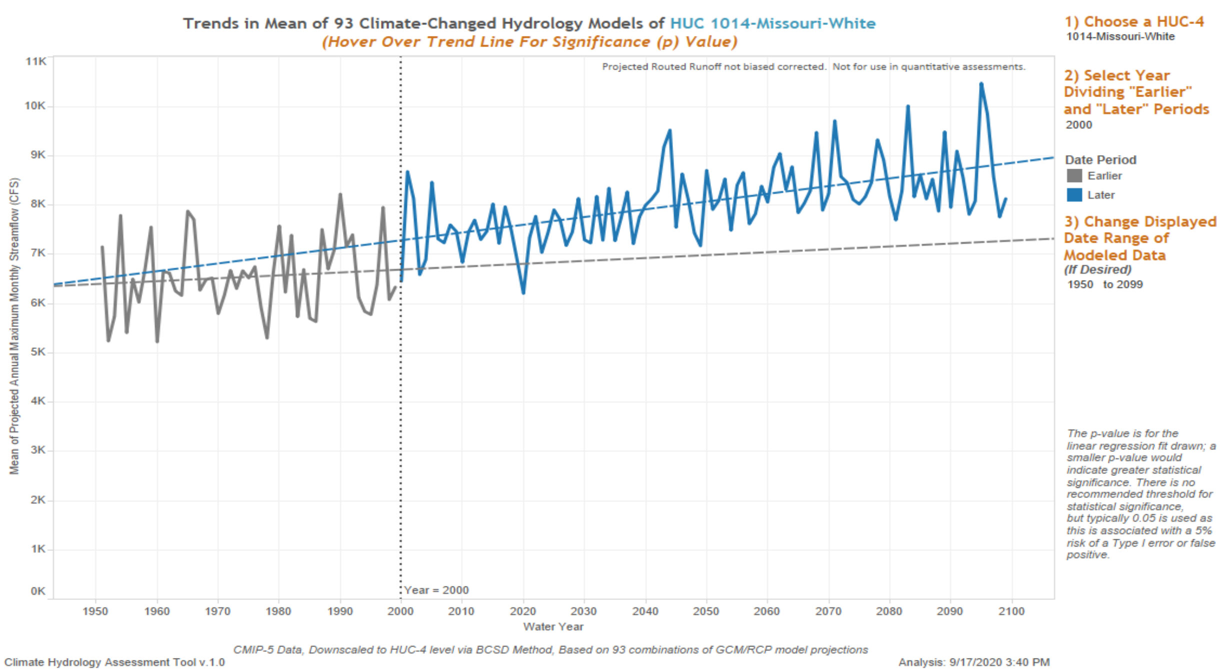

Figure 24. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1014 Missouri-White

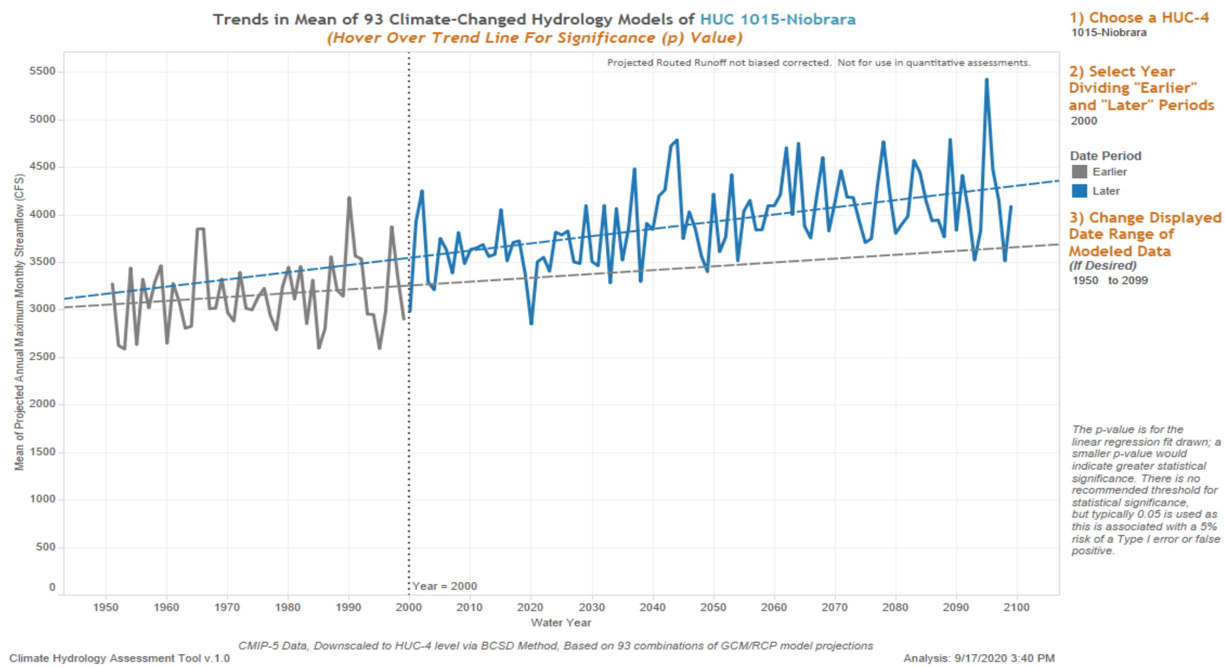

Figure 25. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1015 Niobrara

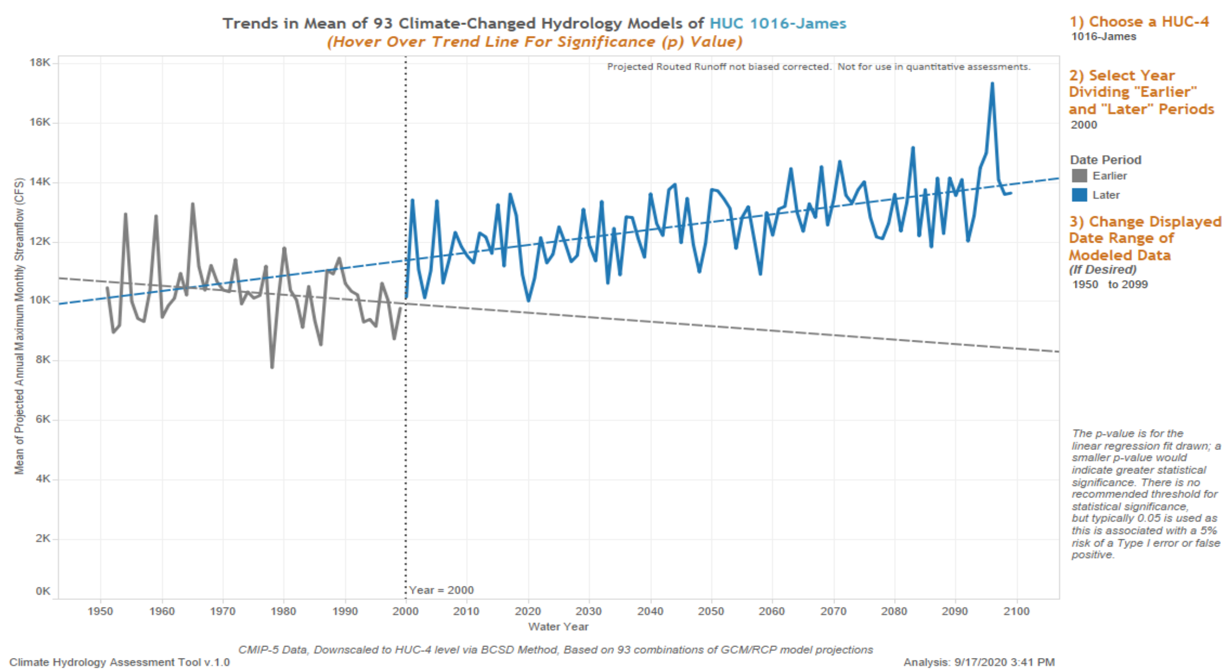

Figure 26. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1016 James

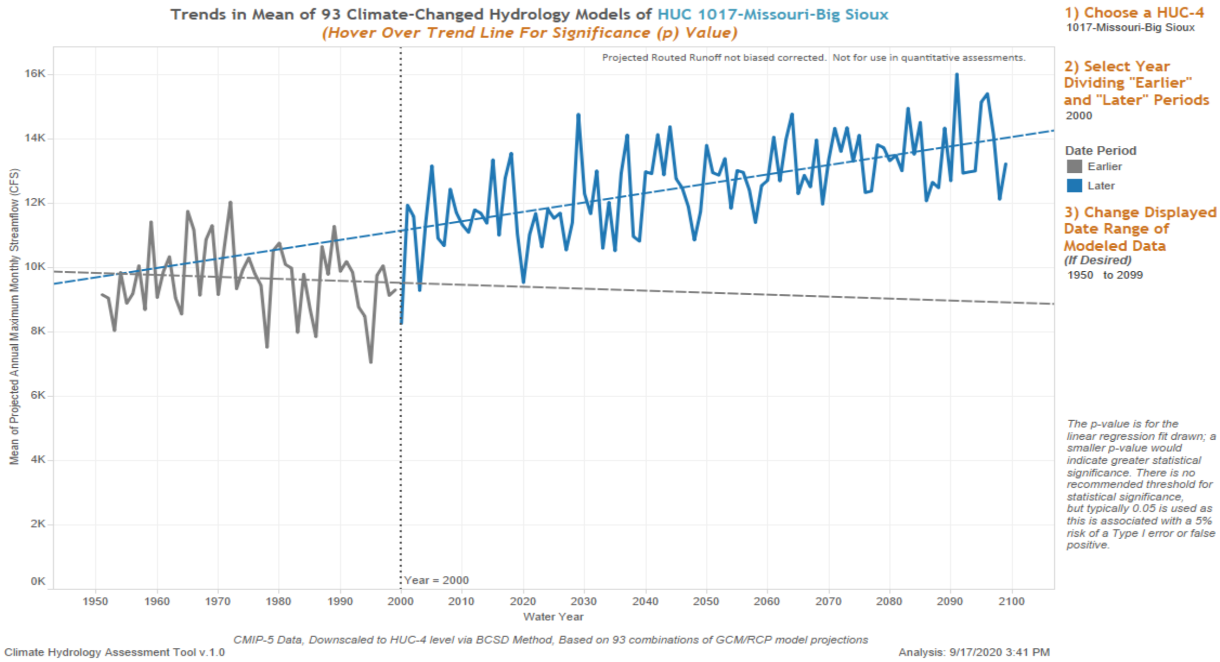

Figure 27. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1017 Missouri-Big Sioux

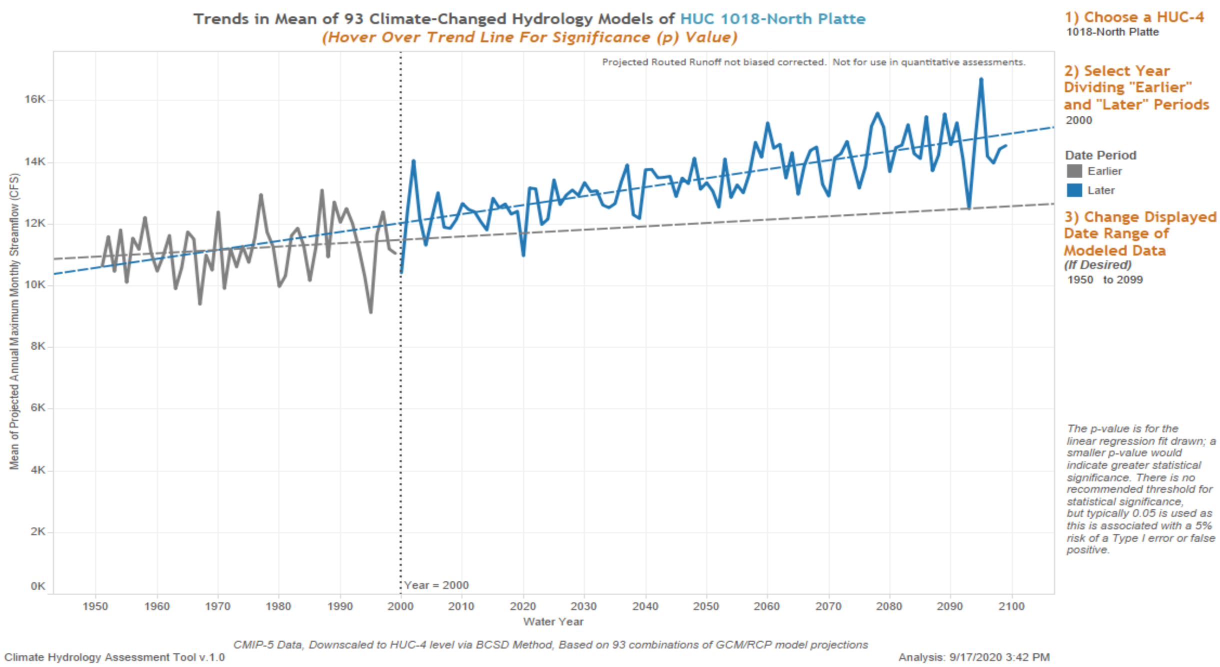

Figure 28. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1018 North Platte

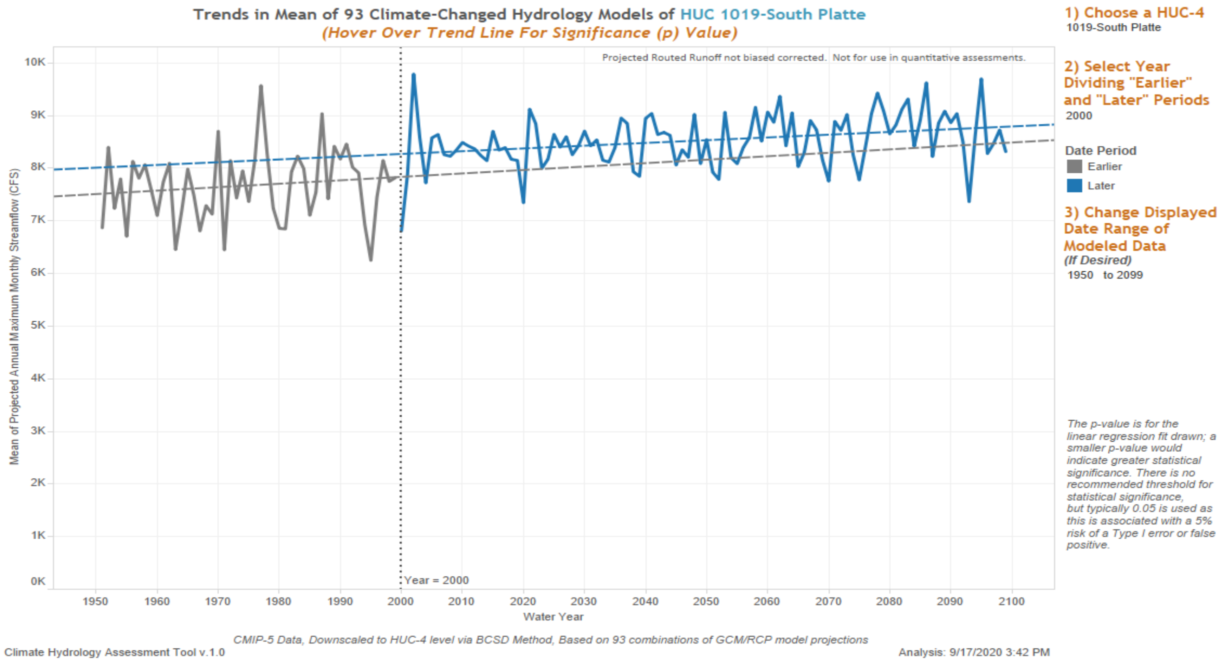

Figure 29. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1019 South Platte

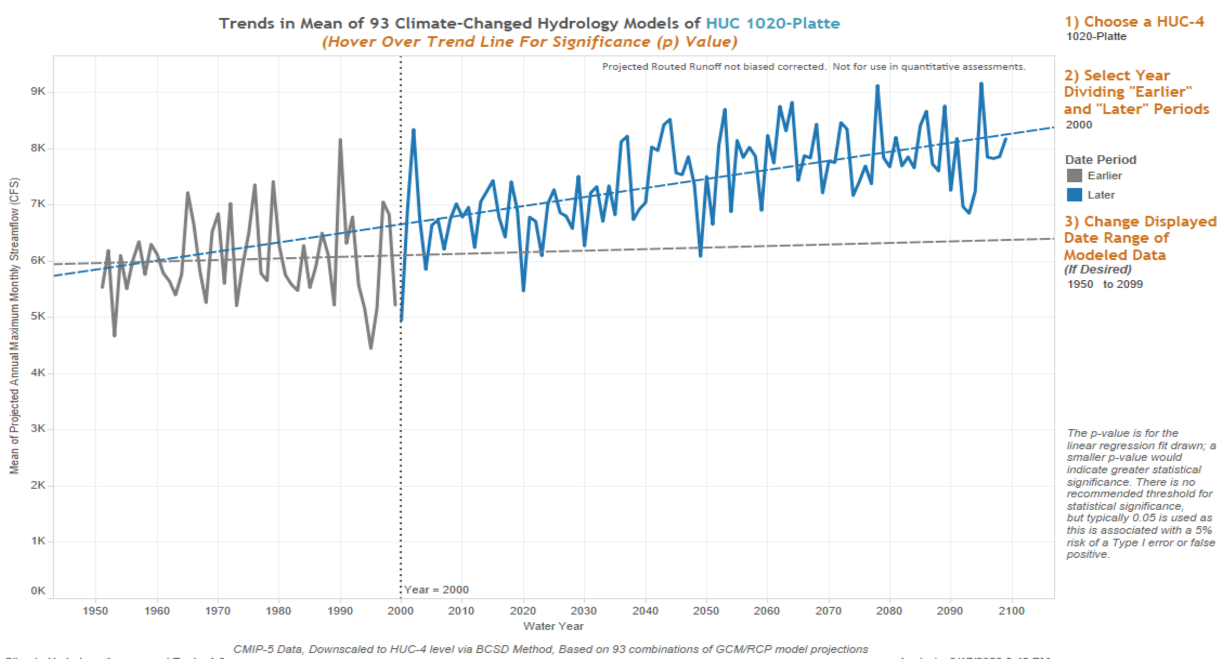

Figure 30. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1020 Platte

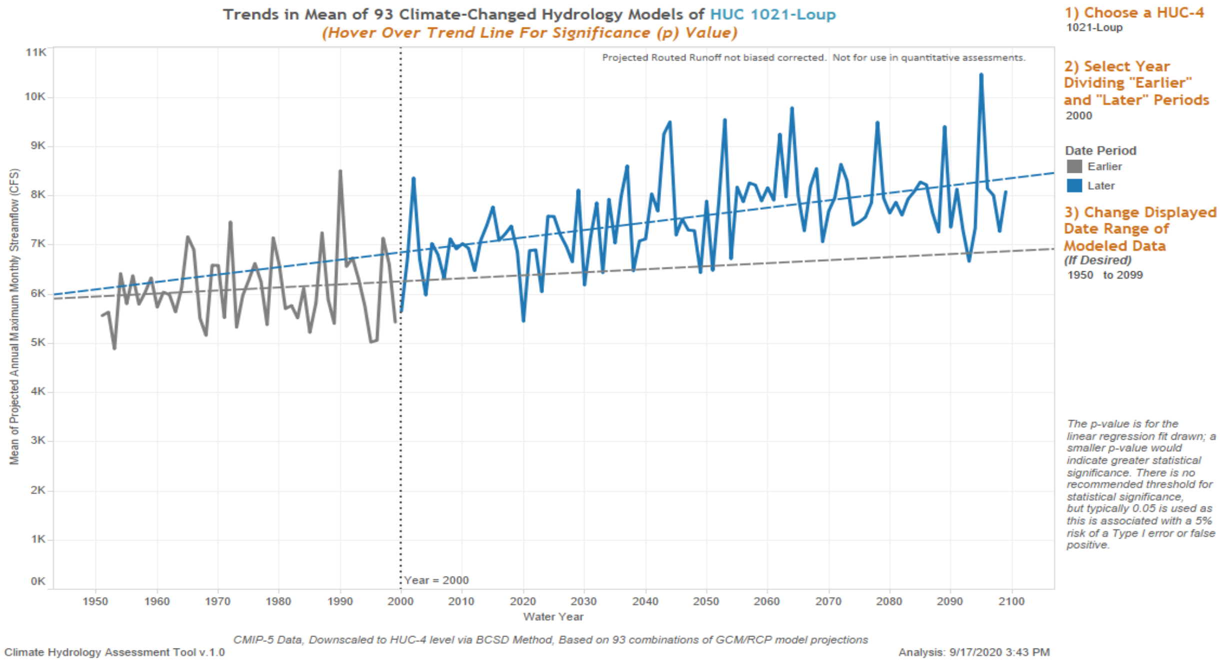

Figure 31. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1021 Loup

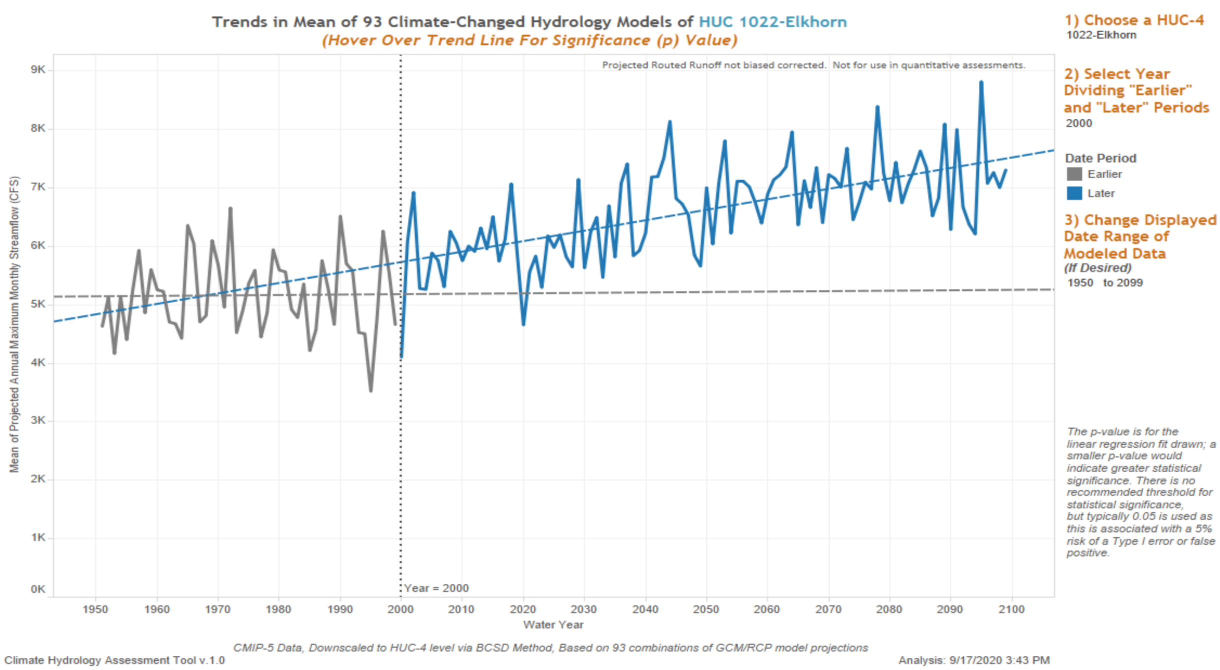

Figure 32. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1022 Elkhorn

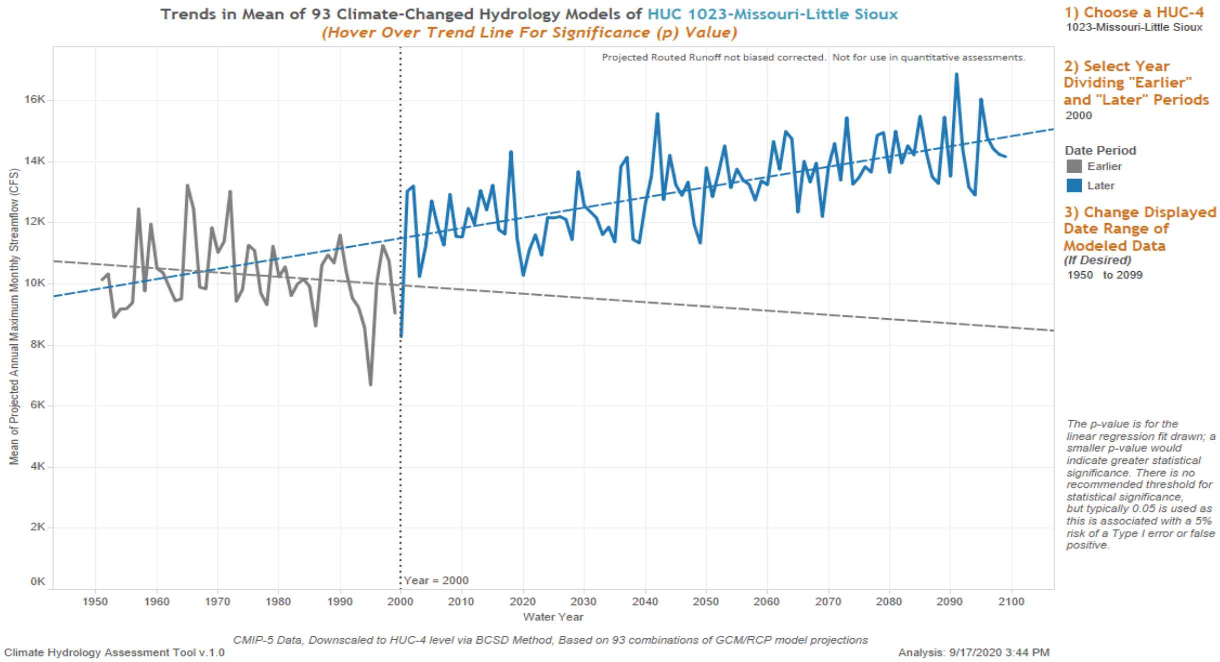

Figure 33. **Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1023 Missouri-Little Sioux**

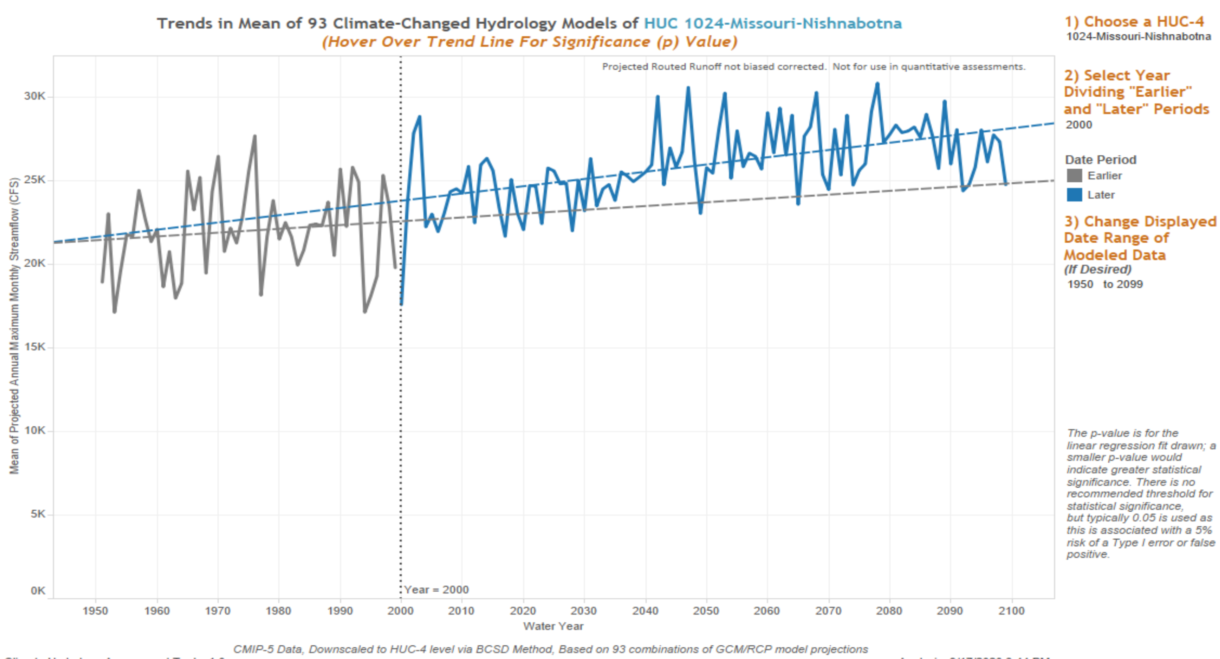

Figure 34 **Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1024 Missouri-Nishnabotna**

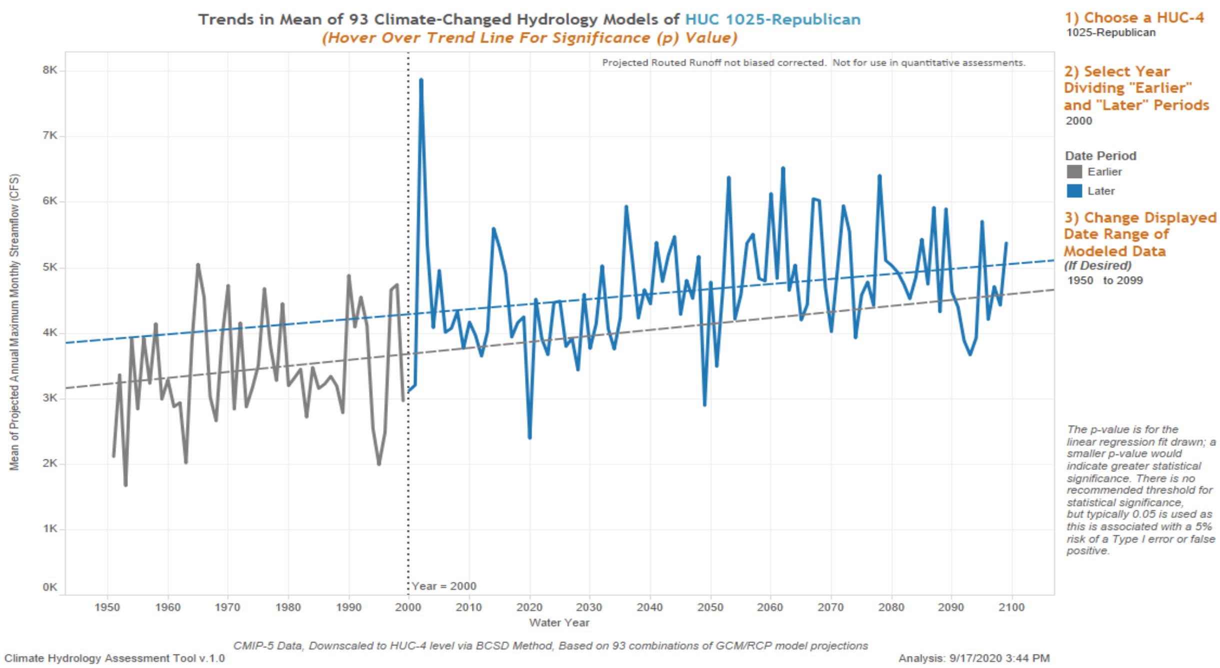

Figure 35. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1025 Republican

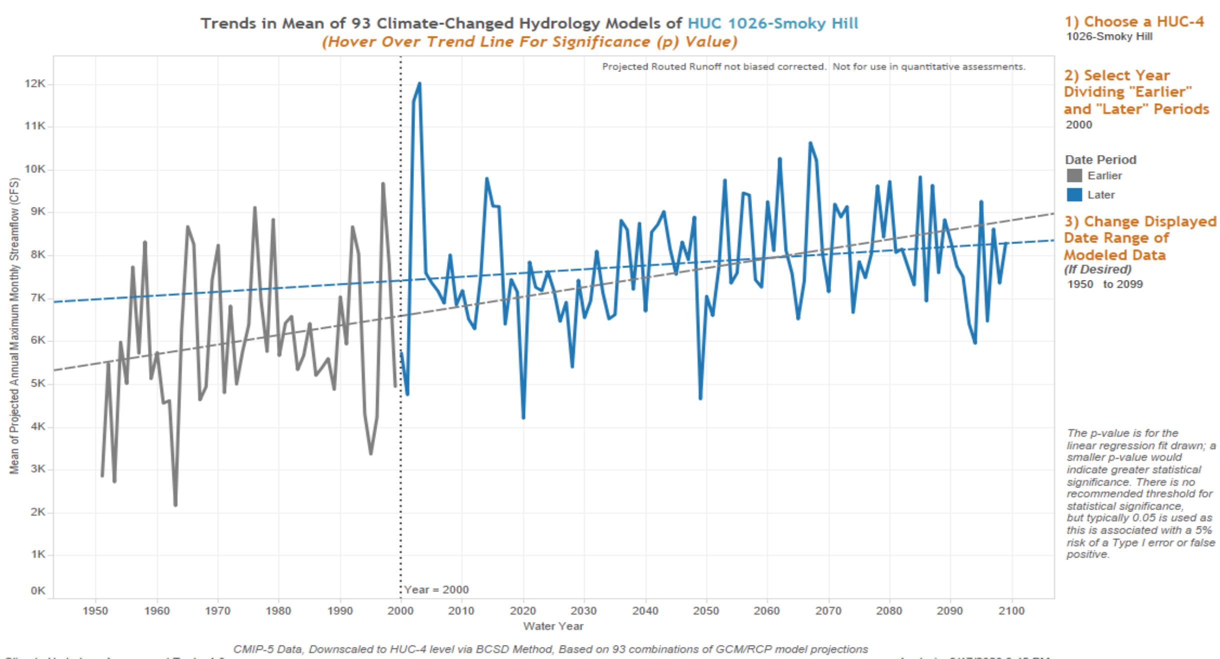

Figure 36. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1026 Smoky Hill

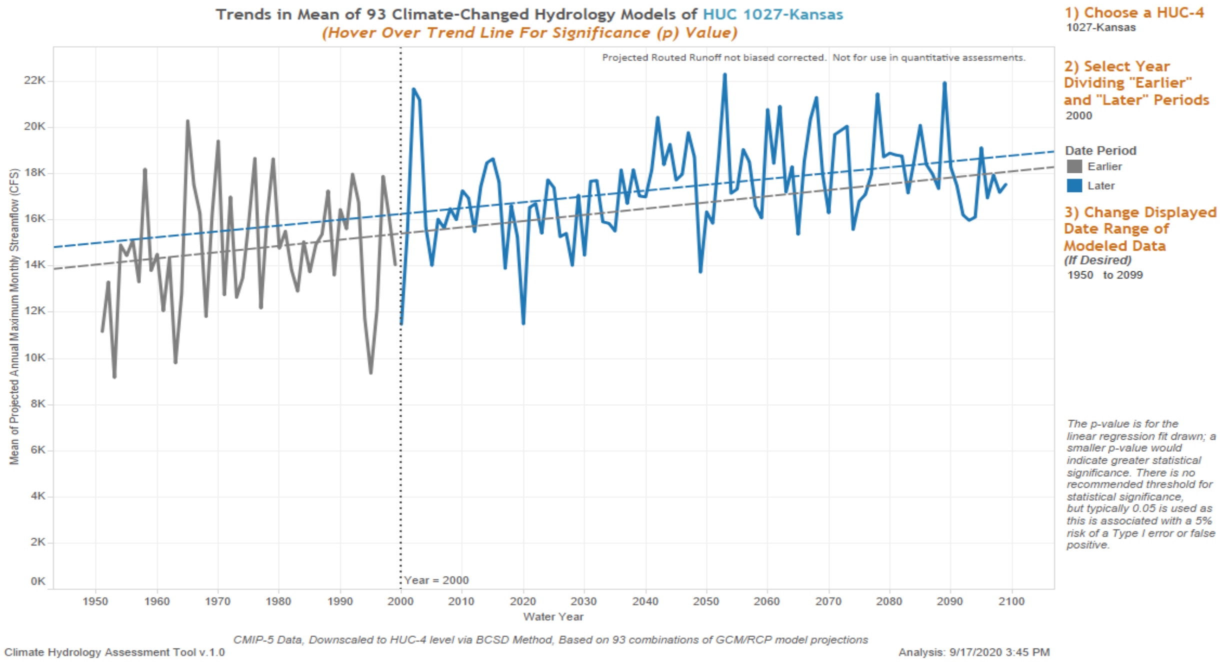

Figure 37. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1027 Kansas

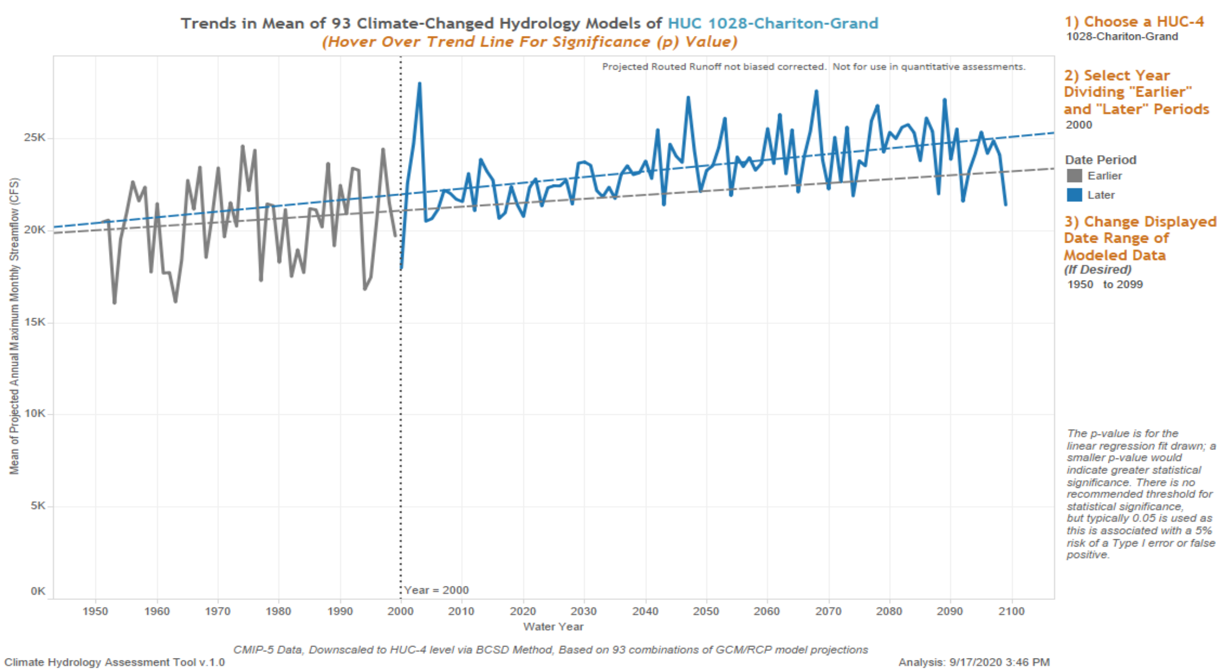

Figure 38. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1028 Chariton-Grand

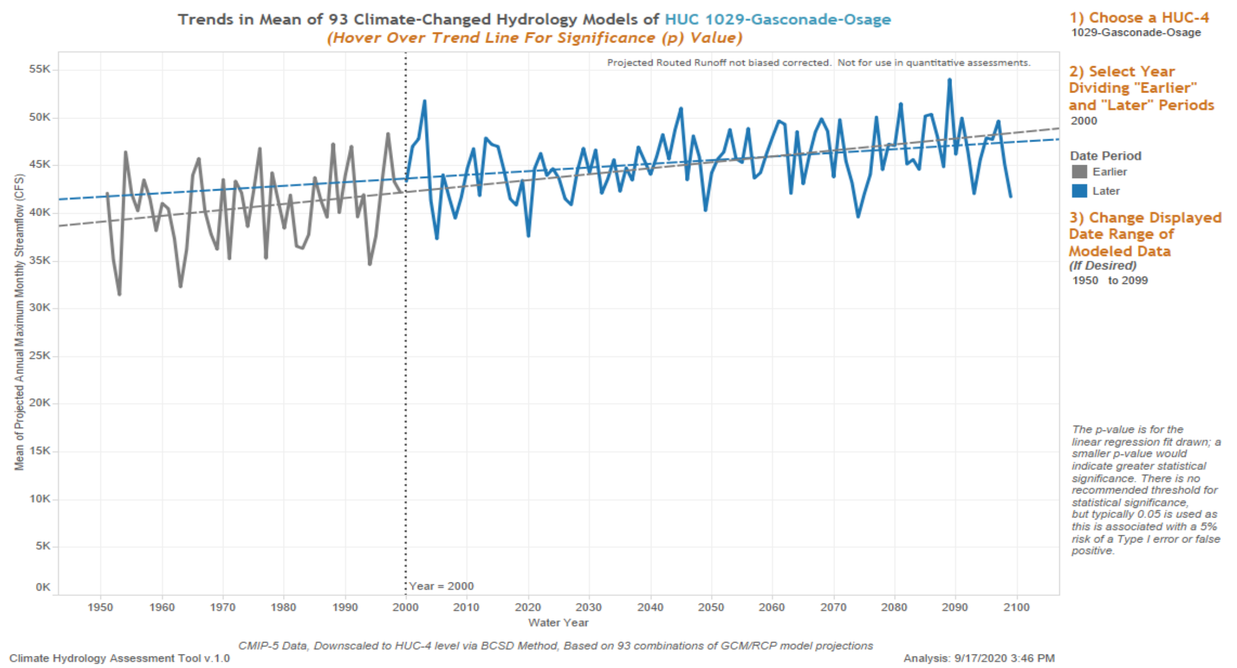

Figure 39. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1029 Gasconade-Osage

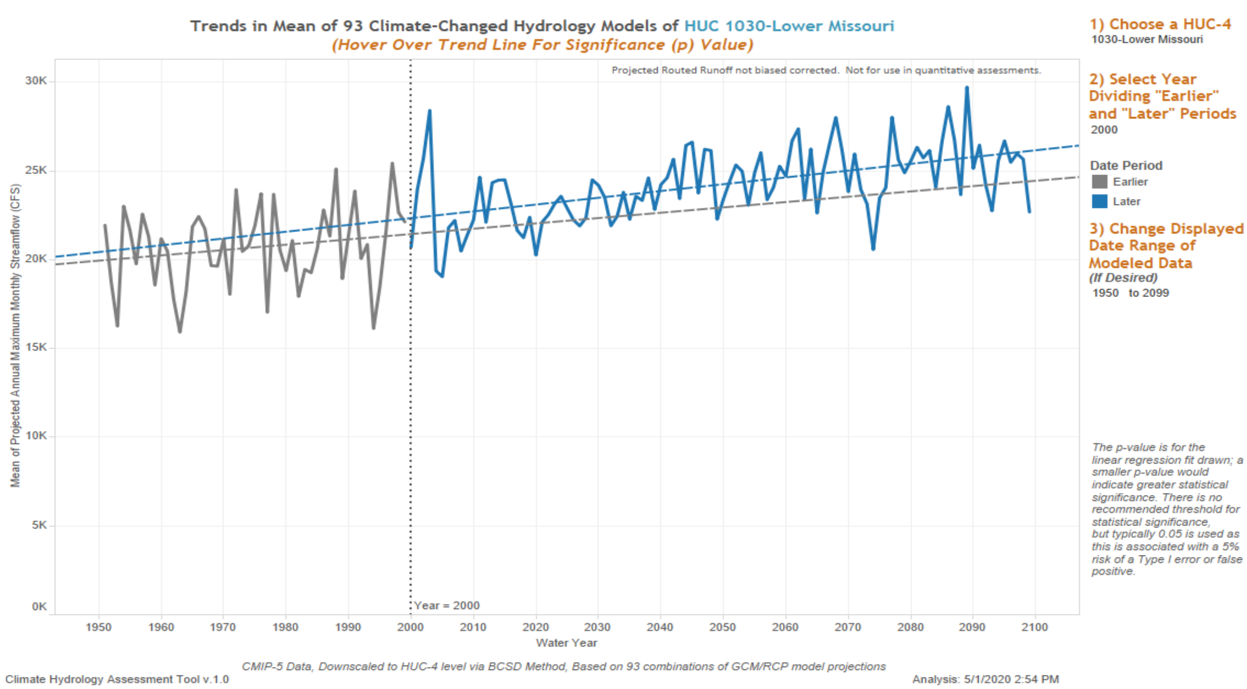

Figure 40. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1030 Lower Missouri

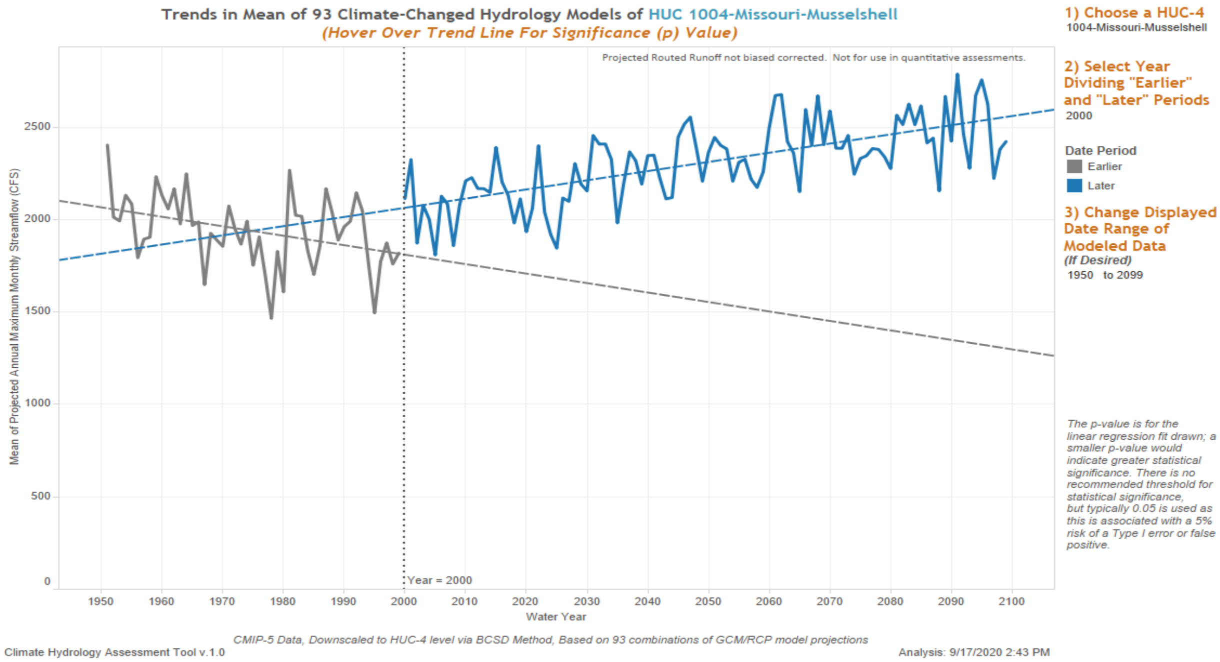

Figure 41. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC Missouri-Musselshell

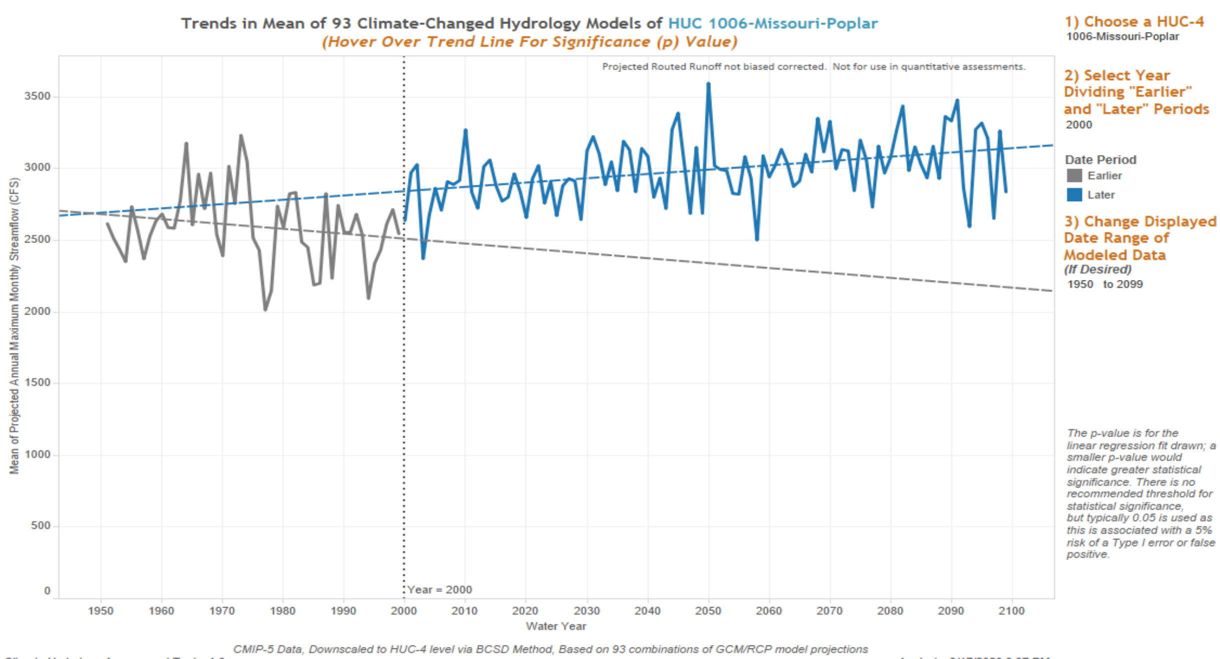

Figure 42. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1006 Missouri-Poplar

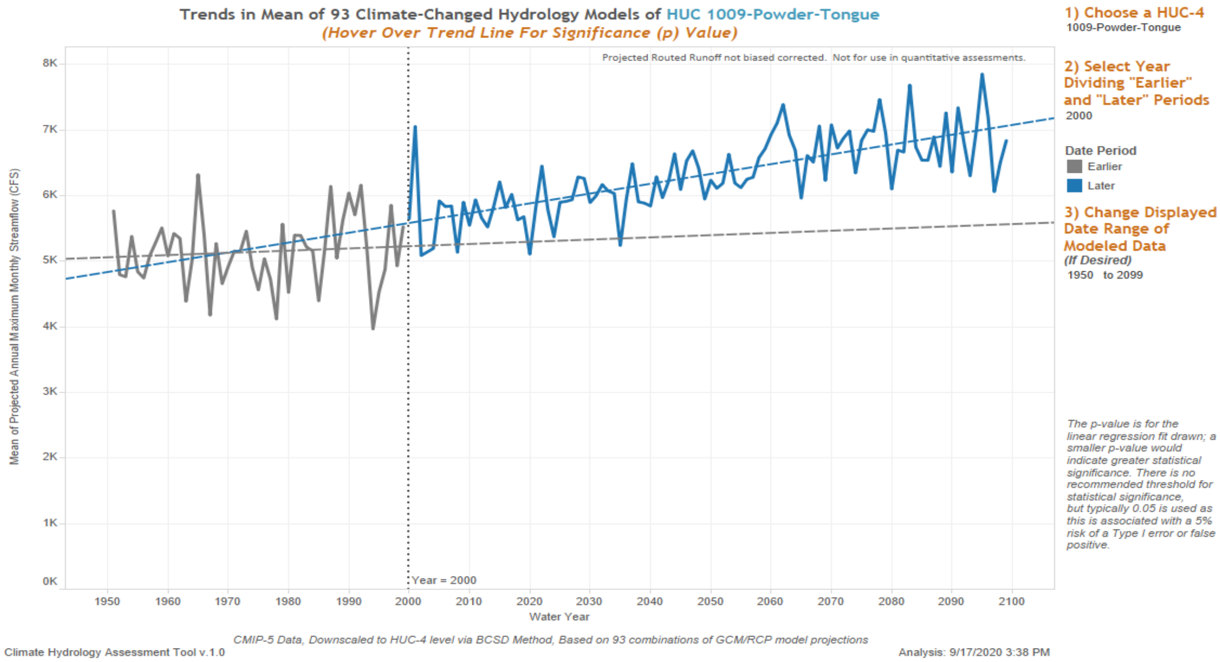

Figure 43. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1009 Powder-Tongue

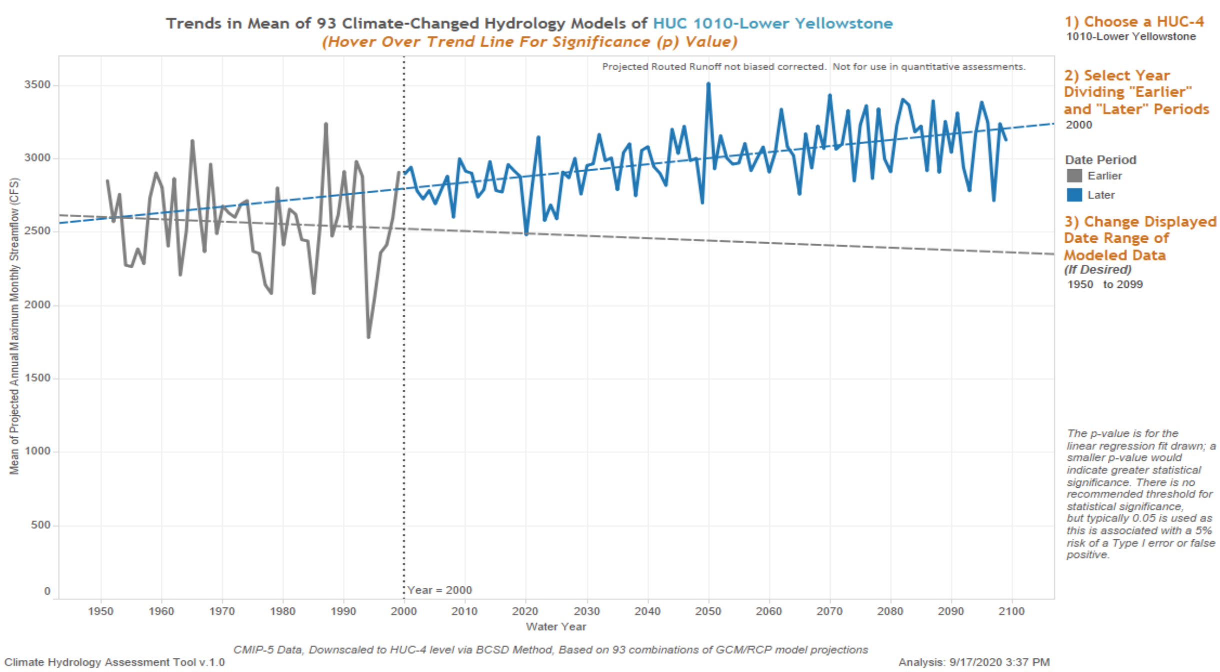

Figure 44. Linear Regression of Mean Projected Annual Maximum Monthly Flow for HUC 1010 Lower Yellowstone

Appendix E: GHCND stations and precipitation and temperature record lengths

Table 26. GHCND Stations Considered for Precipitation and Temperature Trends

GHCND ID	Station Name	Latitude (decimal degrees)	Longitude (decimal degrees)	Network
USC00232503	ELDON, MO US	38.35	-92.58	COOP
USC00233079	FULTON, MO US	38.85	-91.94	COOP
USC00233793	HERMANN, MO US	38.70	-91.43	COOP
USC00234271	JEFFERSON CITY WATER PLANT, MO US	38.59	-92.18	COOP
USC00487115	PAVILLION, WY US	43.25	-108.69	COOP
USC00487760	RIVERTON, WY US	43.03	-108.37	COOP
USC00488209	SHOSHONI, WY US	43.24	-108.11	COOP
USC00140010	ABILENE, KS US	38.93	-97.21	COOP
USC00141435	CHAPMAN, KS US	38.96	-97.01	COOP
USC00141559	CLAY CENTER, KS US	39.37	-97.13	COOP
USC00142574	ENTERPRISE, KS US	38.90	-97.11	COOP
USC00144972	MANHATTAN, KS US	39.20	-96.58	COOP
USC00241297	BUSBY, MT US	45.54	-106.96	COOP
USC00242112	CROW AGENCY, MT US	45.60	-107.45	COOP
USC00243581	GLENDIVE, MT US	47.11	-104.72	COOP
USC00244345	HUNTLEY EXPERIMENTAL STATION, MT US	45.92	-108.25	COOP
USC00390701	BISON, SD US	45.53	-102.47	COOP
USC00392429	DUPREE, SD US	45.05	-101.60	COOP
USC00394864	LEMMON, SD US	45.94	-102.16	COOP
USC00395381	MC INTOSH 6 SE, SD US	45.84	-101.28	COOP
USC00397062	REDIG 11 NE, SD US	45.38	-103.37	COOP
USC00398307	TIMBER LAKE, SD US	45.43	-101.08	COOP
USC00322949	FESSENDEN, ND US	47.65	-99.62	COOP
USC00324418	JAMESTOWN STATE HOSPITAL, ND US	46.88	-98.69	COOP
USC00320766	BEULAH 1 W, ND US	47.26	-101.79	COOP
USC00325638	MAX, ND US	47.82	-101.29	COOP
USW00094014	WILLISTON SLOULIN FIELD, ND US	48.17	-103.64	WBAN
USC00250070	ALBION, NE US	41.69	-98.01	COOP
USC00252770	ERICSON 8 WNW, NE US	41.80	-98.82	COOP
USC00253185	GENOA 2 W, NE US	41.45	-97.76	COOP
USC00253425	GREELEY, NE US	41.55	-98.53	COOP

GHCND ID	Station Name	Latitude (decimal degrees)	Longitude (decimal degrees)	Network
USC00254985	LOUP CITY, NE US	41.28	-98.97	COOP
USC00257515	SAINT PAUL, NE US	41.21	-98.46	COOP
USC00240770	BIG SANDY, MT US	48.13	-110.06	COOP
USC00241722	CHINOOK, MT US	48.59	-109.23	COOP
USC00243089	FORKS 4 NNE, MT US	48.78	-107.45	COOP
USC00243110	FORT ASSINIBOINE, MT US	48.50	-109.80	COOP
USC00243929	HARLEM 4 W, MT US	48.54	-108.80	COOP
USC00244766	KREMLIN, MT US	48.52	-110.11	COOP
USC00142835	FORT SCOTT, KS US	37.84	-94.71	COOP
USC00230204	APPLETON CITY, MO US	38.19	-94.03	COOP
USC00234705	LAMAR 7 N, MO US	37.60	-94.28	COOP
USC00234825	LEBANON 2 W, MO US	37.69	-92.69	COOP
USC00235987	NEVADA WATER PLANT, MO US	37.84	-94.37	COOP
USC00133438	GREENFIELD, IA US	41.29	-94.45	COOP
USC00236866	PRINCETON, MO US	40.40	-93.58	COOP
USC00238444	TRENTON, MO US	40.08	-93.61	COOP
USC00057848	SPICER, CO US	40.47	-106.45	COOP
USC00058756	WALDEN, CO US	40.74	-106.28	COOP
USC00252065	CULBERTSON, NE US	40.23	-100.83	COOP
USC00254110	IMPERIAL, NE US	40.51	-101.65	COOP
USC00255090	MADRID, NE US	40.85	-101.54	COOP
USC00255310	MC COOK, NE US	40.23	-100.61	COOP
USW00024020	HAYES CENTER 1 NW, NE US	40.52	-101.03	WBAN
USC00240364	AUGUSTA, MT US	47.49	-112.40	COOP
USC00242857	FAIRFIELD, MT US	47.62	-111.99	COOP
USC00243489	GIBSON DAM, MT US	47.60	-112.75	COOP
USC00248021	SUN RIVER 4 S, MT US	47.48	-111.74	COOP
USC00050454	BAILEY, CO US	39.41	-105.48	COOP
USC00050848	BOULDER, CO US	39.99	-105.27	COOP
USC00051528	CHEESMAN, CO US	39.22	-105.28	COOP
USC00391076	BROOKINGS 2 NE, SD US	44.33	-96.77	COOP
USC00391519	CASTLEWOOD, SD US	44.73	-97.03	COOP
USC00391739	CLARK, SD US	44.88	-97.73	COOP
USC00392302	DE SMET, SD US	44.38	-97.55	COOP
USW00014946	WATERTOWN REGIONAL AIRPORT, SD US	44.90	-97.15	WBAN

GHCND ID	Station Name	Latitude (decimal degrees)	Longitude (decimal degrees)	Network
USC00132171	DENISON, IA US	42.04	-95.33	COOP
USC00134735	LE MARS, IA US	42.78	-96.15	COOP
USC00134894	LOGAN, IA US	41.64	-95.79	COOP
USC00136800	PRIMGHAR, IA US	43.09	-95.63	COOP
USC00137844	SPENCER 1 N, IA US	43.17	-95.15	COOP
USC00258480	TEKAMAH, NE US	41.78	-96.23	COOP
USC00244038	HEBGEN DAM, MT US	44.87	-111.34	COOP
USC00485345	LAKE YELLOWSTONE, WY US	44.56	-110.40	COOP
USC00489905	YELLOWSTONE PARK MAMMOTH, WY US	44.98	-110.70	COOP

Figure 129. GHCND Precipitation Station Coverage

Figure 130. GHCND Maximum Temperature Observations

Figure 131. GHCND Minimum Temperature Observations

Appendix F: Verification of Scripted NRNI Change Points and Monotonic Trends

The analysis presented in this climate assessment used non-standard NRNI streamflow data that are not readily available in the NSD and CHAT tools. This appendix presents a verification of the scripts developed in this climate assessment to the standard required by ECB 2018-14. The validation was completed on the 7-day peak streamflow NRNI dataset for Bend Dam using the time series toolbox (https://climate-test.sec.usace.army.mil/tst_app/).

The Time Series Toolbox nonstationarity detection points are shown in Figure 132. The comparable nonstationarity detection points from the scripts used in this study are shown in

Table 4. The results from the Time Series Toolbox, and the scripted results agree with each other.

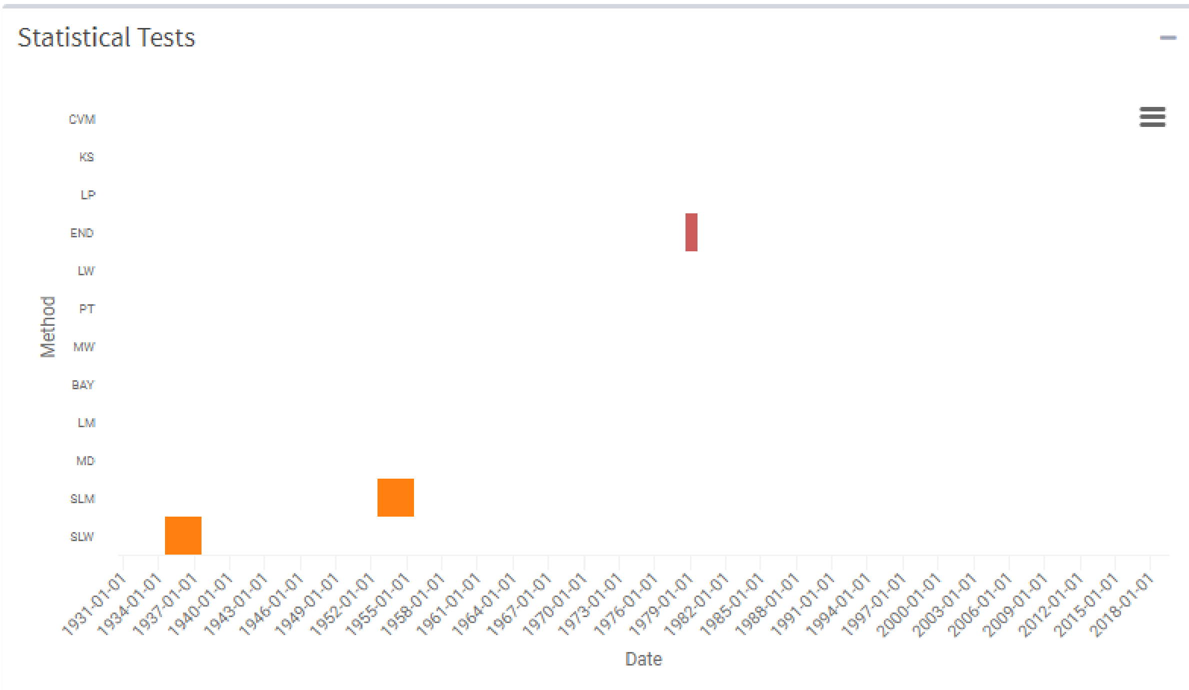

Figure 132. Bend Dam 7-day NRNI Nonstationarity Detection Results from Time Series Toolbox

Table 4. Bend Dam 7-day NRNI Nonstationarity Detection Points Using Scripted Routines

Site	WY	n-day	Test Name
BEND DAM	10/1/1935	7	Smooth Lombard Wilcoxon (Mean Change)
BEND DAM	10/1/1936	7	Smooth Lombard Wilcoxon (Mean Change)
BEND DAM	10/1/1937	7	Smooth Lombard Wilcoxon (Mean Change)
BEND DAM	10/1/1953	7	Smooth Lombard Mood (Variance Change)
BEND DAM	10/1/1954	7	Smooth Lombard Mood (Variance Change)
BEND DAM	10/1/1955	7	Smooth Lombard Mood (Variance Change)
BEND DAM	10/1/1979	7	Energy-Based Divisive Method (Distribution Change)

The trend analysis magnitude and significance outputs from the Time Series Toolbox are shown in Figure 133 and Figure 134, respectively. The scripted trend analysis and significance are provided in Table 28. The results agree between the Time Series toolbox and scripted values.

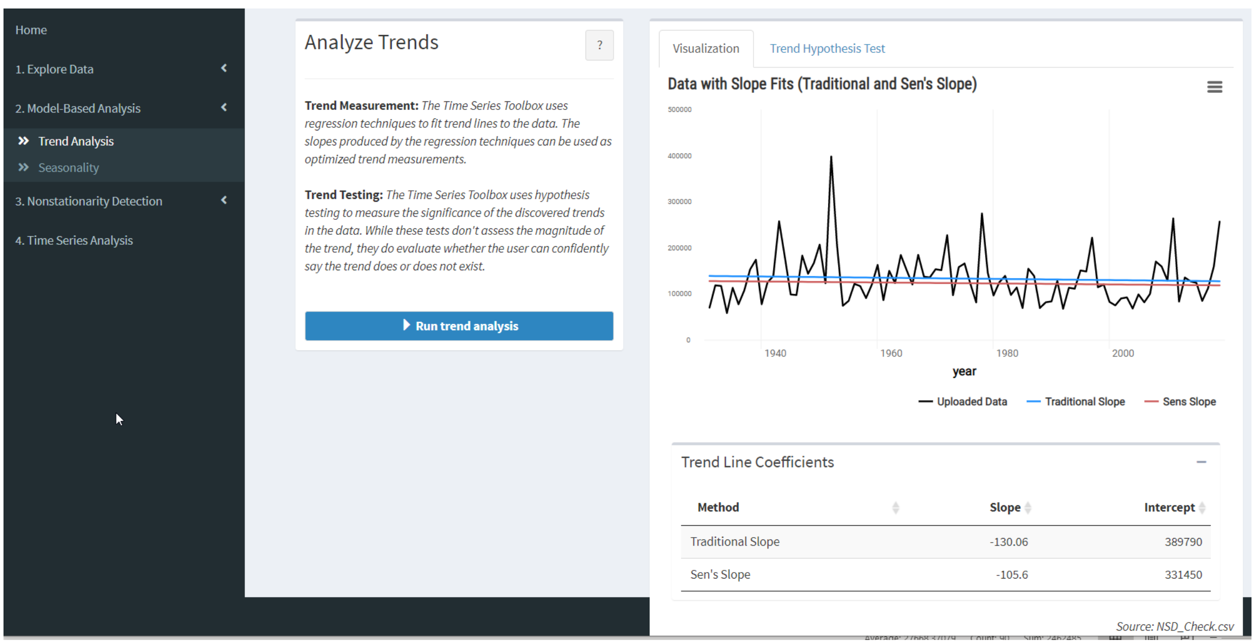

Figure 133. Time Series Toolbox Trend Analysis Output for Bend Dam 7-day NRNI Peak Streamflow Time Series

Visualization | Trend Hypothesis Test

Test	P.Value
t-Test	0.57058
Mann-Kendall	0.5683
Spearman Rank-Order	0.57241

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

Source: NSD_Check.csv

Figure 134. Time Series Toolbox Trend Significance Output for Bend Dam 7-day NRNI Peak Streamflow Time Series

Table 28. Scripted Results Trend Analysis and Significance for Bend Dam 7-day NRNI Peak Streamflow Time Series

Location	Variable	Begin Year	End Year	Mann-Kendall P Value	Sens Slope	Spearman Rank-Order P-value
BEND.DAM	7-Day NRNI	1931	2019	0.568	-105.6	0.572

Appendix G: Vulnerability Analysis Results

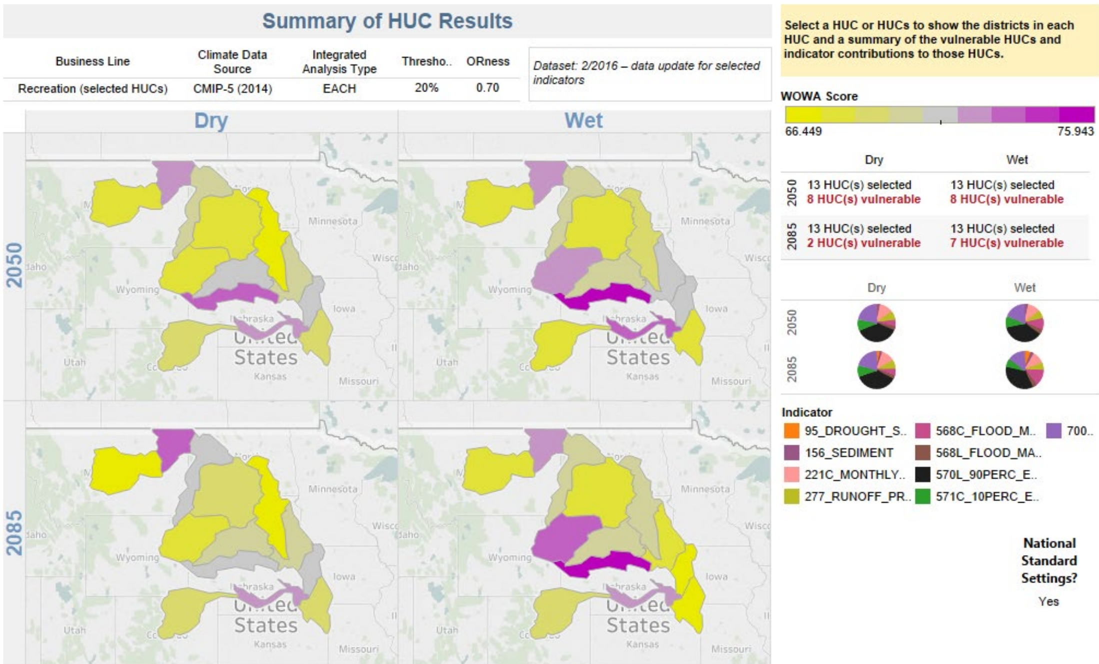

Figure 135. Summary of NWO Recreation Vulnerability Analysis Results

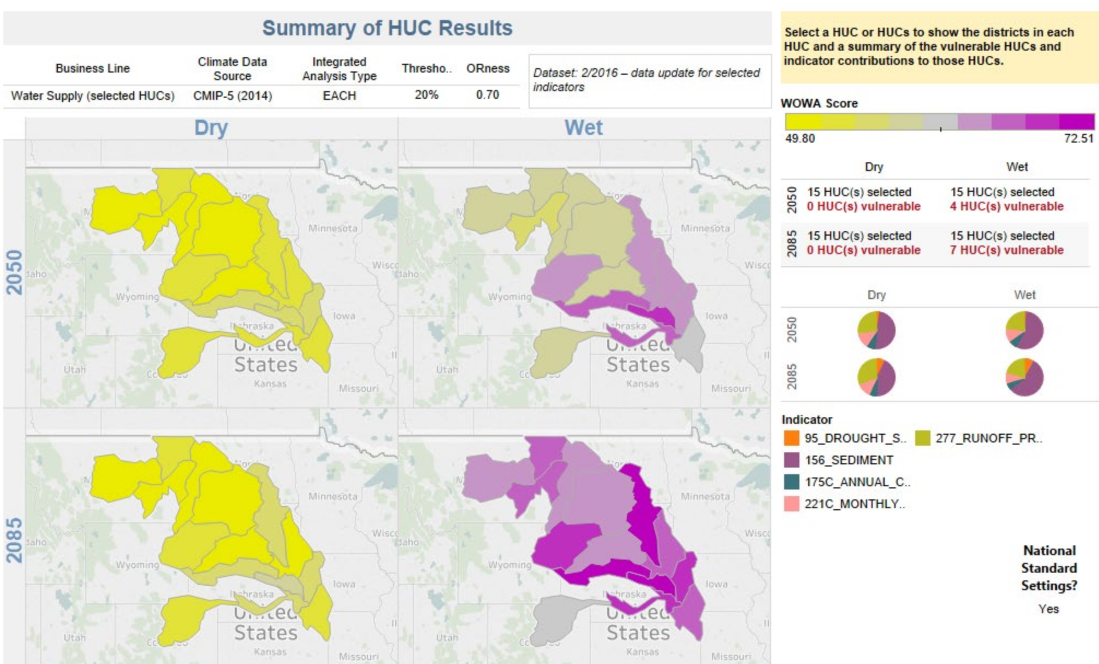

Figure 136. Summary of NWO Water Supply Vulnerability Analysis Results

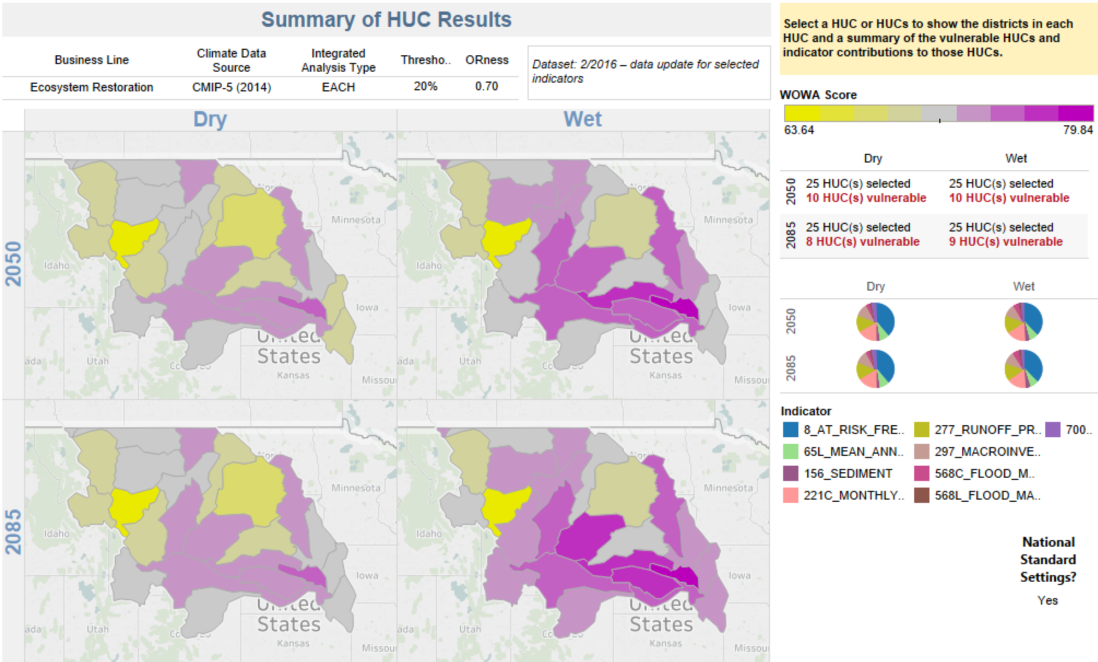

Figure 137. Summary of NWO Ecosystem Restoration Vulnerably Analysis Results

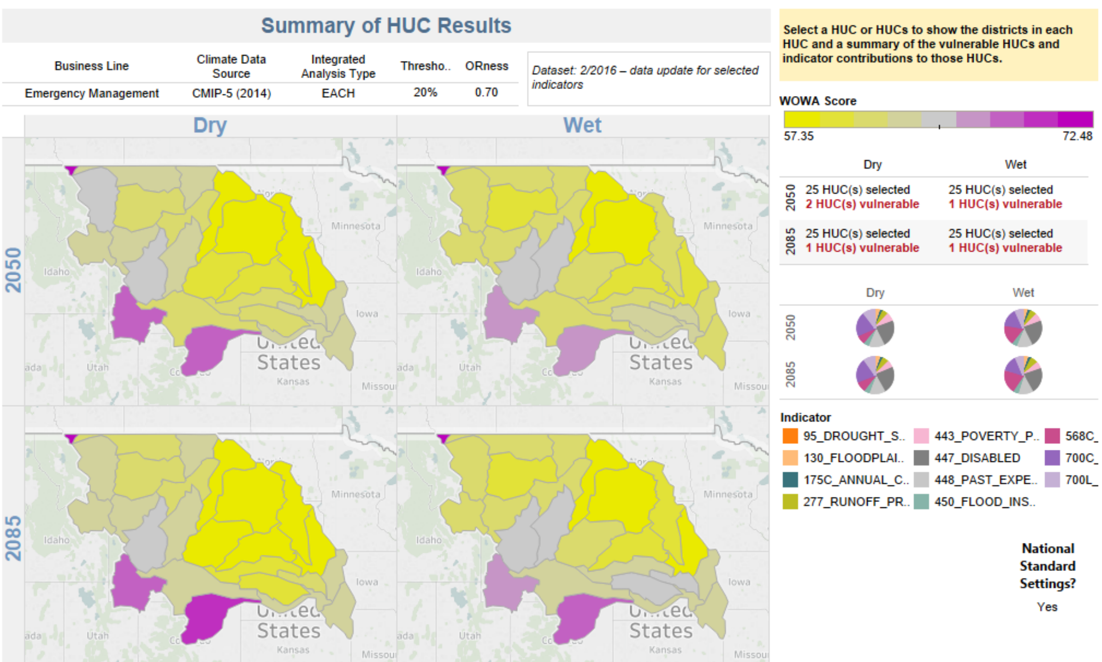

Figure 138. Summary of NWO Emergency Management Vulnerability Analysis Results

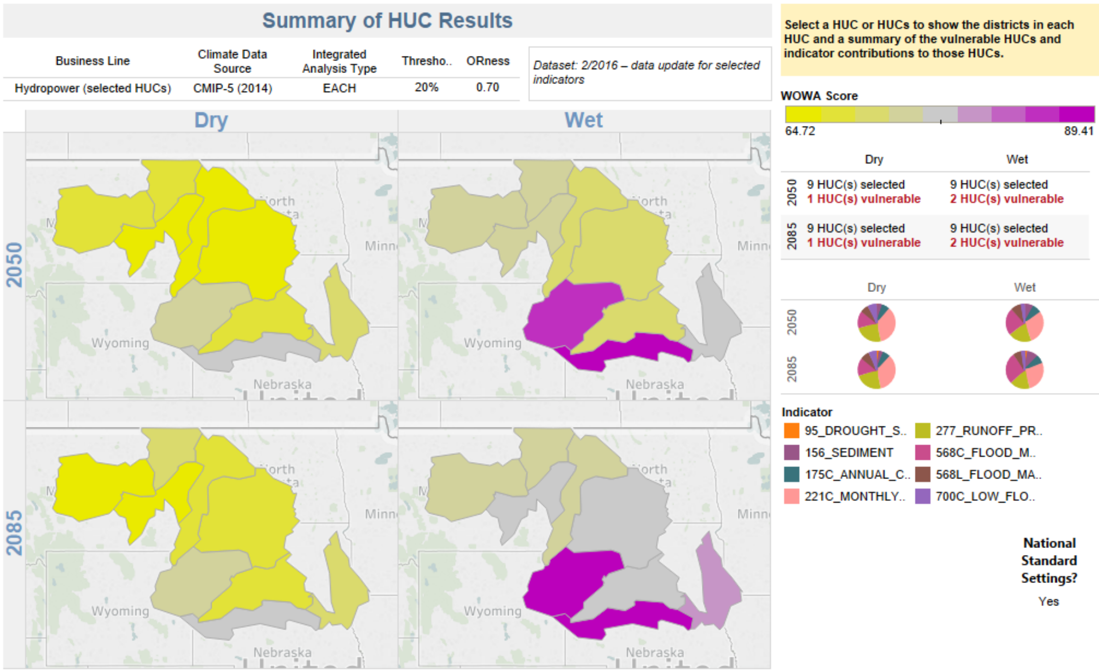

Figure 139. Summary of NWO Hydropower Vulnerability Analysis Results

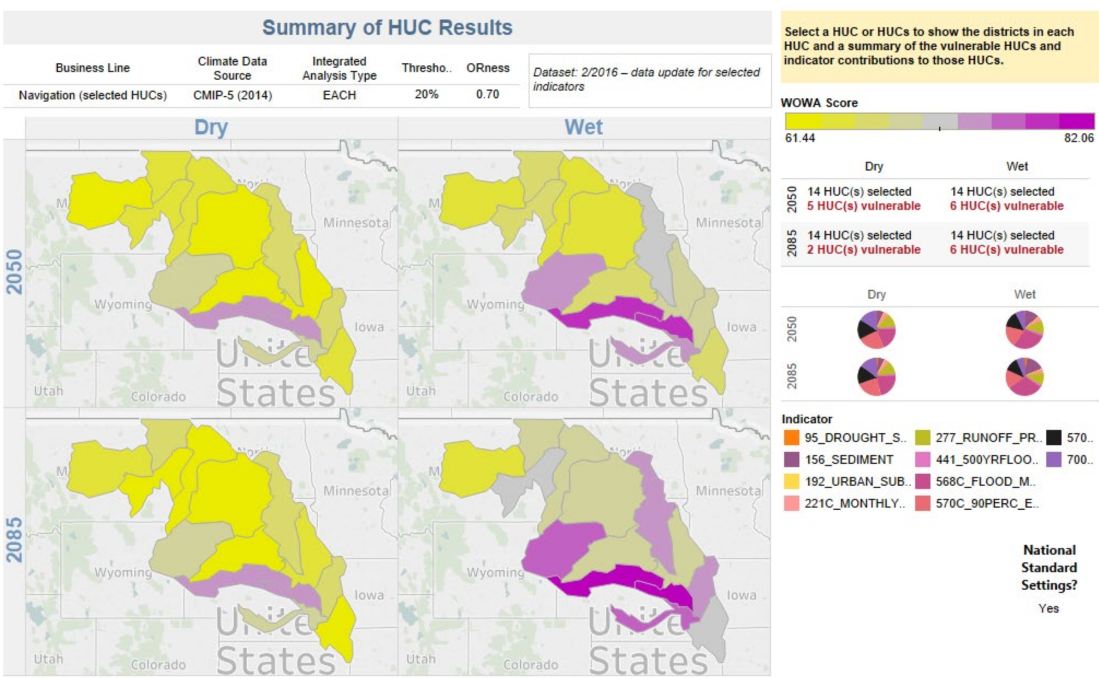

Figure 140. Summary of NWO Navigation Vulnerability Results

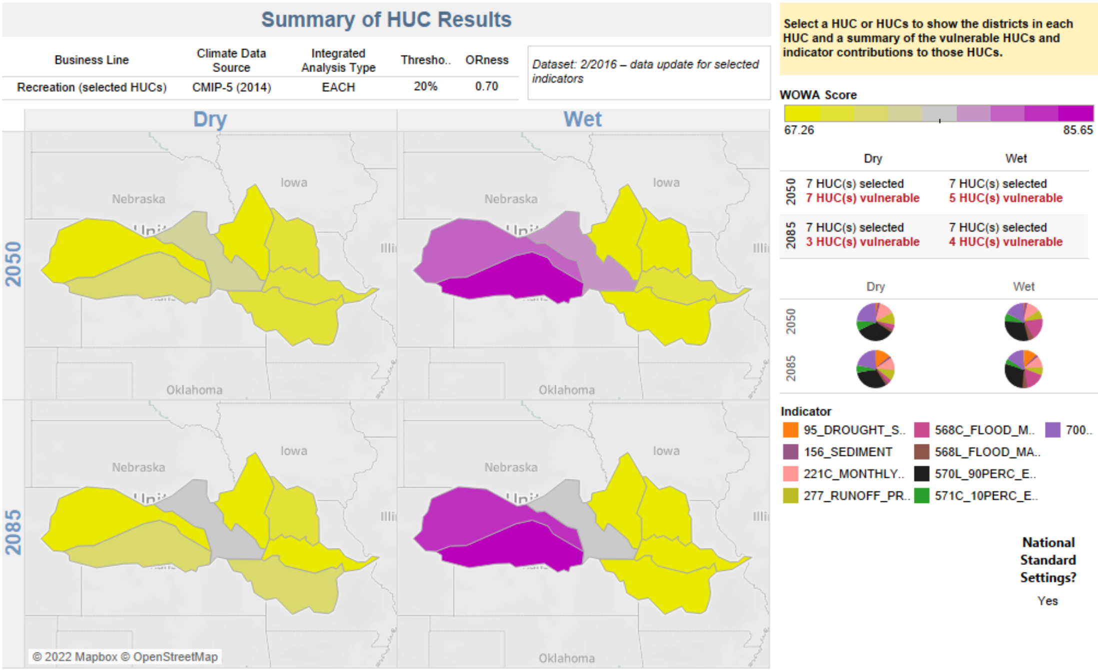

Figure 141. Summary of NWK Recreation Vulnerability Results

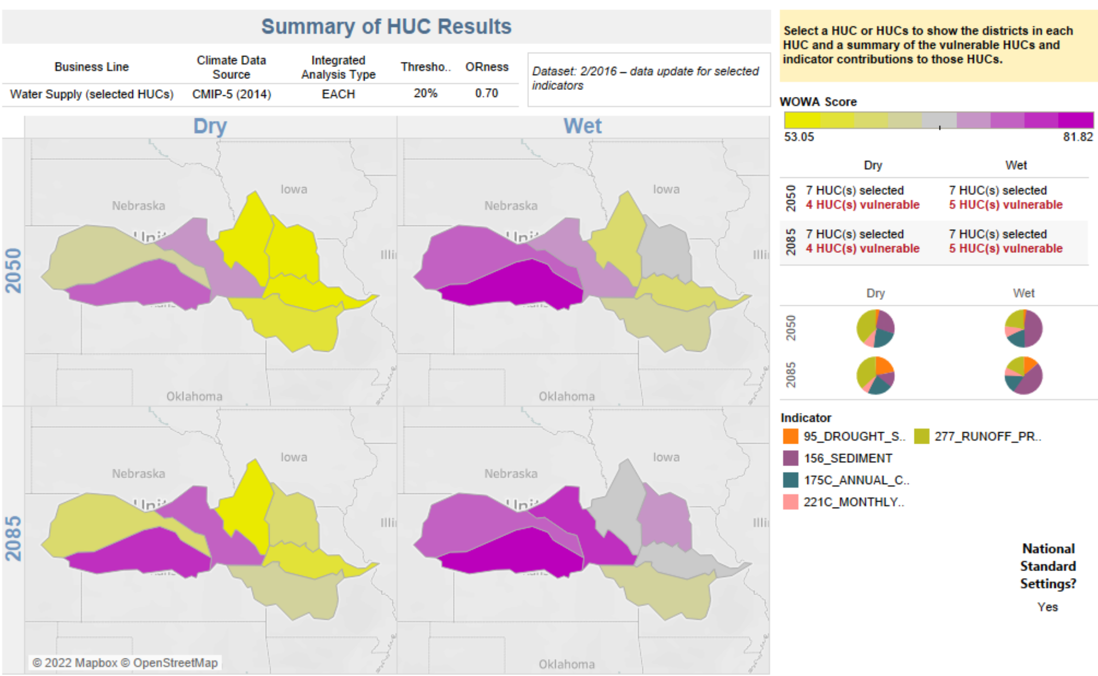

Figure 142. Summary of NWK Water Supply Vulnerability Results

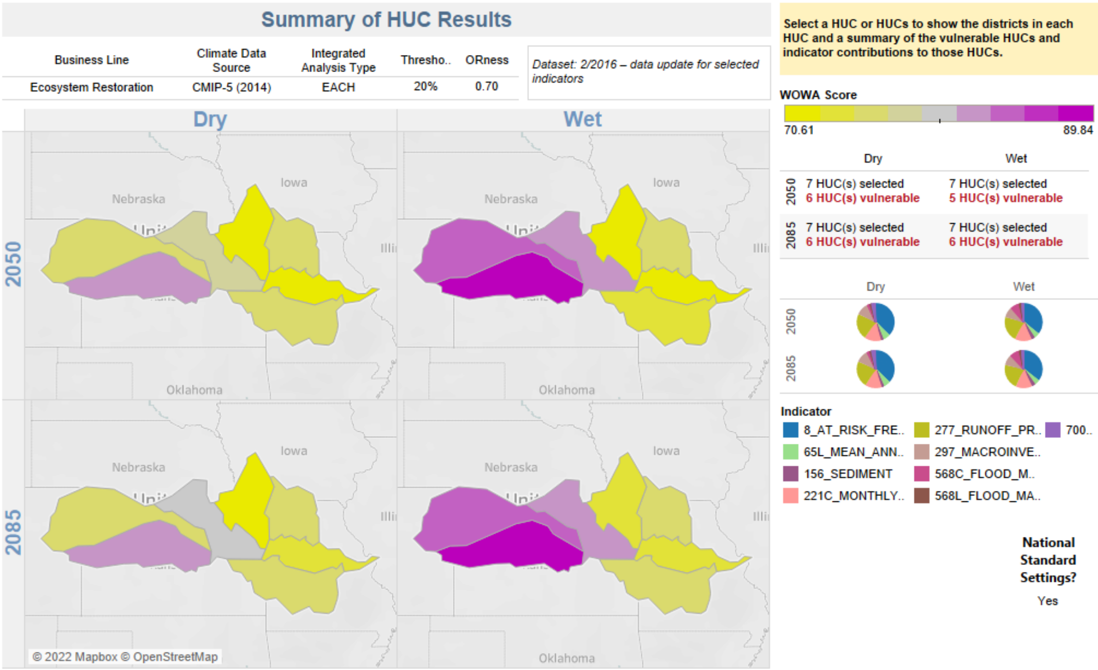

Figure 143. Summary of NWK Ecosystem Restoration Vulnerability Results

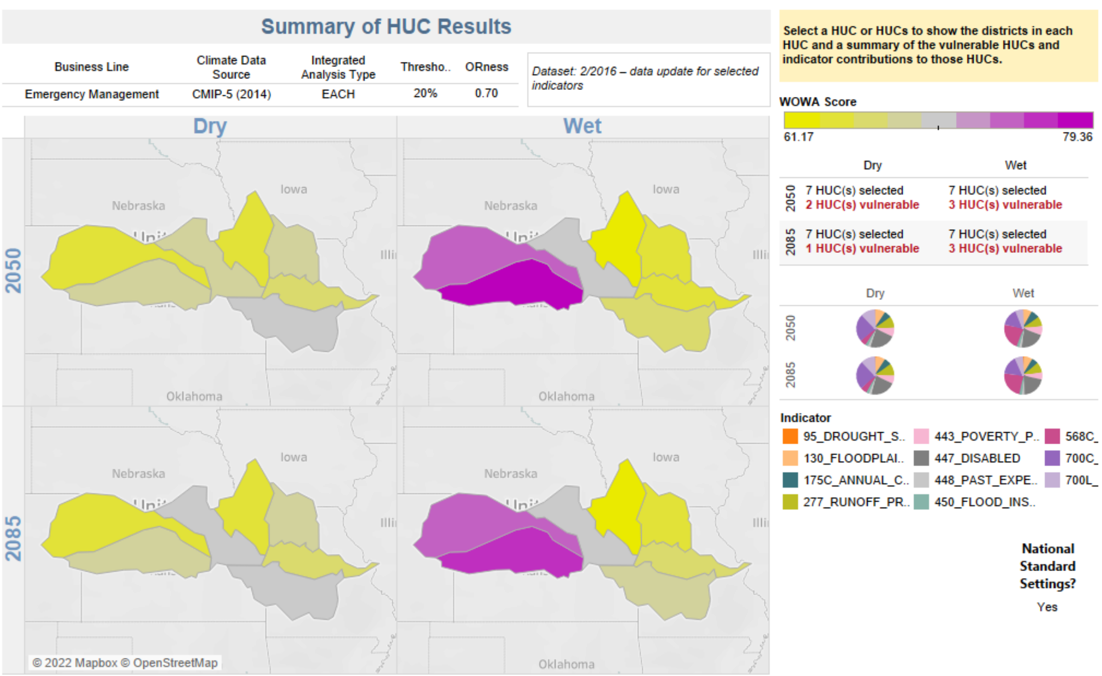

Figure 144. Summary of NWK Emergency Management Vulnerability Results

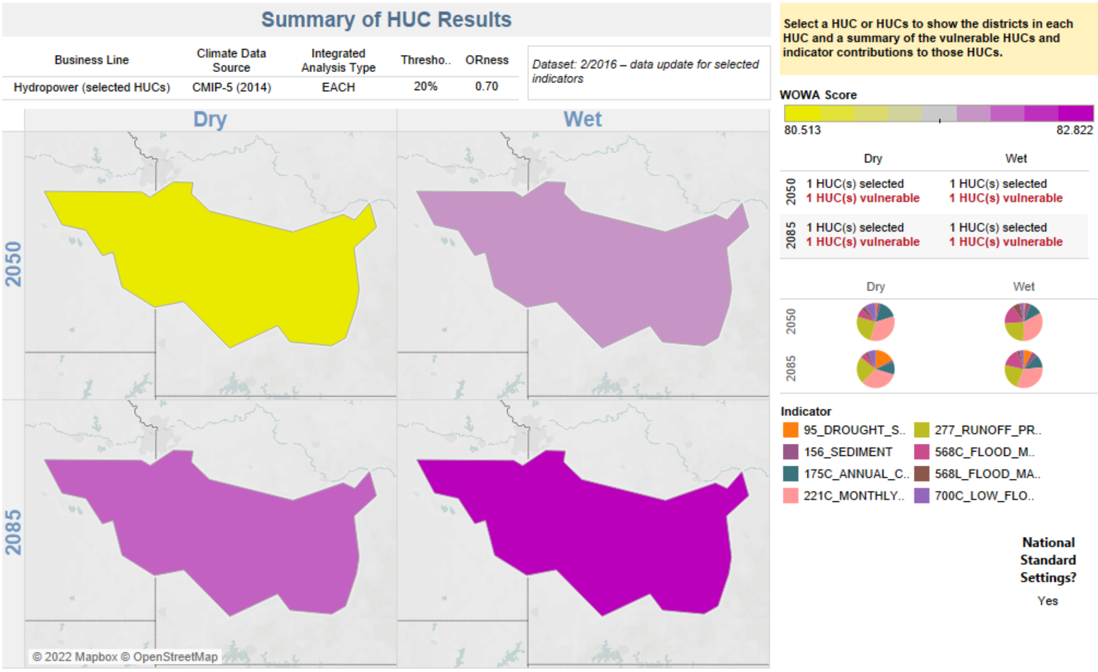

Figure 145. Summary of NWK Hydropower Vulnerability Results

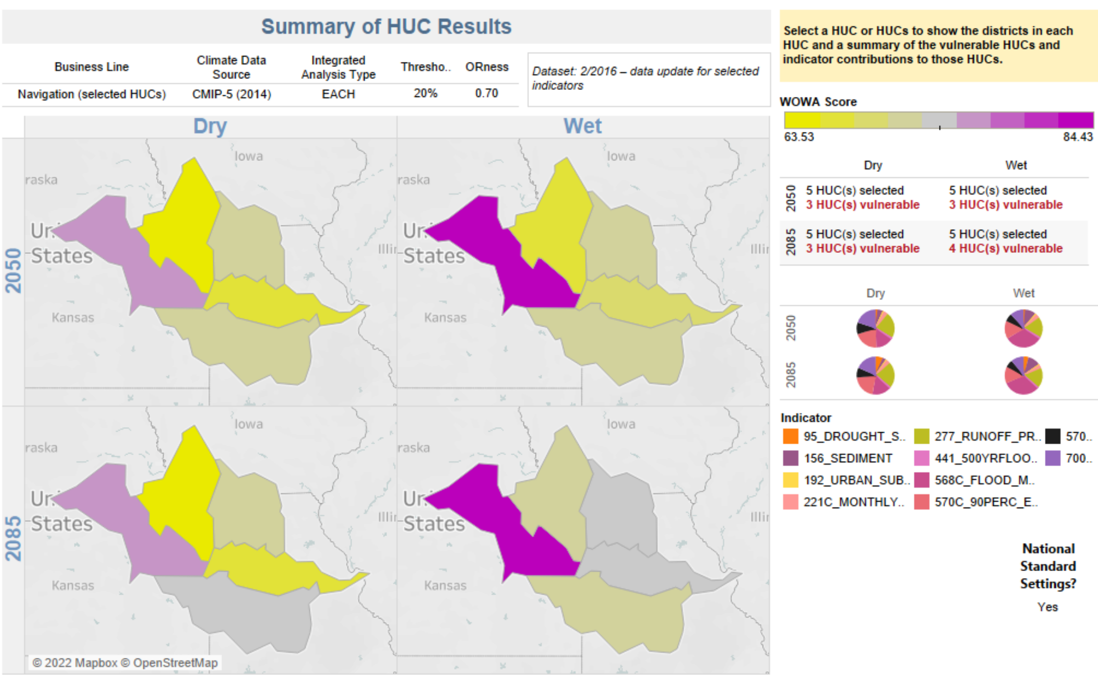

Figure 146. Summary of NWK Navigation Vulnerability Results