Appendix A. Climate Change Assessment

Kansas River Reservoirs Flood and Sediment Study
Draft Watershed Study Report

October 2023

U.S. Army Corps of Engineers
Kansas City District

Kansas City District

Kansas River Reservoirs Flood and Sediment Study

Appendix #: Climate Change Assessment

Hydrologic Engineering Branch

Climate Change Assessment

Kansas River Reservoirs Flood and Sediment Study

Kansas River Watershed

FINAL – 08 July 2021

COVER IMAGE: TUTTLE CREEK LAKE LEVEL NEAR TOP OF SPILLWAY GATES IN MAY 2019. CREDIT: MANHATTAN MERCURY

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Acronyms

ECB – Engineering and Construction Bulletin

ETL – Engineer Technical Letter

KRRFSS – Kansas River Reservoir Flood and Sediment Study (Watershed Study)

USACE – United States Army Corps of Engineers

USBR – United States Bureau of Reclamation

1. Introduction & Background

"USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural climate variability over their operating life spans" (USACE, 2017). However, recent scientific evidence shows that in some places and for some impacts relevant to USACE operations, climate change is shifting the climatological baseline about which that natural climate variability occurs, and may be changing the range of that variability as well. This is relevant to the USACE because the assumptions of stationary climatic baselines and a fixed range of natural variability, as captured in the historic hydrologic record, may no longer be appropriate for long-term projections of flood risk (USACE, 2017).

Climate Change impacts on the hydrology of the Kansas River Basin were considered in accordance to USACE Engineering Construction Bulletin (ECB) 2018-14, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs and Projects (USACE, 2018), as well as USACE Engineer Technical Letter (ETL) 1100-2-3 Guidance for Detection of Nonstationarities in Annual Maximum Discharges (USACE, 2017). ECB 2018-14 was renewed on 10-September-2020 and the expiration date was extended to 10-September-2022.

Engineering Construction Bulletin (ECB) No. 2018-14 (USACE 2018) provides guidance for incorporating climate change information in hydrologic analyses in accordance with the USACE overarching climate change adaption policy. The ECB calls for a qualitative analysis. The goal of a qualitative analysis of potential climate threats and impacts to USACE hydrology-related projects and operations is to describe the observed present and possible future climate threats, vulnerabilities, and impacts of climate change specific to the study goals or engineering designs. As seen in Figure 1, qualitative analysis includes consideration of both past (observed) changes as well as potential future (projected) changes to relevant climatic and hydrologic variables.

The primary objective of the Kansas River Reservoir Flood and Sediment Study is to develop a comprehensive plan to support the Shared Vision, to identify actions within the Kansas River Basin necessary to extend the useful life of our reservoirs, to increase their resiliency and maintain capacity. The study aims to develop sustainable measures to reduce flood risk, improve sediment management, and mitigate drought, while seeking opportunities related to critical infrastructure investment, water supply availability, ecosystem restoration, water quality, and enhancing recreation. Specific study objectives include recommended solutions to:

- Manage sedimentation in reservoirs to reduce loss of volume and decrease the sedimentation rates for sustainment of authorized purposes and benefits.

- Reduce risks to life safety in the Kansas River Basin with a focus on improved flood risk system flexibility under a variety of climate change and land use development patterns.

- Reduce both societal consequences and economic damages associated with flood risk in the study area, with an emphasis on improving system resiliency and increasing the long-term integrity of the flood system.

- Increase the reliability and availability of water supply.

- Reduce both societal consequences and economic impacts associated with drought risk in the study area, with an emphasis on improving system resiliency and increasing the long-term integrity of the water supply system.

- Increase adoption of watershed practices that reduce future loss of reservoir storage.

- Increase the identification of future water related infrastructure investment costs (e.g., reservoirs, lakes, levees, public water supply infrastructure).

- Protect and improve biological resources including vegetation and wetlands, wildlife and wildlife habitat, and fisheries and aquatic species.

- Protect and improve the availability of high-quality water for residential, commercial, industrial, and recreational uses, and for biological communities.

- Protect, promote, and expand recreational opportunities, including boating, fishing, hunting, camping, wildlife viewing, swimming, picnicking.

- Maintain/improve sportfish populations, habitats, and angler access.

- Increase the adaptability and resiliency of the water supply, flood risk management, and ecological systems of the Kansas River Basin in relation to climate change, including planning for extreme events (i.e. flooding and drought).

Changes in the hydrology of the Kansas River Basin due to climate change may significantly affect most, if not all the study objectives. For example, increased intense rainfall events would likely lead to greater flood risk, and greater sediment transport, causing increased sedimentation at reservoirs. Results from this qualitative assessment will be used to inform evaluation of the existing conditions, future without project conditions, and proposed conditions based on implementation of alternatives. Additionally, the information in the assessment will be considered in the screening of measures. Only qualitative impacts of the climate changes will be assessed for the study.

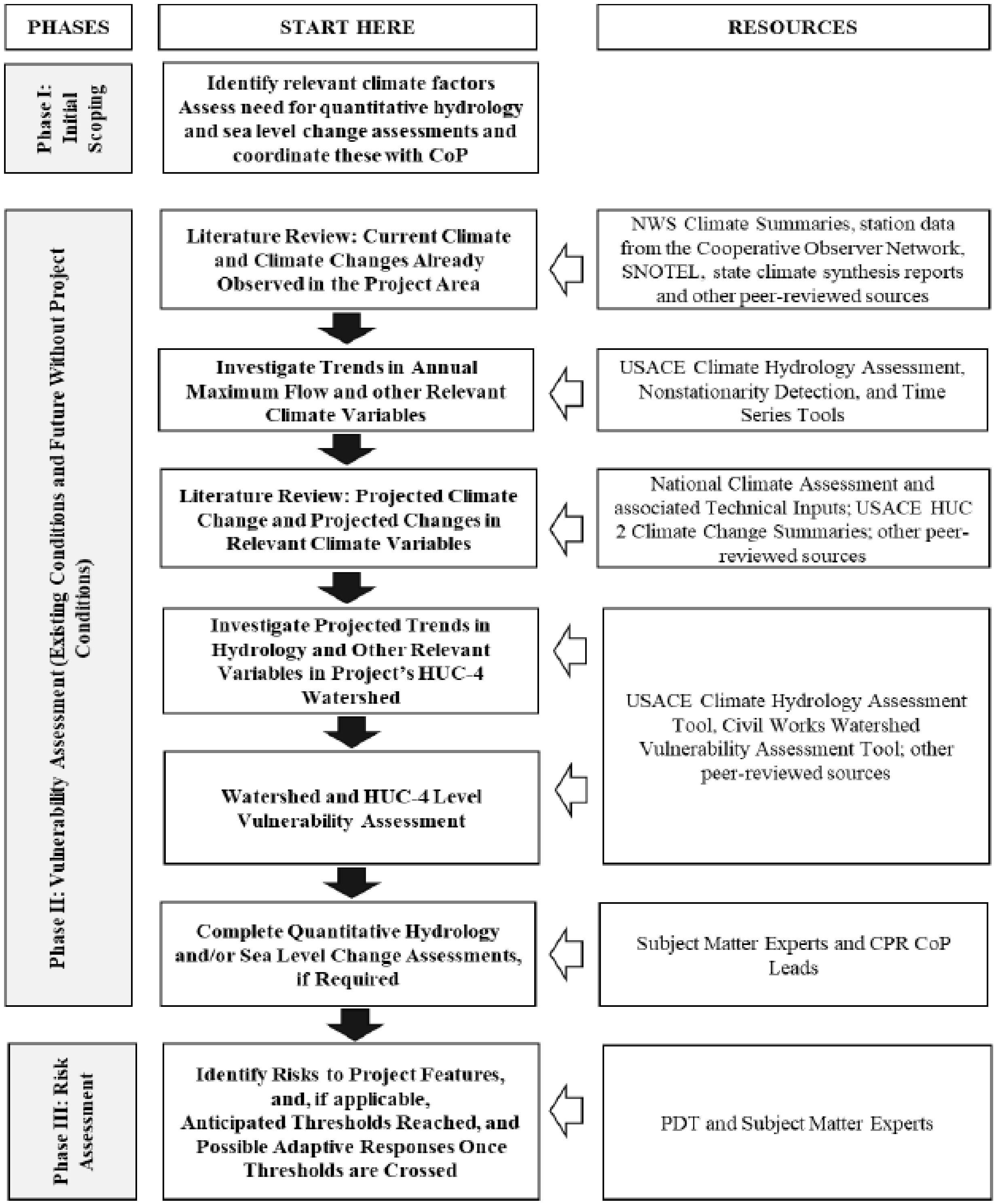


Figure 1: Climate Change Assessment Flowchart, ECB 2018-14 (USACE 2018)

1.1. **Purpose**

In the Kansas River Reservoirs Flood and Sediment Watershed Study (KRRFSS), USACE, Kansas City District is partnering with the State of Kansas and the Kansas Water Office to study impacts of sedimentation on federal reservoirs and the Kansas River Watershed. The study also addresses flood risk in the basin, which has experienced significant flooding in recent years. This qualitative climate change assessment was developed to evaluate the potential impacts of climate change on the study objectives, specifically evaluating impacts to sedimentation and flood risk, as well as ecosystem restoration and water supply within the Kansas River Basin.

The Kansas River Basin includes parts of Kansas, Colorado, and Nebraska. Within the Kansas River Basin, eighteen USACE and U.S. Bureau of Reclamation (Reclamation) dam and reservoir projects serve the purposes of Flood Risk Management, Irrigation, Water Supply, Water Quality, Navigation, Recreation, and Fish and Wildlife. Sedimentation in several of the reservoirs threatens the sustainability of operations to fulfill the authorized purposes. Flood risk is an ongoing concern in the Kansas River basin, especially in relation to USACE dams. Recent flood events have highlighted the operations of the Kansas River basin dams for Missouri River control points, and the influence of Missouri River flooding on the dams' operations.

2. Existing Conditions

2.1. Literature Review: Current Climate and Climate Changes Observed in the Project Area

A literature synopsis was generated to summarize published conclusions regarding both natural and anthropogenic climate trends in the Kansas River Basin established from observed climate changes.

2.1.1. Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions (USACE, 2015)

This report is 1 of 21 regional climate syntheses prepared at the scale of 2-digit USGS Hydrologic Unit Codes (HUC) across the United States. The area covered by the Region 10 report is shown in Figure 2. The red outline shows the extents of the Kansas River Basin. The report for the Missouri River Region 10 summarized observed and projected climate trends.

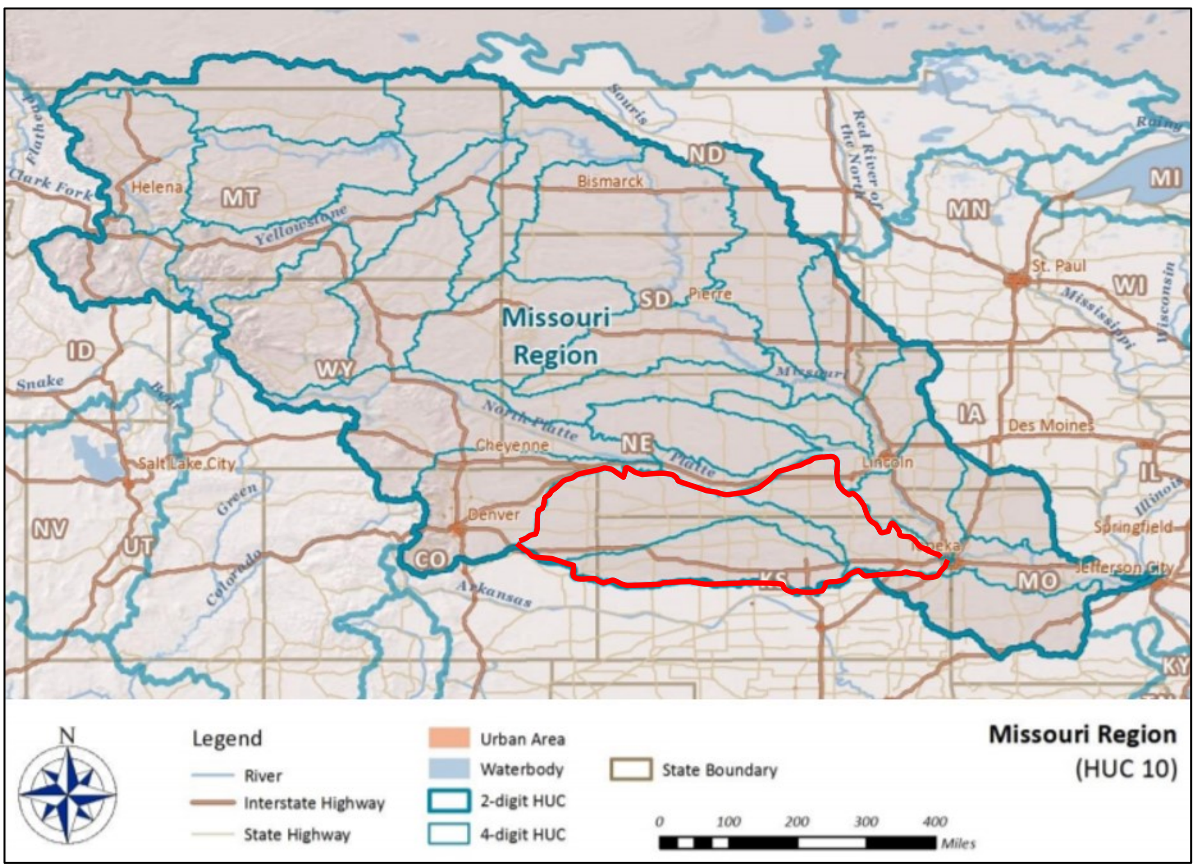


Figure 2. Water Resources Region 10: Missouri River Region Boundary

The general consensus in the literature pointed toward mild increases in average temperature and streamflow in the Missouri River Region over the past century. In some studies, and some locations, statistically significant trends were quantified. In other studies, and locales within the region, apparent trends were merely observed graphically but not statistically quantified. There was a clear consensus that the growing season in the Missouri River Region is lengthening; however, there was little evidence of increased extreme temperature in the region. Spatial variability was observed in the literature review for observed precipitation and precipitation extremes. The lower portion of the region generally showed increasing trends for both observed precipitation and precipitation extremes. There was some evidence of increased frequency in the occurrence of extreme storm events in the lower portion of the region.

2.1.2. Fourth National Climate Assessment (U.S. Global Change Research Program, 2018)

Chapter 8 of the 4th National Climate Assessment states that trends in flooding in the U.S. are mixed with some areas of increase, and others of decrease. Chapter 7 of the report addresses trends in precipitation. Figure 3 depicts the annual and seasonal differences in precipitation between the 1901-1960 and 1986-2015 periods. Average annual precipitation has increased from approximately 0 to 15% in the Kansas River basin.

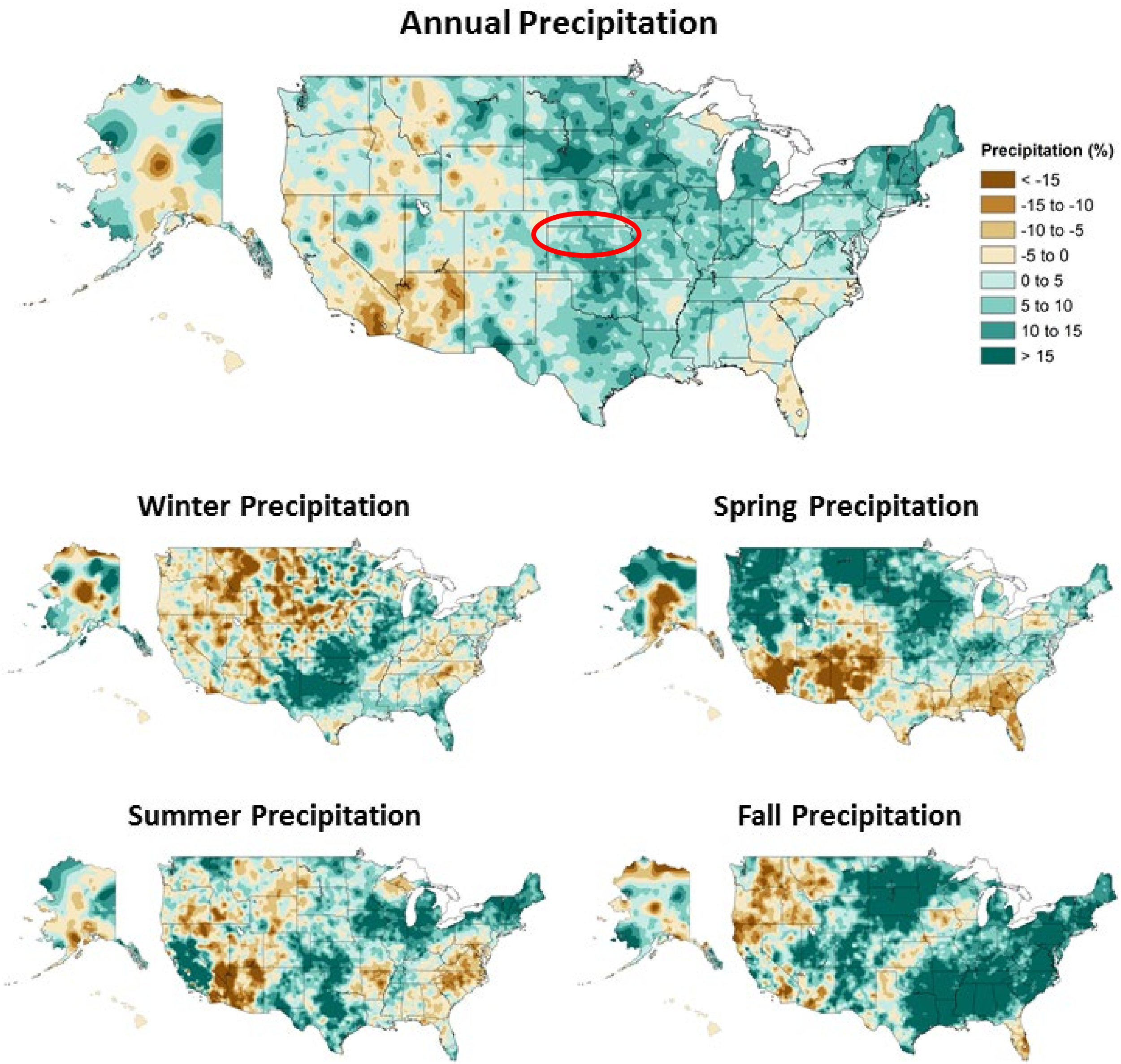


Figure 3: Annual and seasonal changes in precipitation over the United States (NCA4, 2019)

Figure 4 shows the observed annual and seasonal (i.e. winter and summer) temperature changes across the U.S. for the period 1986-2016 compared to a baseline (1901-1960 for the contiguous United States). The Southern Great Plains including the Kansas River Basin has experienced the greatest warming during the winter months, where temperatures have increased between 1°F and 2°F. In the Kansas River Basin, trends for summer temperatures are mixed. Higher temperatures result in increased evapotranspiration potential, drying soils and watersheds. Flood season in the Kansas River Basin is generally in the spring and summer, thus any cooling in summer temperatures may create more favorable antecedent moisture conditions that, when coupled with a large precipitation event, may tend to increase flood potential.

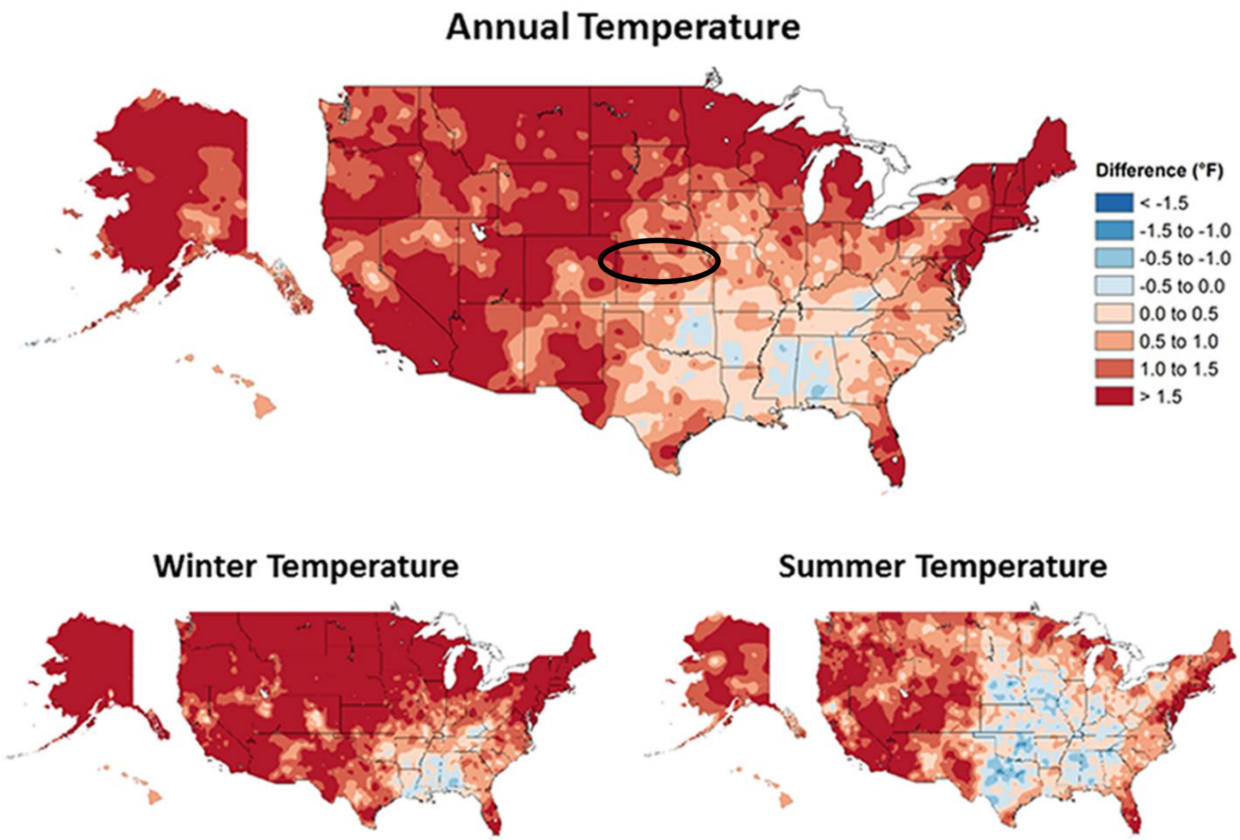


Figure 4: Observed changes in annual, winter, and summer temperature (°F)

2.1.3. USGS Flood Trends Report: Fragmented patterns of flood change across the United States (Archfield, 2016)

The USGS carried out an assessment of whether trends in flood magnitudes were consistent within geographic regions of the United States. Regional trends were assessed in the frequency, duration, peak magnitude, and volume of flood events by 400 km by 400 km grid cells (41 grid cells) across the United States. The study found that although changes in trends in the peak magnitude, frequency, duration, and volume of frequent floods were observed at specific locations throughout the continental U.S, there was not strong geographical cohesion between these site-specific observations. The report also noted that within a given region, the changes for watersheds in close proximity can be very different from each other.

The results of this study indicated there are no notable regional trends in peak magnitude within the Kansas River basin as shown in Figure 5. However, positive trends were present in the Kansas River basin for duration and volume. Frequency displayed a negative trend.

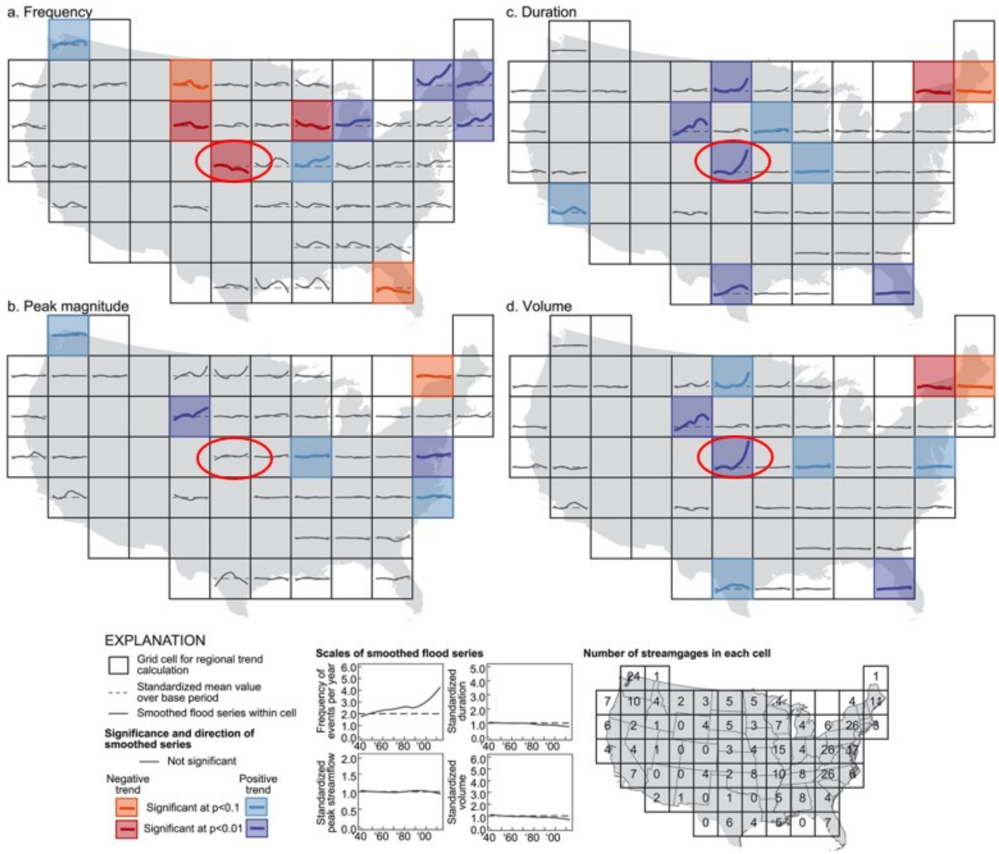


Figure 5. Regional changes in floods across the United States (1940-1969 vs 1970-2013)

2.1.4. Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage (Brikowski 2008)

This study evaluated the effect of decreasing stream flows on federal reservoirs in the Great Plains. Historically, these decreases have been related to groundwater mining, but they are expected to continue under climate change. The area studied includes the upper portions of the Kansas River Basin which are semi-arid. Brikowski indicates that there is a 70% chance of steady decline for Cedar Bluff Reservoir after 2007 with a 50% chance of the inability to make gravity releases from the reservoir due to extreme low pool level between 2007 and 2050. Models from the study predicted greater than a 50% probability of decline in surface water resources between 2007 and 2050 with 95% confidence.

2.1.5. Literature Review Summary

The strongest consensus amongst the literature supports the observed trend of increasing temperatures and precipitation in the basin. The literature is conflicted as to the trends associated with flood frequency and magnitude.

2.2. **Relevant Climate Variables**

For the KRRFSS, relevant climate variables include those that have impact on flood risk and sedimentation processes. Specifically, streamflows, including inflows to reservoirs and streamflows below reservoirs, impact flood risk. Streamflows also influence the amount of sedimentation occurring in the reservoirs. Factors that influence streamflow include precipitation depths, extents, and timing within the year, temperatures throughout the basin, and other non-climate factors (land use, etc.). Streamflow, precipitation, and temperature are relevant climate variables; however, only streamflow was evaluated in this climate change assessment. Temperature is often used to identify sudden snow melt events; however, snow melt generally does not induce flooding in the Kansas River basin and is not a significant driver of streamflow. Temperature and precipitation both affect soil moisture, which affects the amount of runoff that occurs for a given precipitation event. Since changes in temperature and precipitation do not always directly lead to changes in streamflow, no detailed analysis of historic precipitation changes in the Kansas River Basin was performed for this analysis.

The important hydrologic variables affecting the rivers include water surface elevation (stage) and discharge. Stage, although a relevant hydraulic variable, is not a hydroclimate variable, but is dependent on discharges which may be affected by climate change. Besides fluctuations in climate, stage can also be influenced by long-term geomorphic change and gage relocation. Discharge can be influenced by changes in land-use, channel realignment, dams, levees, and measurement techniques. These factors can make it difficult to determine the role of climate change in affecting the hydrologic signal at the project scale. The relevant question to answer at the project scale is whether there has been, or will be, a change that affects conditions in the study area and how this change would impact the resilience of existing or proposed projects. Discharge was chosen as the primary hydrologic variable to analyze for the study. Streamflow can be used to indicate non-stationarities in the record, and therefore in the underlying hydrologic processes.

2.3. **Mainstem Kansas River Nonstationarity and Trend Analyses from Unregulated Streamflow**

The study area, including the reservoirs and mainstem stream gages analyzed, is shown in Figure 6. The five mainstem Kansas River gages were the primary gages used in the nonstationarity analyses. Other gages along the Kansas River were not included due to short or incomplete period of records. A summary of the gages is listed in Table 1. Observed daily flow values at the USGS gage locations were transformed to unregulated flows by USACE, Kansas City District, Water Management to remove regulation impacts from upstream reservoirs. Period of record reservoir inflow and outflow data were used to compute reservoir holdouts (Inflow minus Outflow). Daily holdouts were then routed downstream to applicable gages using spreadsheet coefficient routing and added to the observed flow hydrographs to estimate the unregulated daily flow values. The development of the unregulated flow data set is documented in "Natural Flow Calculation for the Kansas River at Kansas City". Effects of removal of water for irrigation and municipal/industrial uses (streamflow depletions) were not accounted for in the unregulated flows. Irrigation affects are significant in the Kansas River Basin; however, they are not expected to significantly impact flood peaks analyzed for the non-stationarity analysis. Significant non-stationarities not attributable to other events in the basin were not found; therefore, it was not deemed necessary to remove the depletions from the unregulated flow dataset. Annual maxima (calendar year) from the daily time series were used in this analysis. The data were exported from HEC-DSSVue and into Excel as a .csv file so that they could be uploaded into the web-based Time Series Toolbox. Twelve statistical methods were applied in the Nonstationarity Detection Analysis. These methods are listed in Table 2.

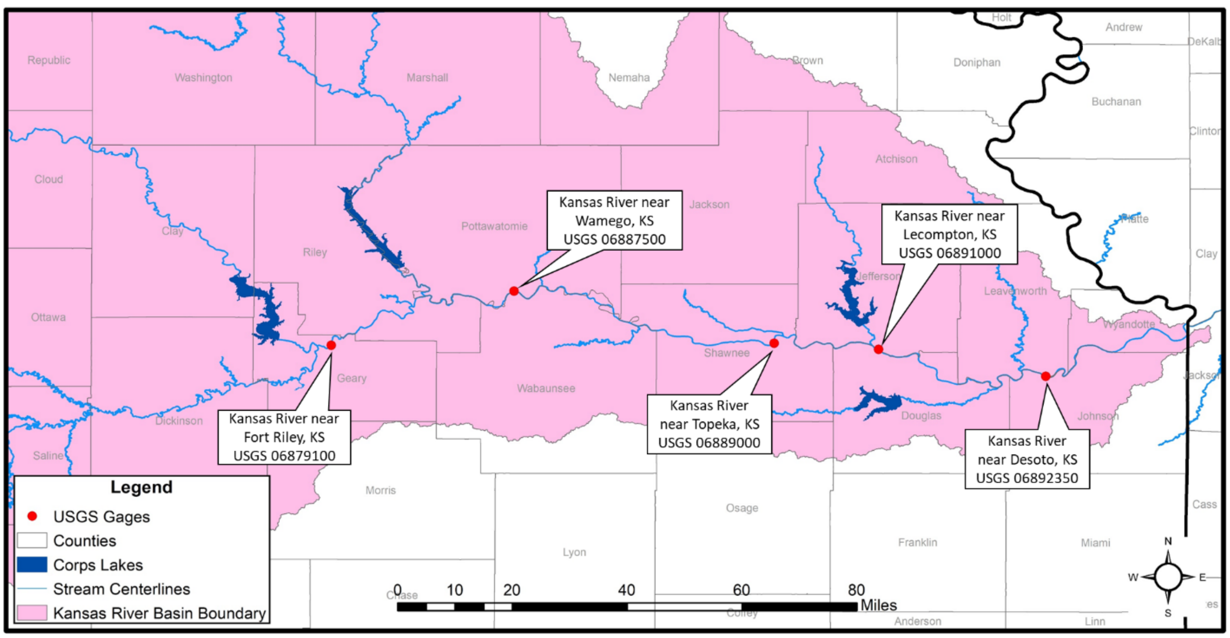


Figure 6. Map of Study Area

Table 1. Summary of Gage Data

USGS Gage	Period of Record	Drainage Area (sq. mi.)	Significant Remarks
Kansas River at Fort Riley, KS (06879100)	1918-2019	44,870	Flow data prior to 1952 was obtained from USGS gage 06879500 Kansas River at Ogden, KS. Data for 1952-1963 was obtained from the Manhattan Feasibility Study, USACE, Kansas City District.

USGS Gage	Period of Record	Drainage Area (sq. mi.)	Significant Remarks
Kansas River at Wamego, KS (06887500)	1919-2019	55,280	
Kansas River at Topeka, KS (06889000)	1918-2019	56,720	
Kansas River at Lecompton, KS (06891000)	1937-2019	58,460	
Kansas River at Desoto, KS (06892350)	1919-2019	59,756	Flow data prior to 1974 was obtained from USGS gage 06892500 Kansas River at Bonner Springs, KS.

Table 2. Statistical Method Abbreviations Applied in the Nonstationarity Analyses

Abbreviation	Statistical Method	Abbreviation	Statistical Method
CVM	Cramer-von-Mises	MW	Mann-Whitney
KS	Kolmogorov-Smirnov	BAY	Bayesian Change Point
LP	LePage	LM	Lombard Mood
END	Energy Divisive	MD	Mood
LW	Lombard Wilcoxon	SLM	Smooth Lombard Mood
PT	Pettitt	SLW	Smooth Lombard Wilcoxon

The strength of a nonstationarity can be determined by the level of consensus and robustness between the various tests. Consensus occurs when two or more statistical methods of the same type (mean, variance, distribution) identify a nonstationarity in the same year or short period of time. A nonstationarity can be discounted if a consensus does not occur. Robust results occur when multiple different methods identify a nonstationarity in the same year or short period of time (USACE, 2018). The Smooth methods, Smooth Lombard Mood and Smooth Lombard Wilcoxon detect gradual changes in the mean, variance/standard deviation, and/or distribution of the annual peak data, whereas the other methods only detected abrupt changes by separating the period of analysis into separate subsets of data.

2.3.1. Fort Riley Gage Flows

The unregulated flows for the Fort Riley gage (USGS 06879100) range from 1918 to 2019, although there is a gap of missing data from 1952 to 1963. The gap was supplemented with unregulated annual maximum daily peak flow values from the Manhattan Feasibility Study, USACE, Kansas City District. Flow data prior to 1952 was taken from the Kansas River at Ogden, KS USGS streamgage (06879500). The Ogden gage location was approximately 6.5 miles downstream of the current Fort Riley gage, with a drainage area (45,240 sq.mi) 0.8% greater than at Fort Riley (44,870 sq.mi.), therefore flows were included in the record without adjustment. The combined streamflow record was uploaded to the Time Series Toolbox and the nonstationarity analysis was performed using the default sensitivity parameters shown in Table 3.

Table 3. Default, Minimum, and Maximum Nonstationarity Detection Tool Sensitivity Parameters

Sensitivity Parameters	Default	Min	Max
CPM Methods Burn-In Period	20	5	50
CPM Methods Sensitivity	1,000	500	10,000
Bayesian Posterior Threshold/Sensitivity	0.5	0	1
Energy Divisive Method Sensitivity	0.5	0.1	0.9
Pettitt Sensitivity	0.05	0.01	0.15
Bayesian Prior Likelihood	0.2	0.05	0.95

Figure 7 shows the results using the default parameters. Multiple tests detected nonstationarities in 1940. Three distribution-based tests (Cramer-Von-Mises, LePage, and Energy Divisive methods) and one mean-based test (Mann-Whitney). The mean-based Lombard-Wilcoxon test also detected a nonstationarity in 1939. There is a consensus between the methods, and results are robust, strongly indicating that a non-stationarity occurred. The changepoint detected in 1939/1940 is likely due to the 1930's drought, and rebounding streamflows following the drought. However, peak flows in the 1920's also appear to be significantly lower than the following decades.

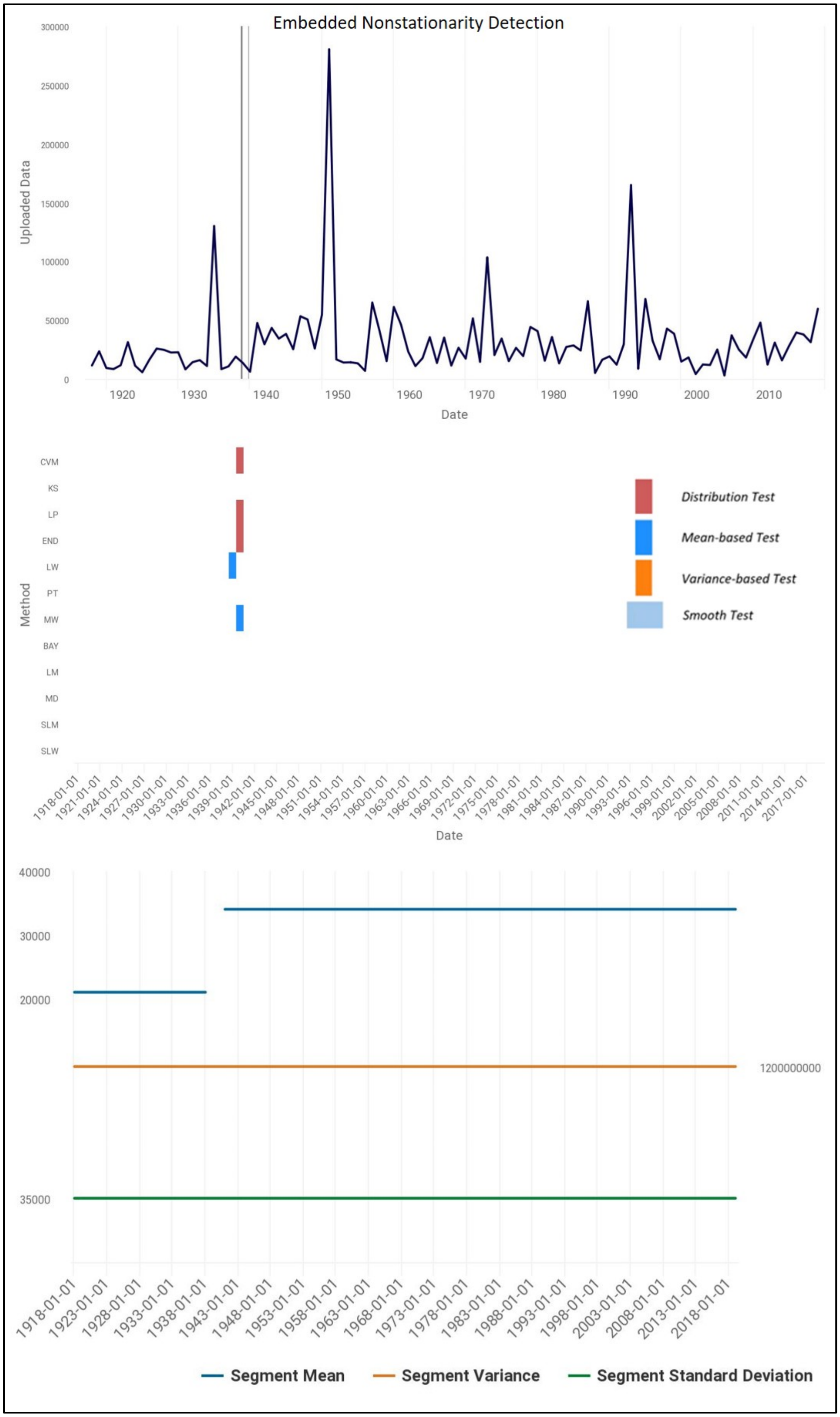


Figure 7. Nonstationarity Detection Analysis for Fort Riley Gage Unregulated Flows using Default Parameters (1918-2019)

A sensitivity analysis was completed to determine if slight adjustments in the parameters would remove the nonstationarities or detect additional nonstationarities. Each parameter was individually adjusted to the minimum and maximum value while the others were kept at the default values. Changes in the results occurred when the CPM Methods Burn-In Period, the CPM Methods Sensitivity, and the Pettitt Sensitivity parameters were adjusted. However, no additional nonstationarities were detected. When the CPM Methods Burn-In Period was adjusted from 20 to 25, the nonstationarity in 1939 was eliminated. When the CPM Methods Sensitivity Parameter was adjusted from 1,000 to 1,250, only the END method detected a nonstationarity in 1940. Figure 8 shows the results with both parameter adjustments. A slight increase in the Burn-In Period is reasonable for the period of record length. Given the cyclical weather patterns this area experiences and the drought occurrence in the 1930’s, it is reasonable to reduce the sensitivity to the CPM parameter by one notch. Results with the adjusted sensitivity parameters do not show consensus between methods, nor robust results; therefore, the entire period of record may be considered stationary.

An additional sensitivity test was performed to determine if the Fort Riley streamflows after 1940 could be considered stationary. No nonstationarities were detected using the Time Series Toolbox, as shown in Figure 9.

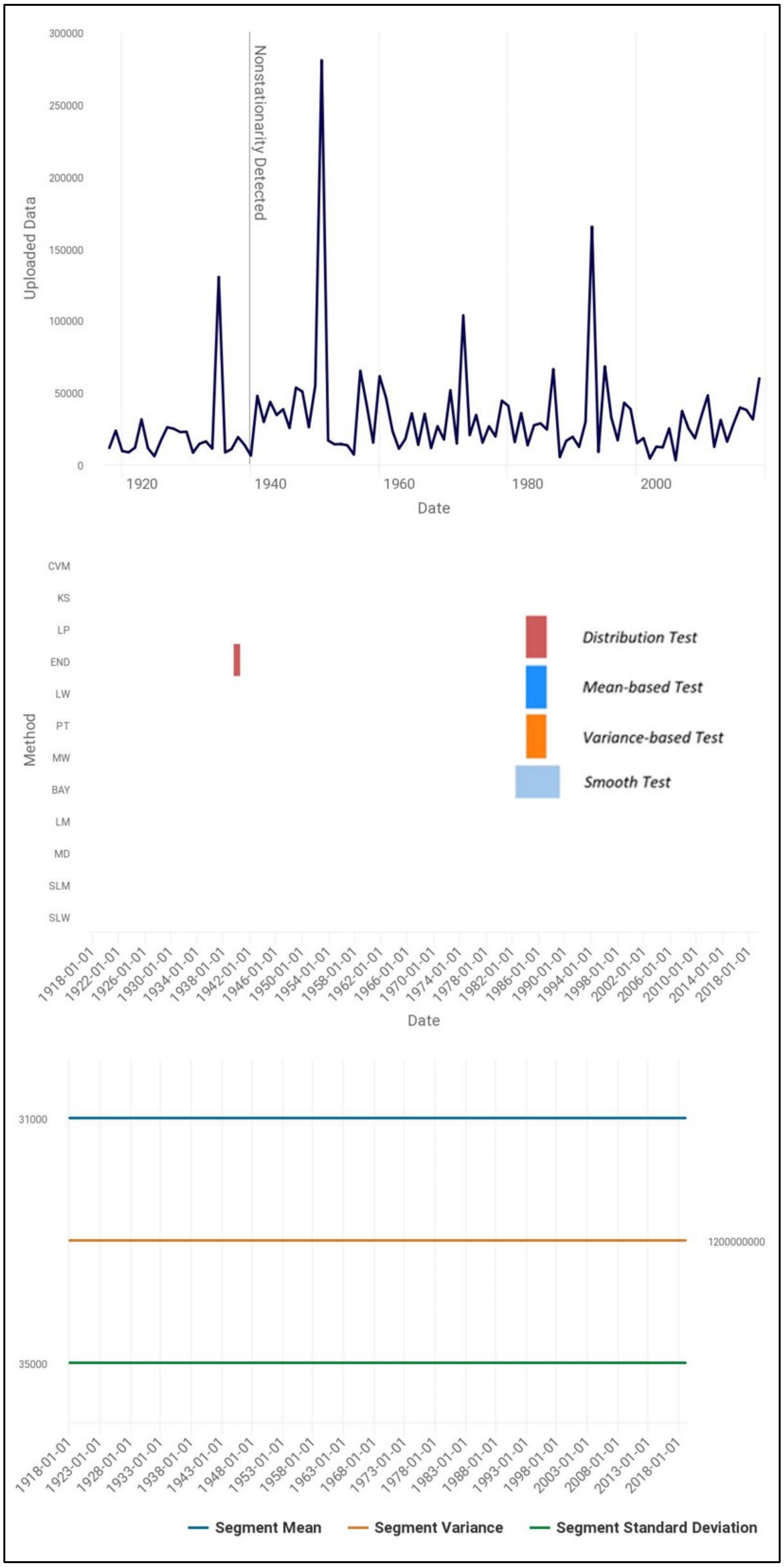
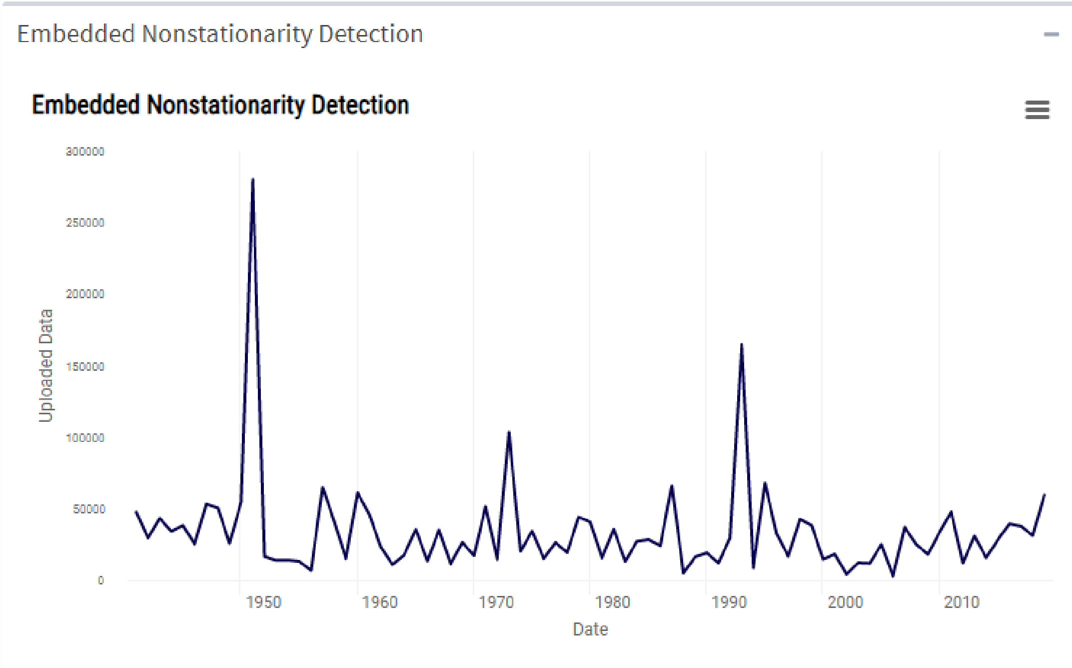


Figure 8. Nonstationarity Detection Analysis for Fort Riley Gage Unregulated Flows (1918-2019) with the CPM Methods Burn-In Period and Sensitivity Parameters Adjusted to 25 and 1,250, Respectively



Statistical Tests

No nonstationarities detected!

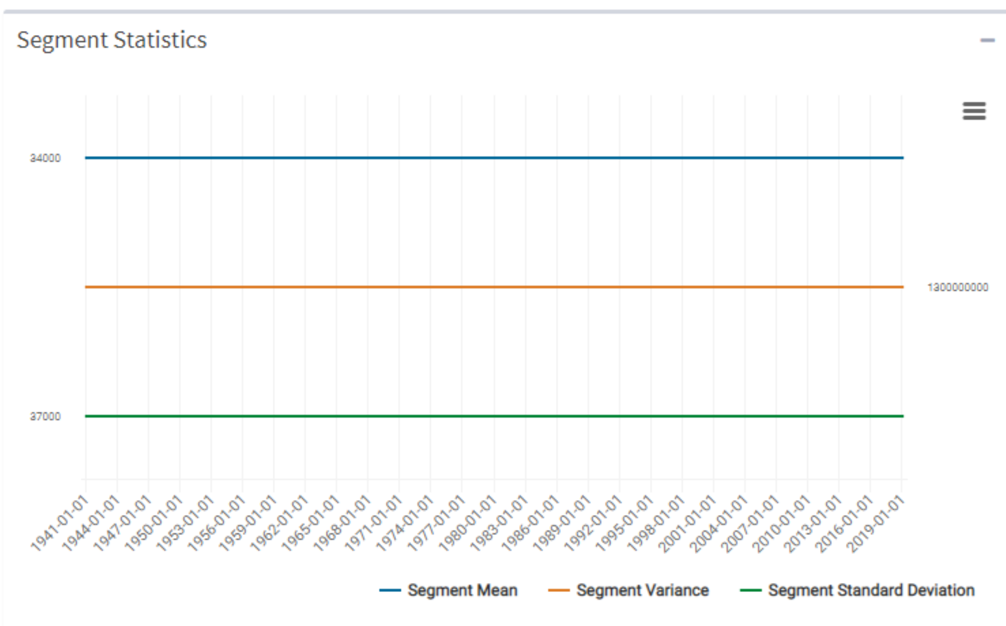
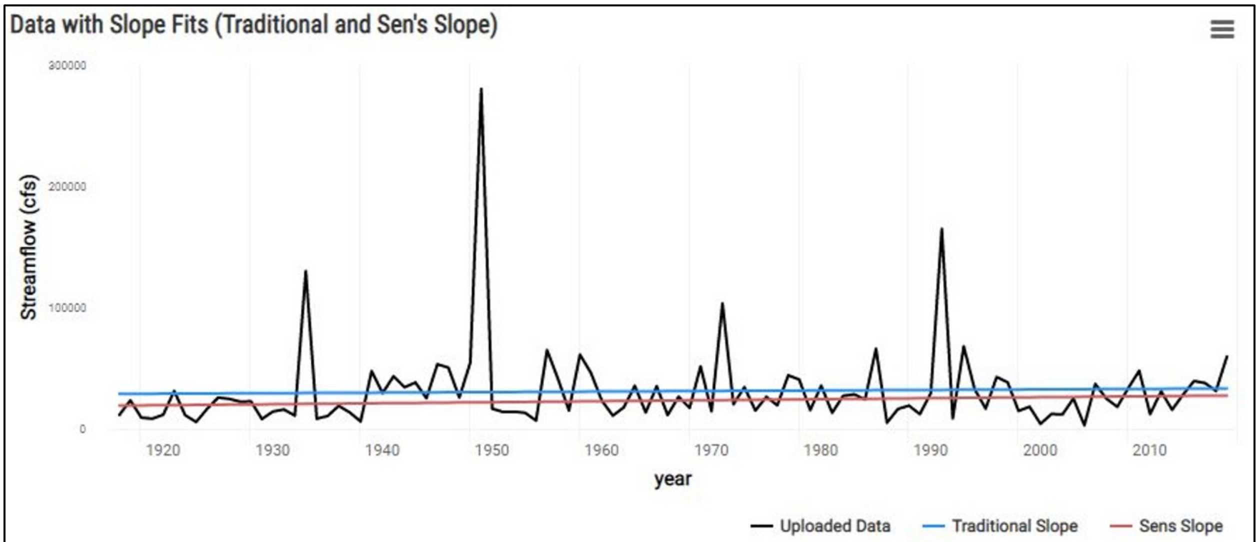


Figure 9: Nonstationarity Detection results for post 1940 Fort Riley flows

A trendline analysis was conducted for the Fort Riley unregulated flow. The results are provided in Figure 10. Both the traditional and Sen's trendlines show an upward slope with a maximum slope of 82.5 cfs/year, indicative of increasing streamflow. However, no statistically significant trends were detected by the Spearman Rank-Order Test or the Mann-Kendall Test.



Trend Line Coefficients

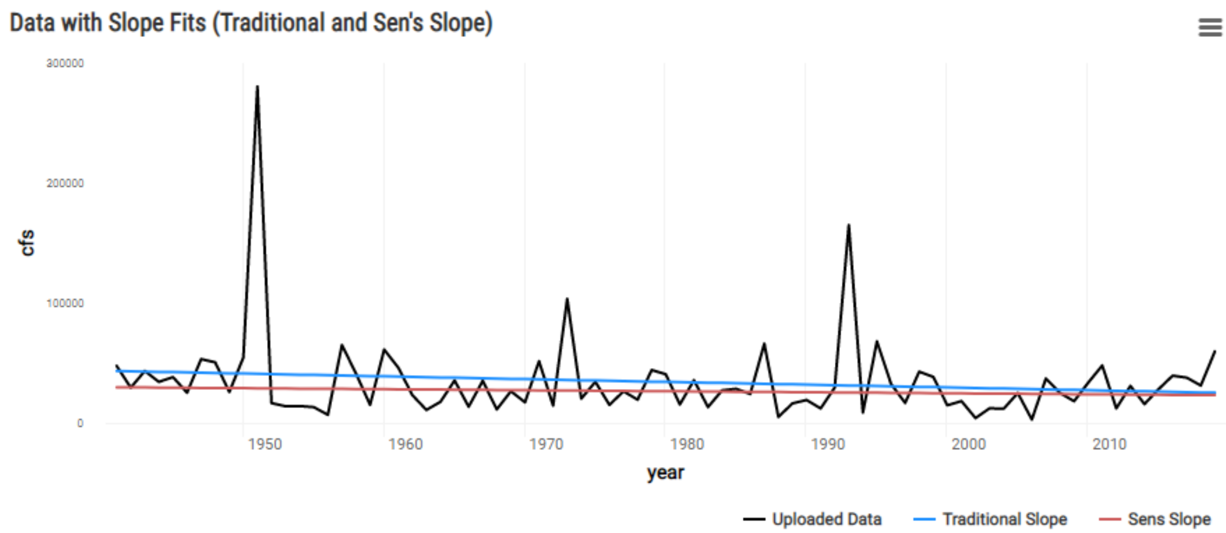
Method	Slope	Intercept
Traditional Slope	44.347	-56286
Sen's Slope	82.513	-139130

Test	P.Value
t-Test	0.70586
Mann-Kendall	0.059407
Spearman Rank-Order	0.051088

- **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.**

Figure 10: Fort Riley Gage Trend Analysis Results from Time Series Toolbox (1918-2019)

Trend analysis was also performed on the peak annual flows after 1940. When using the shortened period of record, no statistically significant trend in annual peak streamflow was detected. Figure 11 shows the trend analysis for the Fort Riley gage post 1940 streamflow record. To confirm there was no influence of the data added from the Ogden gage (pre-1962), the trend analysis was also run with the period of 1962-2019. Figure 12 shows that the analysis did not detect a statistically significant trend. Since only a weak non-stationarity was detected in 1940 with the adjusted detection parameters, and no statistically significant trend in annual peak streamflow was present, the entire period of record of can be considered stationary.



Trend Line Coefficients

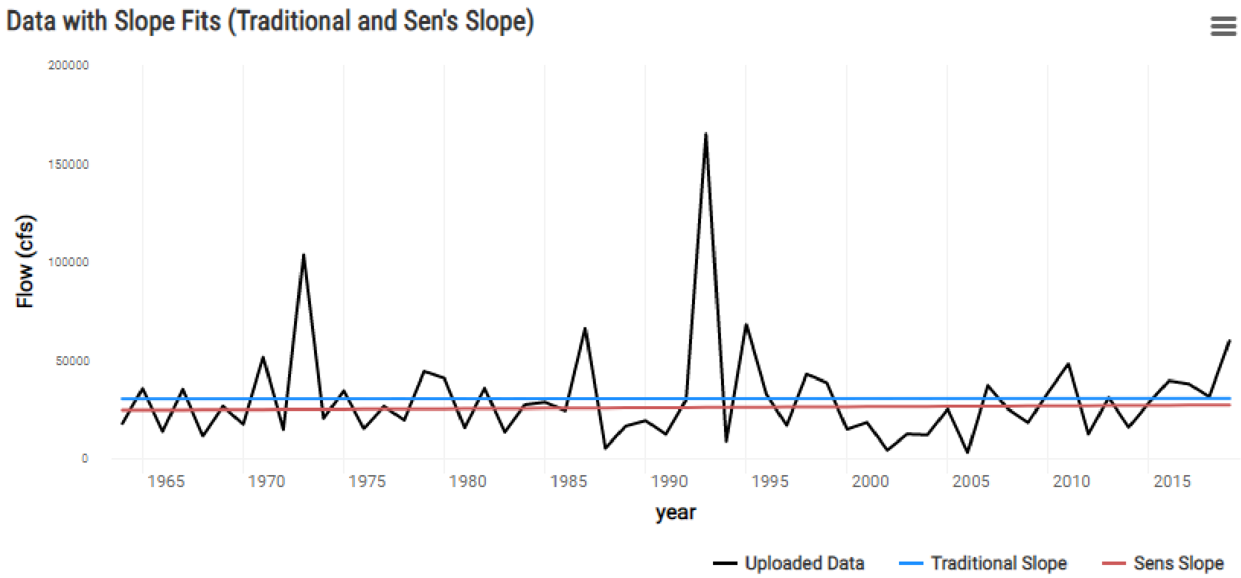
Method	Slope	Intercept
Traditional Slope	-231.3	492190
Sen's Slope	-84.367	193460

Source: Fort_Riley pre-1940 trimmed_Manhattan_FS_supplement.csv

Test	P.Value
t-Test	0.20163
Mann-Kendall	0.30164
Spearman Rank-Order	0.26022

- **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.**

Figure 11: Fort Riley Gage Trend Analysis Results from Time Series Toolbox (Post-1940)



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	4.2239	21838
Sen's Slope	47.688	-69325

Test	P.Value
t-Test	0.9843
Mann-Kendall	0.70797
Spearman Rank-Order	0.69006

- **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.**

Figure 12: Fort Riley Gage Trend Analysis Results from Time Series Toolbox (Post-1962)

2.3.2. Wamego Gage Flows

The unregulated flow record for the Wamego gage ranges from 1919 to 2019. The flow data was uploaded to the Time Series Toolbox and the results for the nonstationarity analysis using the default parameters (see Table 3) is shown in Figure 13. Similar to Fort Riley, there seems to be a significant nonstationarity consensus in 1940 when using the default sensitivity parameters. Four test methods detected change points in 1940, three of which are distribution-based tests. These are the CVM, LP, and END methods. The fourth is the MW method which is a mean-based test. Additionally, the LW method detected a nonstationarity in 1939 which is also a mean-based test. The level of consensus between these tests, and robustness of multiple tested parameters detecting a non-stationarity indicate the non-stationarity detected in 1940 is strong. The changepoint detected is likely a result of the rebound of streamflow following the 1930's drought.

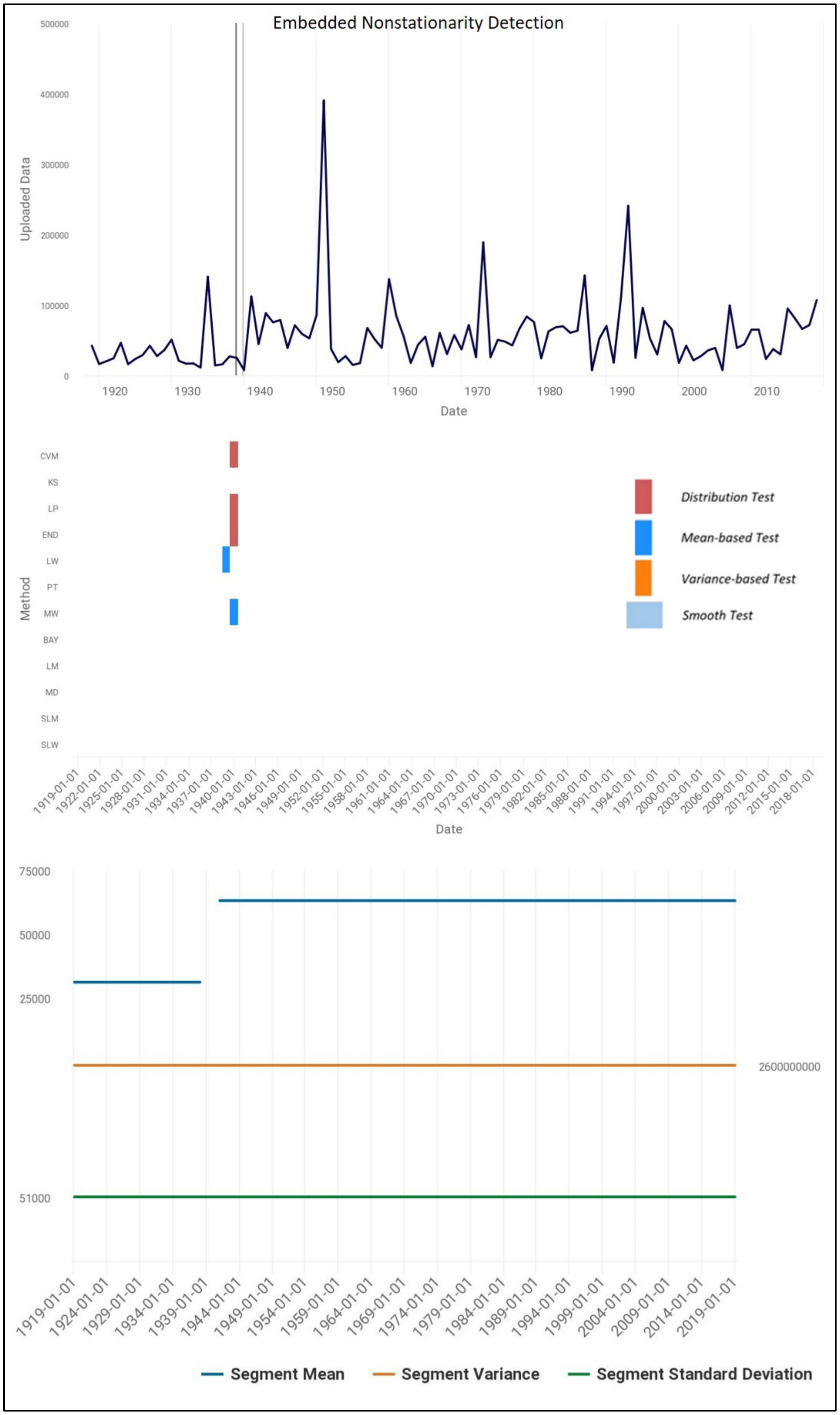


Figure 13**. Nonstationarity Detection Analysis for Wamego Gage Unregulated Flows using Default Parameters (1919-2019)**

A sensitivity analysis was completed to determine if slight adjustments in the parameters would remove the nonstationarities or detect additional nonstationarities. Each parameter was individually adjusted to the minimum and maximum value while the others were kept at the default values. Changes in the results occurred when the CPM Methods Burn-In Period and the CPM Methods Sensitivity parameters were adjusted. However, no additional nonstationarities were detected. When the CPM Methods Burn-In Period was adjusted from 20 to 25, the nonstationarity in 1939 was eliminated. When the CPM Methods Sensitivity Parameter was adjusted from 1,000 to 1,250, only the END method detected a nonstationarity in 1940. Figure 14 shows the results with both parameter adjustments. A slight increase in the Burn-In Period is reasonable for the period of record length. Given the cyclical weather patterns this area experiences and the drought occurrence in the 1930's, it is reasonable to reduce the sensitivity to the CPM parameter by one notch. With the adjusted parameters, only one method detected a non-stationarity. There is not consensus in the 1940 non-stationarity detected by the Energy Divisive method, and results are not robust.

An additional sensitivity test was performed to determine if the Wamego streamflows after 1940 could be considered stationary. Non-stationarity detection was performed on the 1941-2019 period of record, and no non-stationarities were found, as shown in Figure 15.

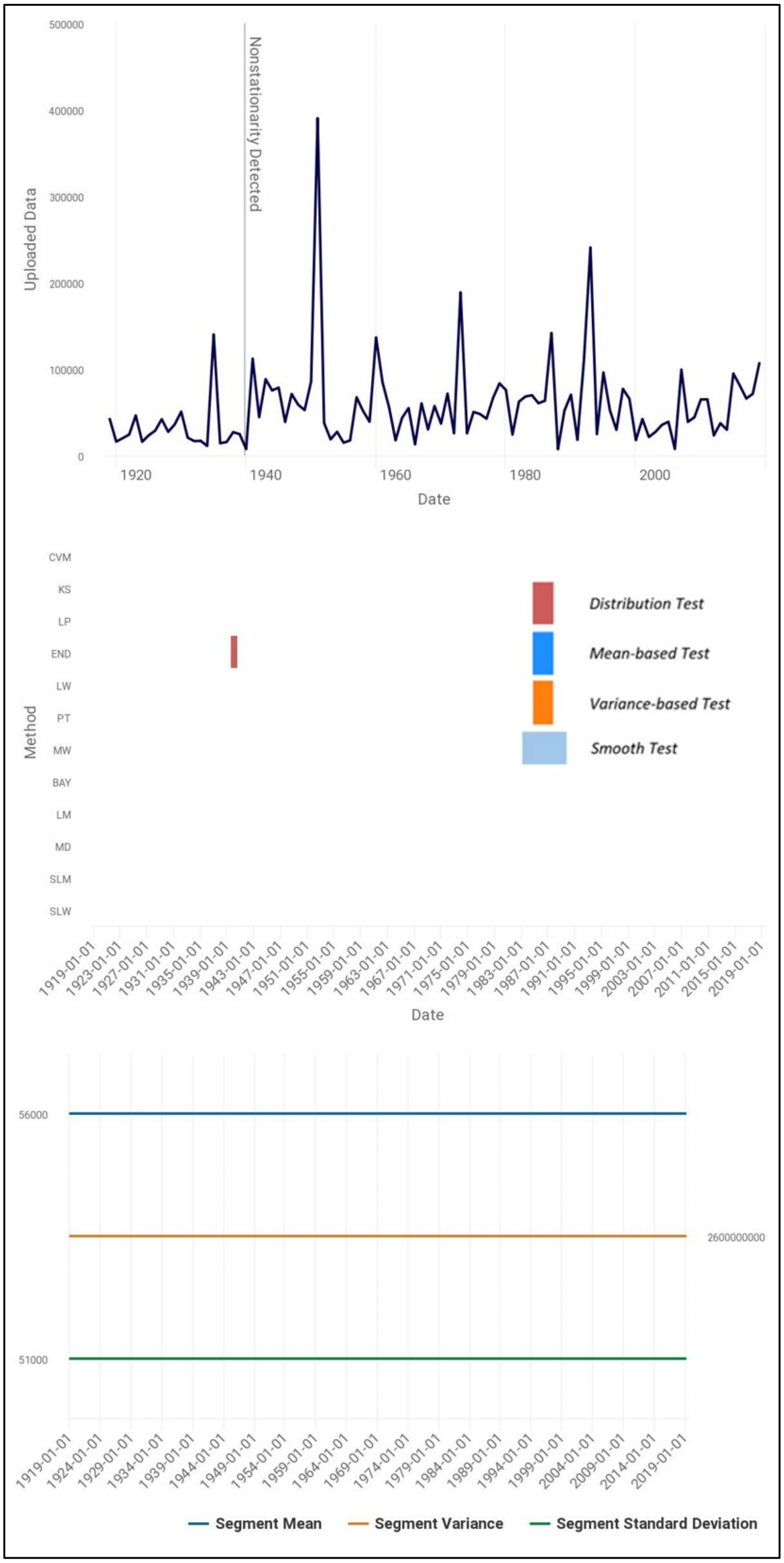
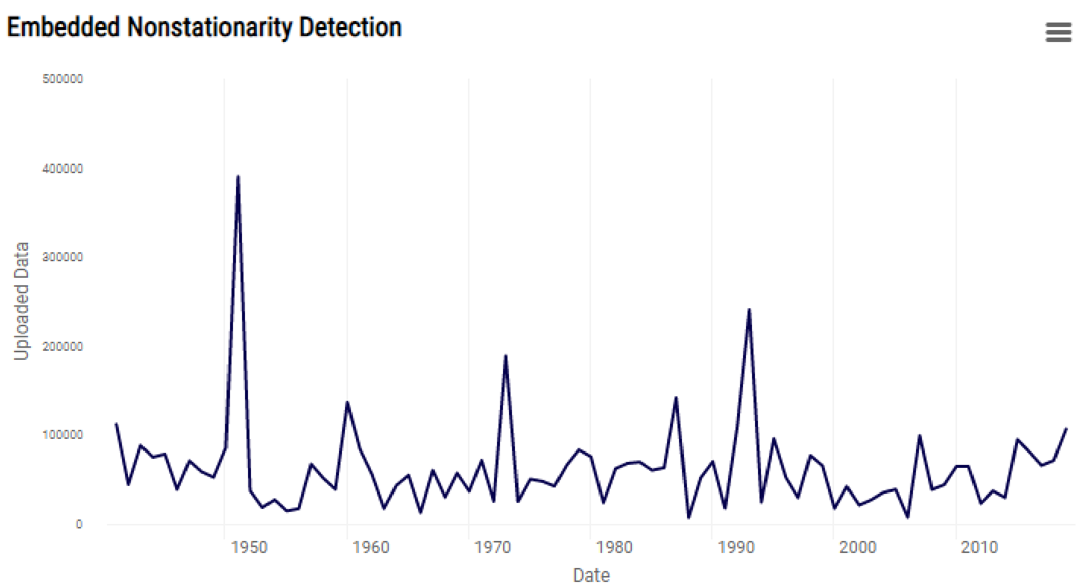


Figure 14. Nonstationarity Detection Analysis for Wamego Gage Unregulated Flows (1919-2019) with the CPM Methods Burn-In Period and Sensitivity Parameters Adjusted to 25 and 1,250, Respectively

Embedded Nonstationarity Detection



Statistical Tests

No nonstationarities detected!

Segment Statistics

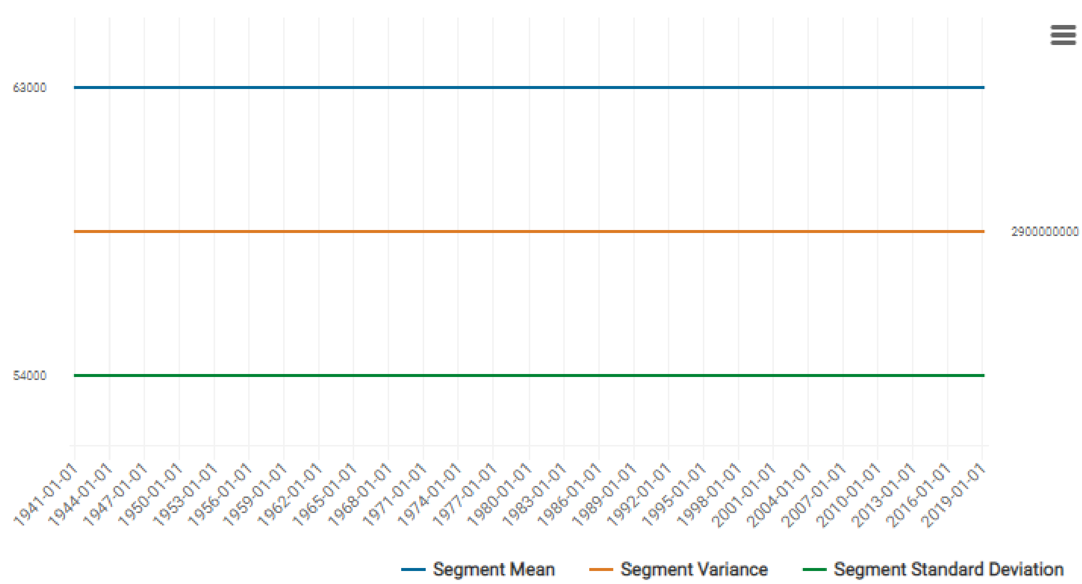
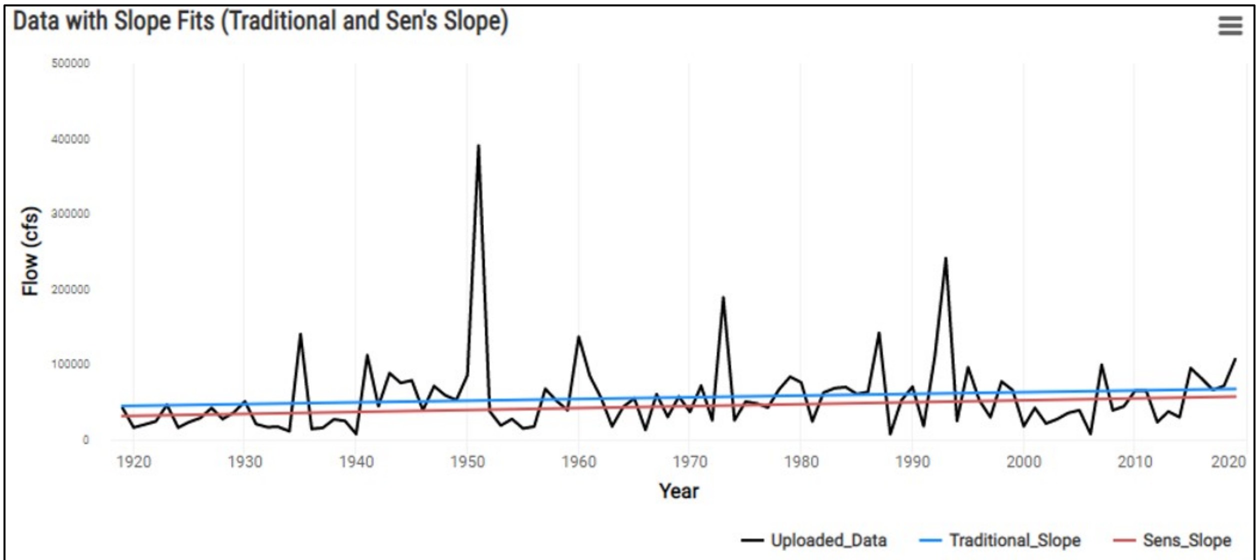


Figure 15: Nonstationarity Detection Analysis for Wamego Gage, 1941-2019

A trendline analysis was run for the Wamego unregulated flow record and the results are shown in Figure 16. Both the Mann-Kendall and the Spearman Rank-Order Test detected a statistically significant trend. The traditional and Sen's slope trendlines are increasing, with the Sen's slope being slightly larger at 257 cfs/year. The trend analysis indicates that the complete period of record should not be treated as stationary.



Trend Line Coefficients

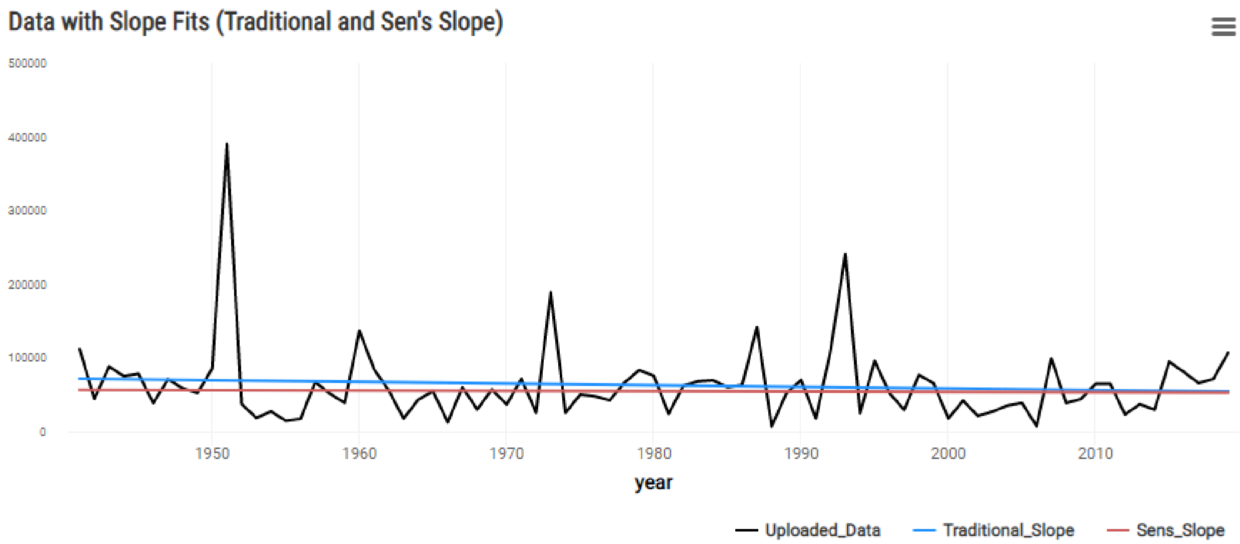
Method	Slope	Intercept
Linear Regression Slope	225.48	-388070
Sens Slope	257.31	-462510

Test	P.Value
t-Test	0.19452
Mann-Kendall	0.0067635
Spearman Rank-Order	0.0052454

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

Figure 16. Wamego Gage Trend Analysis Results from Time Series Toolbox (1919-2019)

Trend analysis was also performed on the peak annual flows after 1940. When using the shortened period of record, no statistically significant trend in annual peak streamflow was detected. Figure 17 shows the trend analysis for the Wamego gage post 1940 streamflow record. These results indicate that the period of record of 1941-2019 can be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-222.77	504130
Sens Slope	-47.113	148070

Test	P.Value
t-Test	0.4026
Mann-Kendall	0.76052
Spearman Rank-Order	0.70251

- **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.**

Figure 17: Wamego Gage Trend Analysis Results from Time Series Toolbox (Post-1940)

2.3.3. Topeka Gage Flows

The unregulated flow data for this gage location ranges from 1918 to 2019. The flow data was uploaded to the Time Series Toolbox and the results for the nonstationarity analysis using the default parameters (see Table 3) are shown in Figure 18. Four nonstationarities were detected using the default sensitivity parameters. The Cramer-Von-Mises, Energy

Divisive, and the Mann-Whitney test methods all detected a changepoint in 1940. The Lombard-Wilcoxon method picked up a change point in 1939. The CVM and END method are both distribution-based tests, while the LW and MW methods are both mean-based tests. These results indicate that the changepoints in 1939-1940 have consensus and are robust. Additionally, the large magnitude shift in the mean lends further evidence that this is a strong non-stationarity.

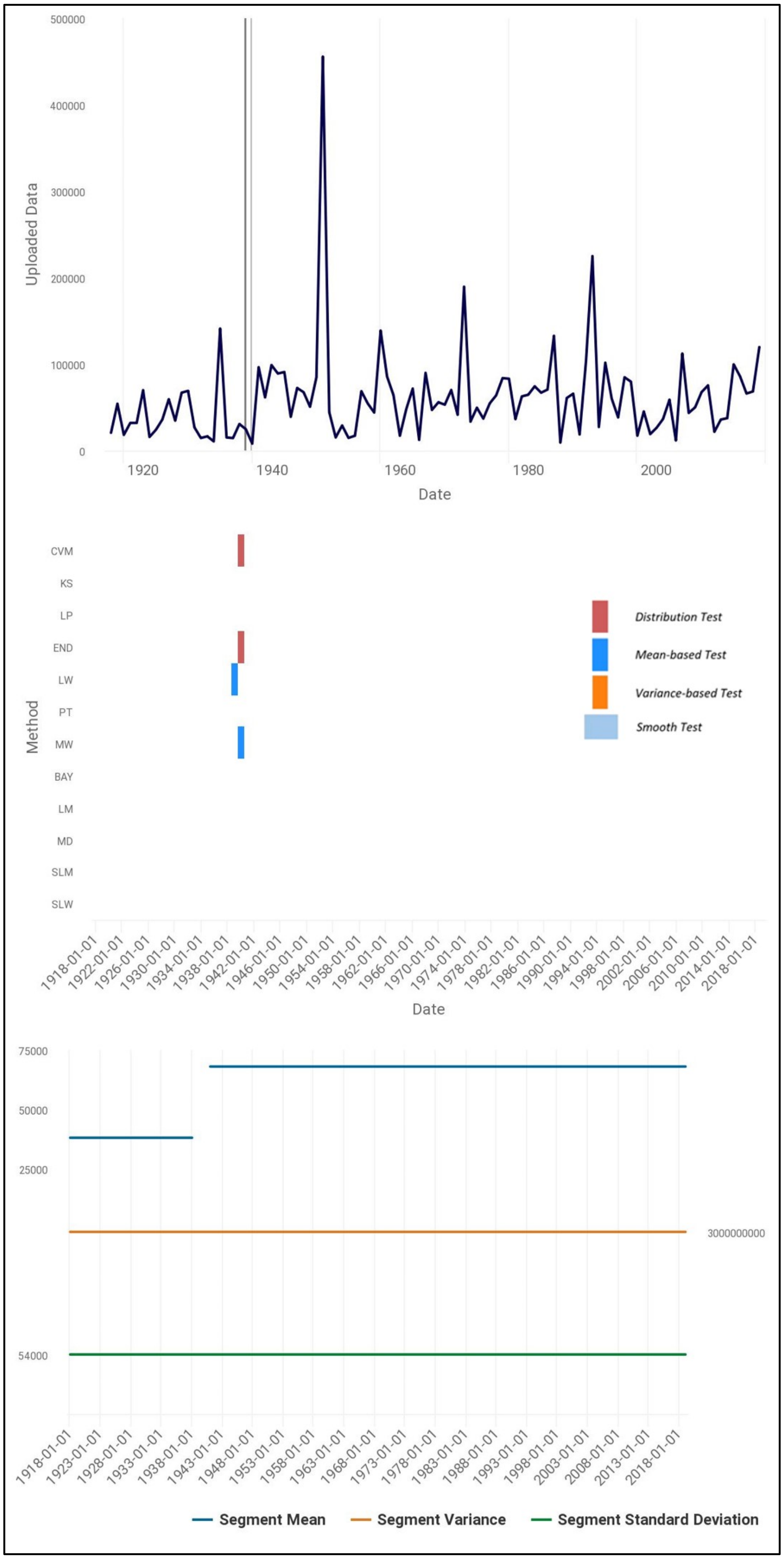


Figure 18. Nonstationarity Detection Analysis for Topeka Gage Unregulated Flows using Default Parameters (1918-2019)

A sensitivity analysis was completed to determine if slight adjustments in the parameters would remove the nonstationarities or detect additional nonstationarities. Each parameter was individually adjusted to the minimum and maximum value while the others were kept at the default values. Changes in the results occurred when the CPM Methods Burn-In Period, the CPM Methods Sensitivity, and the Pettitt Sensitivity parameters were adjusted. Reducing the CPM Methods Sensitivity parameter to 500 resulted in three more nonstationarities being detected as shown in Figure 19. The LePage (another distribution-based test) method detected a change point in 1940, further suggesting the possibility of a climate-related change. In addition, the Mood test detected change points in 1931 and 1945. With no significant agreement between other tests, these are not likely to be significant changepoints. Further adjustments yielded no other additional detections.

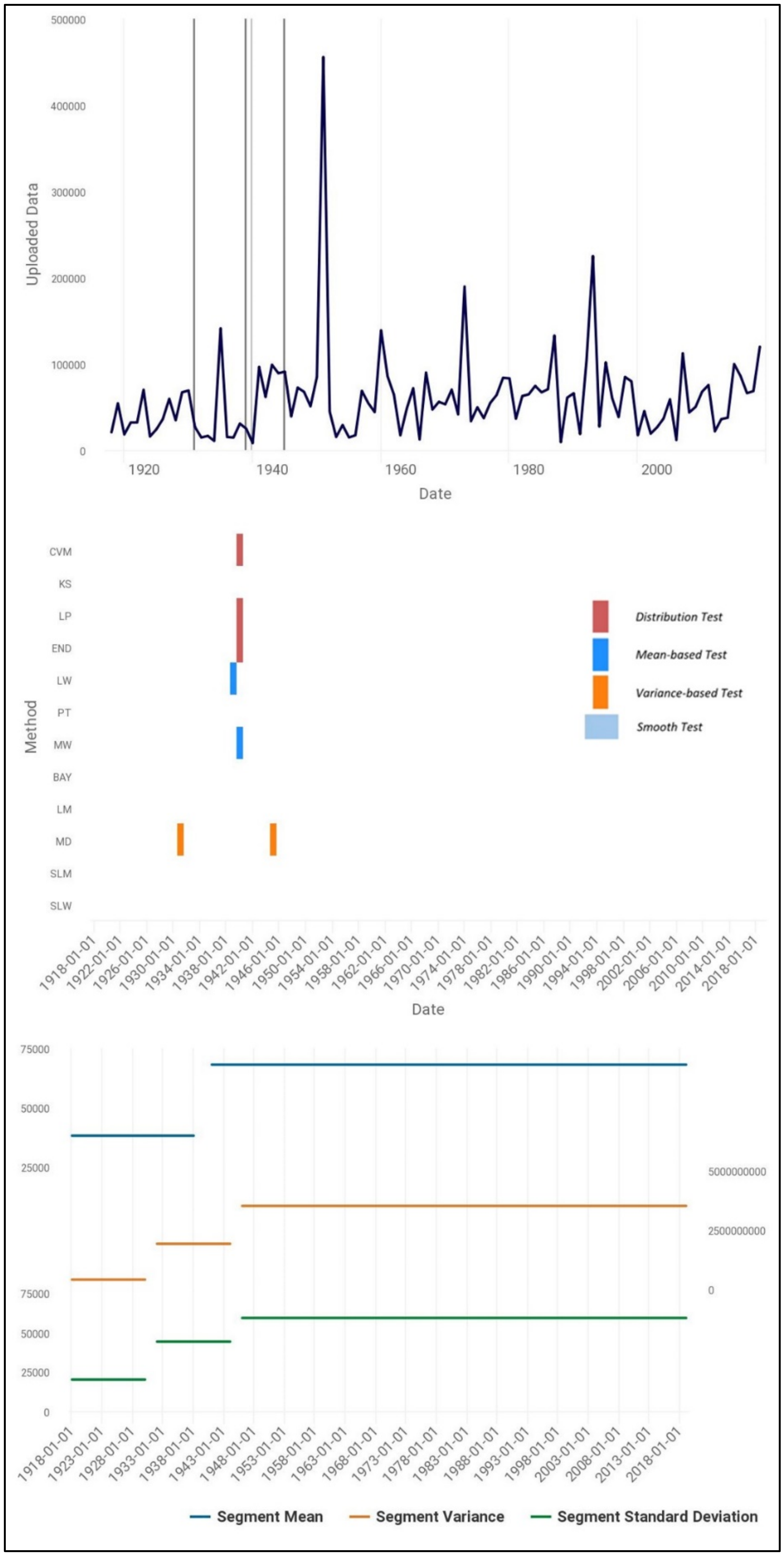


Figure 19. Nonstationarity Detection Analysis for Topeka Gage Unregulated Flows (1918-2019) with the CPM Sensitivity Parameter Adjusted to 500

When the CPM Methods Burn-In Period was adjusted from 20 to 25, the nonstationarity in 1939 was eliminated. When the CPM Methods Sensitivity Parameter was adjusted from 1,000 to 1,250, only the END method detected a nonstationarity in 1940. Figure 20 shows the results with both parameter adjustments. A slight increase in the Burn-In Period is reasonable for the period of record length. Given the cyclical weather patterns this area experiences and the drought occurrence in the 1930's, it is reasonable to reduce the sensitivity to the CPM parameter. With the parameter adjustments, only one method detected a non-stationarity. Due to the lack of consensus between methods, and no robustness in the detected non-stationarity, it is considered weak.

An additional sensitivity test was performed to determine if the Topeka streamflows after 1940 could be considered stationary. Figure 21 shows the results of the nonstationarity detection for 1941-2019. No nonstationarities were detected.

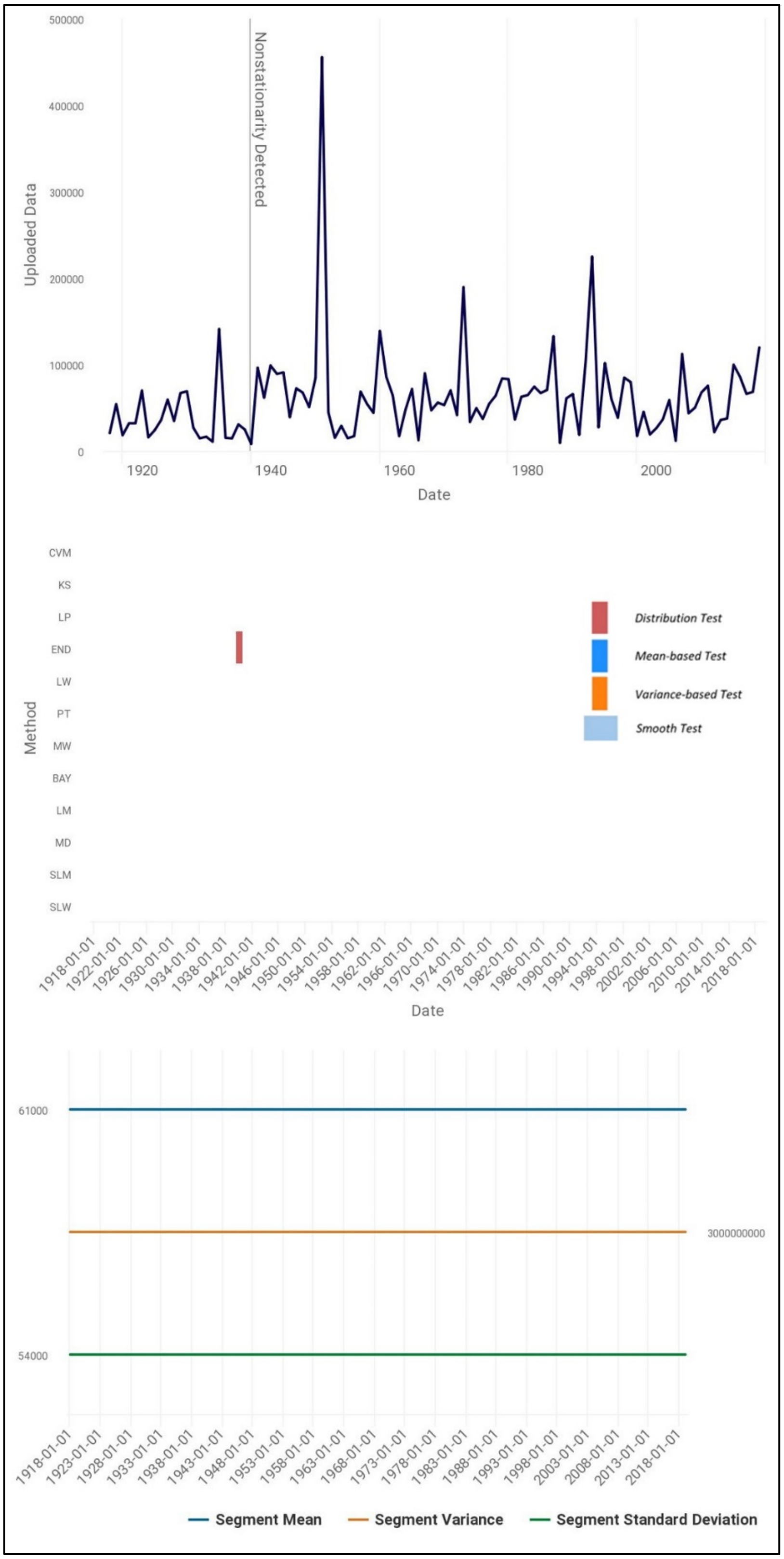


Figure 20. Nonstationarity Detection Analysis for Topeka Gage Unregulated Flows (1918-2019) with the CPM Methods Burn-In Period and Sensitivity Parameters Adjusted to 25 and 1,250, Respectively

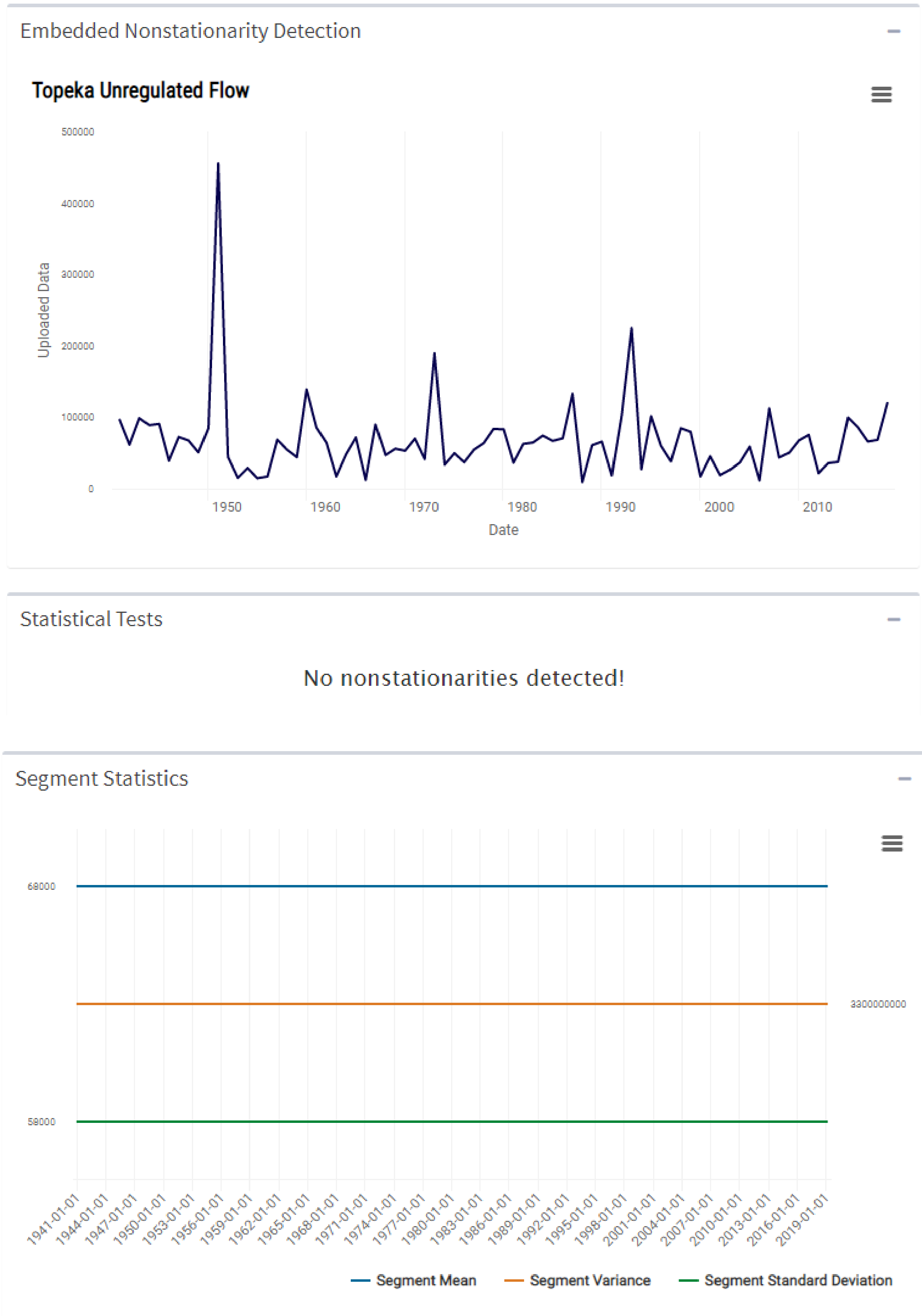
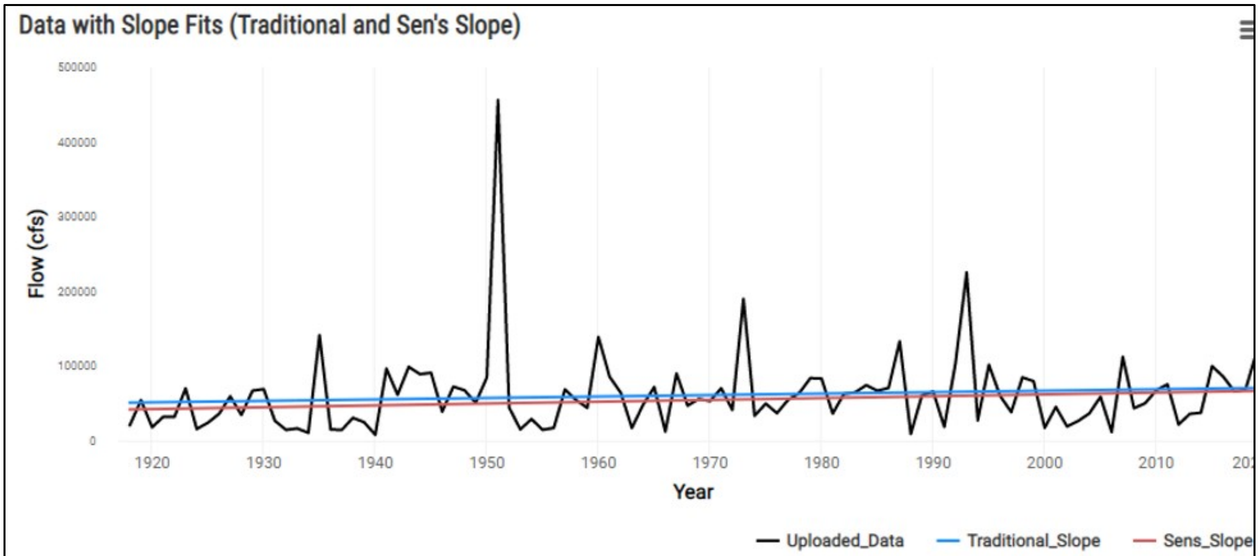


Figure 21: Nonstationarity Detection Analysis, Topeka Gage Unregulated Flow (1940-2019)

The trendline analysis was ran for the Topeka unregulated flow record. The results are provided in Figure 22 below. Both the Mann-Kendall Test and Spearman Rank-Order Test detected a statistically significant trend in the gage data for Topeka. The traditional and Sen's trendlines are increasing. The Sen's trendline is slightly steeper at 245 cfs/year over the period of record. The statistically significant trend indicates that streamflows at Topeka may be increasing over time.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	194.53	-322200
Sens Slope	245.41	-428870

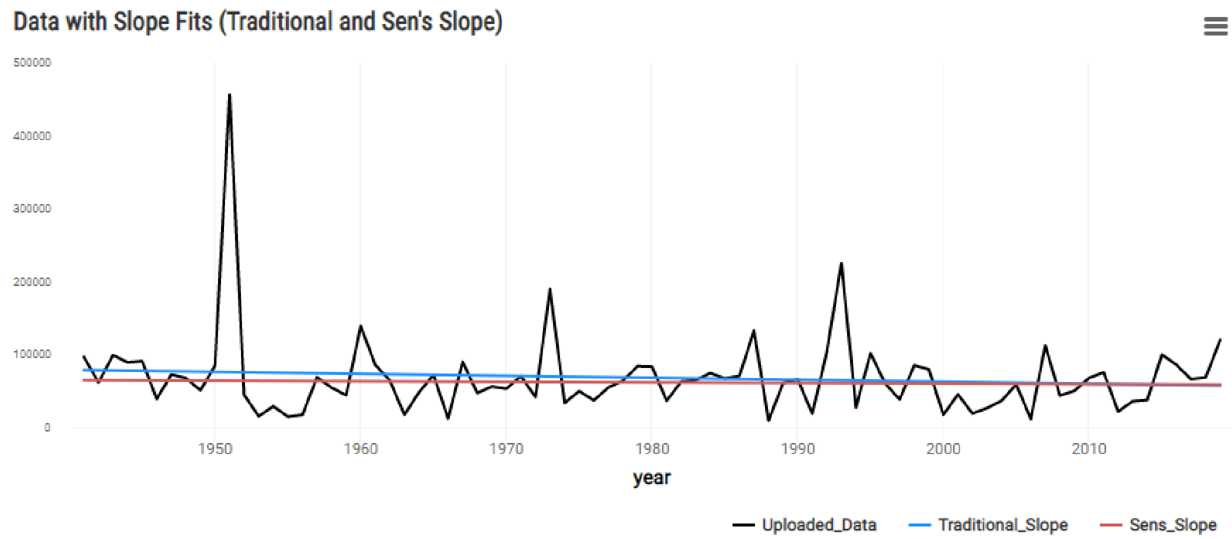
Test	P.Value
t-Test	0.28913
Mann-Kendall	0.023577
Spearman Rank-Order	0.018549

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

Figure 22. Topeka Gage Trend Analysis Results from Time Series Toolbox (1919-2019)

Overall, it appears that the strong non-stationarity detected in 1939/1940 and the increasing trend in streamflow indicate the streamflow data for the 1918-2019 period of record should not be treated as stationary.

Trend analysis was performed on the peak annual flows after 1940. When using the shortened period of record, no statistically significant trend in annual peak streamflow was detected. Figure 23 shows the trend analysis for the Topeka gage post 1940 streamflow record. These results indicate that the period of record of 1941-2019 can be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-272.85	608110
Sens Slope	-76.436	212840

Test	P.Value
t-Test	0.34189
Mann-Kendall	0.68445
Spearman Rank-Order	0.64246

- **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.**

Figure 23: Topeka Gage Trend Analysis Results from Time Series Toolbox (Post-1940)

2.3.4. Lecompton Gage Flows

The unregulated flow data for the Lecompton gage spans from 1937 to 2019. Figure 24 shows the annual peak flows for this location over the period of record. Using the default parameters, the Energy Divisive method detected a non-stationarity in 1967. Since no other methods detected the nonstationarity, it is not robust, and there is no consensus. Reducing the Energy Divisive sensitivity parameter to 0.35 caused the 1967 nonstationarity to no longer be detected. Further investigation was completed to determine if adjustments in the parameters would detect any nonstationarities. Each parameter was individually adjusted to the minimum and maximum value while the others were kept at the default values. No additional nonstationarities were detected after these adjustments. Figure 25 shows the final nonstationarity detection with no nonstationarities detected.

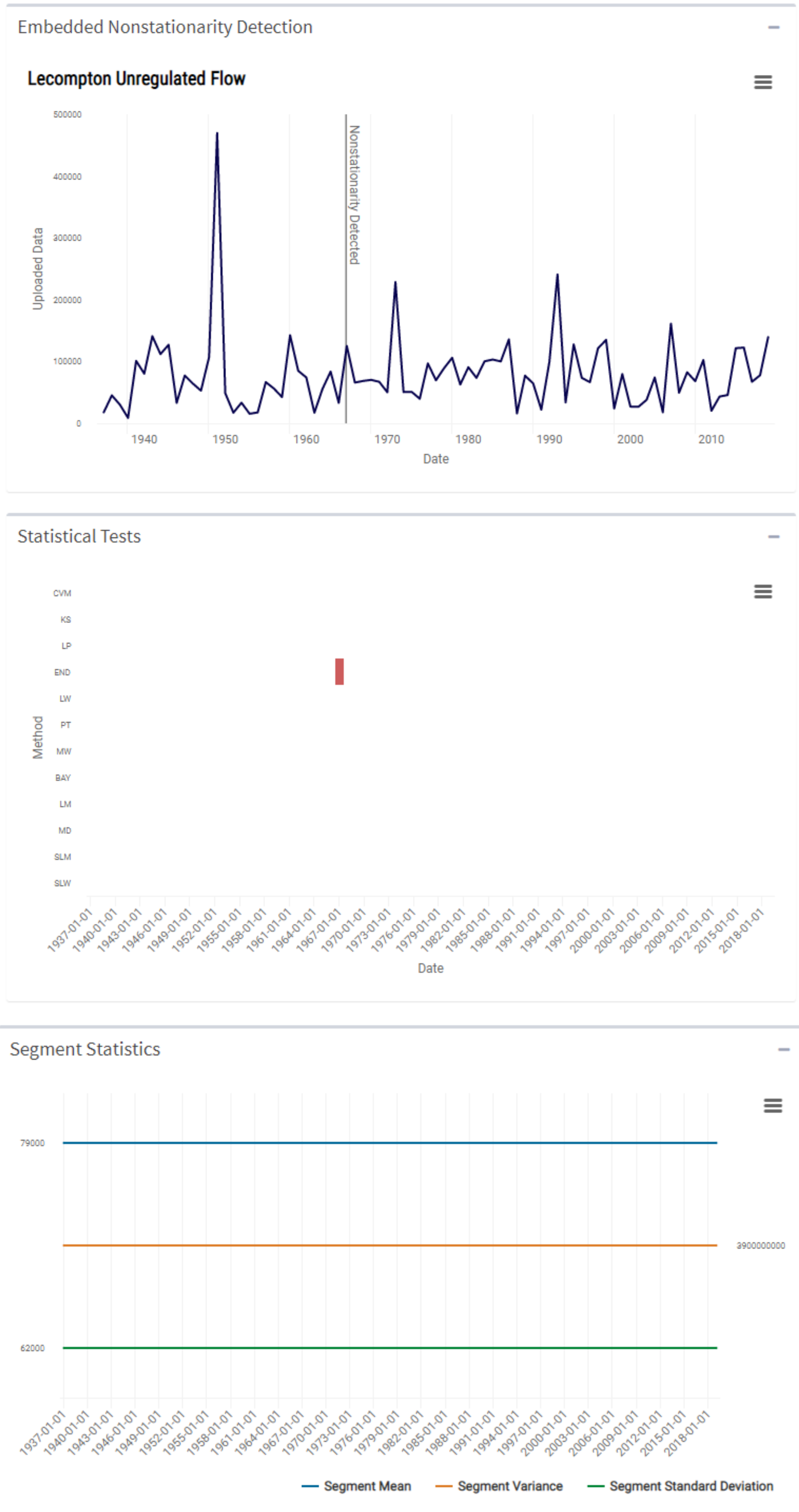


Figure 24. Lecompton Unregulated Flow Nonstationarity Detection (1937-2019)

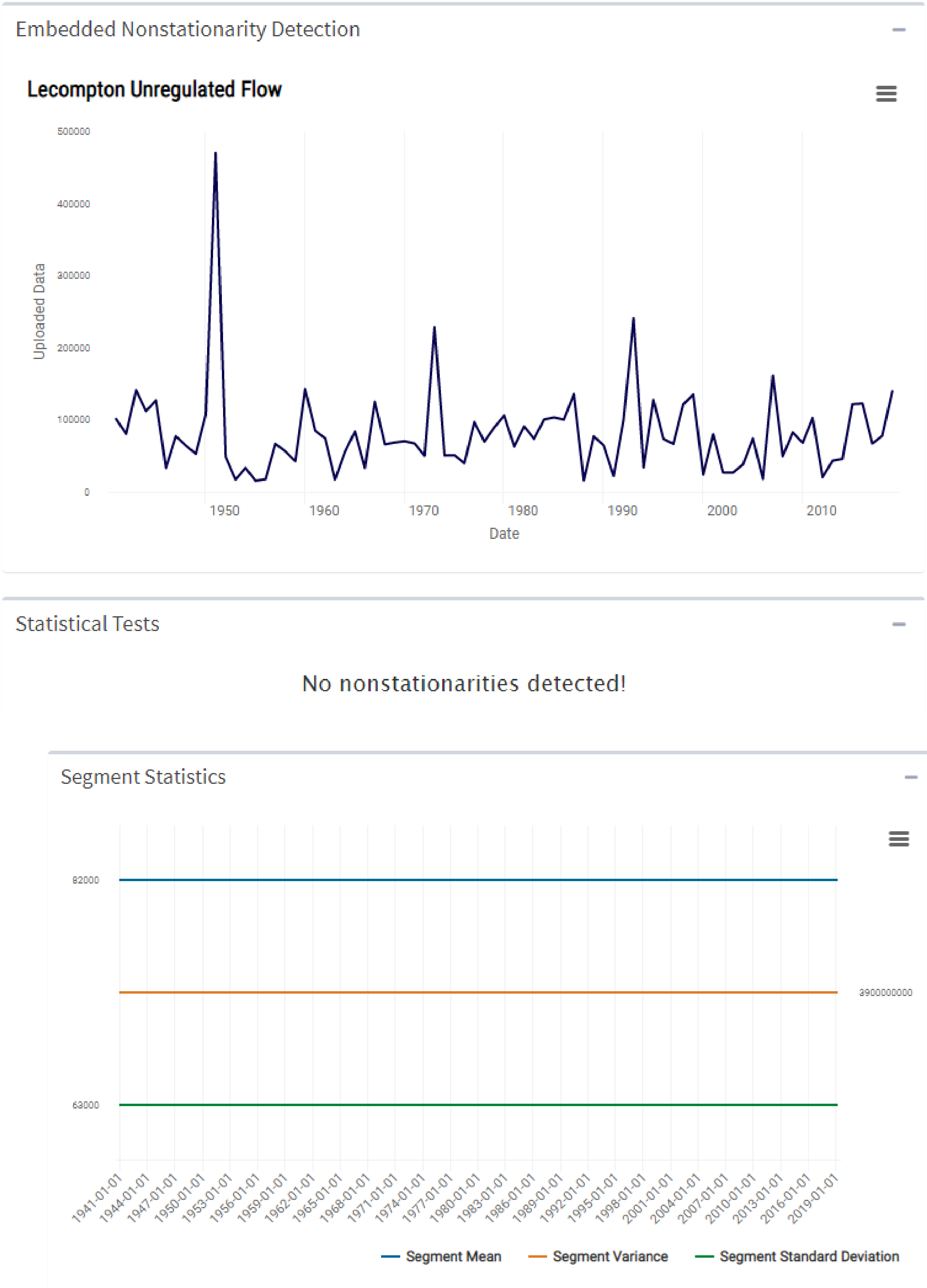
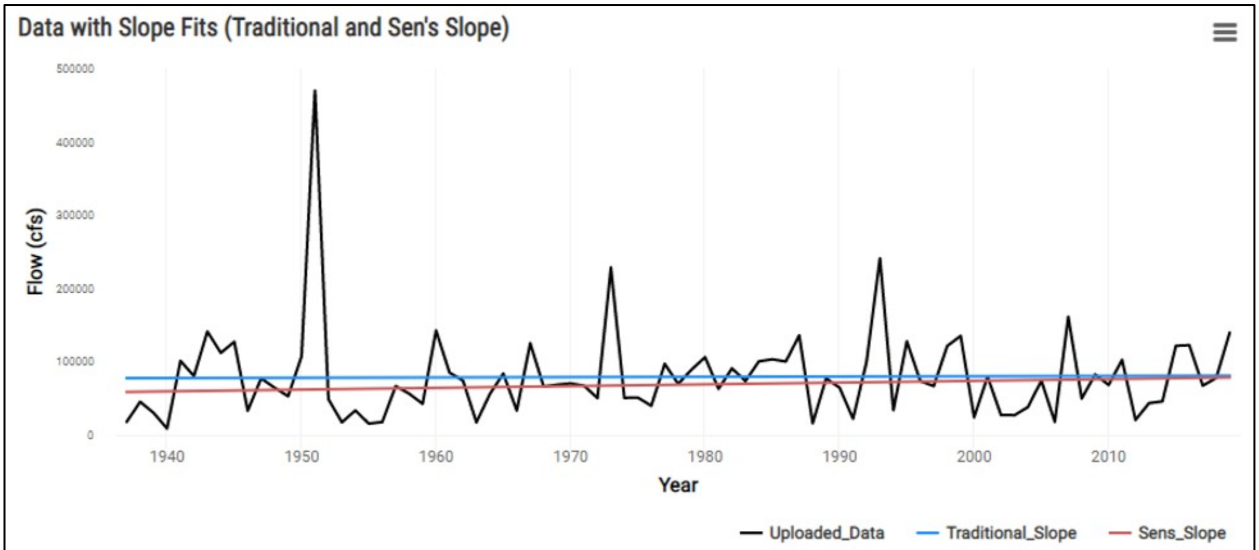


Figure 25: Lecompton Unregulated Flow Nonstationarity Detection (1940-2019)

A trendline analysis was performed for the Lecompton unregulated flow data. Figure 26 below provides the results. Neither the Mann-Kendall nor the Spearman Rank-Order test detected a statistically significant trend. The traditional and Sen's trendlines both showed a positive slope. The Sen's trendline had the largest increase of 240cfs/year for the annual peak flows for the period of record. Due to no non-stationarities being detected and no statistically significant trend in streamflow, the data is considered stationary.



Trend Line Coefficients

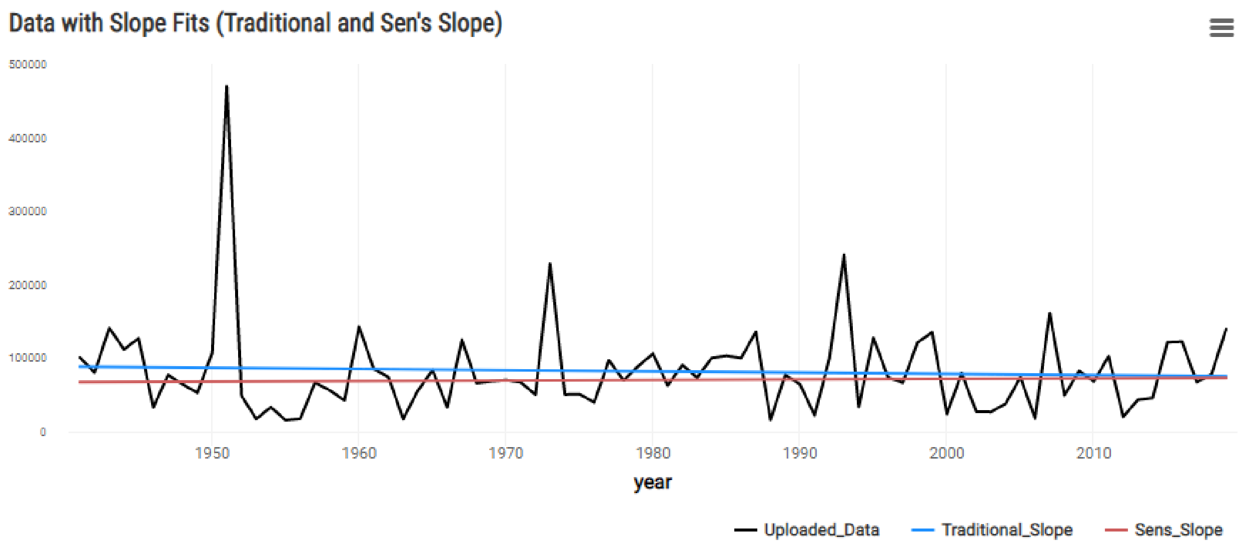
Method	Slope	Intercept
Linear Regression Slope	41.104	-2150.7
Sens Slope	240.42	-407030

Test	P.Value
t-Test	0.88646
Mann-Kendall	0.19982
Spearman Rank-Order	0.26524

- **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.**

Figure 26. Lecompton Gage Trend Analysis Results from Time Series Toolbox (1937-2019)

To be consistent with the analysis for other Kansas River gages, trend analysis on the post 1940 streamflow data was also performed at Lecompton. Figure 27 shows that the analysis also found no statistically significant trend in the post 1940 data.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-168.75	415990
Sens Slope	75.667	-79526

Test	P.Value
t-Test	0.58771
Mann-Kendall	0.72849
Spearman Rank-Order	0.86691

- **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.**

Figure 27: Lecompton Gage Trend Analysis Results from Time Series Toolbox (Post-1940)

2.3.5. De Soto Gage Flows

The period of record for unregulated flows at the De Soto gage is from 1918 to 2019. The flow data was uploaded to the Time Series Toolbox and the results for the nonstationarity analysis using the default parameters (see Table 3) is shown in Figure 28. Three nonstationarities were detected in the unregulated flow record for the De Soto gage. The Lombard Wilcoxon detected a change point in the flow record in 1939. In 1942, a change point was detected by the LePage method. The Energy Divisive method detected a change point in 1959. The relative strength of a detected nonstationarity can be determined by looking at the level of consensus between different methods targeted at detecting the same type of nonstationarities (variance/standard deviation, mean, or overall distribution) in a flow data series. Each of the three changepoints were only detected by a single method which indicates that the relative strength of these points is low and are likely not caused by any sort of climate change. The non-stationarities detected in 1939 and 1942 appear to be related to the rebound in streamflow following the 1930's drought. Other factors such as land-use changes and irrigation withdrawals may also affect the flows.

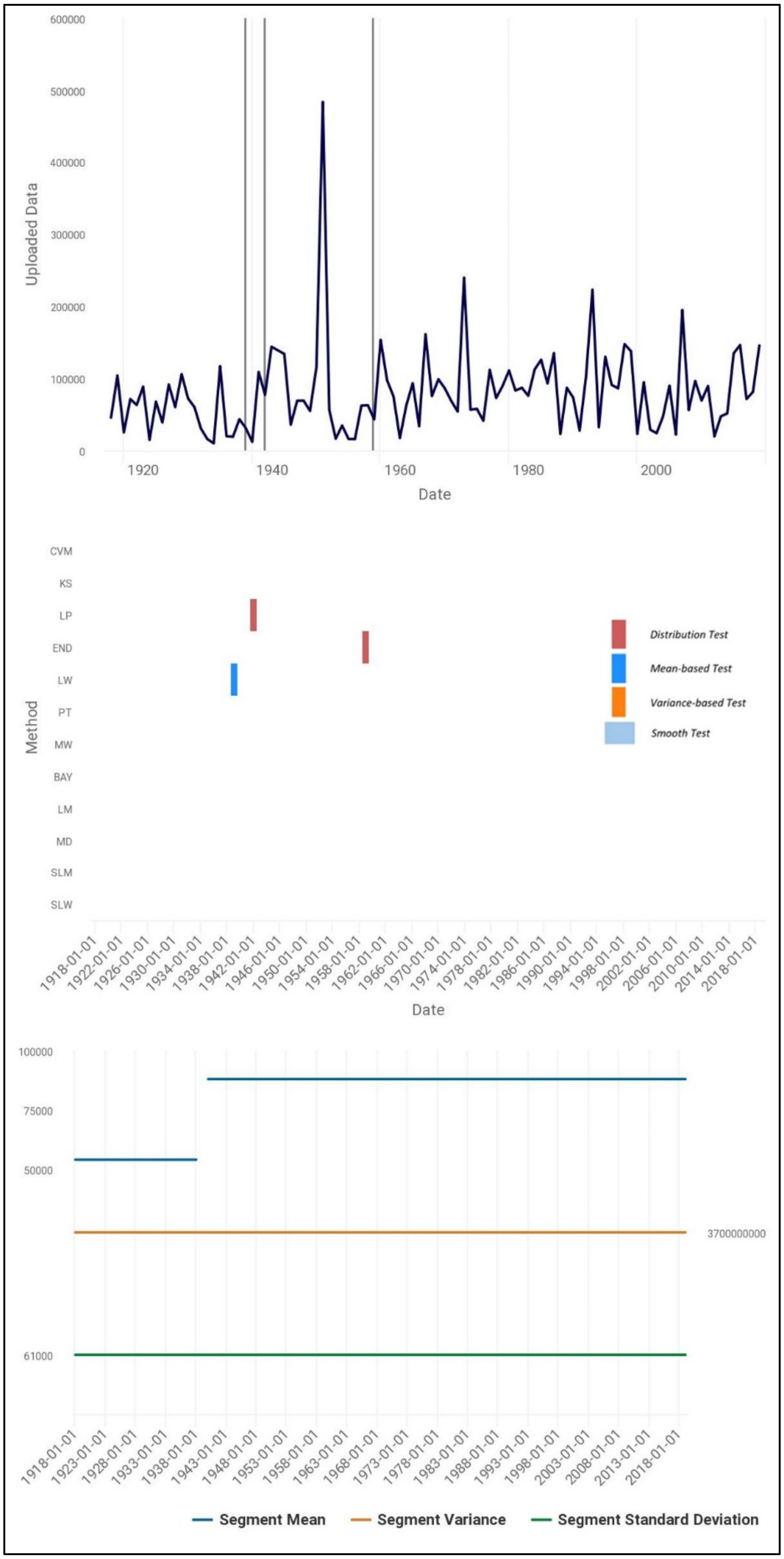


Figure 28. Nonstationarity Detection Analysis for De Soto Gage Unregulated Flows (1918-2019) using Default Parameters

A sensitivity analysis was completed to determine if slight adjustments in the parameters would remove the nonstationarities or detect additional nonstationarities. Each parameter was individually adjusted to the minimum and maximum value while the others were kept at the default values. Changes in the results occurred when the CPM Methods Burn-In Period, the CPM Methods Sensitivity, and the Pettitt Sensitivity parameters were adjusted. However, no additional nonstationarities were detected. When the CPM Methods Burn-In Period was adjusted from 20 to 25, the nonstationarity in 1939 was eliminated. When the CPM Methods Sensitivity Parameter was adjusted from 1,000 to 1,250, the nonstationarity in 1942 was eliminated. The final nonstationarity in 1959 disappeared when the Pettit Sensitivity parameter was adjusted from 0.05 to 0.04. Since these adjustments were small, it showed that the data was very sensitive to the parameters.

An additional sensitivity test was performed to determine if the Desoto streamflows after 1940 could be considered stationary. When using the shortened period of record and the default parameters, non-stationarities were not detected, as shown in Figure 29.

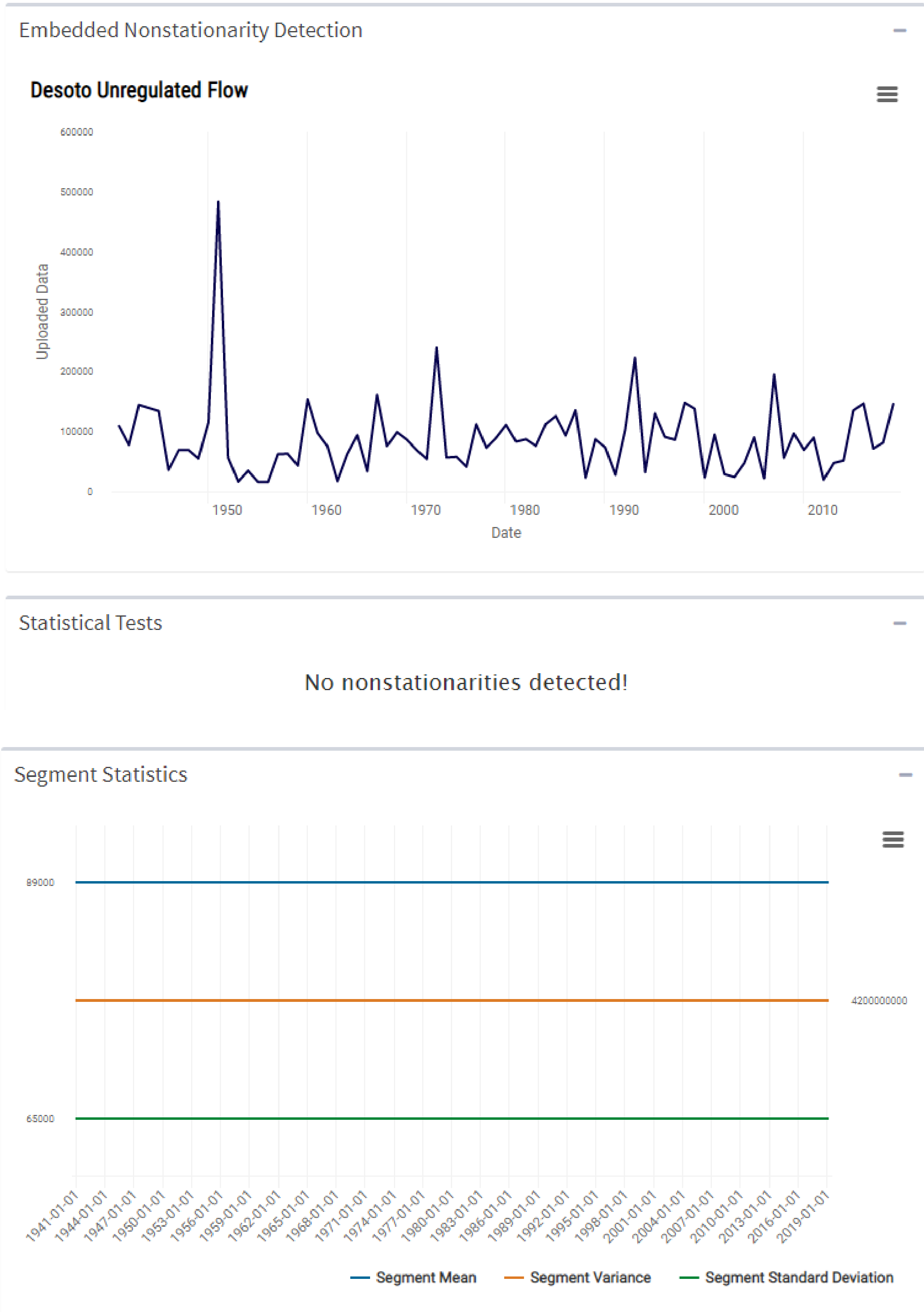
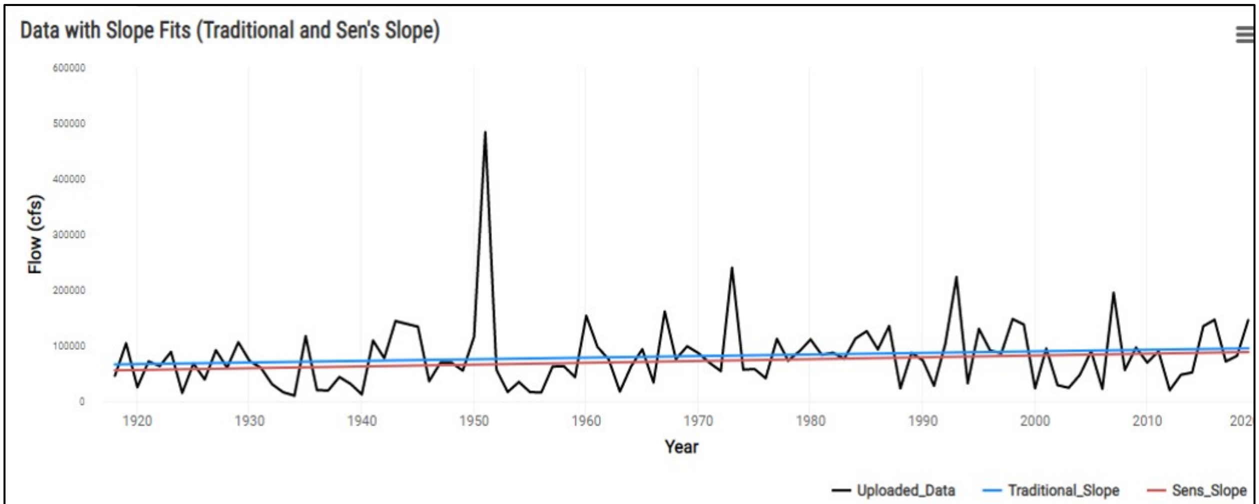


Figure 29: Desoto Nonstationarity Detection (1941-2019)

A trend analysis was also run for the unregulated De Soto flow data. Results are shown in Figure 30. Statistically significant trends were detected by both the Mann-Kendall Test and Spearman Rank-Order test. Both the traditional slope and Sens's slope showed an increasing trend in flow, with the Sen's slope larger at 325 cfs/year.

Nonstationarities detected did not have consensus among methods for the De Soto gage, however the presence of a statistically significant trend in the annual peak stream flows indicates that an increasing trend is present in the period of record. The period of record unregulated flows at Desoto from 1919-2019 should not be considered stationary.



Trend Line Coefficients

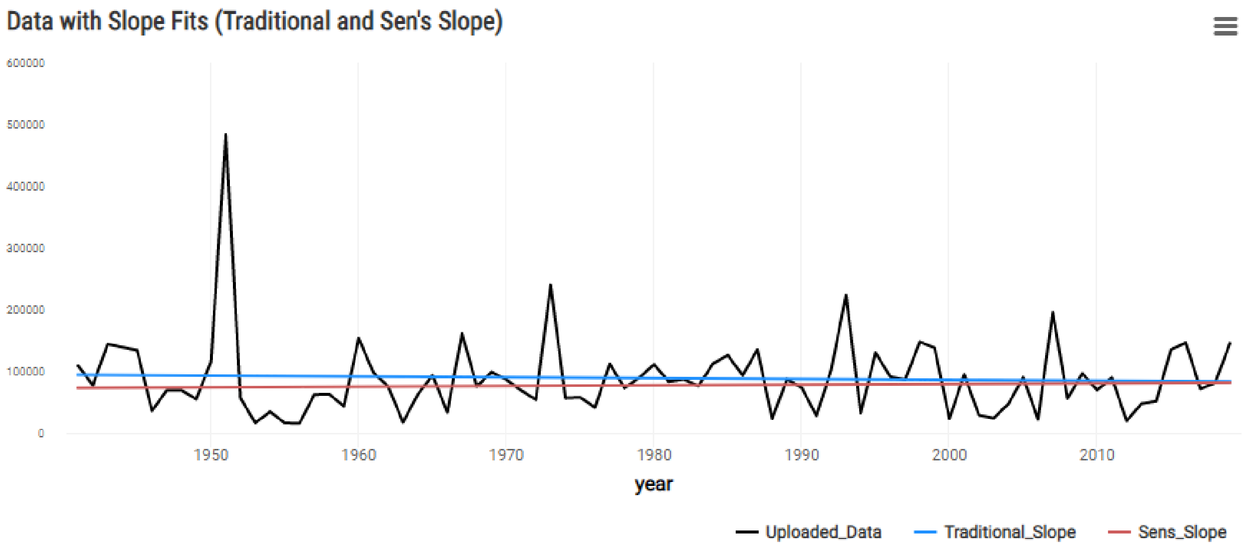
Method	Slope	Intercept
Linear Regression Slope	285.66	-481750
Sens Slope	325.53	-568990

Test	P.Value
t-Test	0.16649
Mann-Kendall	0.025038
Spearman Rank-Order	0.026828

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

Figure 30. De Soto Gage Trend Analysis Results from Time Series Toolbox (1918-2019)

Trend analysis was also performed on the peak annual flows after 1940. When using the shortened period of record and the default parameters, no statistically significant trend in annual peak streamflow was detected. Figure 31 shows the trend analysis for the Desoto gage post 1940 streamflow record. These results indicate that the period of record of 1941-2019 may be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-141.27	368430
Sens Slope	109.88	-140250

Test	P.Value
t-Test	0.66329
Mann-Kendall	0.65974
Spearman Rank-Order	0.7421

- **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.**

Figure 31: De Soto Gage Trend Analysis Results from Time Series Toolbox (Post-1940)

2.3.6. Mainstem Kansas River Gage Analysis Summary

Non-stationarity and linear trend analysis were performed on five long-term gage records for the mainstem Kansas River. Multiple gage sites on the Kansas River detected nonstationarities with a strong consensus and agreement around 1940. After further research, these change points are likely due to the 1930s drought. Cook, Seager, and Smerdon (2014) classified the drought conditions experienced in the western United States in 1934 as the worst drought in the last millennium and indicated that the accompanying dust storms caused by soil disturbance likely worsened the drought. Andreadis, et.al. (2005) state that, as far as droughts in their period of analysis (1920-2003), "the 'Dust Bowl' had the largest impact in terms of streamflow, in the mid-1930's". As seen in the previous annual peak plots, the average annual peak flow seems to increase noticeably after 1940. As a sensitivity analysis, nonstationarity detection and trend line analysis for post 1940 flows were conducted for all five mainstem Kansas River gages to determine whether increasing trends in the data were related to the low average annual peak discharges at the beginning of the observed period of record, and whether the increasing trends were seen in the post 1940s peak flows. Additionally, trend analysis for the Ft. Riley gage was restricted to after 1962 when the current gage began operation. Notably, when the post-1940 data is analyzed for trends, none of the analyses for any of the gages demonstrated a statistically significant trend in unregulated streamflow. Neither were any non-stationarities detected in the post 1940 period when using the default parameters in the Non-stationarity Detection Tool. Thus, the unregulated flow datasets at the five mainstem Kansas River gages for the period 1941 through 2019 may be considered stationary. Table 4 and Table 5 summarize the results of the analyses performed on the five Kansas River mainstem gages.

Table 4: Summary of Non-Stationarities Detected for Kansas River Unregulated Flows

USGS Gage Location and Number	Period of Record Assessed	Years Non-Stationarities Detected	Methods Detecting	Parameter Adjustments
Kansas River at Fort Riley, KS (06879100)	1918-2019	1939, 1940	CVM, LP, END, LW, MW	Default
	1918-2019	1940	END	CPM Burn-In Period =25 CPM Sensitivity Parameter = 1,250
	1941-2019	None	N/A	Default
Kansas River at Wamego, KS (06887500)	1919-2019	1939, 1940	CVM, LP, END, LW, MW	Default
	1919-2019	1940	END	CPM Burn-In Period =25 CPM Sensitivity Parameter = 1,250
	1941-2019	None	N/A	Default

USGS Gage Location and Number	Period of Record Assessed	Years Non-Stationarities Detected	Methods Detecting	Parameter Adjustments
Kansas River at Topeka, KS (06889000)	1918-2019	1939, 1940	CVM, END, LW, MW	Default
	1918-2019	1931, 1939, 1940, 1945	CVM, LP, END, LW, MW, MD	CPM Sensitivity Parameter = 500
	1918-2019	1940	END	CPM Burn-In Period =25 CPM Sensitivity Parameter = 1,250
	1941-2019	None	N/A	Default
Kansas River at Lecompton, KS (06891000)	1937-2019	None	N/A	Default
	1941-2019	None	N/A	Default
Kansas River at Desoto, KS (06892350)	1919-2019	1939, 1942, 1959	LP, END, MW	Default
	1919-2019	None	N/A	CPM Burn-In Period =25 CPM Sensitivity = 1,250 Pettit Sensitivity = 0.04
	1941-2019	None	N/A	Default

Table 5: Summary of P-values for Trend Analysis of Kansas River Unregulated Flow Data

USGS Gage Location and Number	Period of Record Assessed	Test Type		
		Mann-Kendall	Spearman Rank Order	Significant? (P value <0.05)
		P-value		
Kansas River at Fort Riley, KS (06879100)	1918-2019	0.059	0.051	No
	1941-2019	0.30	0.26	No
Kansas River at Wamego, KS (06887500)	1919-2019	0.0068	0.0052	Yes
	1941-2019	0.76	0.70	No
Kansas River at Topeka, KS (06889000)	1918-2019	0.024	0.018	Yes
	1941-2019	0.68	0.64	No
Kansas River at Lecompton, KS (06891000)	1937-2019	0.20	0.27	No
	1941-2019	0.73	0.87	No
Kansas River at Desoto, KS (06892350)	1919-2019	0.025	0.027	Yes
	1941-2019	0.66	0.74	No

2.4. **Kansas River Basin Reservoir Inflows, Nonstationarity and Trend Analyses**

Reservoir inflow data was analyzed for nonstationarity and trends in support of the reservoir sedimentation analysis performed for the study. Reservoir sedimentation computations used past inflows as a pattern for future inflows to the reservoirs; therefore, the stationarity of observed reservoir inflow data was investigated. Reservoirs analyzed are shown in Figure 32. Twelve statistical methods were applied in the Nonstationarity Detection Analysis for the annual maximum reservoir inflow data. Annual maximum data were only considered due to the dependence of reservoir sedimentation on large reservoir inflows. The twelve statistical methods are listed in Table 2 shown in Section 2.3. Daily reservoir inflow records were provided by NWK Water Management. These data are computed from reservoir storage curves and daily pool elevations and are not streamflow data. Some of the inflow data are regulated by upstream reservoirs. Where inflow data were regulated, the period regulated by upstream reservoirs was isolated for analysis. This data was exported from the Hydrologic Engineering Center Data Storage System Visual Utility Engine (HEC-DSSVue) into excel as a .csv file to then import into the Time Series Toolbox.

Table 6: Kansas River Basin Reservoirs analyzed for Inflow Nonstationarity

Reservoir	USGS Stage Gage Number	Inflow Period of Record Begins	Upstream Regulation? Year of Full Regulation	Drainage Area (sq. mi.)
Harlan County Lake	06849000	1952	Yes, 1967	13,500
Waconda Lake	N/A	1967	Yes, 1967	5,076
Wilson Lake	06868100	1964	No	1,917
Kanopolis Lake	06865000	1948	Yes, 1951	7,857
Milford Lake	06857050	1964	Yes, 1967	24,890
Tuttle Creek Lake	06886900	1959	No	9,628
Perry Lake	06890898	1966	No	1,117
Clinton Lake	06891478	1977	No	367

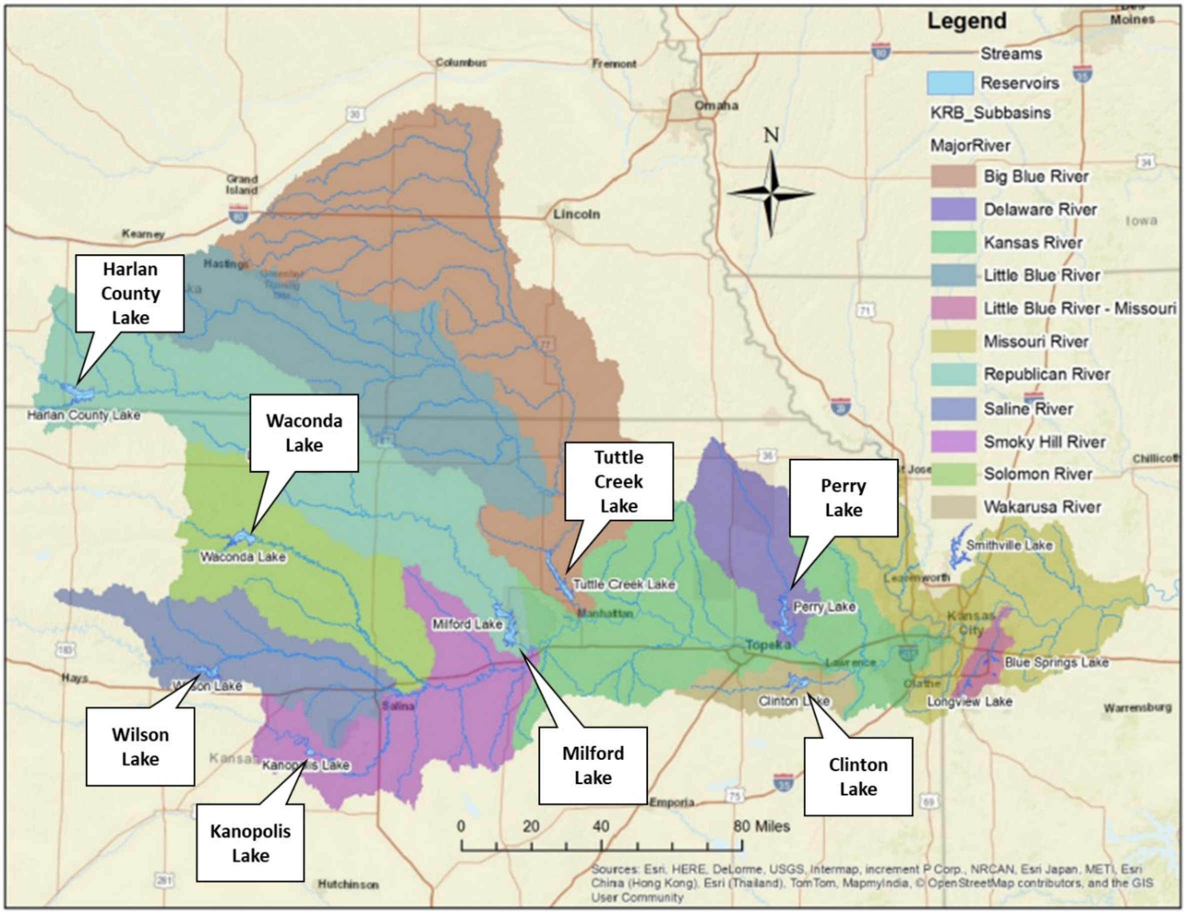
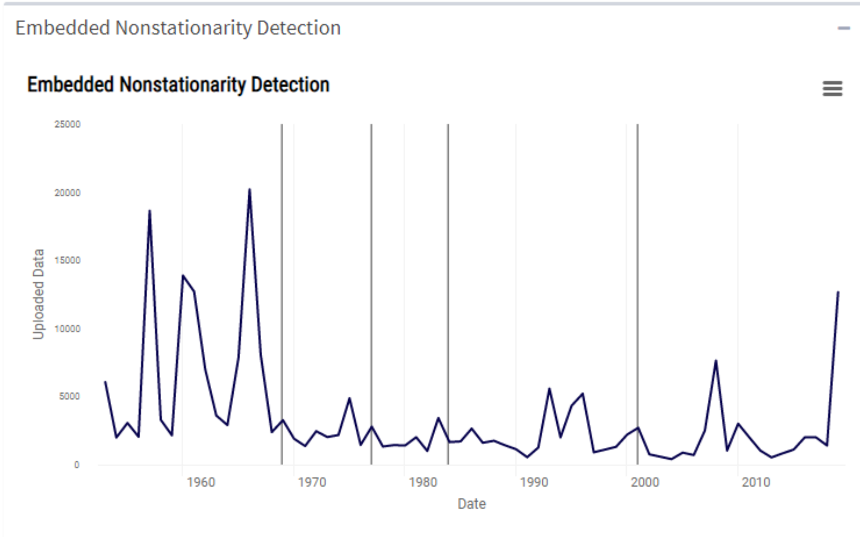


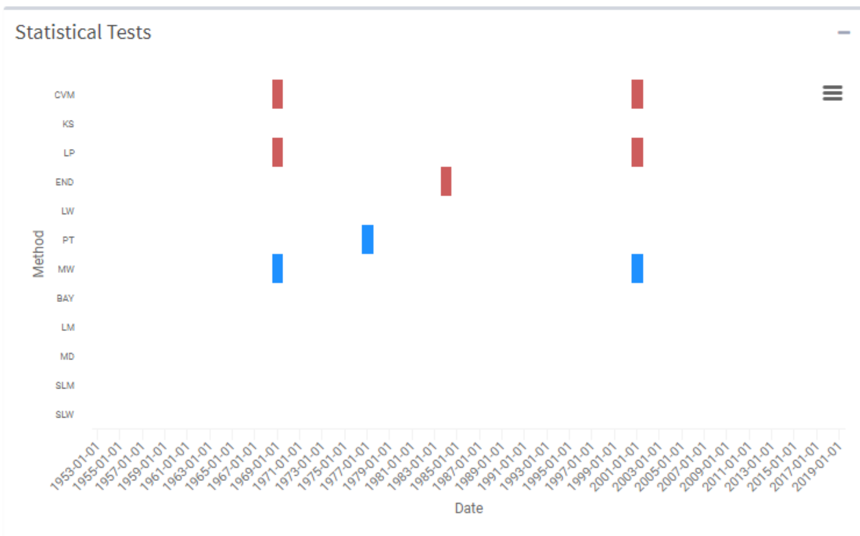
Figure 32: Locations of Lakes analyzed for Reservoir Inflow Non-stationarity and Trends

2.4.1. Harlan County Lake Inflows

Harlan County Lake is located on the Republican River in south central Nebraska. Closure was made at Harlan County Dam on 22-July-1951. Storage began in the reservoir on 14-November-1952, and multipurpose pool level was first reached on 14-June-1957. The full reservoir inflow period of record for the Harlan County Lake dates back to 1952. Inflows are computed from pool elevation data, currently reported at USGS Gage 06849000. Once all upstream USBR dams were constructed and began operations, flow into Harlan County Lake became regulated. The last of the dams to be constructed and reach multipurpose pool was Norton Dam (Prairie Dog Creek) in June 1967. Non-stationarity analysis was conducted for both the full period of record and the fully regulated period. The period of regulated flow used for the nonstationarity detection tool was from 1967 to 2019. The 1967 annual maximum inflow occurred on June 22nd, the day after the pool reached multipurpose level at Norton Dam. Non-stationarity detection analysis of the full period of record is shown in Figure 33. Multiple nonstationarities were detected around 1969. It is suspected that due to the CPM Burn-In Period being during the period of unregulated flow, these tests detected a significant change point around the transition to regulated flow. After importing the regulated flow record, these nonstationarities were no longer present as seen in Figure 34. In Figure 33 and Figure 34, the bottom half of the plot shows the segment mean, variance, and standard deviation of the data segmented by the detected nonstationarities.

As seen in Figure 34, nonstationarities were detected for Harlan County Lake with the default sensitivity parameters. The LM test detected a non-stationarity in the flow record in 1989. Change points were detected in 2001 by the CVM method, the LP method, and the MW method. The relative strength of a detected nonstationarity can be determined by looking at the level of consensus between different methods targeted at detecting the same type of nonstationarities (variance/standard deviation, mean, or overall distribution) in a flow data series. Only one method detected a nonstationarity for 1989, which indicates there is not a significant agreement between the different methods. There seems to be some consensus and robustness among the change point in 2001 which could be indicative of climate-related change. The drought of the early 2000's seems to be the immediate cause of the change point detected in 2001. Further research would need to be conducted to determine if any other causes could be responsible for this nonstationarity. For instance, Kustu, Fan, and Robock (2010) reported that large scale irrigation pumping in the high plains has led to decreases in surface water discharges over the period of irrigation development (post-1940). The sensitivity parameters were adjusted to see if any additional change points were detected. Upon reducing the CPM Method sensitivity from 1000 to 500, the Mood test detected a change point in 1990. These results are shown in Figure 35. There was consensus with the nonstationarity detected by the LM method in 1989, however this nonstationarity was not robust. The rest of the sensitivity parameters were adjusted individually and no additional nonstationarities were detected. Since the 1989/90 nonstationarity is not robust, and since the nonstationarity detected in 2001 is likely a result of the early 2000's drought, there are likely no climate related change in the period of record. Figure 35 shows the final nonstationarity analysis with parameter adjustments.





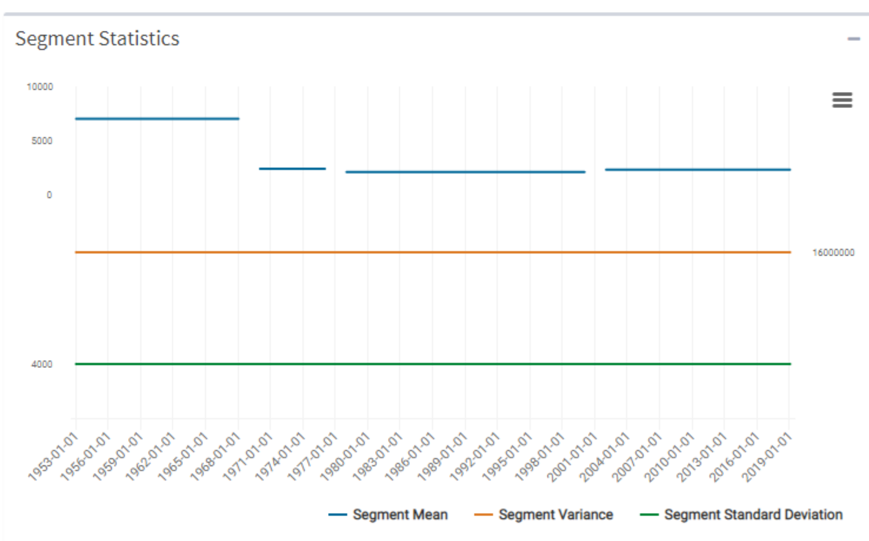


Figure 33: Nonstationarities Detected in Harlan County Lake Full Period of Record (1953-2019)

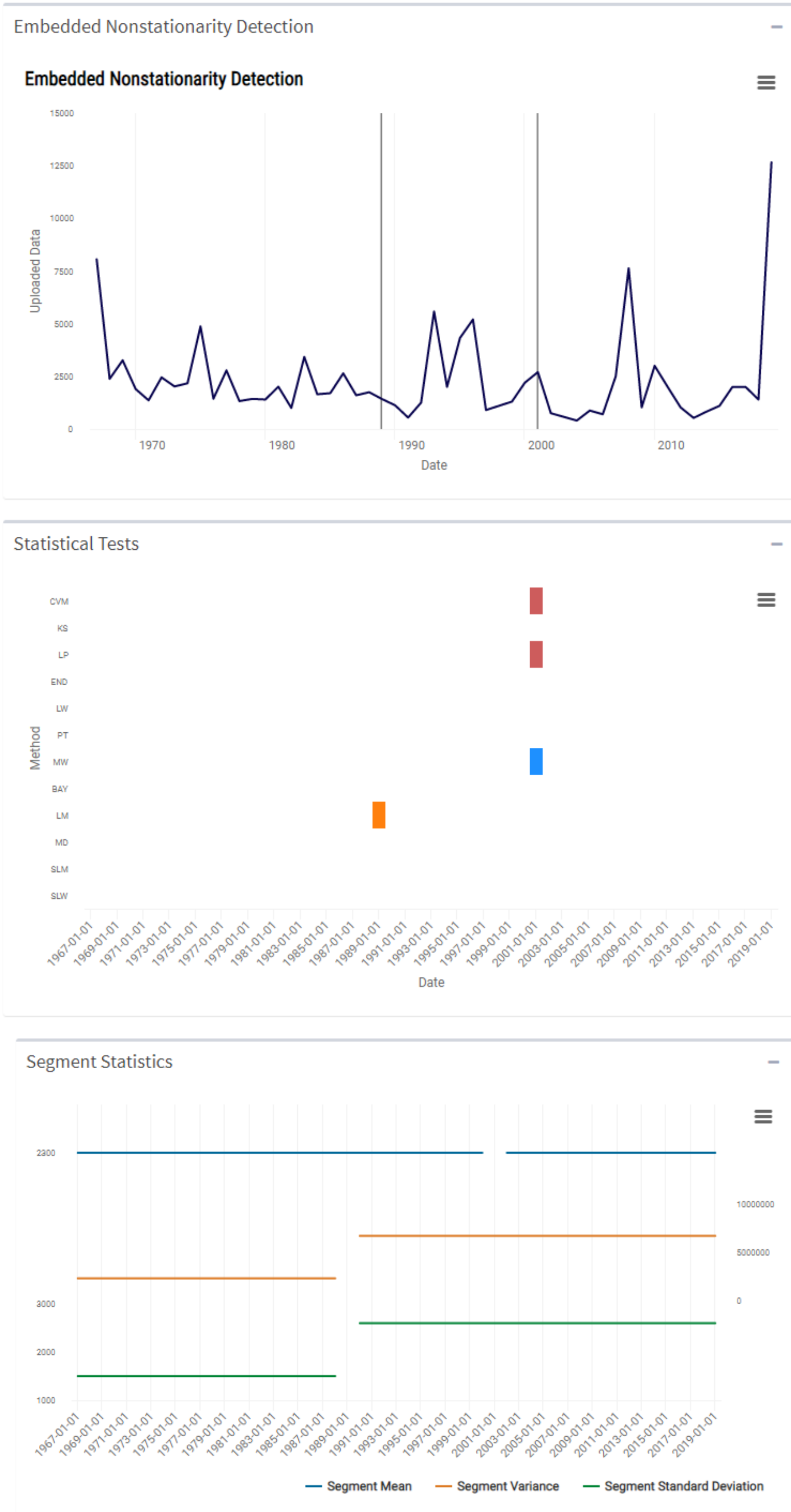


Figure 34: Nonstationarities Detected in Harlan County Lake Regulated Inflows (1967-2019)

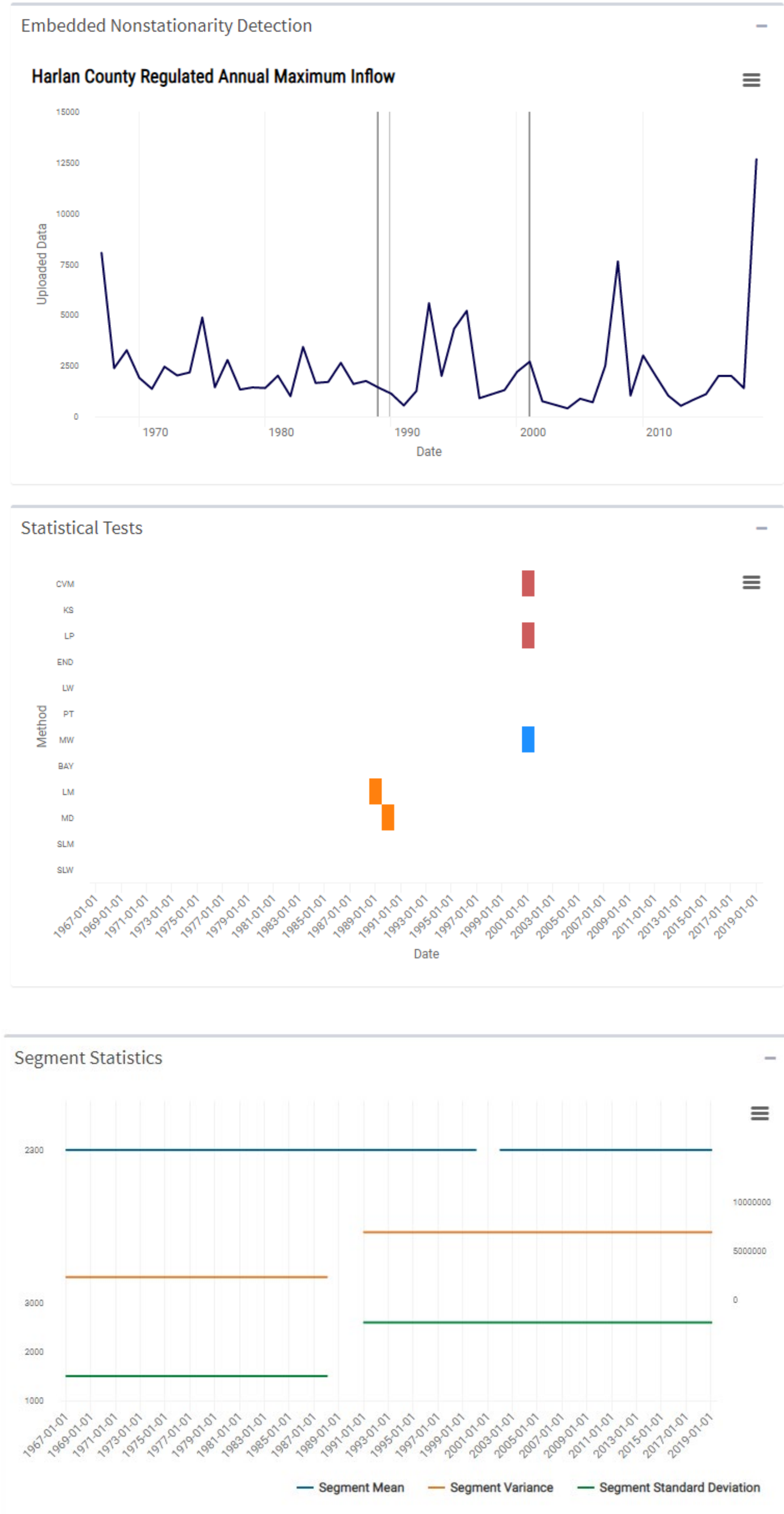
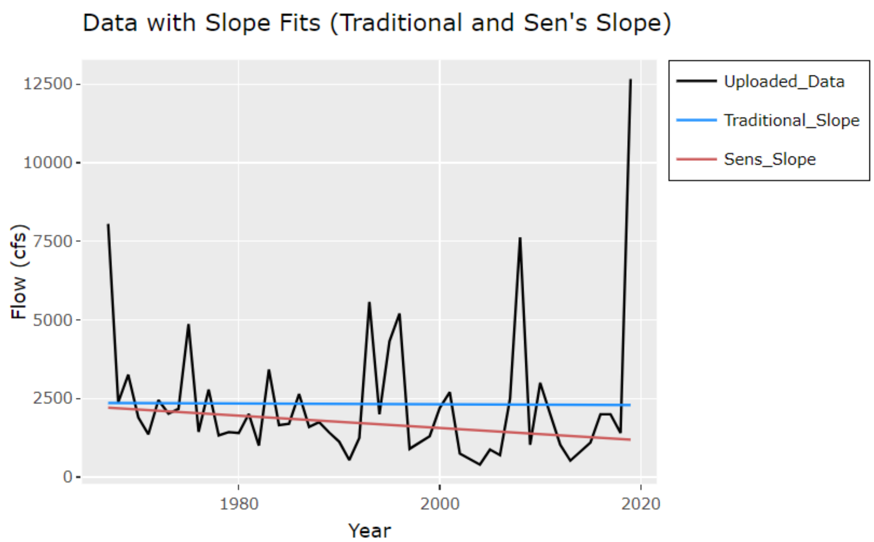


Figure 35: Nonstationarities Detected in Harlan County Lake Regulated Inflows (1967-2019), CPM Method sensitivity adjusted to 500

In addition to the Non-Stationarity Detection, Trend Analysis was run for the Harlan County Inflow data. Results are shown in Figure 36. A statistically significant trend was detected by both tests applied. Both the traditional slope and Sen's slope indicated a decreasing trend in annual maximum daily inflow, but the Sen's slope estimated a much greater negative slope of almost 20 cfs/year. It is unknown if the detected decrease in annual peak inflows to the lake is climate related, or a consequence of increasing consumptive use, especially irrigation in the watershed. Harlan County Lake has been at the center of disagreements between the States of Kansas and Nebraska regarding flow quantities in the Republican River Basin. Note that despite the negative trend, 2019 produced the greatest post-regulation annual maximum inflow to Harlan County Lake. The large inflow also resulted in a new record pool level.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-1.2359	4788.4
Sens Slope	-19.562	40688

Test	P.Value
t-Test	0.95019
Mann-Kendall	0.036192
Spearman Rank-Order	0.046022

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

Figure 36: Trend Analysis Results for Harlan County Lake Annual Maximum Daily Inflows (1967-2019)

Since the analysis detected a statistically significant trend in reservoir inflow, additional evaluation of inflows to Harlan County Lake was performed by examining the flow data at three USGS stream flow gages that empty into the lake. The three gages considered are listed in Table 7, with their locations shown in Figure 37. These gages drain approximately 66%, 25%, and 7% of the contributing drainage area of Harlan County Lake, or 98% of the total contributing drainage area.

Table 7: USGS Inflow Gages for Harlan County Lake

USGS Gage	Period of Record	Drainage Area (sq. mi.)	Significant Remarks
Republican River near Orleans, NE (06844500)	1947-2019	15,580	Included as Harlan Co. Lake Inflow gage. See Section 2.4.1.1.
Prairie Dog Creek near Woodruff, KS (06848500)	1929-2017	1,007	Included as Harlan Co. Lake Inflow gage. See Section 2.4.1.2.
Sappa Creek near Stamford, NE (06847500)	1944-2019	3,840	Included as Harlan Co. Lake Inflow gage. See Section 2.4.1.3.

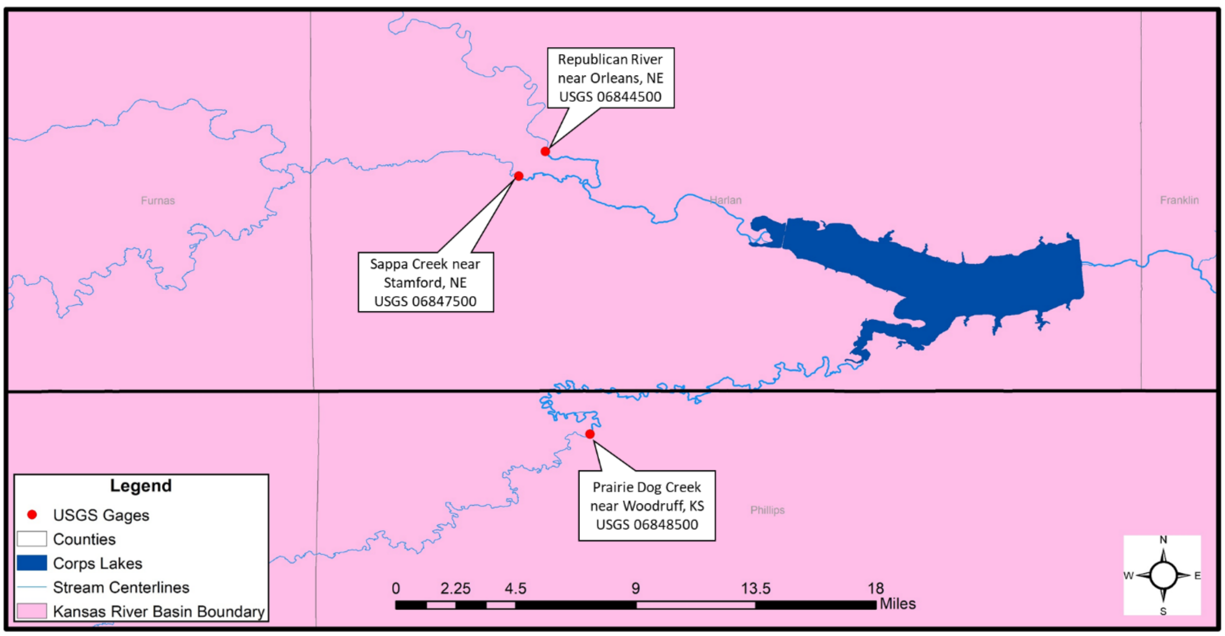


Figure 37: Location of Harlan County Lake Inflow gages

2.4.1.1. Republican River near Orleans, NE

The regulated flow record annual peaks for the Republican River near Orleans, NE are shown in Figure 38. The last dam that went into operation above this gage was at Hugh Butler Lake (Red Willow Dam), which began storage in September 1961. The Time Series Toolbox was used for analysis with data extended from 1962 through 2020.

As shown in Figure 38, nonstationarities were detected in 1989-1990, 1996, and 2000-2001. The 1989-1990 non-stationarity was detected by the LW and PT methods, both of which evaluate the mean of the data. The 1996 non-stationarity was identified by the CVM and LP methods (distribution based), and the mean-based MW method, indicating a robust nonstationarity. The 2000-2001 nonstationarity was detected by the LM and MD methods which are both variance based. Additionally, the Smooth Lombard Wilcoxon detected an ongoing non-stationarity up through 2001. Overall, the mean of the segments was decreasing over time; however, following the 2000-2001 detected nonstationarity, the segment standard deviation and variance increased. The segment mean from the pre-1995 data of 2,200 cfs decreased significantly to 1,300 cfs. The segment standard deviation from the pre-2000 data was 2,100 cfs, which increased to 2,900 cfs following the non-stationarity detected in 2000-2001.

Adjustments were made to the parameters to test sensitivity of detected non-stationarities. Increasing the CPM methods sensitivity to 1,250 removed the 1996 non-stationarity (all methods) as well as the 2001 non-stationarity detected by the Mood method. Adjusting the CPM methods Burn-in period to 35 years removed the 1989 non-stationarity detected by the Lombard Wilcoxon method. 35 years is more than 50% of the period of analysis, thus this was not deemed a reasonable adjustment. Further adjustments did not remove non-stationarities, or detect additional non-stationarities. Figure 39 shows the final non-stationarity detection with the CPM methods sensitivity adjusted to 1,250.

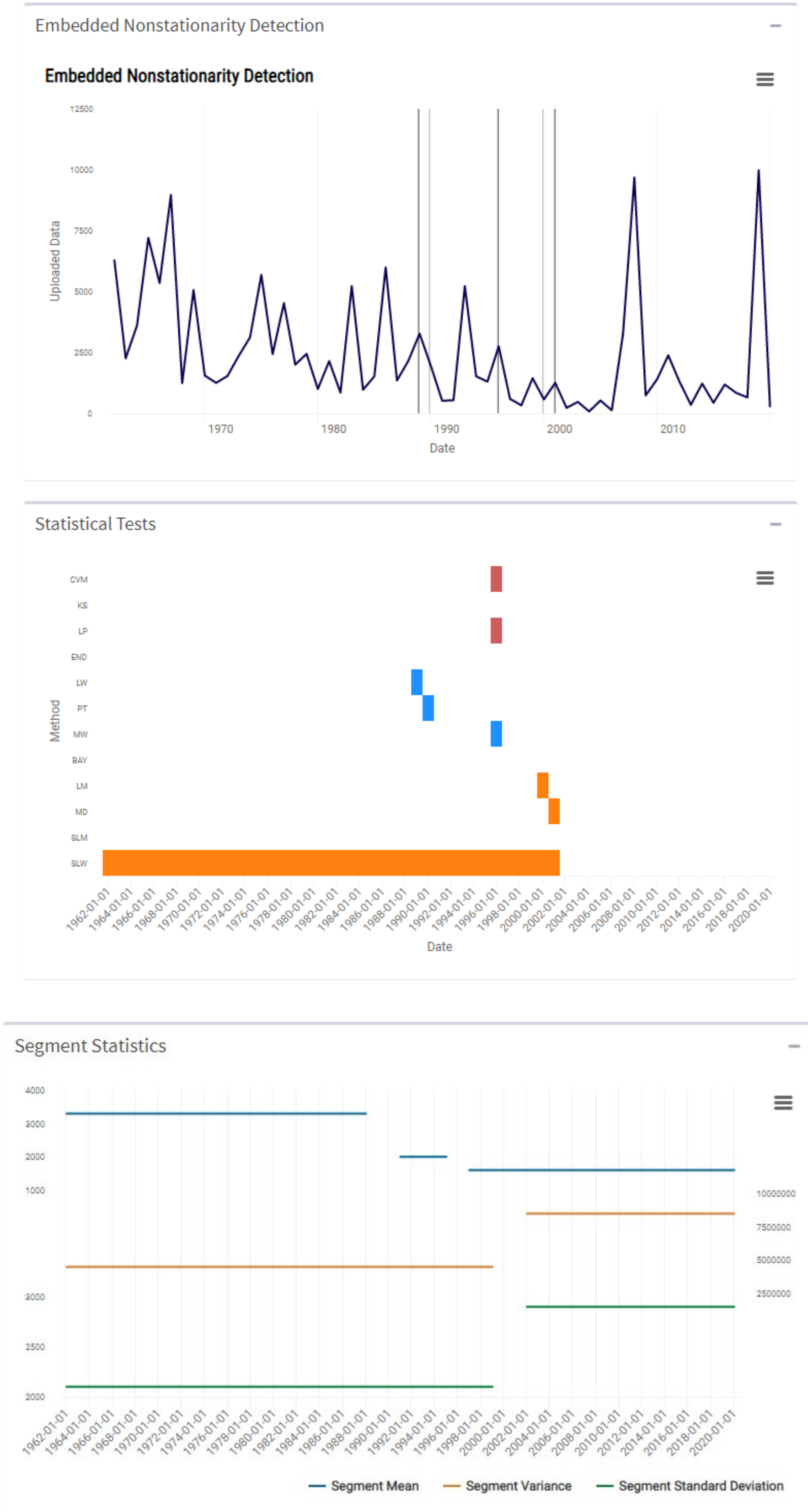


Figure 38: Republican River near Orleans, NE Non-stationarity Detection with extended period of regulated flows (1962-2020)

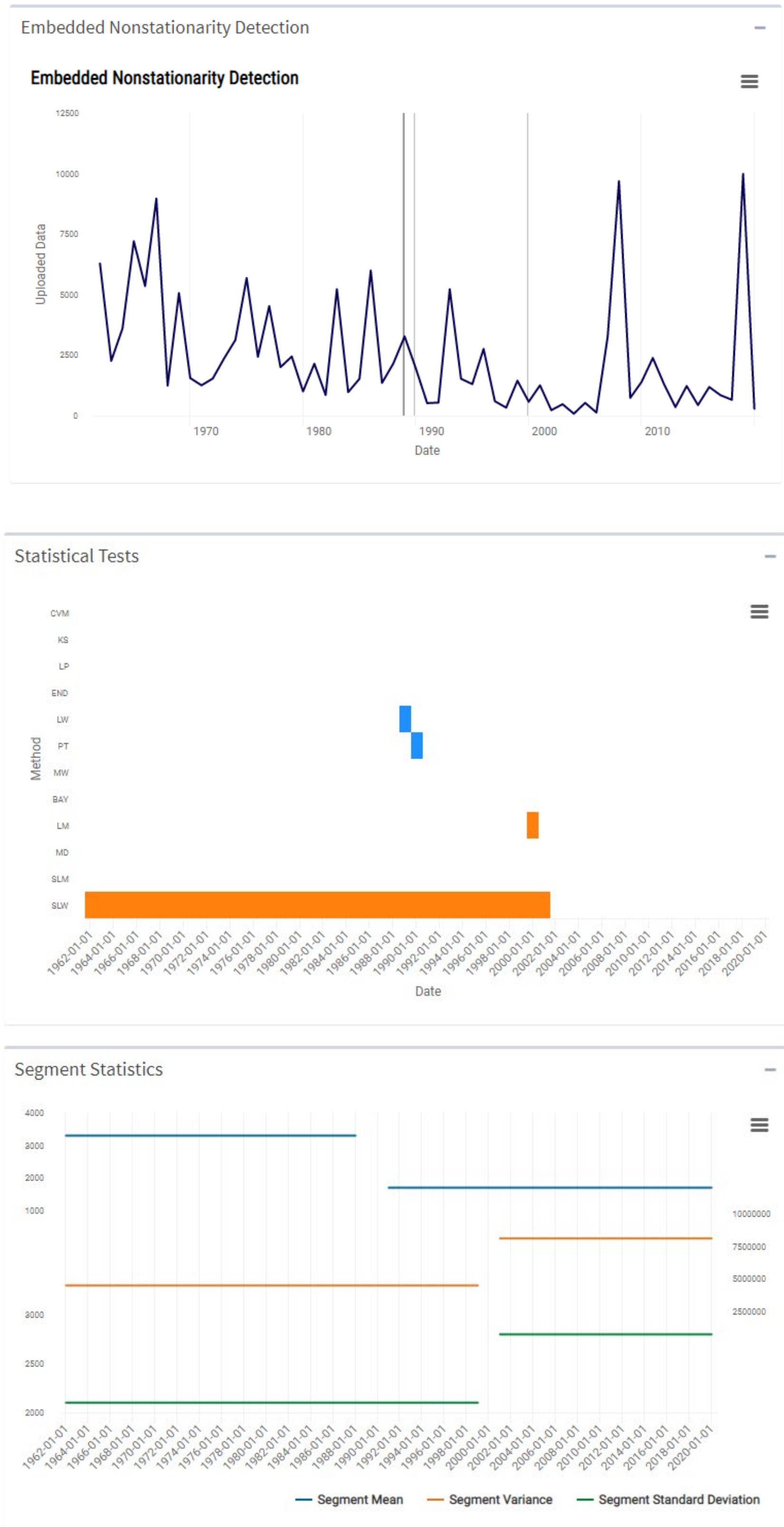
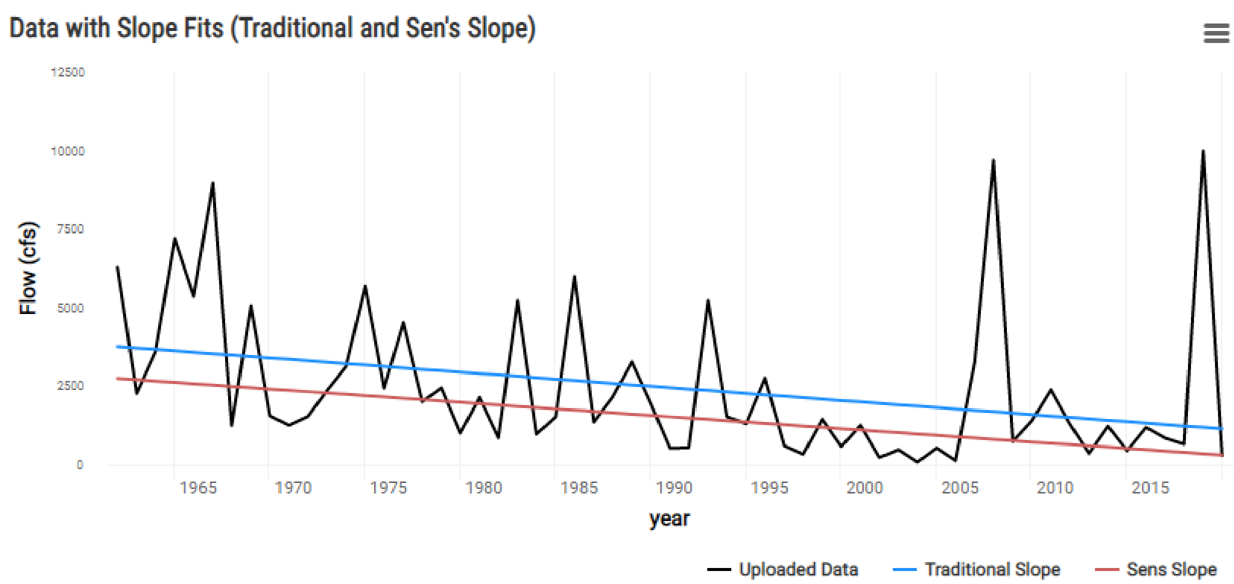


Figure 39: Republican River near Orleans, NE Non-stationarity Detection with CPM methods Sensitivity adjusted to 1,250 (1962-2020)

Additionally, trend analysis was performed, and a statistically significant decreasing trend was indicated by both methods, as seen in Figure 40. Flows at the Republican River near Orleans have been affected by changing conditions as evidenced by the detection of several non-stationarities and a statistically significant trend. These data should not be considered stationary, and the period of analysis should be carefully considered before using for flow frequency analysis.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-45.151	92342
Sen's Slope	-42.079	85299

Test	P.Value
t-Test	0.013173
Mann-Kendall	0.000026844
Spearman Rank-Order	0.000031474

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

Source: Repub_R_Orleans_1962-2020_Inst.csv

Figure 40: Monotonic Trend Analysis, Republican River near Orleans, NE (1962-2020)

2.4.1.2. Prairie Dog Creek, Woodruff, KS

Norton Dam on Prairie Dog Creek was the final dam to begin storage in the Republican River Basin upstream of Harlan County Dam. Storage began at Norton Dam (Keith Sebelius Lake) in October 1964. Figure 41 is a plot of the annual maximum flow values for the gage on Prairie Dog Creek near Woodruff, KS. Generally, there is no discernable trend based on a visual inspection of the data. The 2019 annual maximum flow was the third greatest in the regulated period of record. The Nonstationarity Detection Tool did not detect any abrupt nonstationarities, nor did trend analysis indicate statistically significant trend as shown in Figure 42 and Figure 43. The two smooth methods detected non-stationarities through 1968/1969. The data was filtered to remove pre-1970 data, which removed these non-stationarities. The smooth detection methods likely detected non-stationarities due to the presence of large flows at the beginning of the period of analysis. Additionally, the period of analysis was extended through 2020 using the Time Series Toolbox. Analysis of the 1970-2020 period in the Time Series Toolbox detected one non-stationarity from the Smooth Lombard Wilcoxon method through 1974 as shown in Figure 44. Adjustments did not remove this non-stationarity, but there was no consensus with other methods. Based on the lack of strong non-stationarities and no statistically significant trend, the Prairie Dog Creek flows for the period of 1970-2020 may be considered stationary.

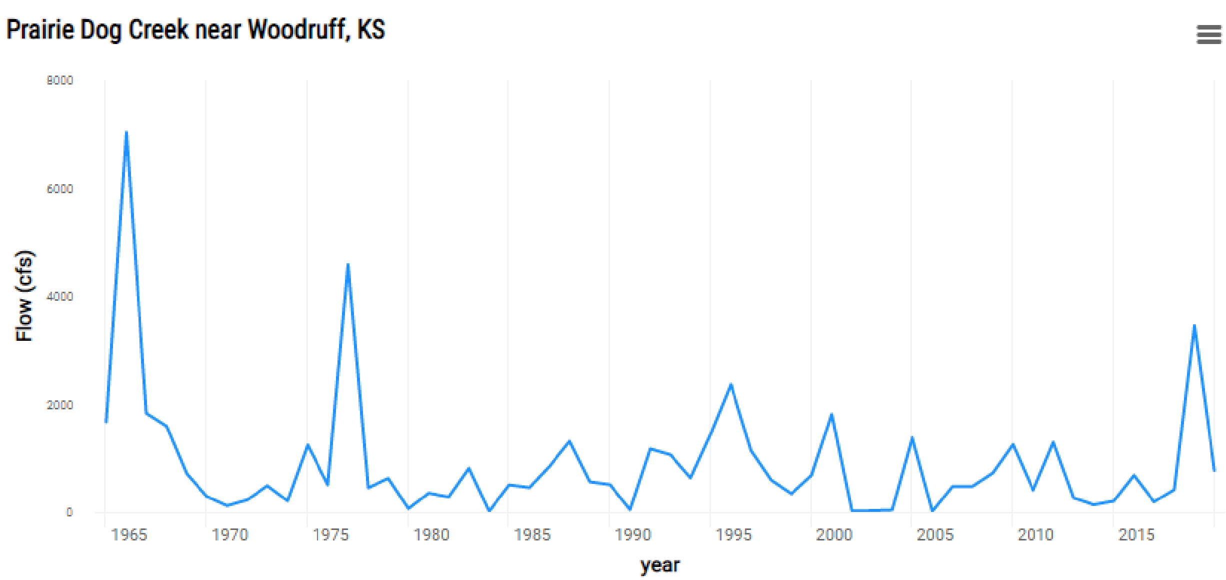


Figure 41: Regulated Annual Peak flows, Prairie Dog Creek near Woodruff, KS (1965-2020)

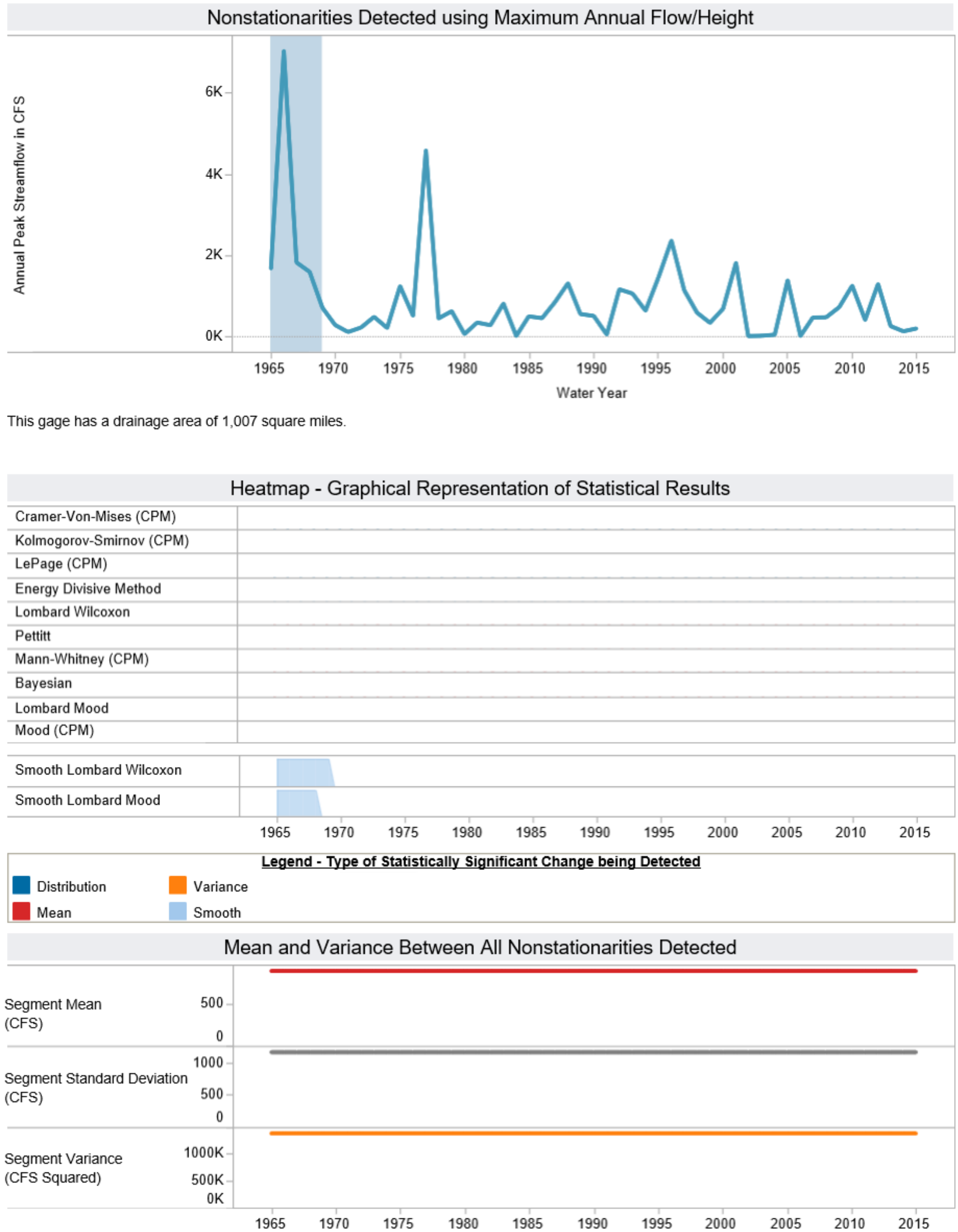
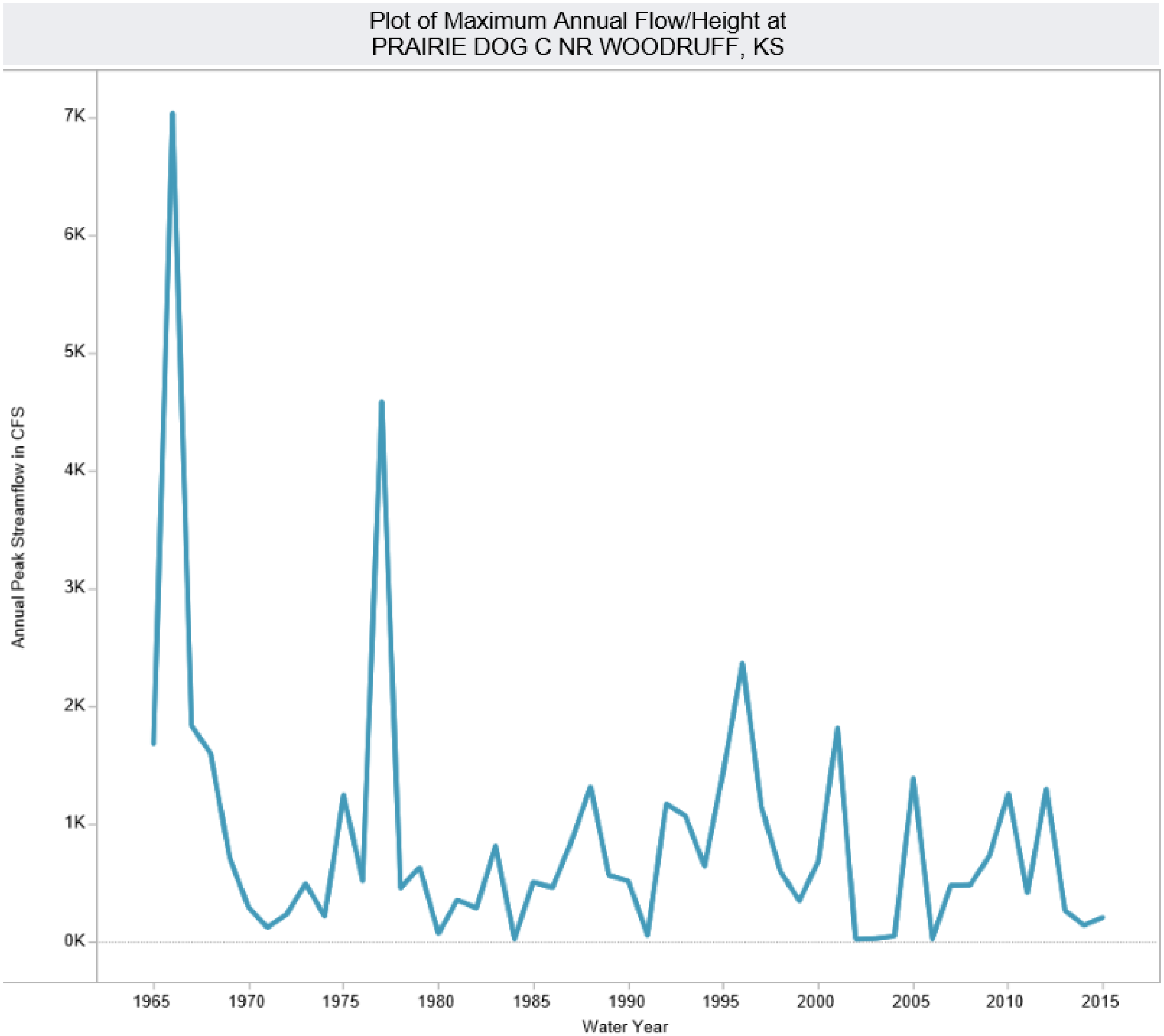


Figure 42: Non-Stationarity Detection Tool Results, Prairie Dog Creek near Woodruff, KS (1965-2015)



Monotonic Trend Analysis

Is there a statistically significant trend?
No, using the Mann-Kendall Test at the .05 level of significance. The exact p-value for this test was 0.226.
No, using the Spearman Rank Order Test at the .05 level of significance. The exact p-value for this test was 0.166.

What type of trend was detected?
Using parametric statistical methods, **no trend** was detected.
Using robust parametric statistical methods (Sen's Slope), **no trend** was detected.

Figure 43: Monotonic Trend Analysis, Prairie Dog Creek near Woodruff, KS (1965-2015)

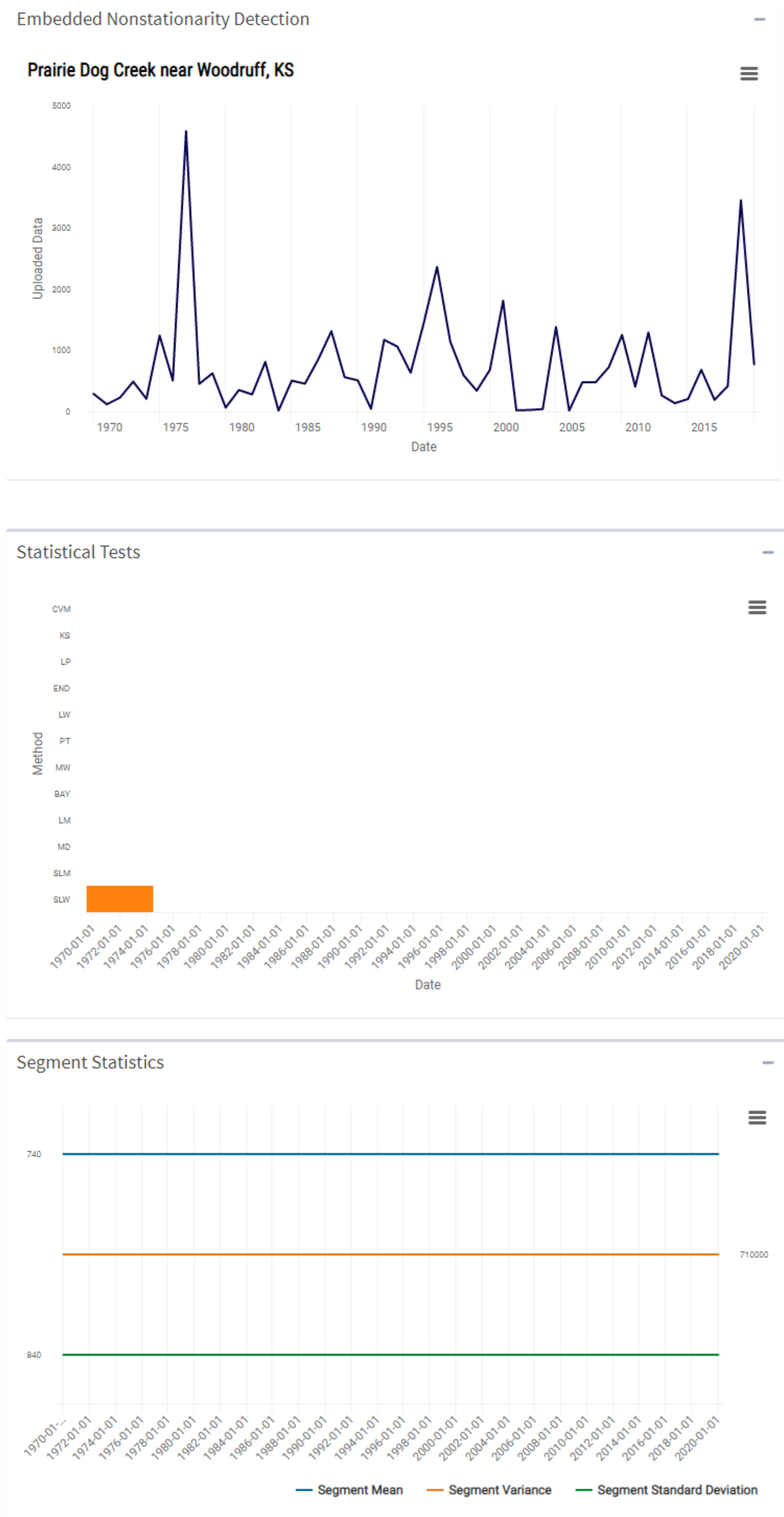


Figure 44: Non-Stationarity Detection Tool Results, Time Series Toolbox, Prairie Dog Creek near Woodruff, KS (1970-2020)

2.4.1.3. Sappa Creek near Stamford, NE

Figure 45 shows the period of record flows on Sappa Creek near Stamford, NE. An obvious shift occurs in the annual peak data around 1968. There are no major regulating dams on Sappa Creek. Peak annual discharges for Beaver Creek near Beaver City, NE, upstream of the Sappa Creek near Stamford gage also indicate a significant decrease in peak flows after approximately 1968 as shown in Figure 46. The significant decrease in peak annual streamflow is likely related to streamflow depletions caused by groundwater pumping for agricultural irrigation. Figure 47, taken from Wen and Chen (2006), shows the cumulative number of irrigation wells developed in the Republican River basin. The sudden decrease in peak flows around 1968 corresponds with an acceleration in the development of irrigation wells in the basin. Other anthropogenic affects in the basin may also contribute to decreasing peak flows including modified agricultural practices such as no-till farming and terrace and/or farm pond construction.

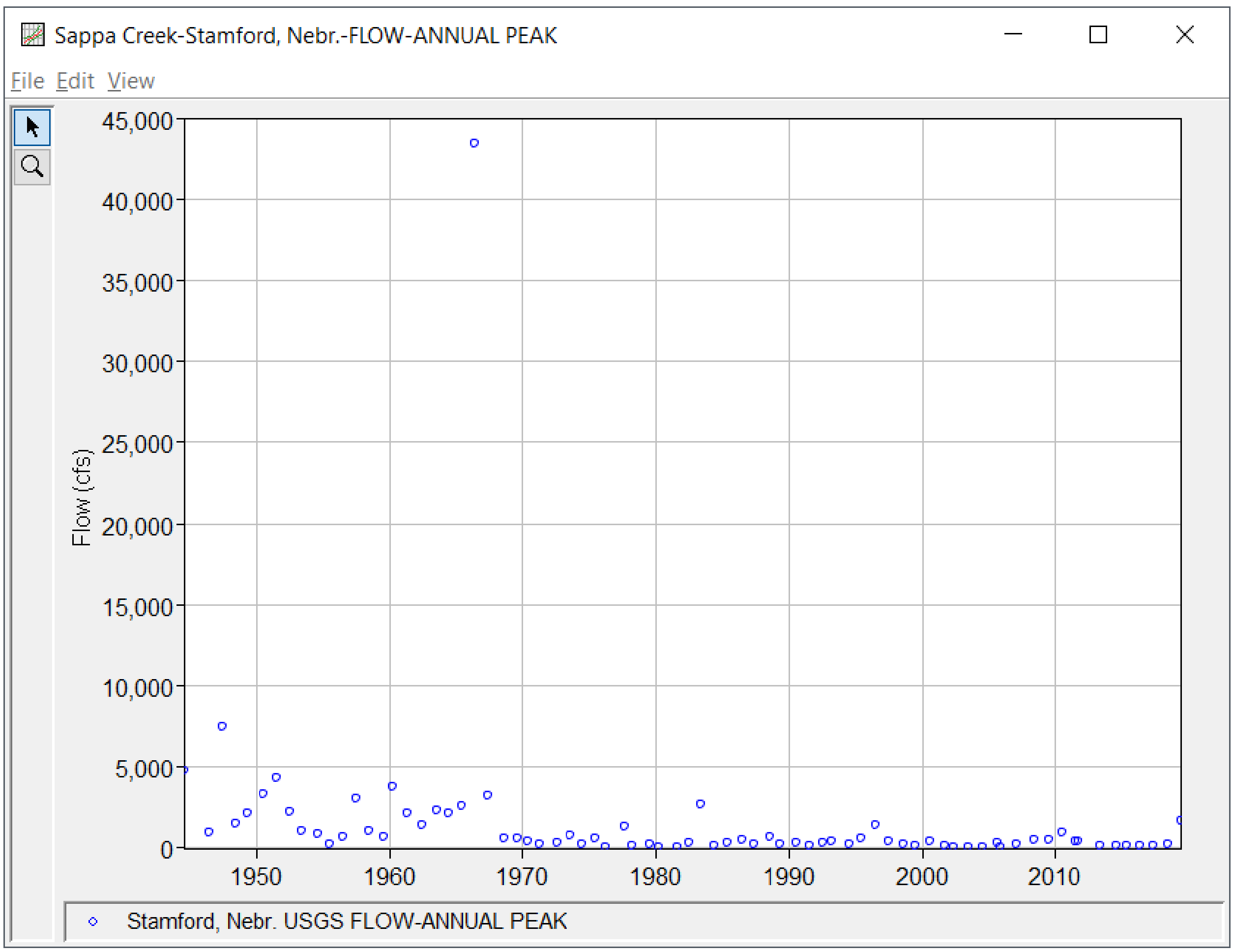


Figure 45: Period of record flows, Sappa Creek near Stamford, NE (1955-2019)

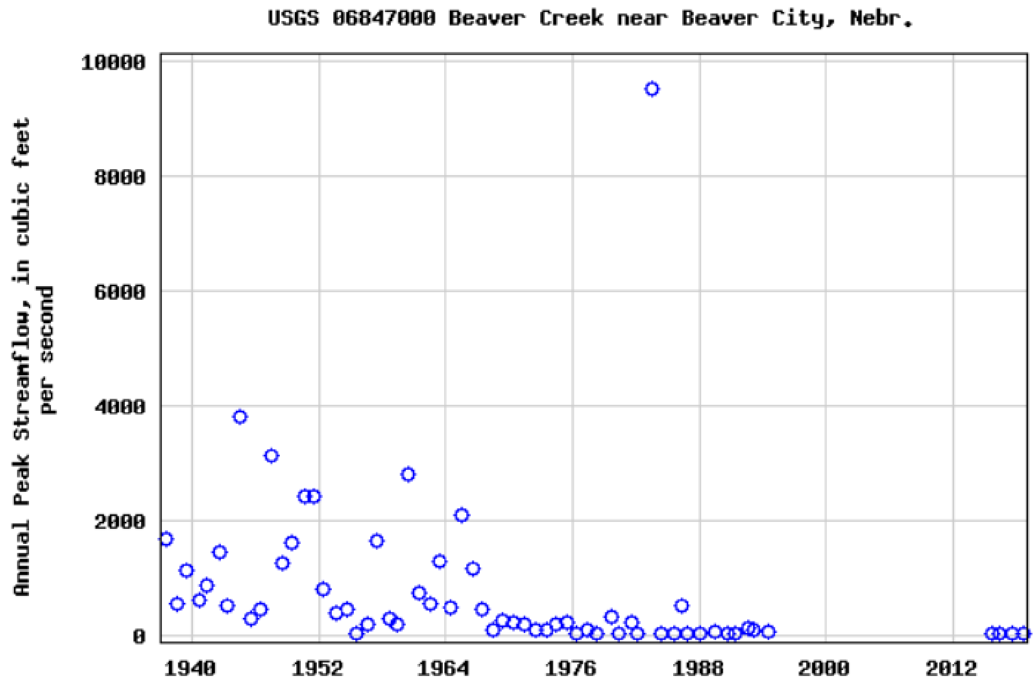


Figure 46: Sappa Creek basin Beaver Creek gage demonstrating the major decrease in peak flows after approximately 1968.

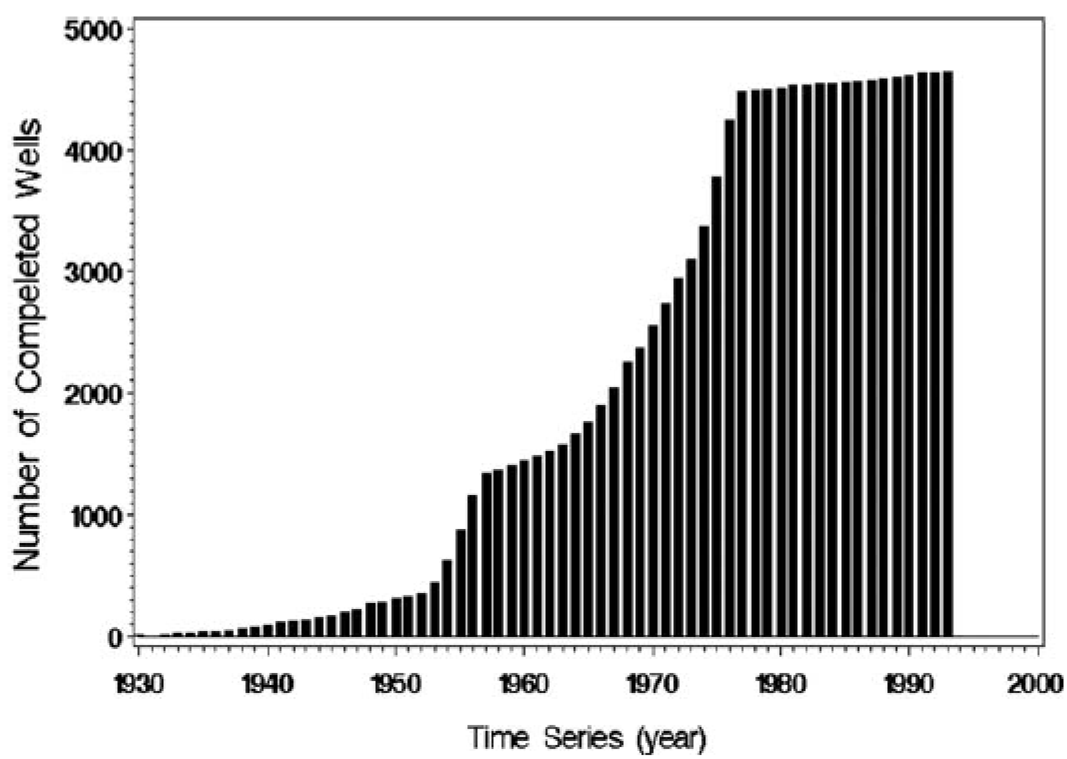
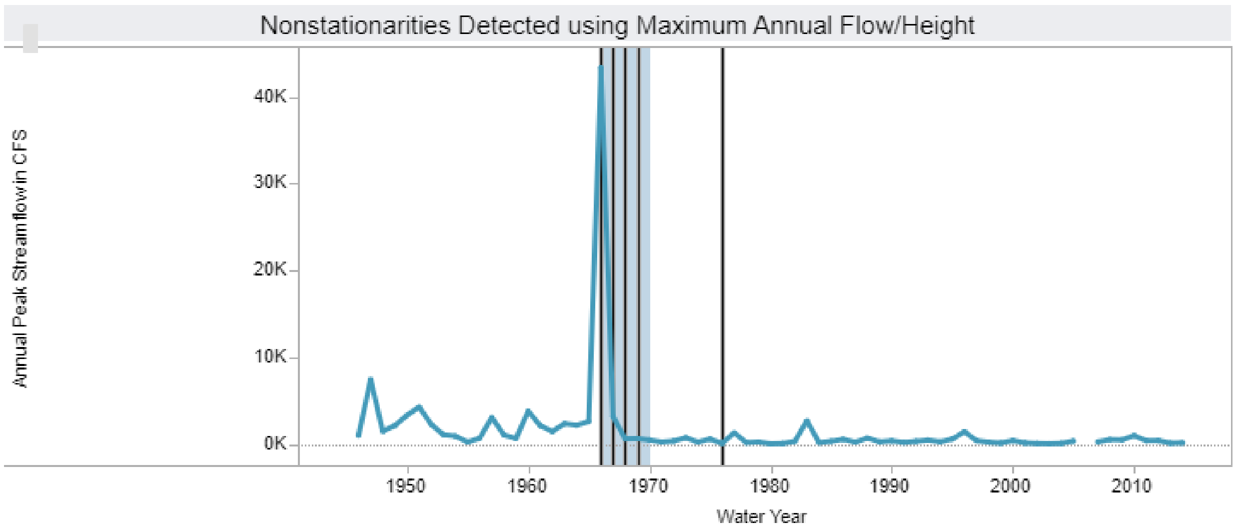


Figure 47: Cumulative number of registered irrigation wells in the Republican River basin, Nebraska, Figure 4 from Wen and Chen (2006)

Nonstationarity analysis was performed on the complete period of record shown in Figure 48, and a strong nonstationarity was identified by several methods in the late 1960's. Additionally, the Energy Divisive method identified a nonstationarity in 1976 that was not identified by other methods. Additionally, trend analysis shown in Figure 49 indicates a statistically significant trend is present. Due to the presence of a strong nonstationarity and a statistically significant trend, the complete period of record should not be considered stationary.

The post 1970 data was also analyzed in the time series toolbox to determine if a truncated period of analysis could be considered stationary. It appears in the analysis that there was a missing peak flow in 2006, however, the observed peak streamflow in 2006 was zero (no flow). The analysis did not detect any non-stationarities (Figure 50), or a statistically significant trend as shown in Figure 51. Thus, the period of 1970-2020 may be considered stationary.



This gage has a drainage area of 3,840 square miles.

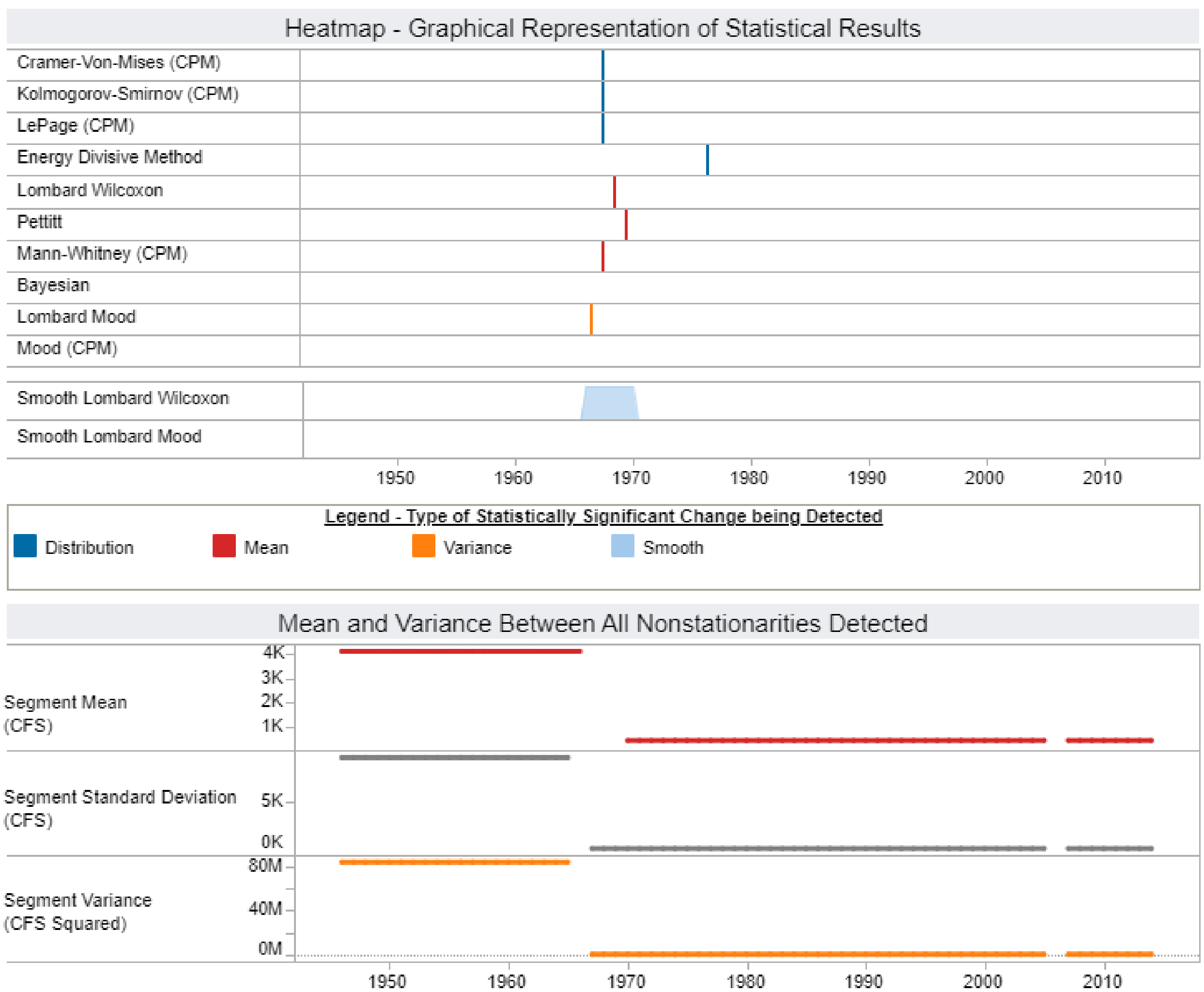
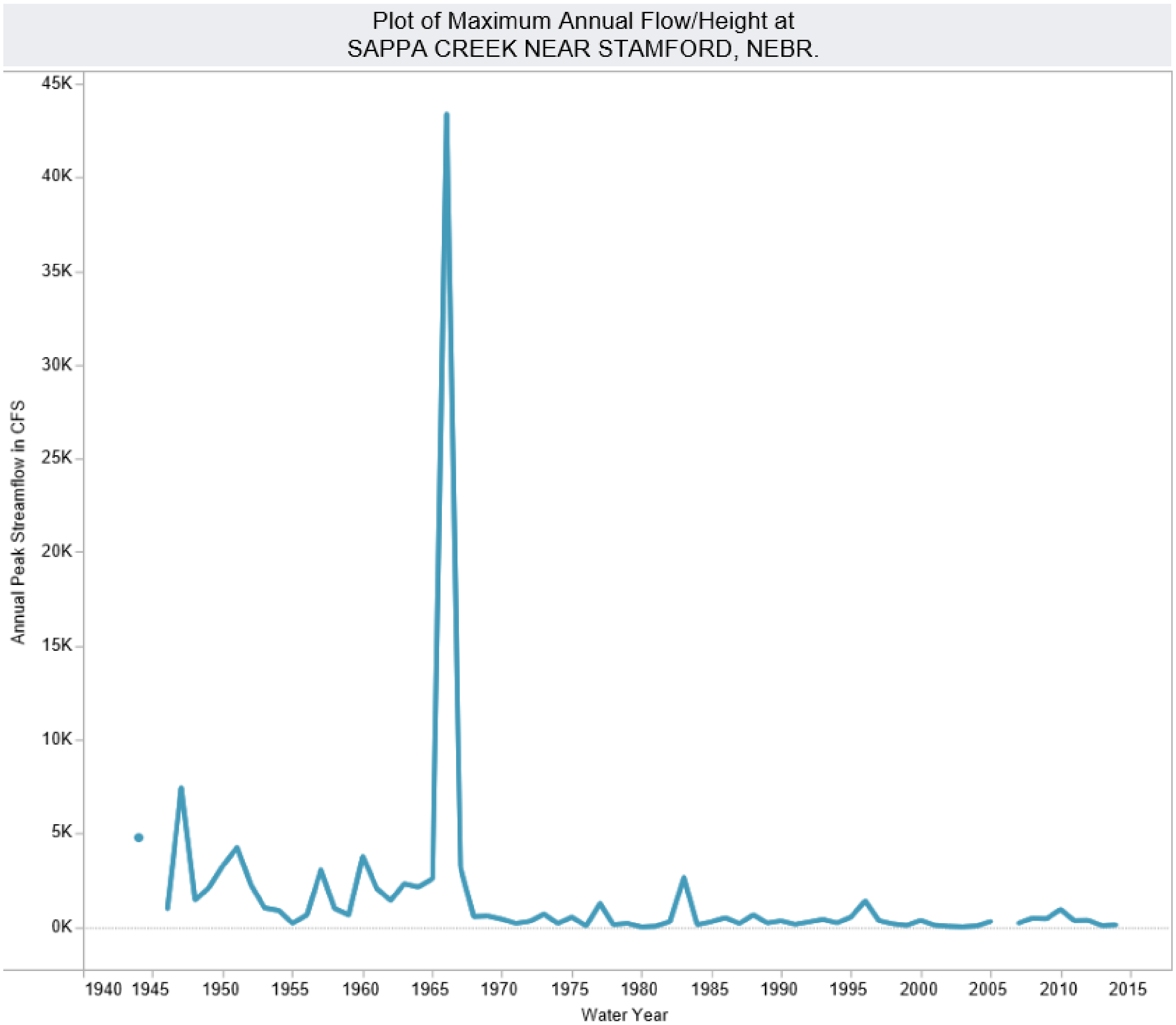


Figure 48: Non-Stationarity Detection Tool Results, Sappa Creek near Stamford, NE (1946-2014)



WARNING: The period of record selected has missing data points. There are potential issues with the trends detected.

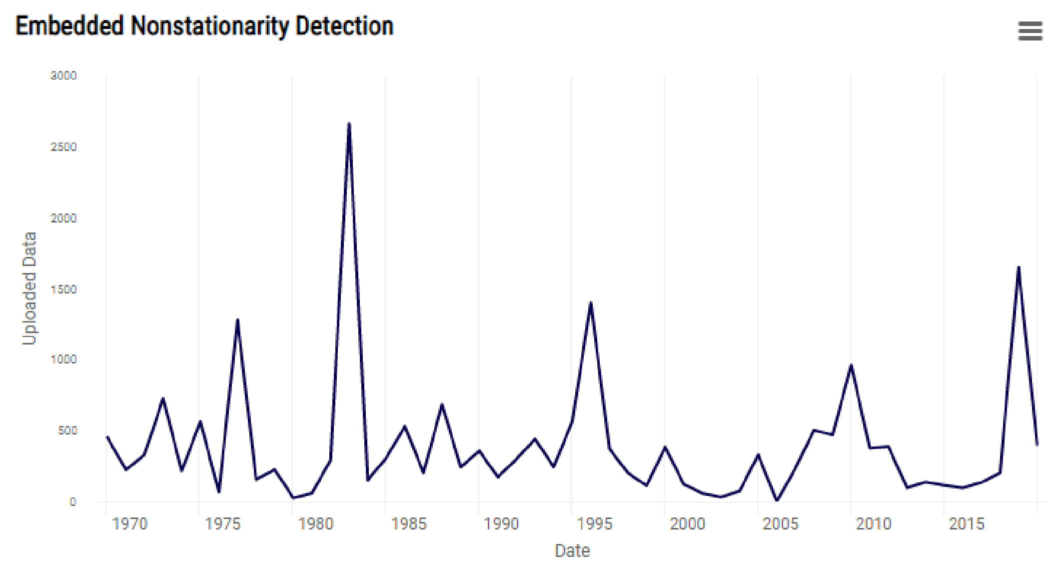
Monotonic Trend Analysis

Is there a statistically significant trend?
Yes, using the Mann-Kendall Test at the .05 level of significance. The exact p-value for this test was less than 1e-3.
Yes, using the Spearman Rank Order Test at the .05 level of significance. The exact p-value for this test was less than 1e-3.

What type of trend was detected?
Using parametric statistical methods, **a negative trend** was detected.
Using robust parametric statistical methods (Sen's Slope), **Null** was detected.

Figure 49: Monotonic Trend Analysis, Sappa Creek near Stamford, NE (1944-2014)

Embedded Nonstationarity Detection



Statistical Tests

No nonstationarities detected!

Segment Statistics

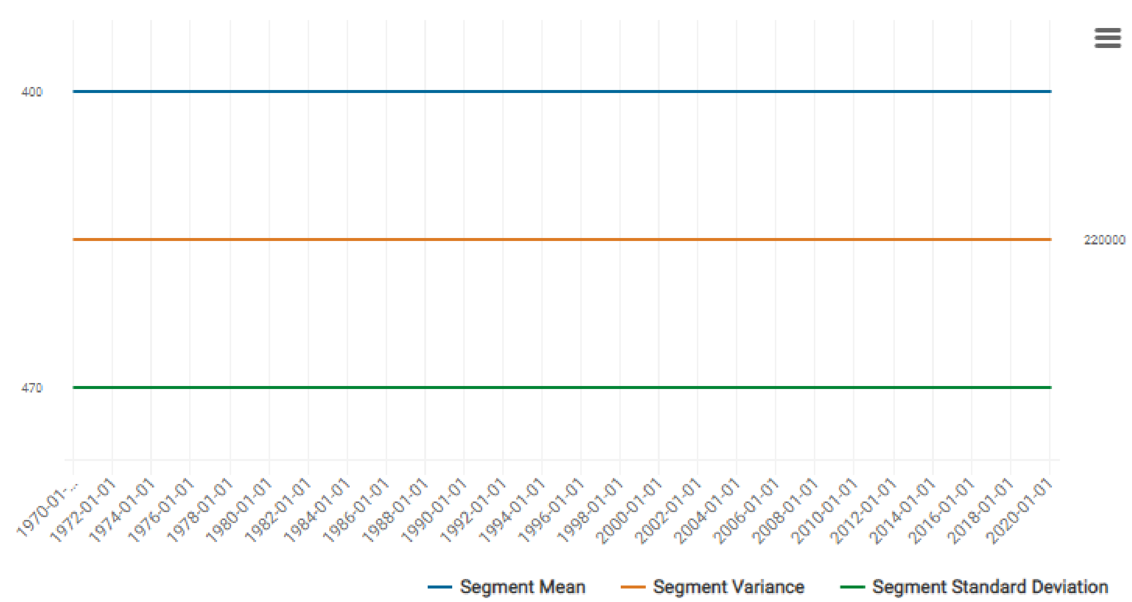
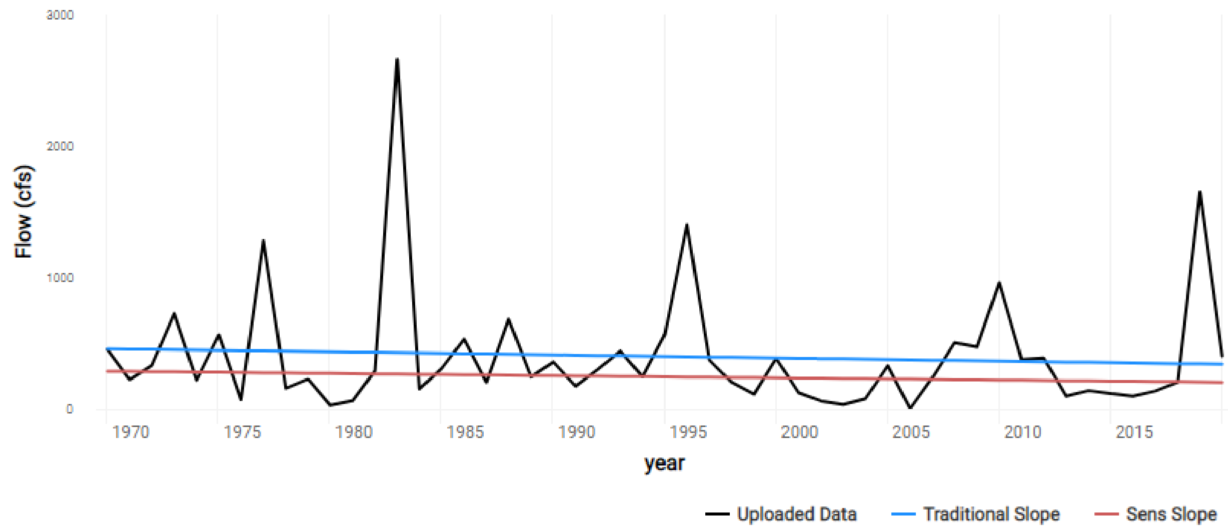


Figure 50: Non-Stationarity Detection Results, Sappa Creek near Stamford, NE (1970-2020)

Data with Slope Fits (Traditional and Sen's Slope)



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-2.3532	5093.1
Sen's Slope	-1.6875	3610.6

Test	P.Value
t-Test	0.60271
Mann-Kendall	0.46974
Spearman Rank-Order	0.41368

- **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: Sappa_Cr_1970-2020_inst.csv

Figure 51: 1970-2020 Monotonic Trend Analysis, Sappa Creek near Stamford, NE

2.4.2. Waconda Lake (Glen Elder Dam) Inflows

Waconda Lake is formed by Glen Elder Dam, and located on the Solomon River in Mitchell County, Kansas. Waconda Lake is operated by the U.S. Bureau of Reclamation (USBR), except in flood operation USACE assumes responsibility for determining releases. Closure was made at Glen Elder Dam on 18-October-1967. Storage began in Waconda Lake on 24-July-1968, and multipurpose pool level was reached on 16-May-1973. The full period of record for the Waconda Lake inflows dates back to 1967. Flow into Waconda was already regulated prior to its construction with upstream USBR dams, Kirwin and Webster, being constructed in 1955, and 1956 respectively. The period of record analyzed is from 1968 to 2019, as 1967 was an incomplete year. The period of record inflows (annual maxima) are plotted in Figure 52.

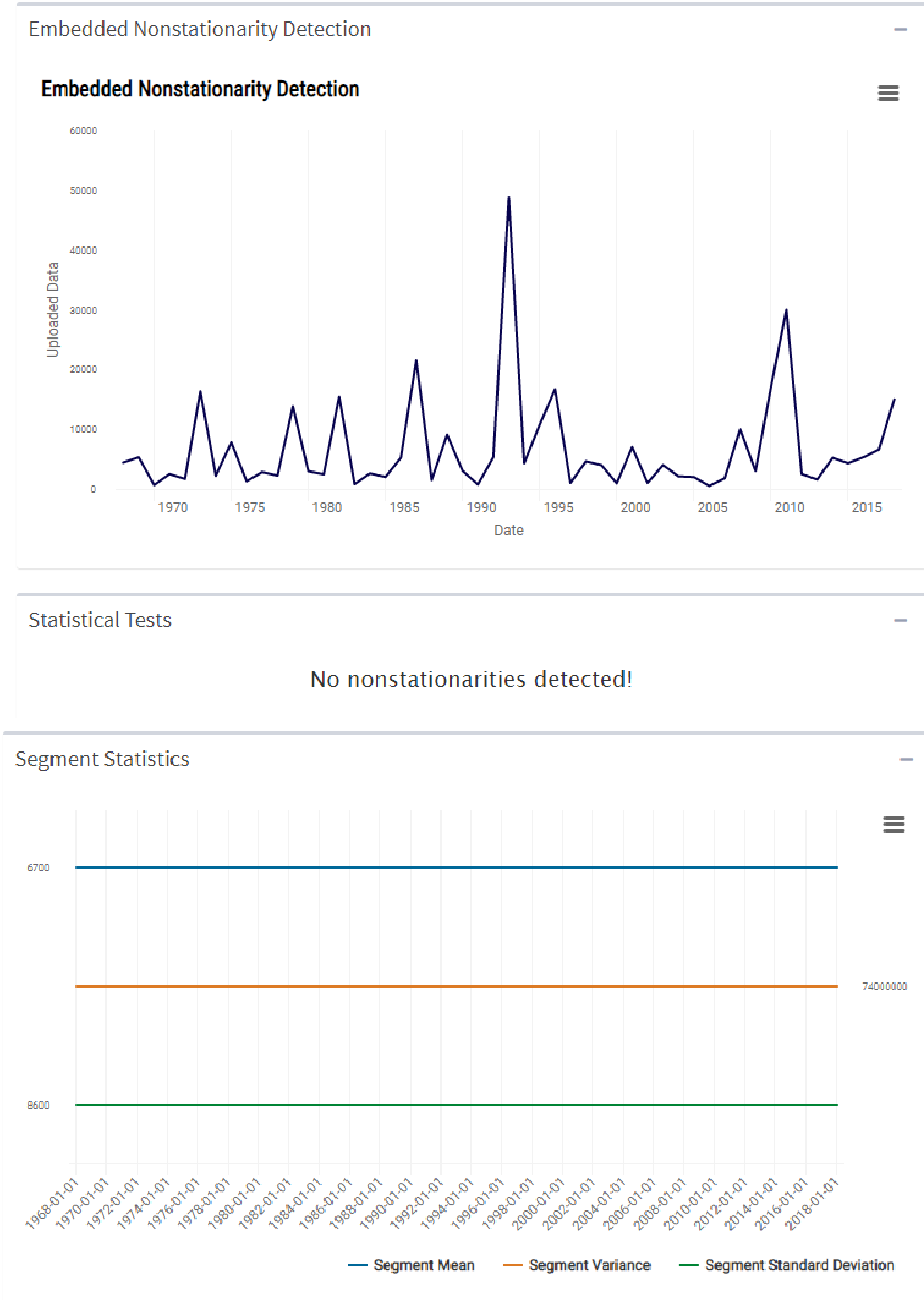
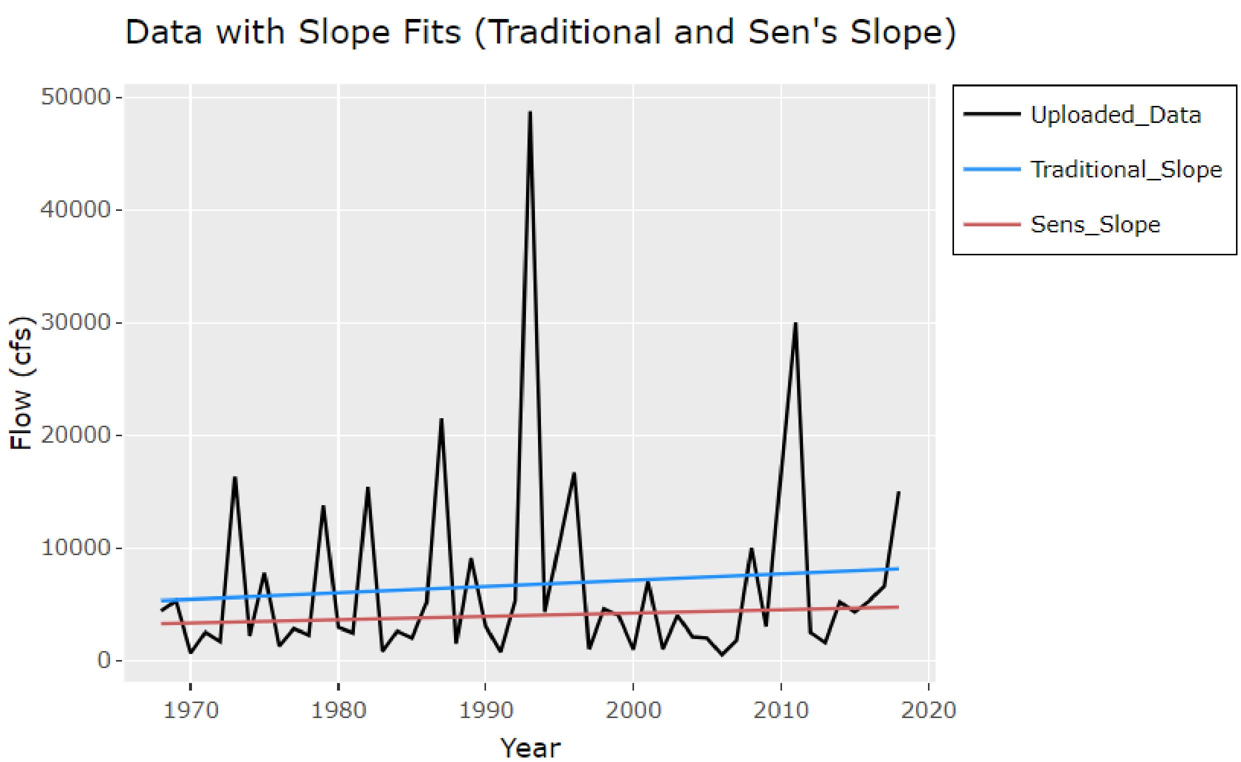


Figure 52: Non-Stationarity Detection for Waconda Lake Inflows (1968-2019)

Nonstationarities were not detected for the Waconda Lake inflows using default sensitivity parameters. Further testing was done by reducing the CPM Burn-In Period as well as reducing the parameter sensitivities one by one. No nonstationarities were detected after making these adjustments. Trend line analysis was also performed for the period of record annual maximum inflows for Waconda Lake. No statistically significant trends were detected. Results are shown in Figure 53. Therefore, the period of record lake inflows for Waconda Lake may be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	56.806	-106480
Sens Slope	29.821	-55434

Test	P.Value
t-Test	0.49369
Mann-Kendall	0.34601
Spearman Rank-Order	0.36925

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

Figure 53: Trend Analysis for Waconda Lake Annual Maximum Daily Inflows (1968-2019)

2.4.3. Wilson Lake Inflows

Wilson Lake is located on the Saline River in Russell County, Kansas. Closure was made at Wilson Dam on 03-September-1963, storage began on 29-December 1964, and the lake reached multipurpose pool level on 12-March-1973. Wilson Lake inflows are computed from pool elevation data, currently reported at USGS Gage 06868100. The period of record from 1964 to 2019 for the Wilson Lake inflows were used for analysis in the Time Series Toolbox due to the incomplete year in 1963. Flow into Wilson Lake is not regulated.

As shown in Figure 54, nonstationarities were not detected for the Wilson Lake inflows using default sensitivity parameters. Further testing was done by adjusting the sensitivity parameters. No nonstationarities were detected after making adjustments for the Wilson Lake inflow period of record.

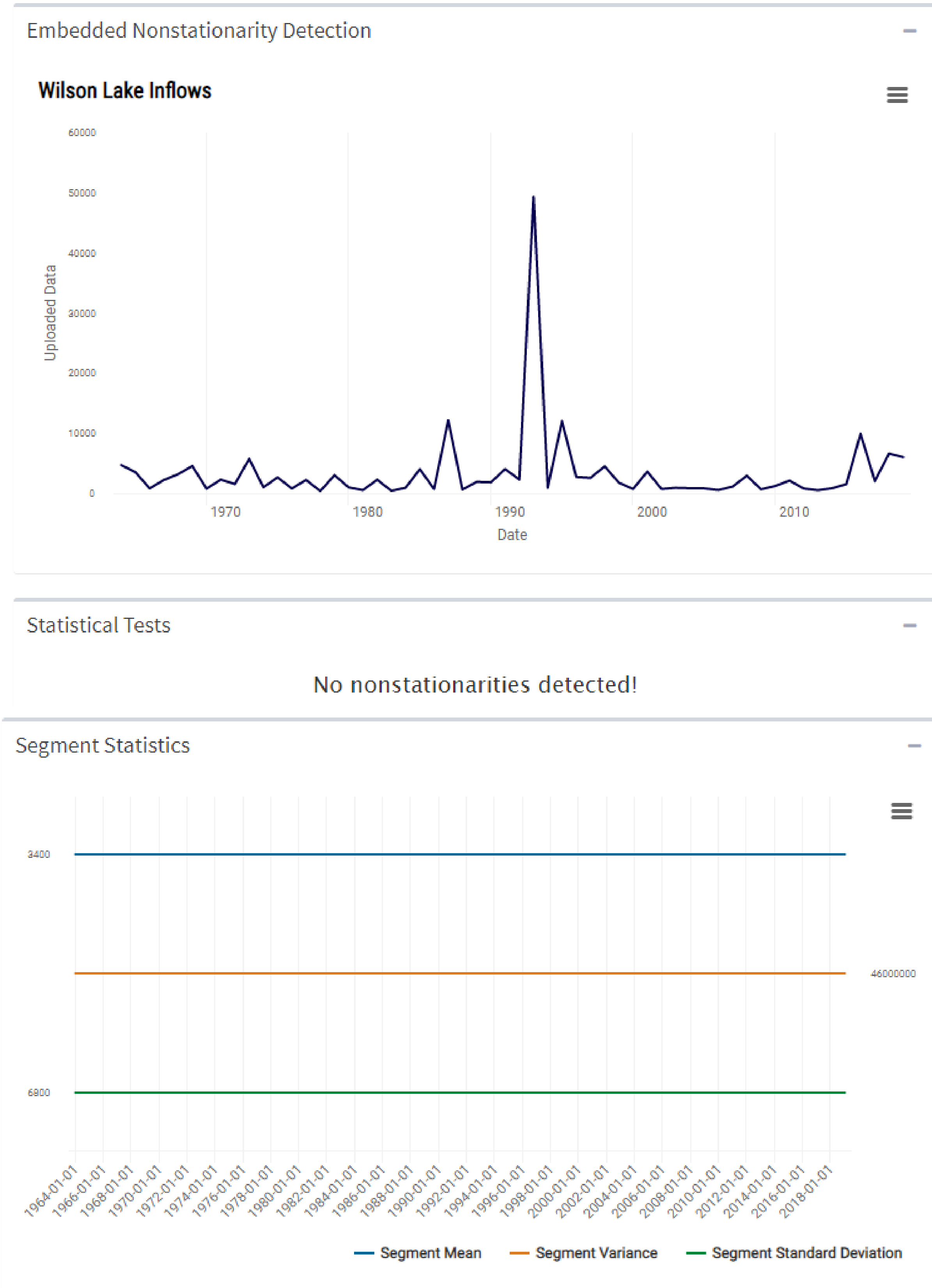
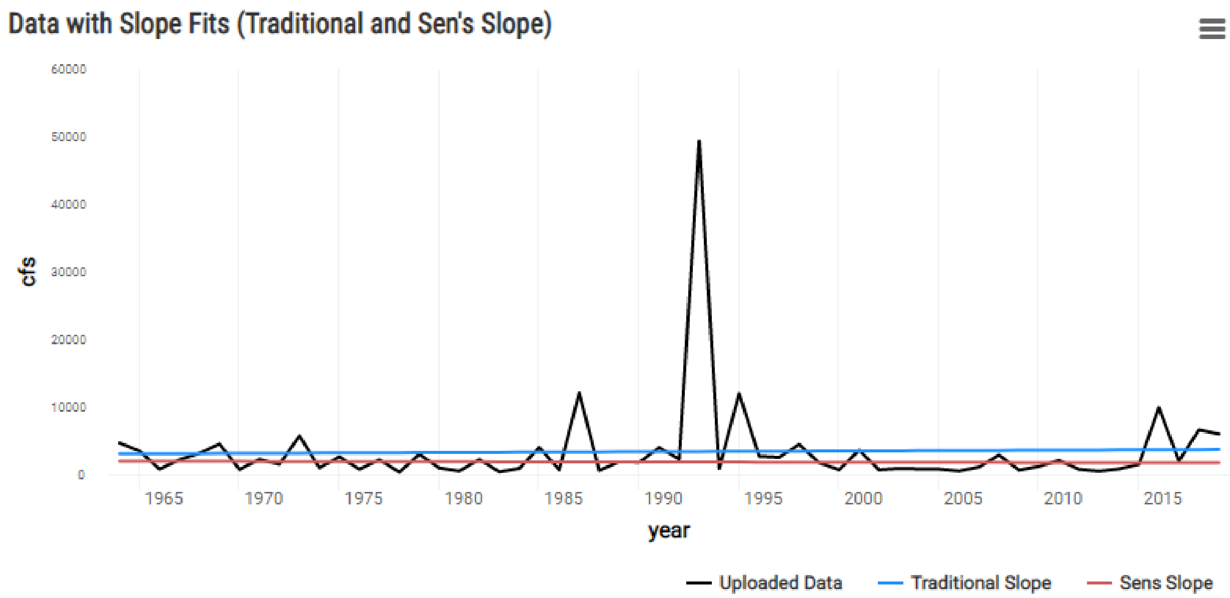


Figure 54: Nonstationarity Detection for Wilson Lake Inflows (1964-2019)

Trend analysis for Wilson Lake annual maximum inflows is shown in Figure 55. No statistically significant trends were found. Since no statistically significant trend or non-stationarity was detected for the Wilson Lake inflows, the period of record may be treated as stationary.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	11.509	-19542
Sen's Slope	-4.631	11073

Test	P.Value
t-Test	0.83929
Mann-Kendall	0.5479
Spearman Rank-Order	0.60763

- **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: Wilson_1964-2019.csv

Figure 55: Trend Analysis of Wilson Lake Annual Maximum Daily Inflows (1964-2019)

2.4.4. Kanopolis Lake Inflows

Kanopolis Lake is located on the Smoky Hill River in Ellsworth County, Kansas. Closure was made at Kanopolis Dam on 26-July-1946. Storage began in the lake on 17-February-1948, and multipurpose pool level was reached on 19-July-1948. The full period of record for Kanopolis Lake Inflows dates back to 1948. Inflows are computed from pool elevation data, currently reported at USGS Gage 06865000. Flow became regulated in 1951 when upstream dam, Cedar Bluff, was constructed and reached multipurpose pool on 21-June-1951. The 1951 annual maximum inflow at Kanopolis Lake occurred on 12-July. The flow record used for the nonstationarity detection tool was from 1951 to 2019.

Two nonstationarities were detected in the inflow record of Kanopolis with the default sensitivity parameters as shown in Figure 56. The Lombard Wilcoxon method detected a nonstationarity in 1974. The non-stationarity detected in 1974 results in a relatively large decrease in the segment mean from 8,700 cfs to 5,800 cfs after the changepoint. The Energy Divisive method detected a non-stationarity in 1981. Increasing the Pettitt sensitivity parameter to 0.10 detected an additional non-stationarity in 1975. Increasing the burn in period from 20 to 25 years for the 69-year regulated flow record resulted in the nonstationarity detected by the Lombard Wilcoxon method disappearing. The adjusted burn in period of 25 years is 36% of the available period of record. The Energy Divisive method sensitivity was reduced to 0.15 to remove the 1981 non-stationarity. Further adjustments yielded no changes. The final nonstationarity analysis with adjustments is shown in Figure 57. Due to the lack of consensus and robustness in the detected non-stationarities, the non-stationarities are not considered strong.

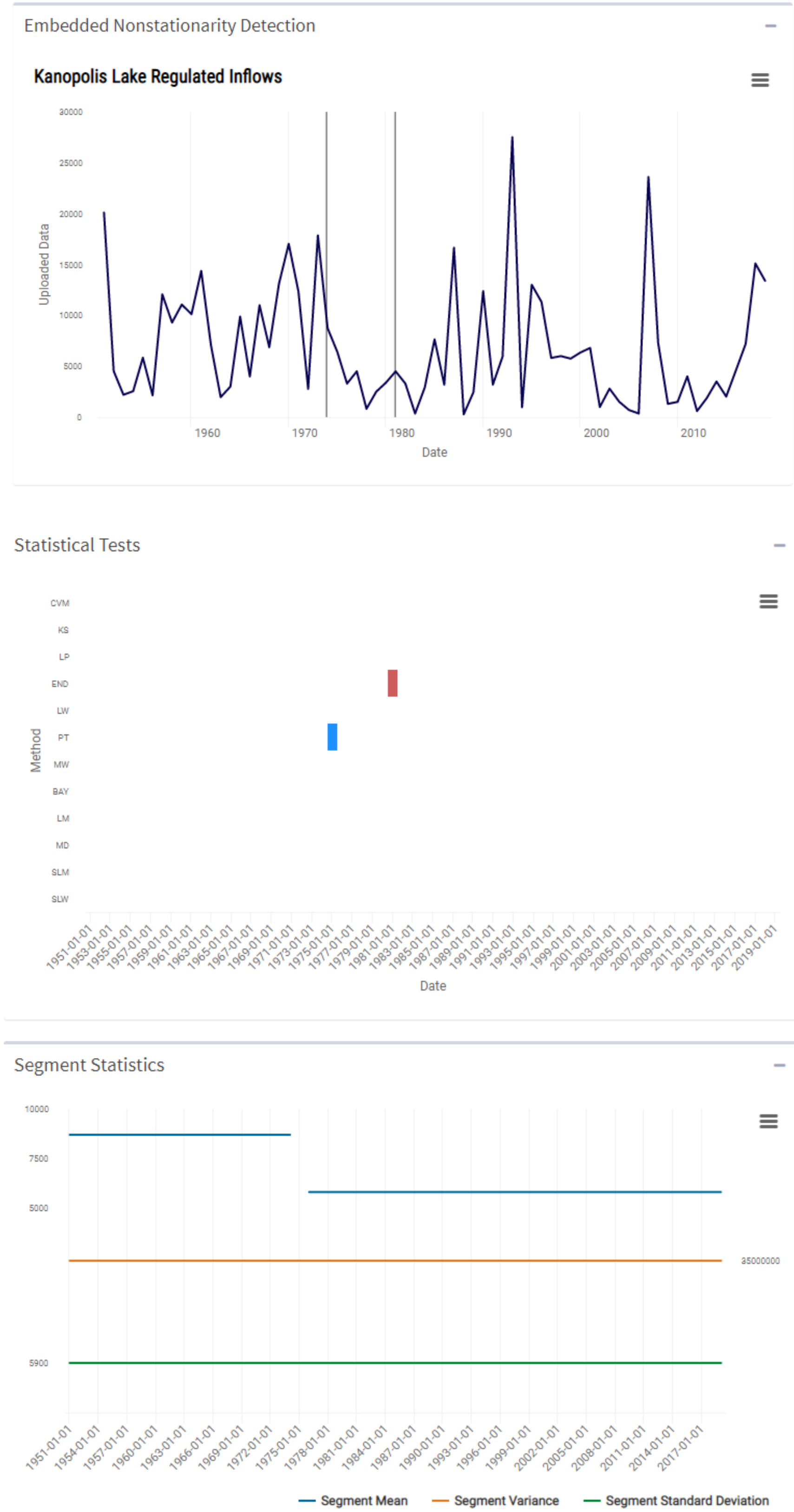


Figure 56: Nonstationarities Detected from Kanopolis Lake Inflows with Default Sensitivity Parameters (1951-2019)

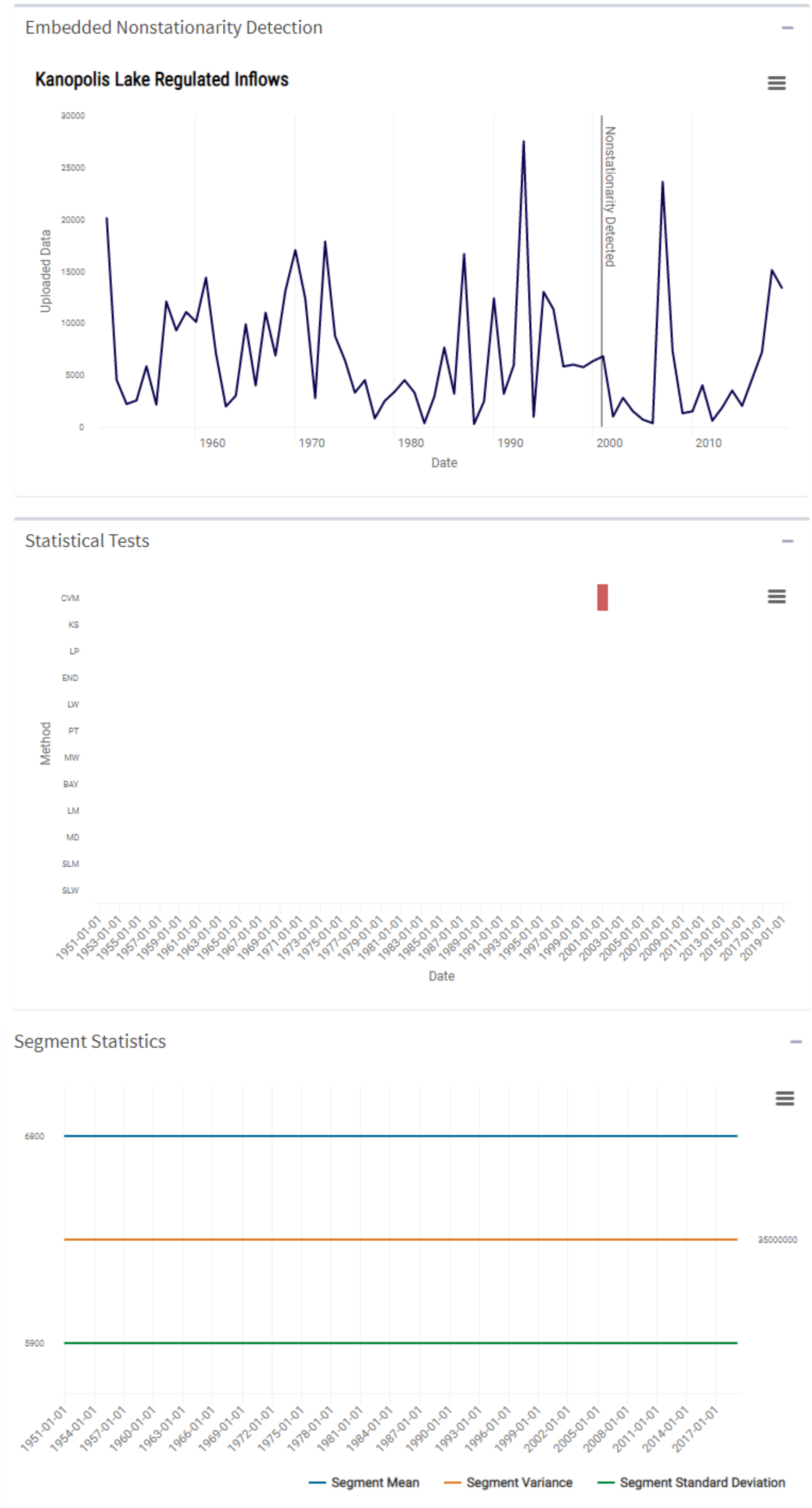
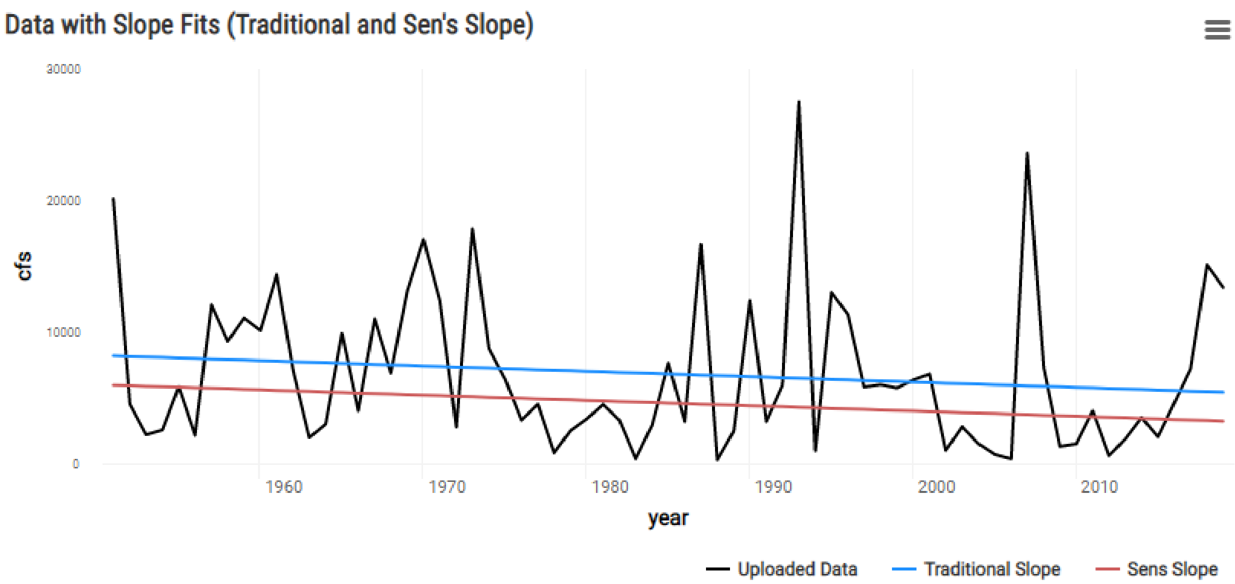


Figure 57: CPM Burn-In Period raised to 30 and CPM Method Sensitivity reduced to 500 for Kanopolis, Energy Divisive Sensitivity reduced to 0.15 (1951-2019)

In addition to nonstationarity detection, trend analysis was performed on the annual maximum inflow data. No statistically significant trends were found, as shown in Figure 58. The trends indicated a decrease in the annual maximum flows, even though it was not statistically significant. Due to the lack of a statistically significant trend, and lack of a strong non-stationarity, the Kanopolis Lake inflow regulated period of record may be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-40.691	87577
Sen's Slope	-40.14	84279

Test	P.Value
t-Test	0.25738
Mann-Kendall	0.10833
Spearman Rank-Order	0.10289

- **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: Kanopolis - Regulated.csv

Figure 58: Trend Analysis for Kanopolis Lake Annual Maximum Inflow (1951-2019)

2.4.5. Milford Lake Inflows

Milford Lake is located on the Republican River northwest of Junction City, Kansas. Storage began in Milford Lake on 16-January-1967, and multipurpose pool level was reached on 14-July-1967. The full period of record for Milford Lake inflows dates back to 1964. Inflows are computed from pool elevation data, currently reported at USGS Gage 06857050. Flow regulation reached its current level in 1967 when Hugh Butler Lake and Keith Sebelius Lakes (Norton Dam) reached multipurpose pool. The flow record used for the nonstationarity detection analysis was from 1967 to 2019.

Nonstationarities were only detected by the Smooth Lombard Wilcoxon (SLW) method for the Milford Lake inflows using default sensitivity parameters. The SLW method detected nonstationarities in 2013-2015 as seen in Figure 59. Further testing was done by reducing the CPM Burn-In Period as well as increasing the parameter sensitivities one by one. No additional nonstationarities were detected. Due to a lack of consensus with other testing methods after further adjustment the nonstationarity detected by the SLW method is likely insignificant.

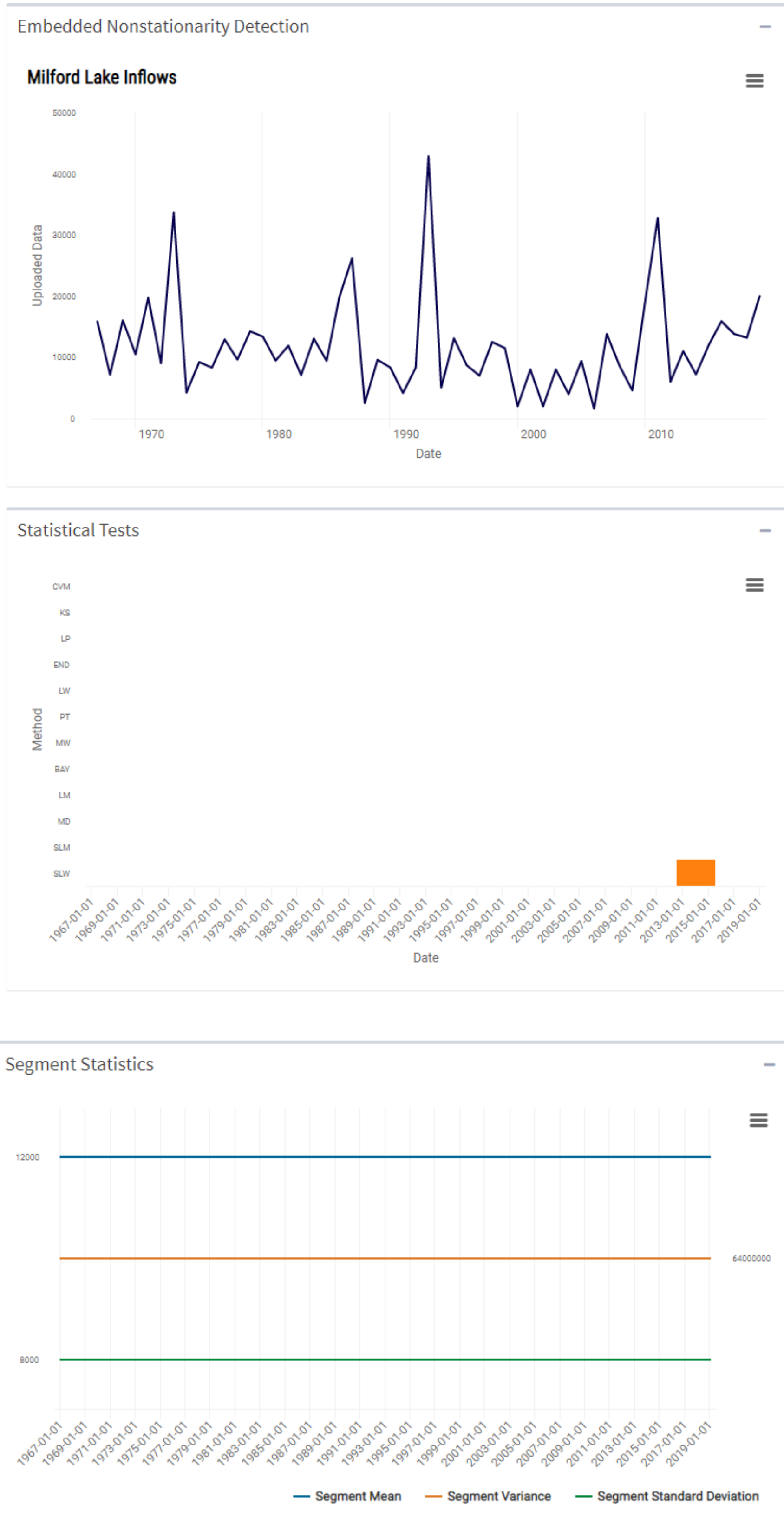
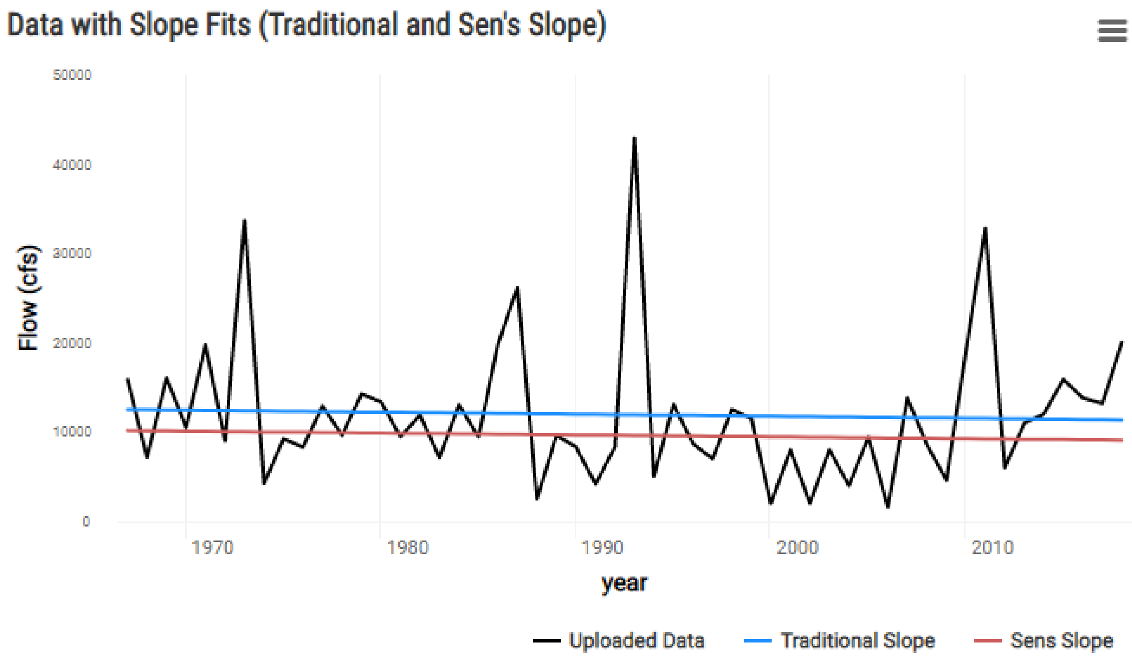


Figure 59: Nonstationarities detected for Milford Lake Inflow Record (1967-2019)

Trend analysis was also performed on the dataset, but no statistically significant trend was detected as shown in Figure 60. Since no strong non-stationarities are present, and no statistically significant trend was detected, the inflow dataset can be considered stationary.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-22.517	56792
Sen's Slope	-21.184	51820

Test	P.Value
t-Test	0.76517
Mann-Kendall	0.66424
Spearman Rank-Order	0.70287

- **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.**

Figure 60: Trend Analysis for Milford Lake Regulated Inflows (1967-2019)

2.4.6. Tuttle Creek Lake Inflows

Tuttle Creek Lake is located on the Big Blue River north of Manhattan, Kansas. Storage began in Tuttle Creek Lake on 07-March-1962, and multipurpose pool level was reached on 30-April-1963. Closure was made at the dam on 20-July-1959. Tuttle Creek Lake inflows are computed from pool elevation data, currently reported at USGS Gage 06886900. The full period of record for the Tuttle Creek Lake inflows was used for the Time Series Toolbox. The period of record ranges from 1959 to present. 1959 was an incomplete year and was removed from the analysis. Flow into Tuttle Creek Lake is not regulated. Figure 61 shows a plot of the inflow data and non-stationarity detection.

Nonstationarities were not detected for the Tuttle Creek Lake inflows using default sensitivity parameters. Further testing was done by adjusting the sensitivity parameters. When the Energy Divisive Method Sensitivity parameter was adjusted to 0.73, the method detected a non-stationarity in 1990. No other non-stationarities were detected. Due to the lack of consensus with other methods, and the adjustment away from the default parameters, the non-stationarity in 1990 is weak.

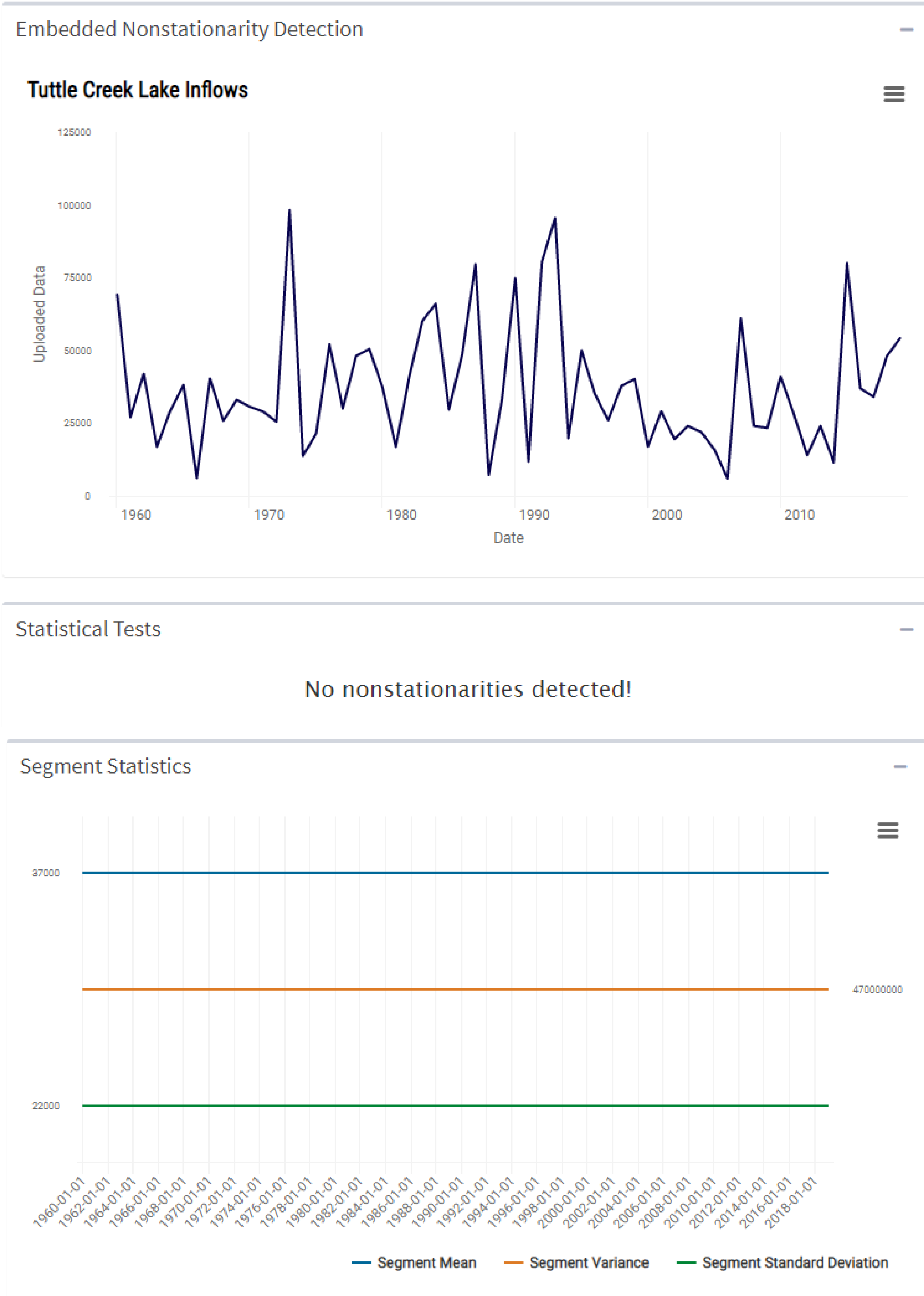
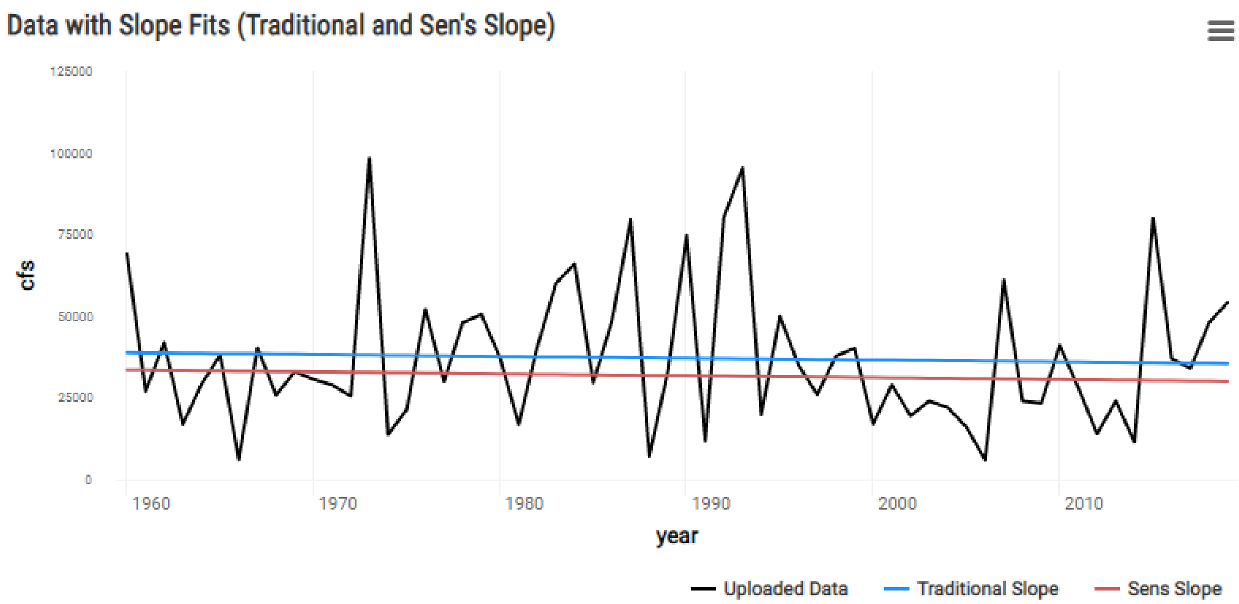


Figure 61: Nonstationarity Detection for Tuttle Creek Lake Inflows

Figure 62 shows the trend analysis on the annual maximum inflows for Tuttle Creek Lake. No statistically significant trends were detected. Since no statistically significant trend or strong non-stationarity was detected for the Tuttle Creek Lake inflows, the period of record may be treated as stationary.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-57.002	150580
Sen's Slope	-58.919	149040

Test	P.Value
t-Test	0.72846
Mann-Kendall	0.62785
Spearman Rank-Order	0.58127

- **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: Tuttle Creek.csv

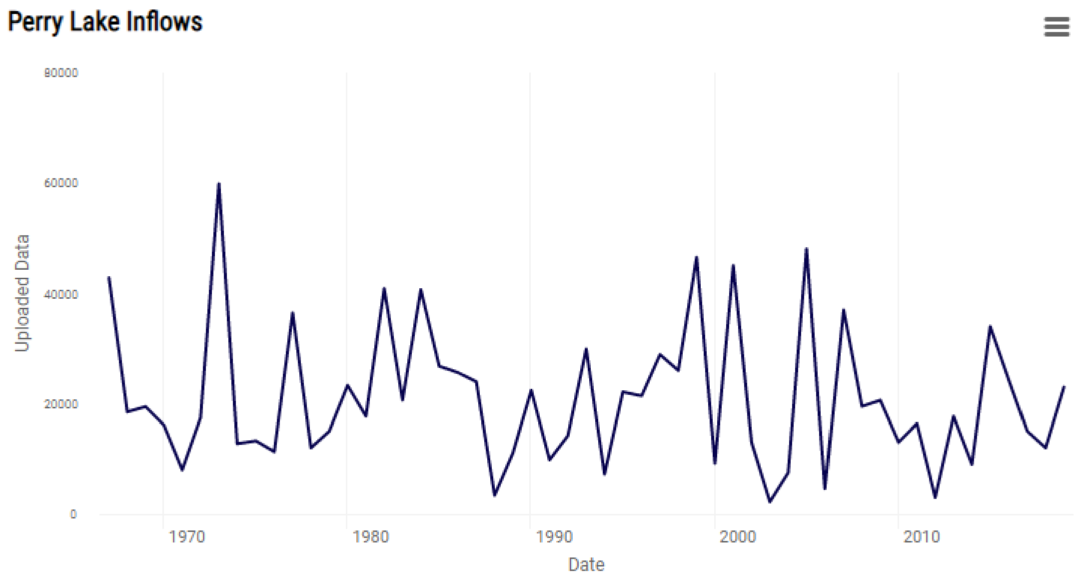
Figure 62: Trend Analysis for Tuttle Creek Lake Annual Maximum Inflows (1960-2019)

2.4.7. Perry Lake Inflows

Perry Lake is located on the Delaware River in Jefferson County, Kansas. Storage began in Perry Lake on 15-January-1969, and multipurpose pool level was reached on 3-June-1970. Closure was made at the dam on 2-August-1966, so the period of record for the Perry Lake inflows dates back to 1966. Inflows are computed from pool elevation data, currently reported at USGS Gage 06890898. The flow record used for the Time Series Toolbox was from 1967 to 2019 due to an incomplete year of data in 1966. Flow into Perry Lake is not regulated. Figure 63 shows the Perry Lake maximum annual inflows and non-stationarity detection results.

Nonstationarities were not detected for the Perry Lake inflows using default sensitivity parameters. Further testing was done by adjusting the sensitivity parameters. No nonstationarities were detected after making adjustments for the Perry Lake inflow period of record.

Embedded Nonstationarity Detection



Statistical Tests

No nonstationarities detected!

Segment Statistics

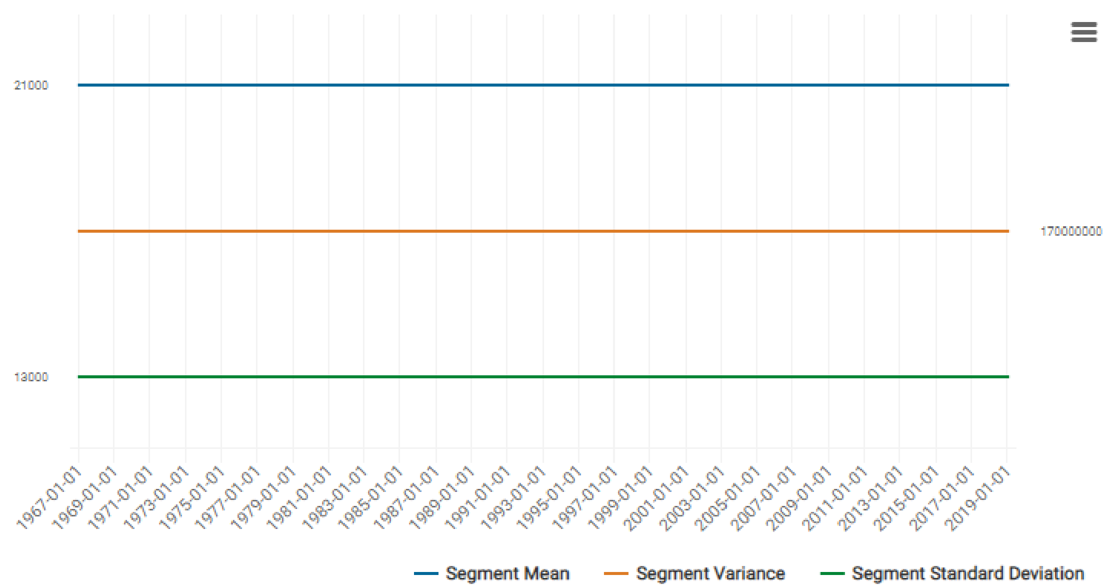
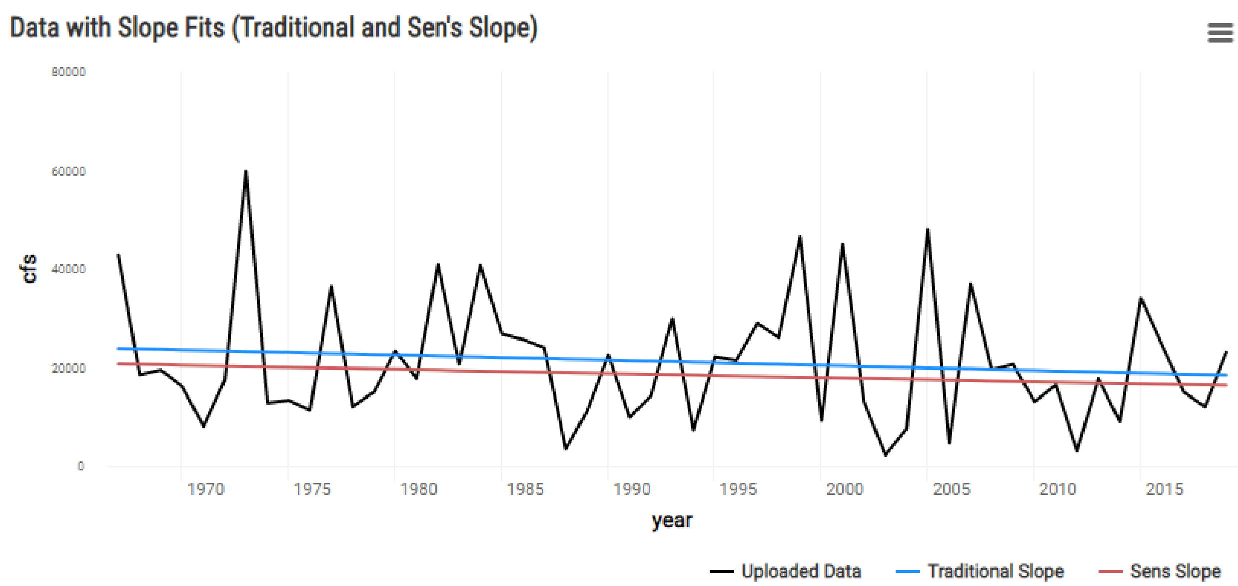


Figure 63: Nonstationarity Detection for Perry Lake Inflows (1967-2019)

Additionally, trend analysis for Perry Lake inflows was performed. No statistically significant trend was detected as shown in Figure 64. Since no statistically significant trend or non-stationarity was detected for the Perry Lake inflows, the period of record may be treated as stationary.



Trend Line Coefficients

Method	Slope	Intercept
Traditional Slope	-104.2	228790
Sen's Slope	-83.667	185250

Test	P.Value
t-Test	0.3739
Mann-Kendall	0.48033
Spearman Rank-Order	0.49575

- **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: Perry_1966-2019.csv

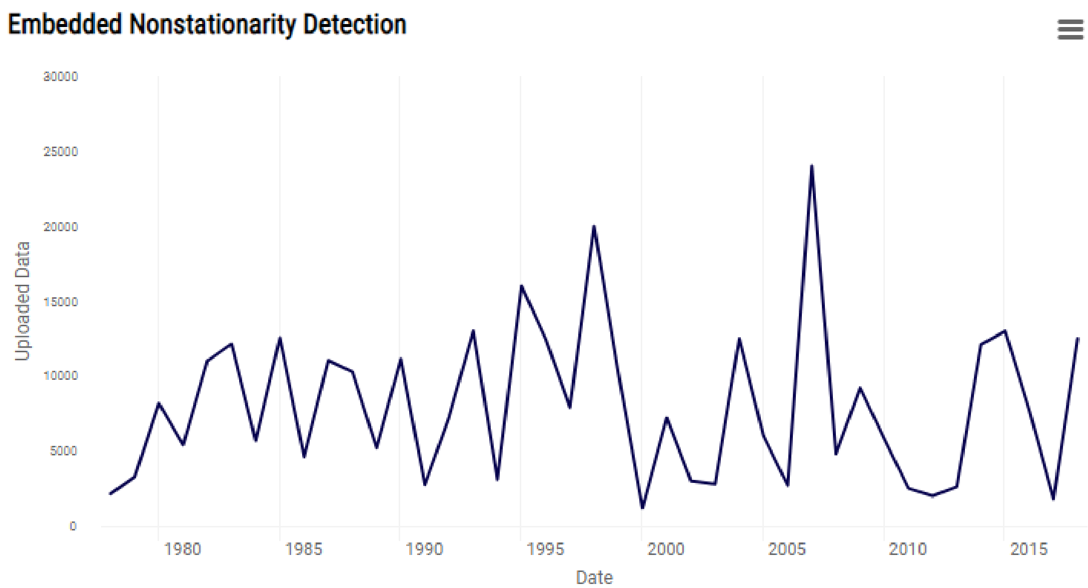
Figure 64: Trend Analysis for Perry Lake Inflows (1967-2019)

2.4.8. Clinton Lake Inflows

Clinton Lake is located on the Wakarusa River southwest of Lawrence, Kansas. The period of record for the Clinton Lake inflows is from 1977 to present (2019). Closure at Clinton Dam was made on 23-August 1975. Storage began in Clinton Lake in November 1977, and multipurpose pool was reached on April 3, 1980. Lake elevations used for computation of reservoir inflows are currently reported as USGS gage 06891478. The period of 1978 to 2019 was used for the web-based analysis in the Time Series Toolbox. An incomplete year was removed from the beginning of the data set (1977), but 2019 was left in with data up to September since the 2019 annual peak happened in the period of available data. The flow is unregulated as there are no upstream dams controlling releases. Figure 65 shows the Nonstationarity Detection Analysis for Clinton Lake.

The analysis was first ran using the default sensitivity parameters which can be found in Table 3 along with the minimum and maximum sensitivities for each parameter. No nonstationarities were detected with default sensitivity parameters. Each of the parameters were adjusted individually to increase sensitivity and tested. Even with adjustments to the parameters, nonstationarities were not detected for the Clinton Lake inflow period of record.

Embedded Nonstationarity Detection



Statistical Tests

No nonstationarities detected!

Segment Statistics

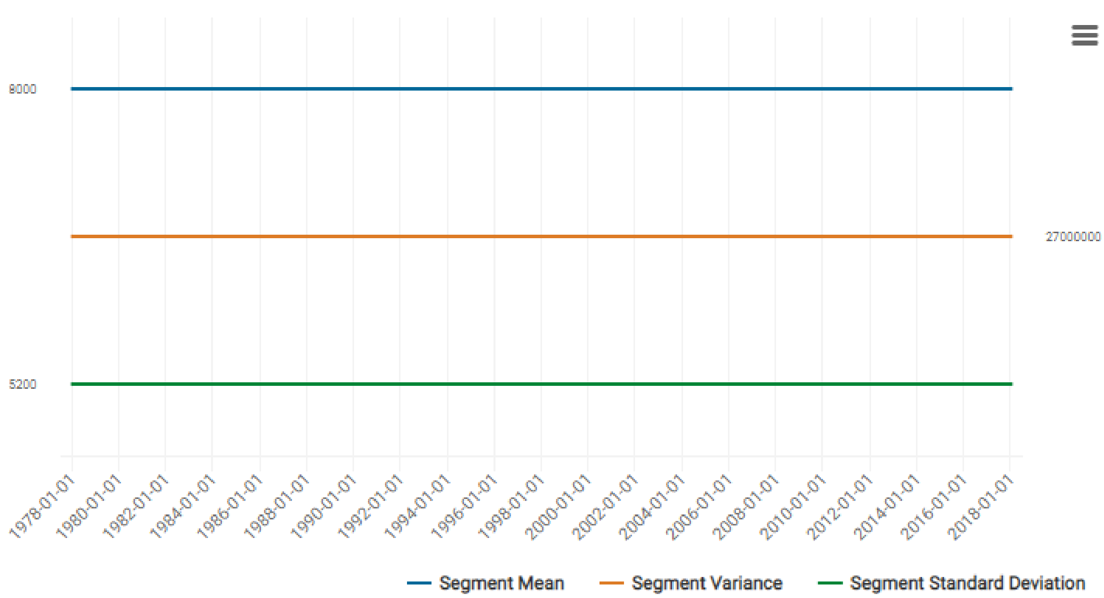
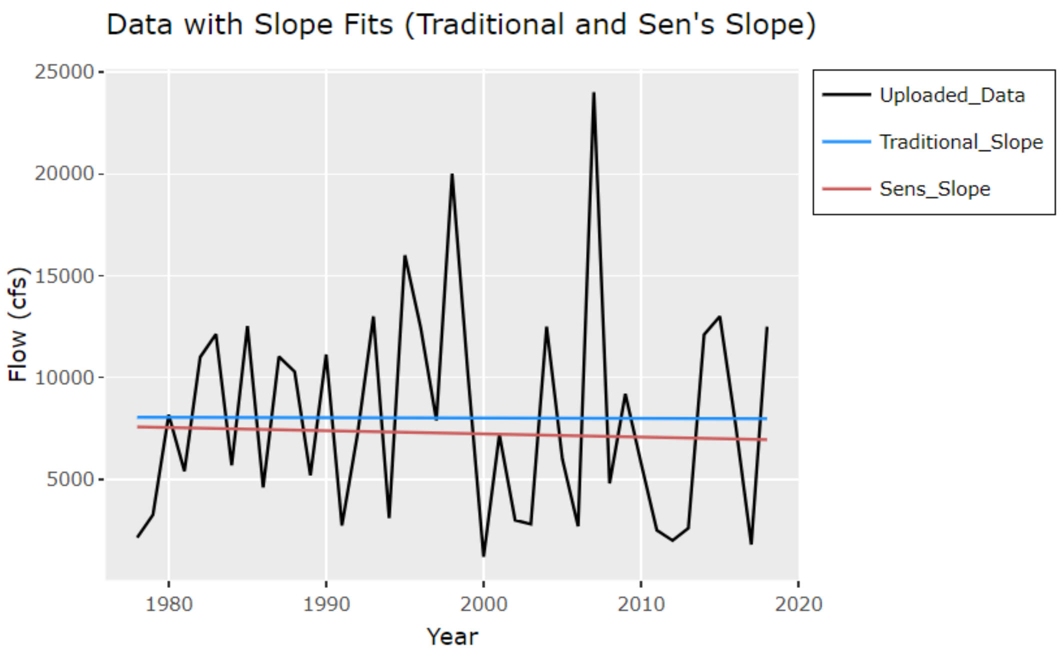


Figure 65: Non-Stationarity Detection for Clinton Lake Inflows (1978-2019)

Trend Line analysis was also performed using the Time Series Toolbox. Figure 66 shows the trend line analysis results for the Clinton Lake daily inflow annual maximum data. No statistically significant trends were identified in the annual maximum data. Since the analysis detected neither non-stationarities nor a statistically significant trend, the reservoir inflow data for Clinton Lake may be treated as a stationary data set.



Trend Line Coefficients

Method	Slope	Intercept
Linear Regression Slope	-1.7544	11521
Sens Slope	-15.588	38410

Test	P.Value
t-Test	0.98006
Mann-Kendall	0.67768
Spearman Rank-Order	0.69524

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

Figure 66: Clinton Lake Inflow Trend Analysis Results from Time Series Toolbox (1978-2019)

2.4.9. Kansas River Basin Reservoir Inflow Summary

Non-stationarity and linear trend analysis were performed on inflows for eight federal reservoirs in the Kansas River Basin. Analysis of most of the reservoirs' inflow data did not detect significant non-stationarities or trends in the annual maximum daily inflows. Only the Harlan County Lake inflow data exhibited behavior to strongly question its stationarity. Additional reservoir inflow stream gages were analyzed for Harlan County Lake since strong non-stationarities and a statistically significant trend in reservoir inflow were found. The additional inflow gages analyzed for Harlan County also demonstrated a number of non-stationarities, and statistically significant trends, except for Prairie Dog Creek. A shorter period of analysis for Sappa Creek did not exhibit a statistically significant trend in stream flows. Of the eight reservoir inflow dataset analyzed, only the Harlan County inflow data should not be considered stationary. Table 8 and Table 9 summarize the results of the analyses performed on the Kansas River reservoir inflow data.

Table 8: Summary of Non-Stationarities Detected for Kansas River Unregulated Flows

Reservoir/USGS Gage Location and Number	Period of Record Assessed	Years Non-Stationarities Detected	Methods Detecting	Parameter Adjustments
Clinton Lake (USGS 06891478)	1977-2019	None	N/A	Default
Waconda Lake (Glen Elder Dam)	1968-2019	None	N/A	Default
Harlan County Lake (USGS 06849000)	1952-2019	1967, 1969, 1977, 1982, 2001, 1965-1978	CVM, LP, END, PT, MW, Smooth LW	Default
	1967-2019	1989, 2001	CVM, LP, MW, LM	Default
	1967-2019	1989, 1990, 2001	CVM, LP, MW, LM, MD	CPM Sensitivity Parameter = 500
Republican River near Orleans, NE (USGS 06844500)	1962-2020	1989, 1990, 1996, 2000, 2001, 1962-2001	CVM, LP, LW, PT, MW, LM, MD, Smooth LW	Default
	1962-2020	1989, 1990, 2000, 1962-2001	LW, PT, LM, Smooth LW	CPM Sensitivity Parameter = 1250

Reservoir/USGS Gage Location and Number	Period of Record Assessed	Years Non-Stationarities Detected	Methods Detecting	Parameter Adjustments
Prairie Dog Creek near Woodruff, KS (USGS 06848500)	1965-2020	1965-1968, 1965-1969	Smooth LM, Smooth LW	Default
	1970-2020	1970-1974	Smooth LW	Default
Sappa Creek near Stamford, NE (USGS 06847500)	1944-2014	1967, 1968, 1969, 1976, 1950-1952, 1966-1970	CVM, KS, LP, END, LW, PT, MW, Smooth LW, Smooth LM	Default
	1970-2020	None	N/A	Default
Kanopolis Lake (USGS 06865000)	1951-2019	1974, 1981	LW, END	Default
	1951-2019	2001	CVM	CPM Burn-In Period =30, CPM Sensitivity =500, END Sensitivity =0.15
Milford Lake (USGS 06857050)	1967-2019	2013-2015	Smooth LW	Default
Perry Lake (USGS 06890898)	1967-2019	None	N/A	Default
Tuttle Creek Lake (USGS	1960-2019	None	N/A	Default
	1960-2019	1990	END	END Sensitivity =0.73
Wilson Lake (USGS 06868100)	1964-2019	None	N/A	Default

Table 9: Summary of P-values for Trend Analysis of Kansas River Unregulated Flow Data

Reservoir/ USGS Gage Location and Number	Period of Record Assessed	Test Type		
		Mann-Kendall	Spearman Rank Order	Significant? (P value <0.05)
		P-value		
Clinton Lake (USGS 06891478)	1977-2019	0.68	0.70	No
Waconda Lake (Glen Elder Dam)	1968-2019	0.35	0.37	No
Harlan County Lake (USGS 06849000)	1967-2019	0.036	0.046	Yes

Reservoir/ USGS Gage Location and Number	Period of Record Assessed	Test Type		
		Mann-Kendall	Spearman Rank Order	Significant? (P value <0.05)
		P-value		
Republican River near Orleans, NE (USGS 06844500)	1962-2020	2.7×10^{-5}	3.1×10^{-5}	Yes
Prairie Dog Creek near Woodruff, KS (USGS 06848500)	1965-2020	0.226	0.166	No
Sappa Creek near Stamford, NE (USGS 06847500)	1944-2014	$<1 \times 10^{-3}$	$<1 \times 10^{-3}$	Yes
	1970-2020	0.47	0.41	No
Kanopolis Lake (USGS 06865000)	1951-2019	0.11	0.10	No
Milford Lake (USGS 06857050)	1967-2019	0.66	0.70	No
Perry Lake (USGS 06890898)	1967-2019	0.48	0.50	No
Tuttle Creek Lake (USGS	1960-2019	0.63	0.58	No
Wilson Lake (USGS 06868100)	1964-2019	0.55	0.61	No

3. Future Without Project Condition

3.1. Literature Review: Projected Climate Change and Projected Changes in Climate Variables

A literature synopsis was generated to summarize published conclusions regarding both natural and anthropogenic climate trends in the Kansas River Basin identified through analysis of future conditions.

3.1.1. Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions (USACE, 2015)

This report is 1 of 21 regional climate syntheses prepared at the scale of 2-digit USGS Hydrologic Unit Codes (HUC) across the United States. The area covered by the Region 10 report is shown in Figure 2. The report for the Missouri River Region 10 summarized observed and projected climate trends. Figure 67 summarizes the observed and projected trends from the literature review.

The general consensus in the literature indicated increasing air temperatures in the Missouri River Region over the next century. Reasonable consensus, regardless of emission scenarios, was seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to recent past. Projections of precipitation in the study region were less certain than those associated with air temperature. On the whole, more studies appeared to point toward a wetter, rather than drier, future climate in the Missouri River Region. A majority of the projections forecasted an increase in annual precipitation and in the frequency of large storm events. However, statistically significant trends in the projection data were lacking. Similarly, clear consensus was lacking in the hydrologic projection literature. The direction of the streamflow trend appeared to be dependent on modeling assumptions. Of the limited number of studies reviewed, more results indicated a potential increase in streamflows.

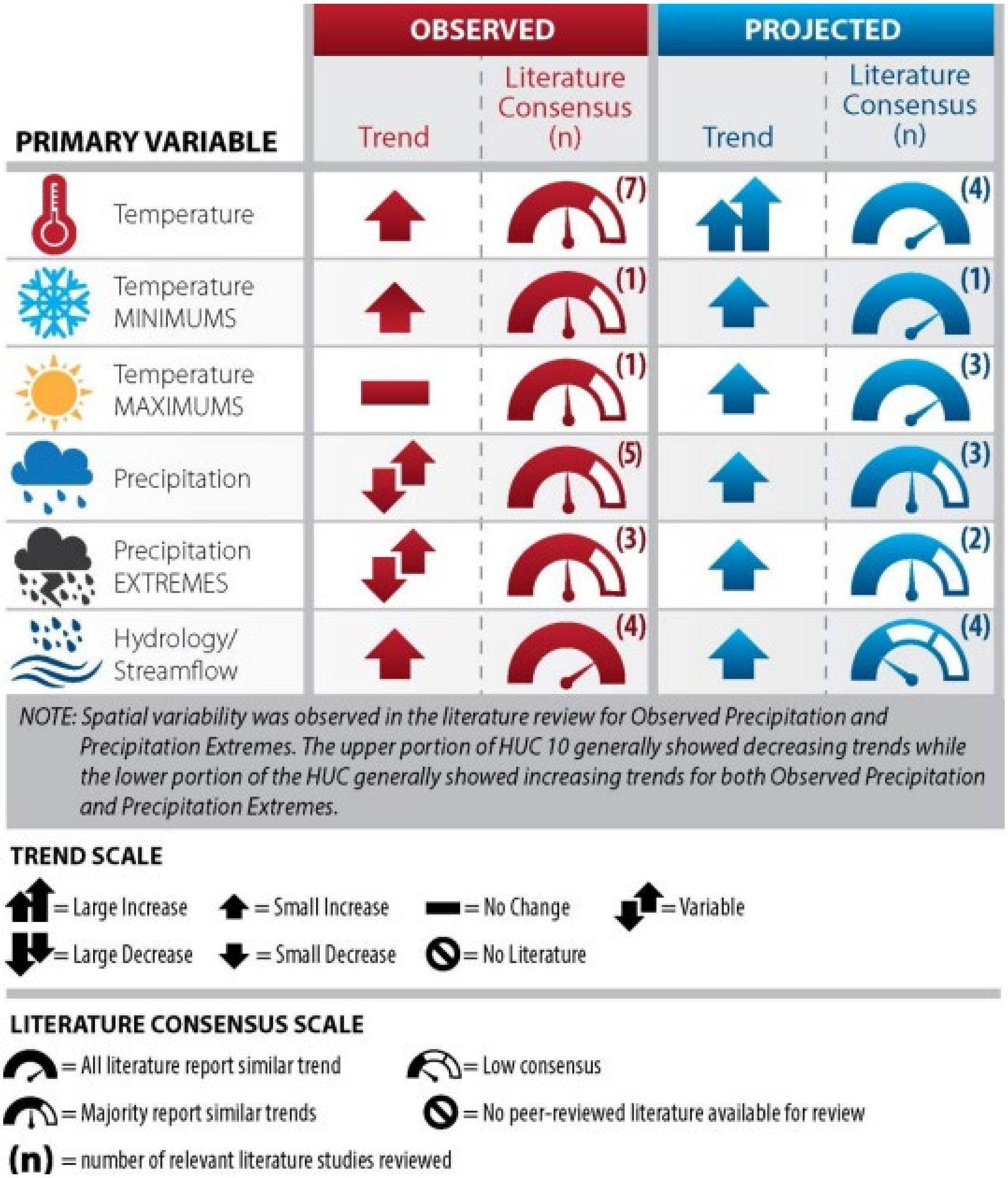


Figure 67: Summary matrix of observed and projected climate trends and literary consensus for the Missouri River Basin.

3.1.2. Fourth National Climate Assessment (USGCRP, 2018)

Figure 68 shows the projected changes in total seasonal precipitation for the period 2070-2099. Generally, for the Kansas River basin, total precipitation is expected to increase in the winter and spring, and decrease in the summer. Fall projections show the Kansas River basin on the border between increases/decreases. The magnitude of this change is small compared to natural variation.

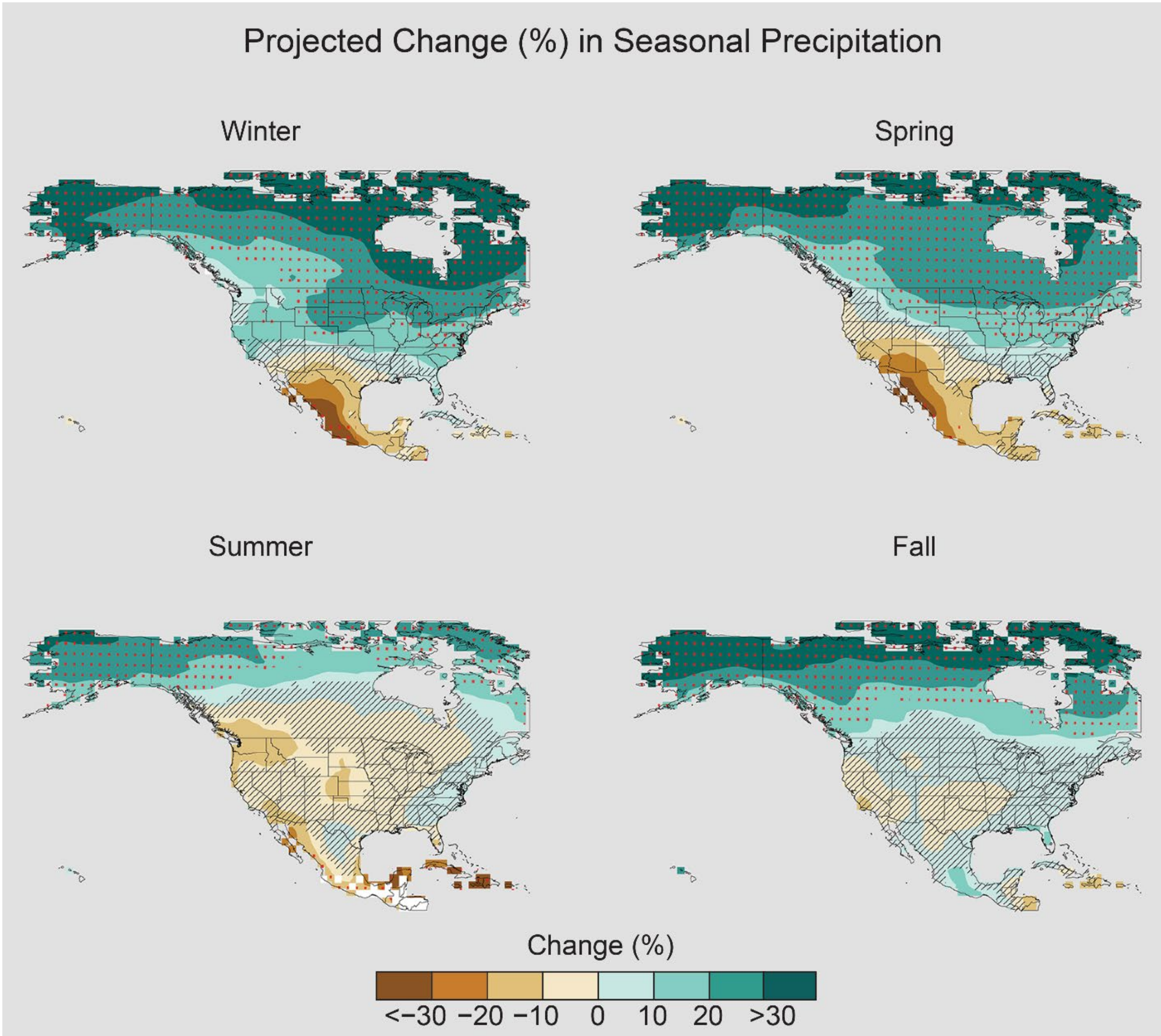


Figure 68: Projected change (%) in total seasonal precipitation from CMIP5 simulations for 2070–2099

Projections for extreme precipitation events indicate the upward trend will continue with the number of events exceeding a 5-year return period increasing from 50% to 300%. Figure 69 provides temperature change estimates for a range of potential emissions scenarios. Average temperatures are projected to continue to increase across the United States by an average of 2.5°F (2.9°F) in most areas over the next several decades and to 5.0°F (8.7°F) by the end of the century for a low (high) emission scenario. The effect of increased temperatures will be felt more in higher elevations than at sea level. In the Southern Great Plains (includes Kansas), average annual temperatures are expected to increase about 4.5°F by 2050 and increase more than 8°F by the end of the century under the high emissions scenario (RCP 8.5) (see Figure 69) (Pierce et al 2014, Sun et al 2015). Warmer temperatures are expected to increase evaporative demand, leading to more frequent and severe droughts (Wehner et al 2017).

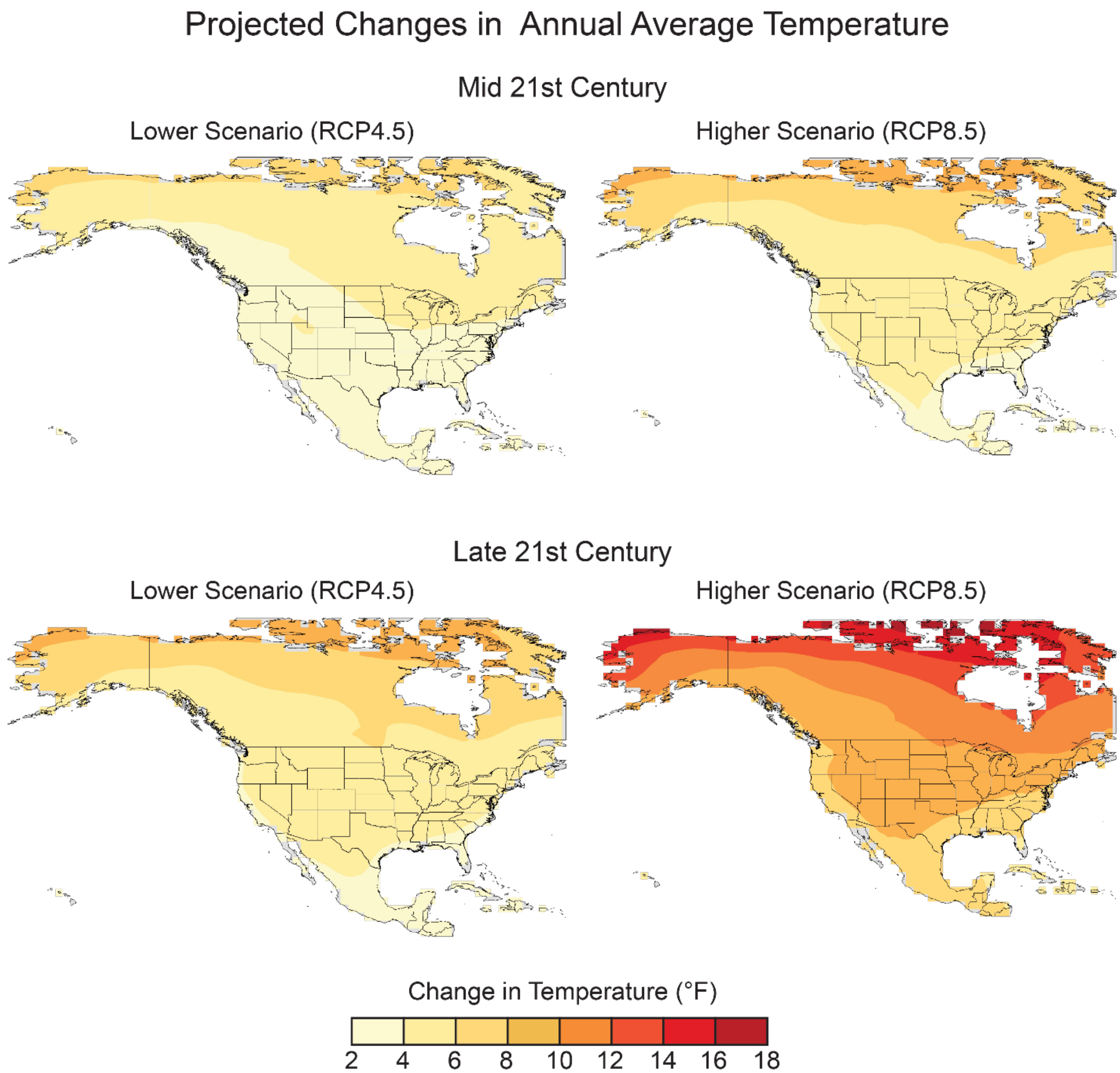


Figure 69: Projected changes in annual average temperatures (°F)

3.1.3. NOAA State Climate Summary, Kansas (Frankson et.al. 2017)

The State Climate Summary from NOAA indicates similar findings as the National Climate Assessment for Kansas. Longer growing seasons have been observed in the beginning of the 21st century compared to the 20th century. The frequency of heavy rain events has been highly variable with a general increase; the number of 3-inch rain events has been near to above average during the last two decades.

3.1.4. Projected climate change impacts on hydrologic flow regimes in the Great Plains of Kansas (Chatterjee et. al. 2017)

As an example of climate change impacts to hydrology in the Kansas River Basin, this paper by Chatterjee et.al. (2017) looked at the Smoky Hill River watershed between Cedar Bluff Dam (USBR) and Kanopolis Dam (USACE). The team ran 50-year and 100-year projected climate data from several Global Circulation Models through a hydrologic model (SWAT) and evaluated the results. They concluded that climate change will lead to drying of the basin with more low flow days along with more frequency high flow events of shorter duration.

3.1.5. Literature Review Summary

Trends in temperature across the Kansas River Basin are clear, with increasing temperatures expected over the next century. Increased occurrence of extreme precipitation events is also expected. Stream flows in the basin may increase also, but consensus in the reviewed literature is lacking. The specific study reviewed indicated the potential for decreases in low flows, coupled with increasing frequency of high flows.

3.2. **Regional Scale Analysis: Trends in Projected Streamflow**

This portion of the climate change assessment focused on carrying out first order statistical analysis at a HUC-4 watershed scale. The watersheds analyzed include HUC (Hydrologic Unit Code) 1025, Republican River Basin, HUC 1026 Smoky Hill River Basin, and HUC 1027, Kansas River Basin. The Smoky Hill and Republican Rivers join at Junction City, KS to form the Kansas River.

3.2.1 Climate Hydrology Assessment Tool (CHAT): Projected Trends in Streamflow and Climate Change at a Regional Scale

The USACE CHAT was used to investigate potential future trends in streamflow for the three identified HUC's, shown in Figure 70 below. Figure 71 through Figure 73 display the range of projected annual maximum monthly streamflows computed from 93 different climate change hydrologic model runs for the period of 1950-2099 for each HUC. Climate changed hydrology output is generated using various greenhouse gas emission scenarios and global circulation models (GCMs) to project precipitation and temperature data into the future. These meteorological outputs are spatially downscaled using the Bias Corrected Spatial Disaggregation (BCSD) statistical method and then input in the U.S. Bureau of Reclamation's Variable Infiltration Capacity (VIC) precipitation-runoff model to generate a streamflow response. As expected for this type of analysis, there is considerable spread in the projected annual maximum monthly flows for the Kansas River Basin. The spread in the projected annual maximum monthly flows is indicative of the high degree of uncertainty associated with projected climate changed hydrology. These hydrologic simulations do not account for regulation by reservoirs.

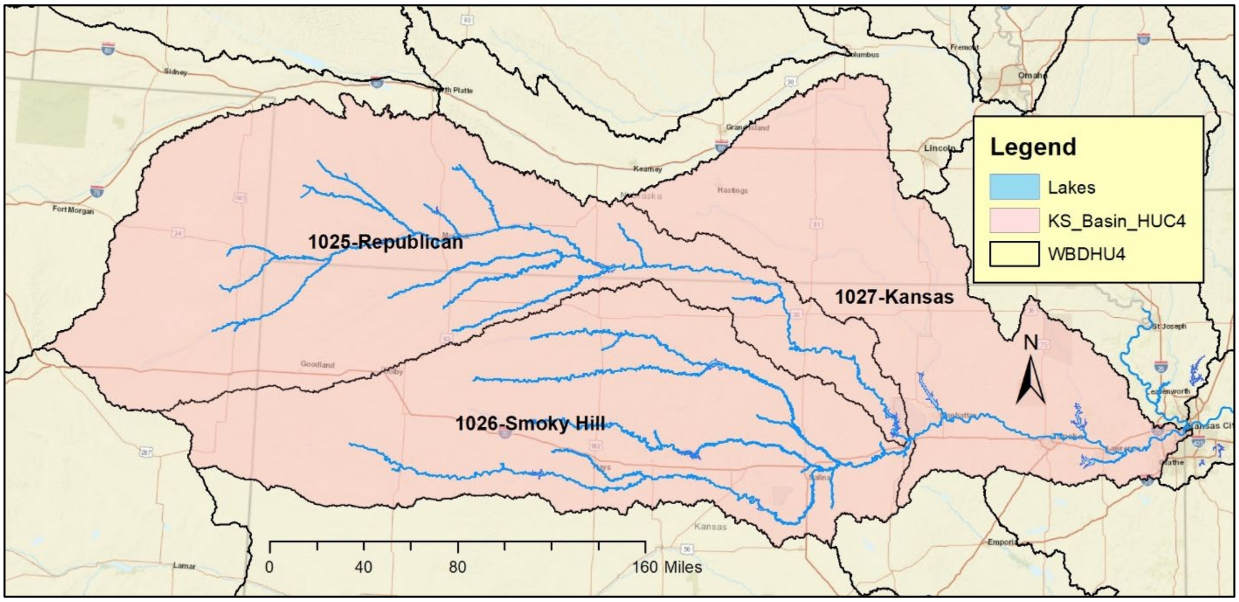


Figure 70: Map of 4-digit HUC's analyzed

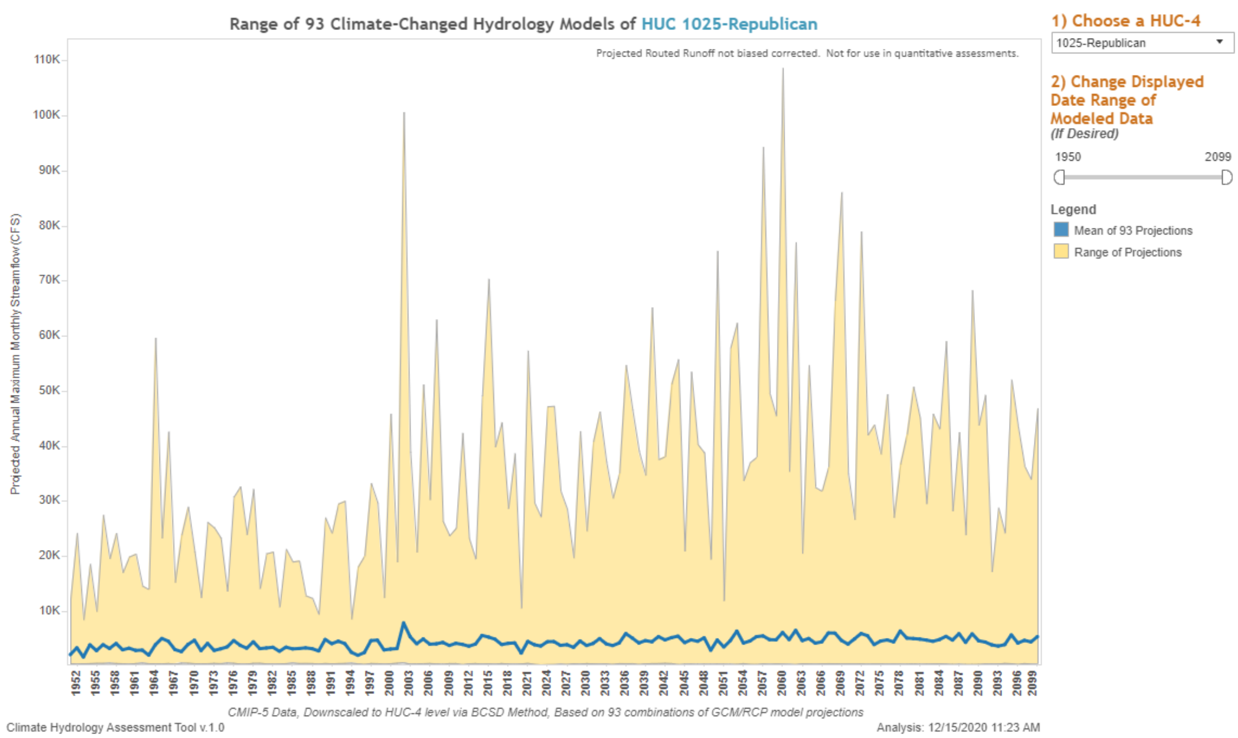


Figure 71: Republican River Basin Projected Annual Maximum Monthly Flows

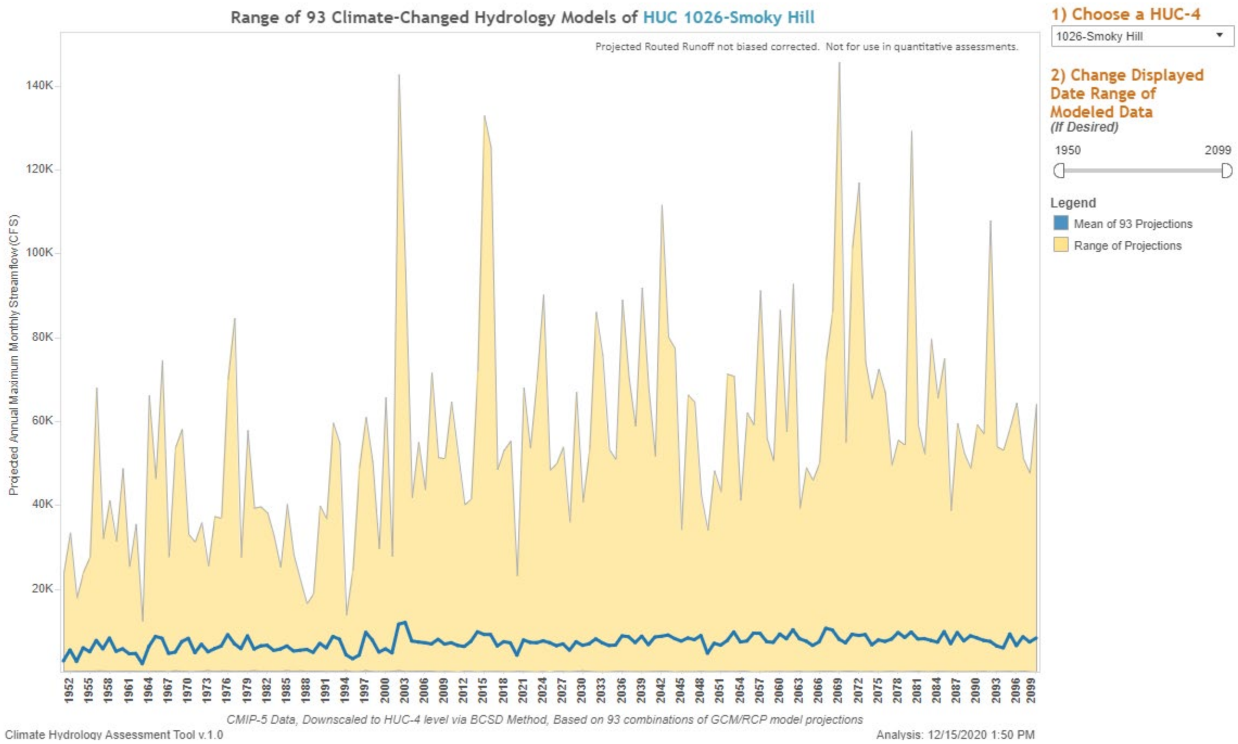


Figure 72: Smoky Hill River Basin Projected Annual Maximum Monthly Flows

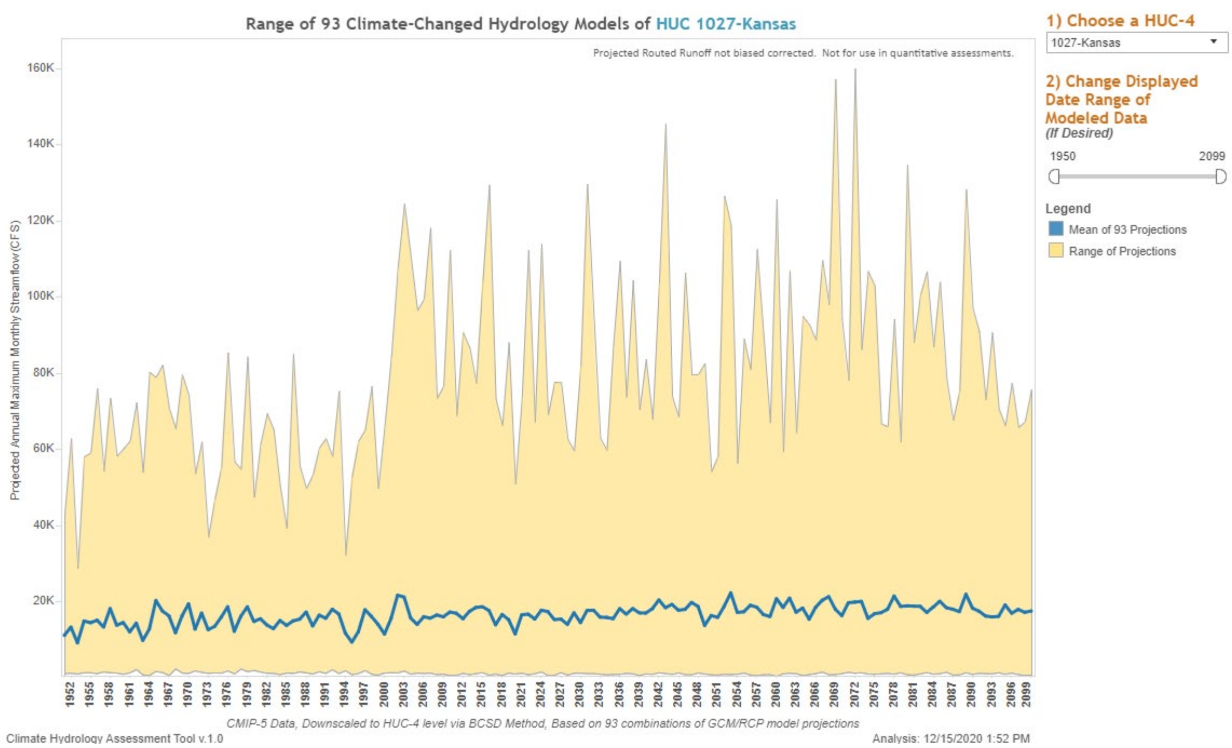


Figure 73: Kansas River Basin Projected Annual Maximum Monthly Flows

The overall trend in the mean climate changed hydrology annual maximum monthly streamflow increased over time, as shown in Figure 74 through Figure 76. For the Republican River (HUC 1025, Figure 74), there is a statistically significant increasing trend for the later time period with p-values significantly less than the generally accepted threshold for significance of 0.05. For the Smoky Hill River (HUC 1026, Figure 75), trend lines indicate increasing flows, but the results are not statistically significant for the later period. The p-value for the later period is near the threshold for statistical significance, however. For the Kansas River (HUC 1027, Figure 76), results show a statistically significant increasing trend in streamflow for the later period. These findings, summarized in Table 10, suggest that there is potential for flood risk to increase in the future in the study area, relative to the current conditions. Although the p-values indicate that the trend magnitudes for the Republican and Kansas basins are different from zero, it does not reveal the magnitude of change. Nevertheless, the most likely value of the trend in the data is the one that is the best fit to the data, which is approximately 7.7 cfs/year for the Republican River basin, and 25 cfs/year for the Kansas River Basin. The trends, while indicative of increasing flows over time, are not relatively large in magnitude. These results are qualitative only.

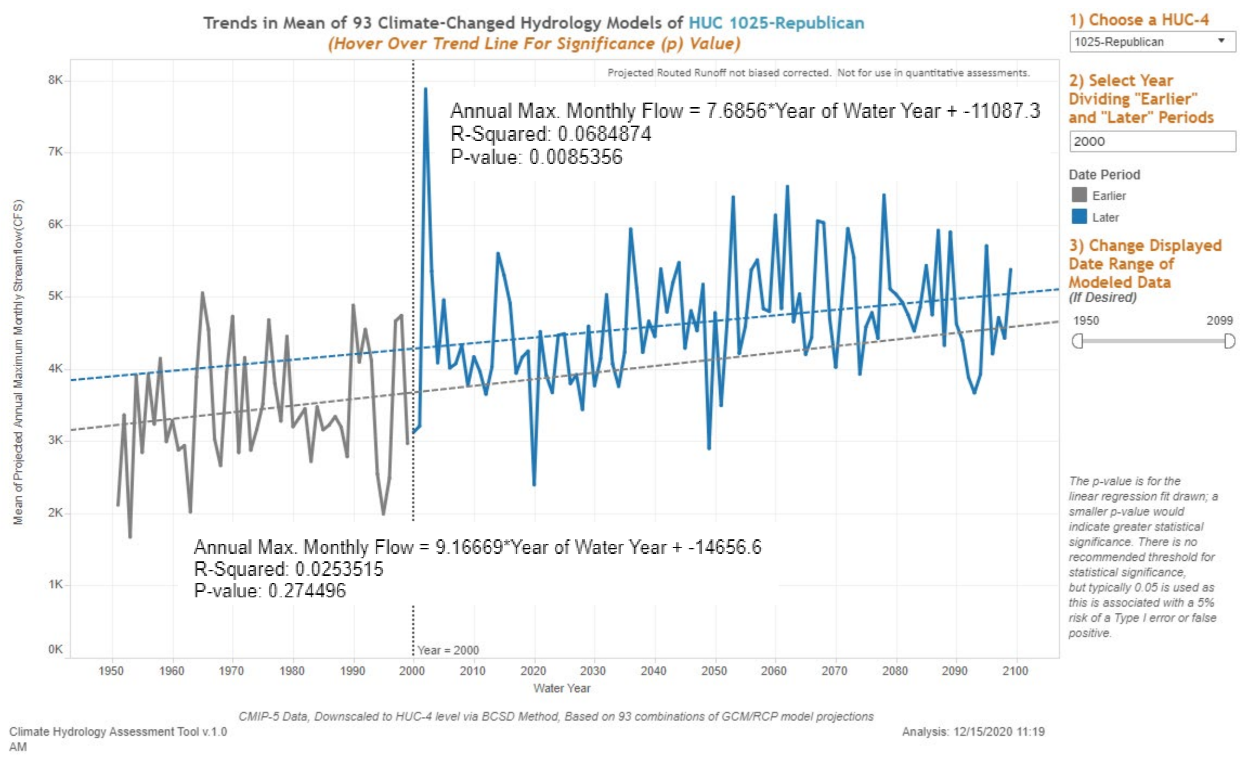


Figure 74: Republican River Mean Climate Changed Hydrology Annual Max Streamflow

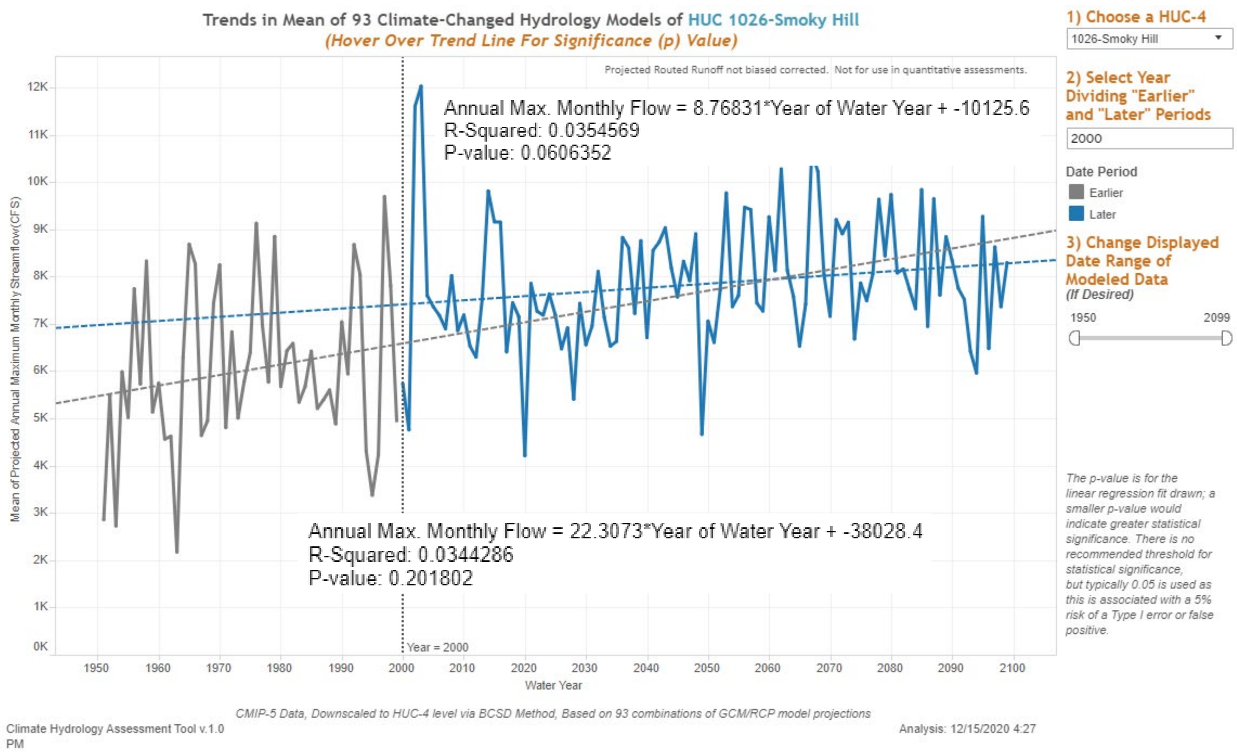


Figure 75: Smoky Hill River Mean Climate Changed Hydrology Annual Max Streamflow

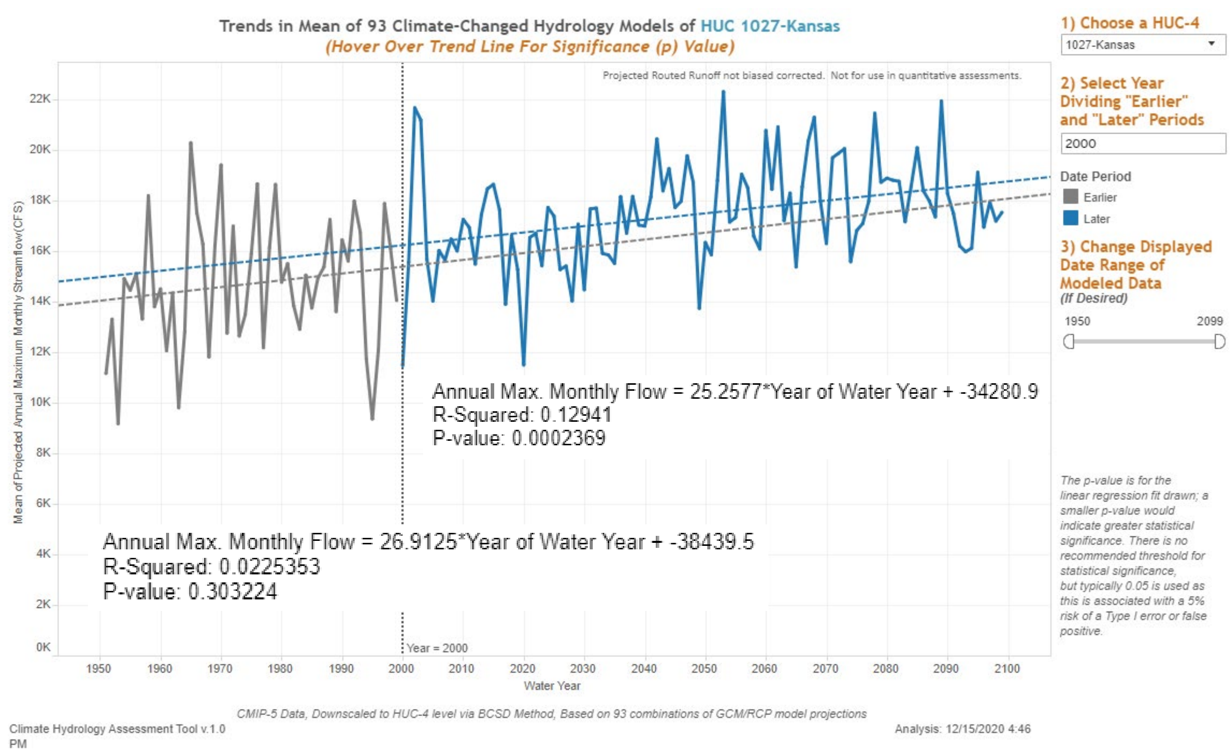


Figure 76: Kansas River Climate Changed Hydrology Mean Annual Max Streamflow

Table 10: Significance of Linear Regression for Mean Projected Annual Maximum Monthly Streamflows

HUC-4 Watershed	Trendline Period Assessed	Trendline Significance (p-value)	Coefficient of Determination R^2	Significant? (P-value < 0.05)
Republican (1025)	Earlier: 1950 - 2000	0.27	0.025	NO
	Later: 2000 - 2099	0.0085	0.068	YES
Smoky Hill (1026)	Earlier: 1950 - 2000	0.20	0.034	NO
	Later: 2000 - 2099	0.061	0.035	NO
Kansas (1027)	Earlier: 1950 - 2000	0.30	0.023	NO
	Later: 2000 - 2099	0.00024	0.129	YES

4. Screening Level Vulnerability Assessment to Climate Change Impacts

The USACE Watershed Climate Vulnerability Assessment Tool facilitates a screening level, comparative assessment of how vulnerable a given HUC-4 watershed is to the impacts of climate change relative to the other 202 HUC-4 watersheds within the continental United States (CONUS). The tool can be used to assess the vulnerability of a specific USACE business line such as "Ecosystem Restoration" or "Flood Risk Reduction" to projected climate change impacts. Assessments using this tool help to identify and characterize specific climate threats and particular sensitivities or vulnerabilities, at least in a relative sense, across regions and business lines. The tool uses the Weighted Ordered Weighted Average (WOWA) method to represent a composite index of how vulnerable a given HUC-4 watershed (Vulnerability Score) is to climate change specific to a given business line. The HUC-4 watersheds with the top 20% of WOWA scores are flagged as being vulnerable. WOWA scores should be considered relative to other basins, and are not a representation of absolute value of vulnerability. The most pertinent USACE business lines for the Kansas River Flood and Sediment Study are Ecosystem Restoration, Flood Risk Reduction, Recreation, and Water Supply. Other business lines available for analysis in the tool are Emergency Management, Hydropower, Navigation, and Regulatory. These additional business lines were not considered in this assessment, as they were not considered as prevalent in the Kansas River Basin, nor as pertinent to the study objectives. These business lines were analyzed with the USACE Climate Vulnerability Assessment Tool. Table 11 lists the weights used for computation of the WOWA scores for the four pertinent business lines. Blank cells signify that the indicator was not used.

Table 11: Indicator Weighting for WOWA scores by USACE Business Line

	USACE Business Line			
Indicator	**Ecosystem Restoration**	**Flood Risk Reduction**	**Recreation**	**Water Supply**
8_AT_RISK_FRESHWATER_PLANT	2			
65L_MEAN_ANNUAL_RUNOFF	1.3			
95_DROUGHT_SEVERITY			2	2
156_SEDIMENT	1.5		1	2
175C_ANNUAL_COV		1.25		1.5
221C_MONTHLY_COV	1.75		1.2	1
277_RUNOFF_PRECIP	1.75	1	1	1.3
297_MACROINVERTEBRATE	2			
568C_FLOOD_MAGNIFICATION	1.5	1.8	1.4	
568L_FLOOD_MAGNIFICATION	1	1.4	1	
570L_90PERC_EXCEEDANCE			1.5	
571C_10PERC_EXCEEDANCE			1	

	USACE Business Line			
Indicator	**Ecosystem Restoration**	**Flood Risk Reduction**	**Recreation**	**Water Supply**
590_URBAN_500YRFLOODPLAIN_AREA		1.75		
700C_LOW_FLOW_REDUCTION	1		1.3	

When assessing future risk projected by climate change, the USACE Climate Vulnerability Assessment Tool makes an assessment for two 30-year epochs of analysis centered at 2050 and 2085. These two periods were selected to be consistent with many of the other national and international analyses. The Vulnerability tool assesses how vulnerable a given HUC-4 watershed is to the impacts of climate change for a given business line using climate hydrology based on a combination of projected climate outputs from the general circulation models (GCMs) and representative concentration pathway (RCPs) resulting in 100 traces per watershed per time period. The top 50% of the traces is called “wet” and the bottom 50% of the traces is called “dry.” Meteorological data projected by the GCMs is translated into runoff using the Variable Infiltration Capacity (VIC) Macroscale hydrologic model. For this assessment, the default National Standards Settings were used to carry out the vulnerability assessment.

4.1. Ecosystem Restoration

Vulnerability indicators considered within the WOWA score for Ecosystem Restoration include: change in sediment load, short-term variability in hydrology, sensitivity of the basin runoff to increased precipitation, macroinvertebrate index (sum score of six metrics indicating biotic condition), two indicators of flood magnification (indicator of how much high flows are projected to change over time), mean annual runoff, change in low runoff, and percent of at risk freshwater plant communities.

Based on the results of the USACE Screening-Level Climate Vulnerability Assessment Tool, relative to the other 202 HUC-4 watersheds in the CONUS, the Republican (HUC 1025), Smoky Hill (HUC 1026), and Kansas (HUC 1027) watersheds are among the 20% most vulnerable to the impacts of climate change on Ecosystem Restoration. As seen in Figure 77, several vulnerability indicators are driving the watershed’s vulnerability for Ecosystem Restoration. Primary vulnerability indicators for Ecosystem Restoration include at risk freshwater plants, runoff elasticity, and short-term variability in hydrology for all three HUC-4’s. Figure 78 through Figure 80 show the breakdown of the WOWA scores for the three HUC-4’s. The overall height of the bar indicates the total WOWA score. As seen in the figures, although these are the primary factors driving the vulnerability scores, for the most part, the WOWA scores for these factors remained relatively constant with the exception of short term variability in hydrology (Monthly CoV) for the Republican River Basin, which increased. Other factors combined to differentiate the total vulnerability score for each epoch (Base, 2050, 2085) and scenario (Wet/Dry). Overall, Ecosystem Restoration scores remained relatively constant for the Dry scenarios compared to the base, but increased for the Wet scenarios, mainly due to increases in the Cumulative Flood Magnification score. The Flood magnification score greater than 1.0 indicates that flood flows (monthly flow exceeded 10% of the time) are expected to increase. Table 12 summarizes the WOWA Vulnerability scores by epoch and scenario for the three HUC-4's for Ecosystem Restoration.

The vulnerability for Ecosystem Restoration is likely driven by the projected, future streamflow and precipitation data used as inputs to the vulnerability tool. The freshwater plants indicator measures the percentage of wetland and riparian plant communities that are at relative risk of extinction and is representative of biodiversity. Both runoff precipitation/runoff elasticity and monthly COV are dependent on runoff. As runoff increases, the vulnerability attributable to these indicators also increases. The coefficient of variation (COV) in cumulative monthly flow is another significant indicator for HUC 1027 (Kansas). The cumulative monthly COV is a measure of short-term variability in hydrology and is a ratio of the standard deviation of monthly runoff to the monthly runoff mean, including upstream flows.

Recommendations by the watershed study for any ecosystem restoration measures should consider the vulnerabilities identified, particularly the possible increases in flood flows in the Kansas River Basin. Some of the ecosystem restoration measures being considered for recommendation in the study are wetland construction/maintenance, improved management of invasive species, habitat development, community outreach, and environmental monitoring. For example, any wetland construction project should consider how increased short term (monthly) variability of stream flows would impact conditions at the wetland, as well as potentially greater flood conditions, and consider resilience features that could offset any expected impacts. From the WOWA results, it appears that vulnerability to ecosystem restoration based on macroinvertebrate indices will likely be at lower risk under future climate scenarios.

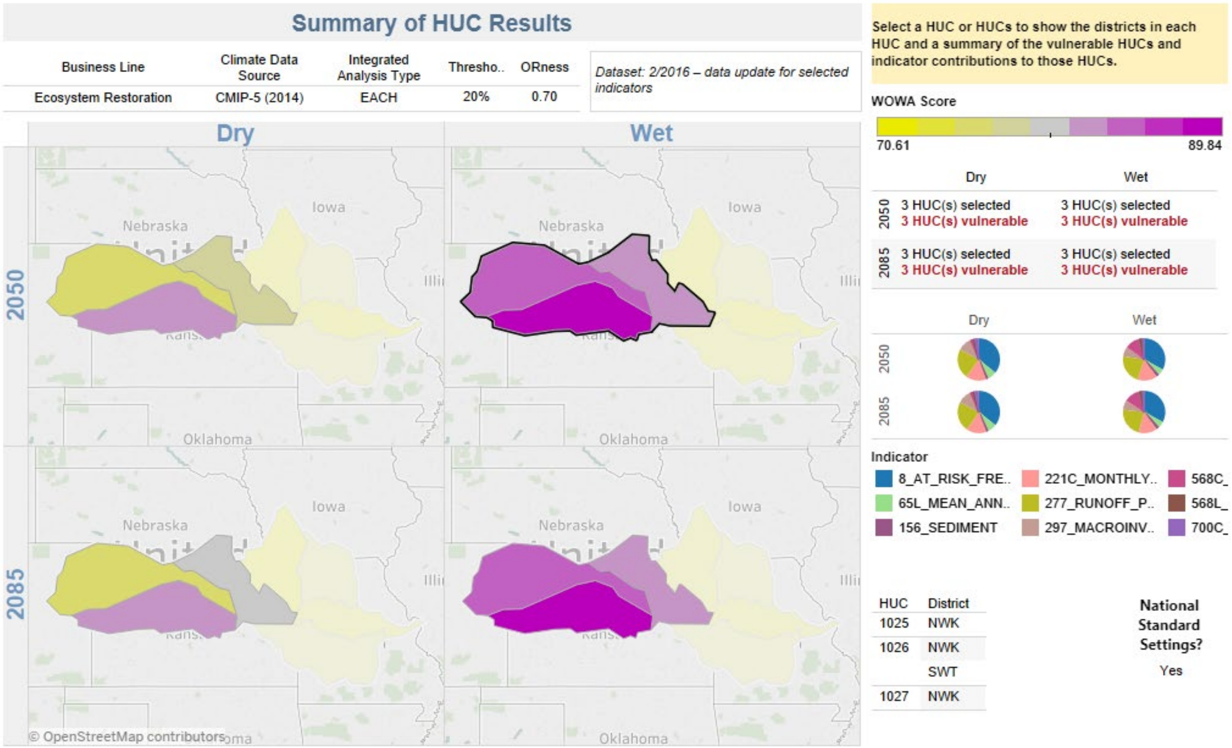


Figure 77: Screening-Level Climate Vulnerability Assessment Tool results for Ecosystem Restoration

Table 12. Ecosystem Restoration Projected Vulnerability for Kansas River Basin

Business Line	HUC-4 Watershed	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Ecosystem Restoration	Republican (1025)	74.43	75.87	83.78	75.28	85.23
Ecosystem Restoration	Smoky Hill (1026)	80.63	81.73	89.84	81.85	89.43
Ecosystem Restoration	Kansas (1027)	78.32	78.87	82.84	79.78	83.03

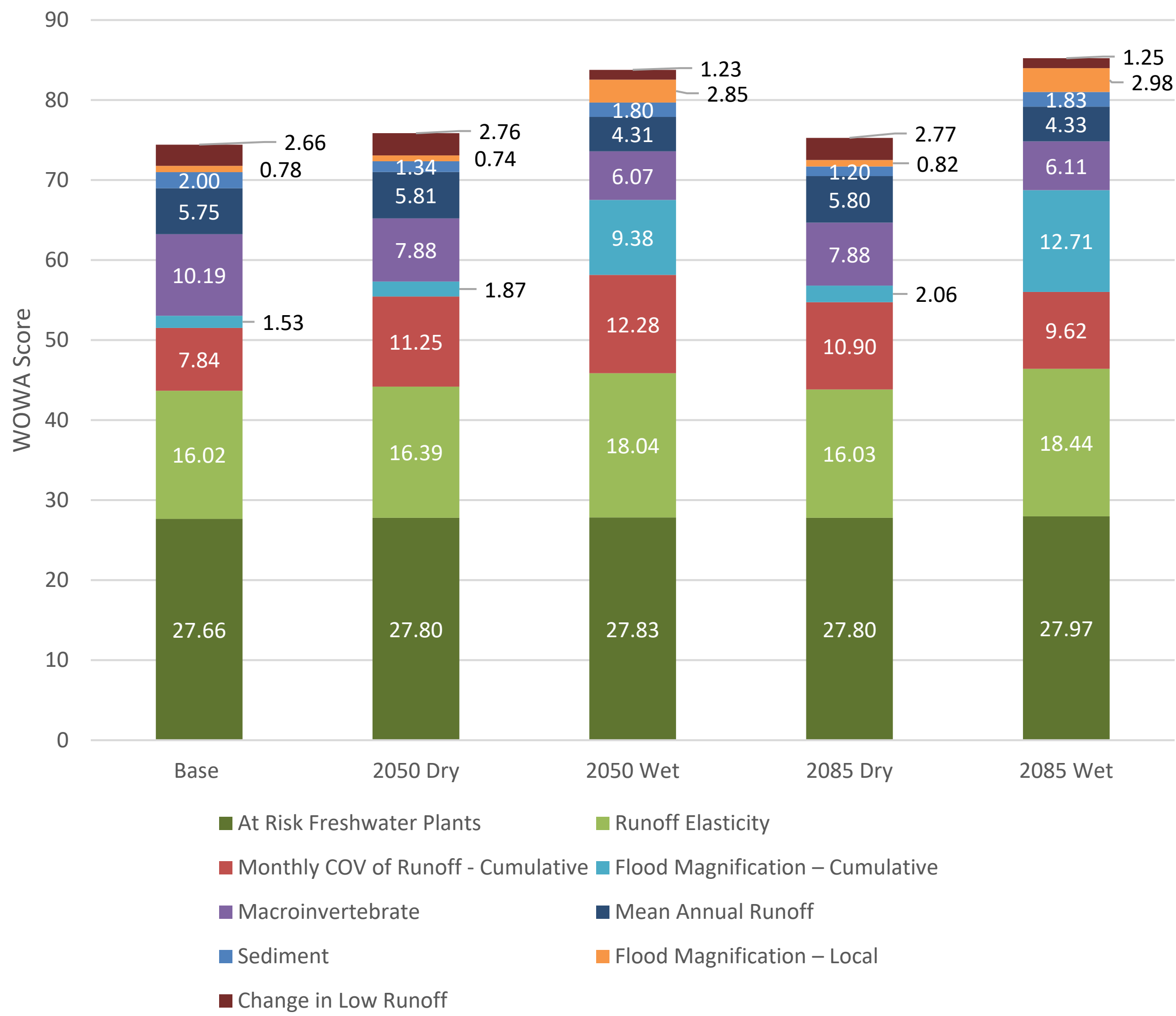


Figure 78: Ecosystem Restoration Vulnerability Scores by Indicator, Republican River (HUC 1025)

Figure 79: Ecosystem Restoration Vulnerability Scores by Indicator, Smoky Hill River Basin (HUC 1026)

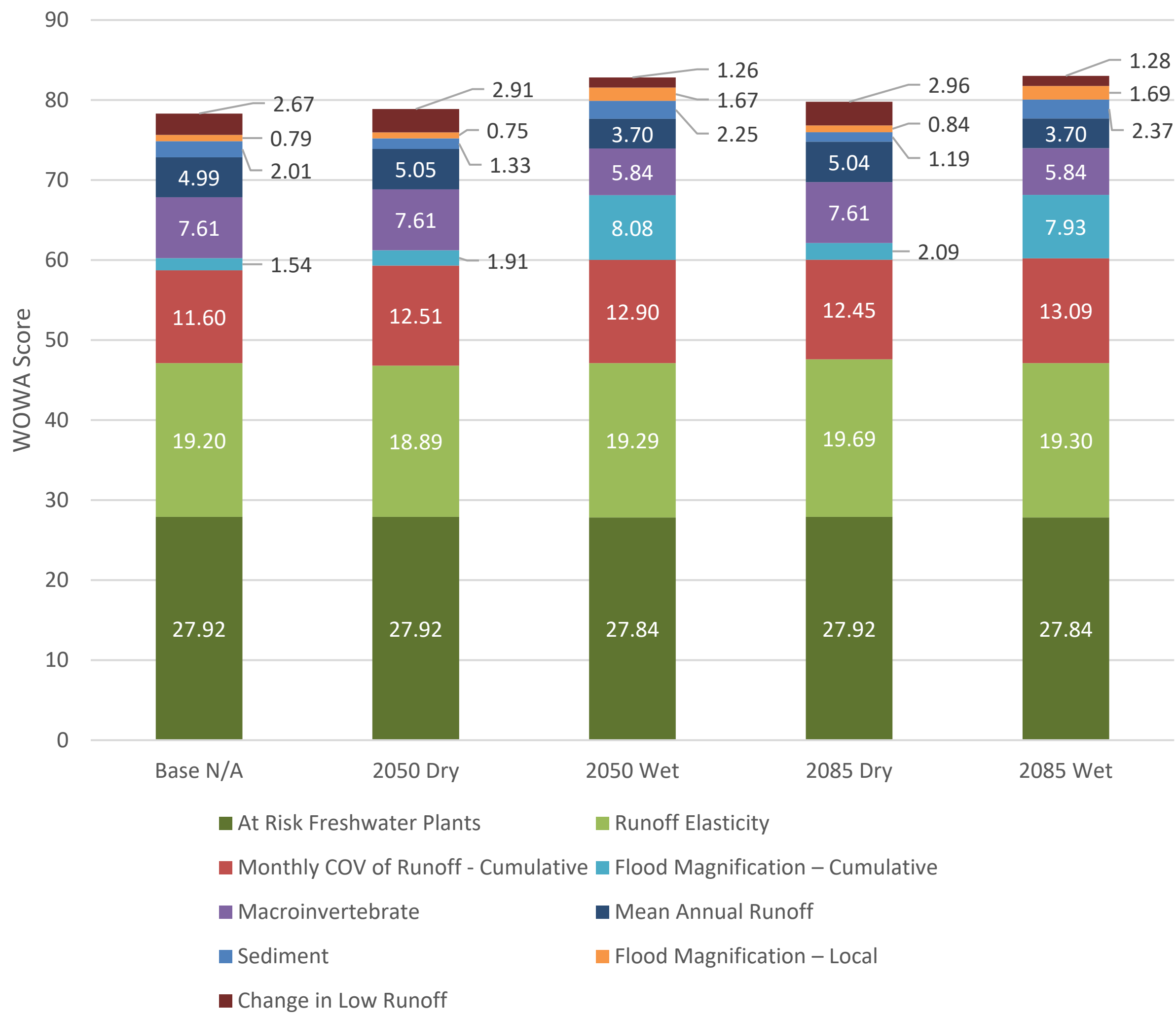


Figure 80: Ecosystem Restoration Vulnerability Scores by Indicator, Lower Kansas River Basin (HUC 1027)

4.2. Flood Risk Reduction

Vulnerability indicators considered for the Flood Risk Reduction business line include two flood magnification factors (local and cumulative), urban areas in the 500-year floodplain, long term (annual) variability in hydrology, and sensitivity of the basin runoff to increased precipitation (runoff elasticity). Figure 81 depicts the WOWA scores for the Kansas River basin geographically. Long-term variability of the hydrology and runoff elasticity drive the vulnerability scores for the Dry scenarios, while cumulative and local Flood Magnification drive the vulnerability for the Wet scenarios. Figure 82 through Figure 84 show the breakdown of the vulnerability scores by HUC-4. Urban areas in the 500-year floodplain was a significant contributor to vulnerability for the Lower Kansas River Basin (HUC 1027). The Lower Kansas Basin is not as sensitive to the effects of climate change with respect to flood risk as the Republican and Smoky Hill basins; however, the WOWA scores indicate that the basin is still vulnerable. Overall vulnerability scores for Flood Risk Reduction are decreasing to slightly increasing in the dry scenarios for the Kansas River Basin, but significant increases in vulnerability to Flood Risk are seen for the Wet scenarios, especially in the Republican and Smoky Hill River Basins, mainly due to expected increases in flood volumes. On the positive side, in the wet scenarios, long term variability of runoff is decreased.

Recommendations by the watershed study for any flood risk reduction measures should consider the vulnerabilities identified, particularly the possible increases in flood flows in the Kansas River Basin under the wet scenarios. Some of the Flood Risk Reduction measures being considered for recommendation in the study are reservoir water control manual updates along with potential control point modifications, new or modified levees, new reservoirs, channel modifications, high flow diversions, climate/extreme flood event planning, setting up a flood information center, floodplain regulations, improved flood forecasting, flood emergency planning, floodplain mapping, floodplain management plans, and detailed flood risk studies. For example, increased flood flows would negatively impact many of the structural measures (levees, reservoirs, channel modifications, etc.). Resilience features for structural FRM measures would need to consider the potential for increased flooding. Potential increased vulnerability due to urban areas in the floodplain is a good reason to perform flood emergency and floodplain management planning as well as mapping. These activities can also consider the increased flood potential.

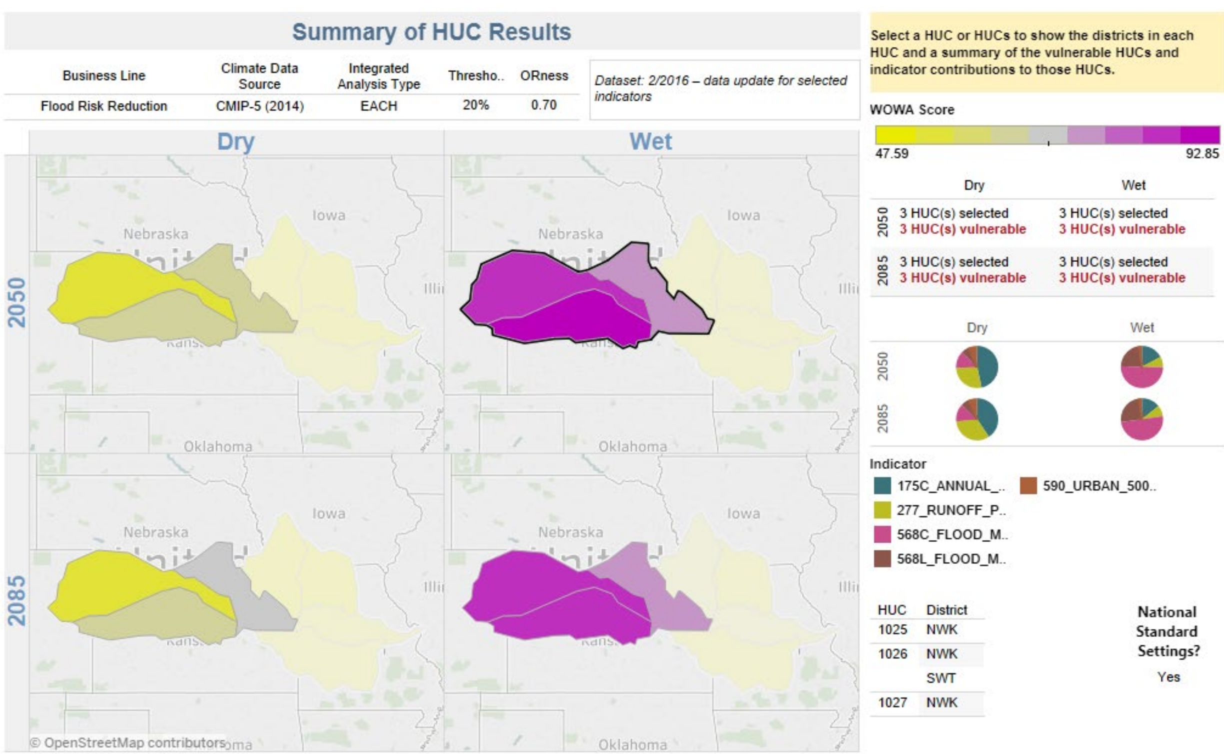


Figure 81: Screening-Level Climate Vulnerability Assessment Tool results for Flood Risk Reduction

Table 13: Flood Risk Reduction Projected Vulnerability for Kansas River Basin

Business Line	HUC-4 Watershed	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Flood Risk Reduction	Republican (1025)	58.31	55.39	84.42	56.78	85.81
Flood Risk Reduction	Smoky Hill (1026)	70.89	66.43	92.85	67.31	86.71
Flood Risk Reduction	Kansas (1027)	66.37	66.14	76.78	69.10	75.14

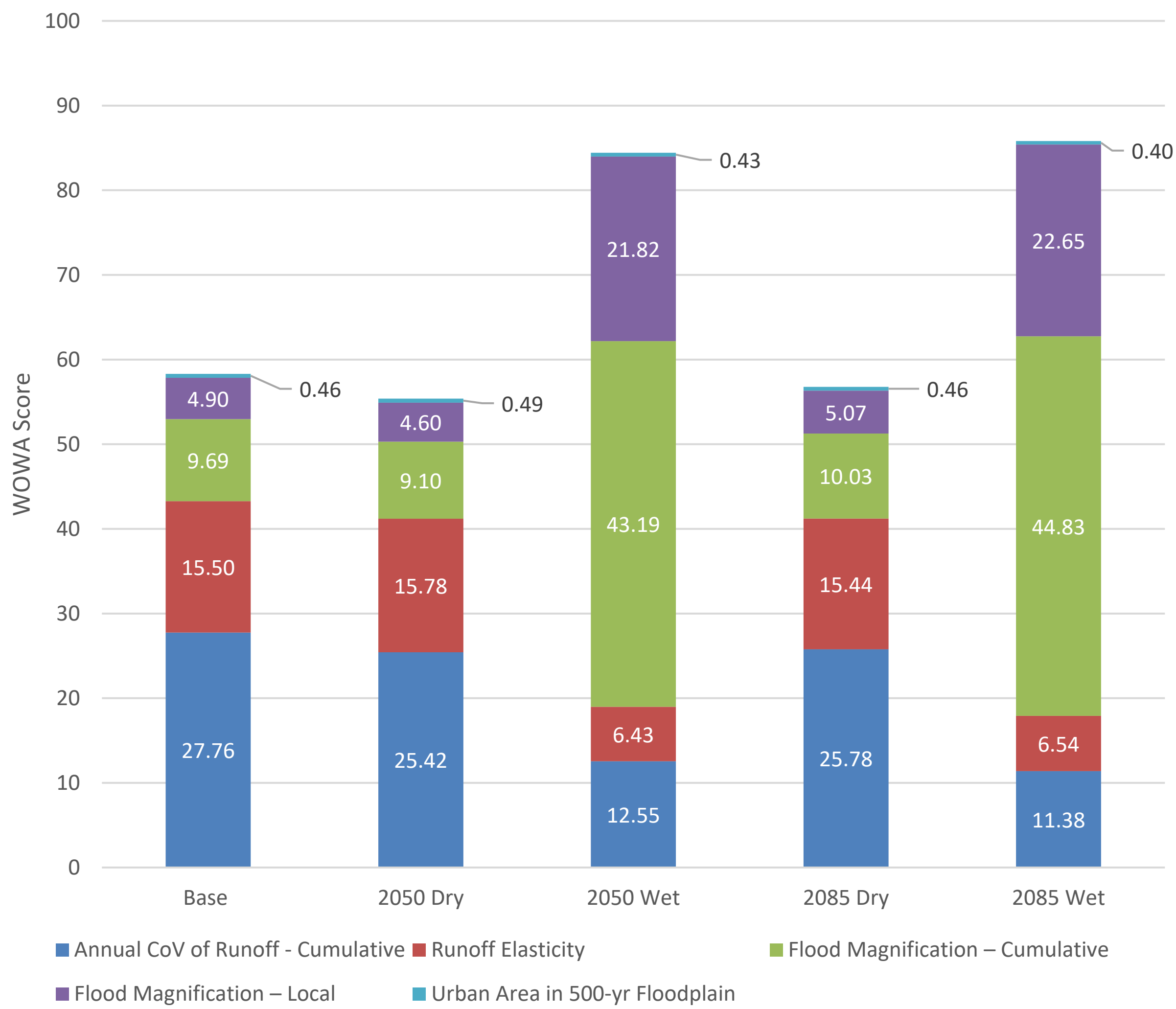


Figure 82: Flood Risk Reduction Vulnerability Scores by Indicator, Republican River Basin (HUC 1025)

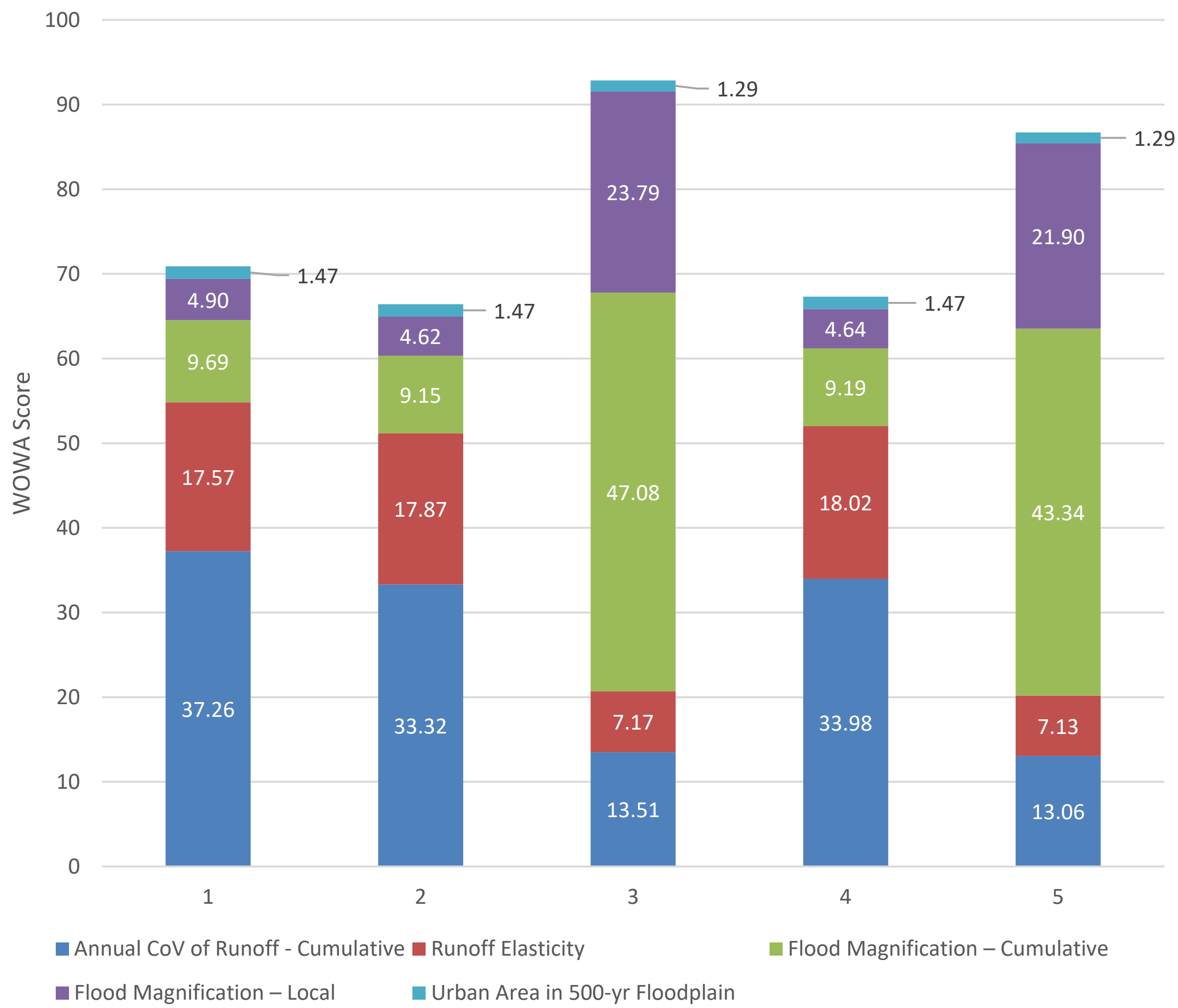


Figure 83: Flood Risk Reduction Vulnerability Scores by Indicator, Smoky Hill River Basin (HUC 1026)

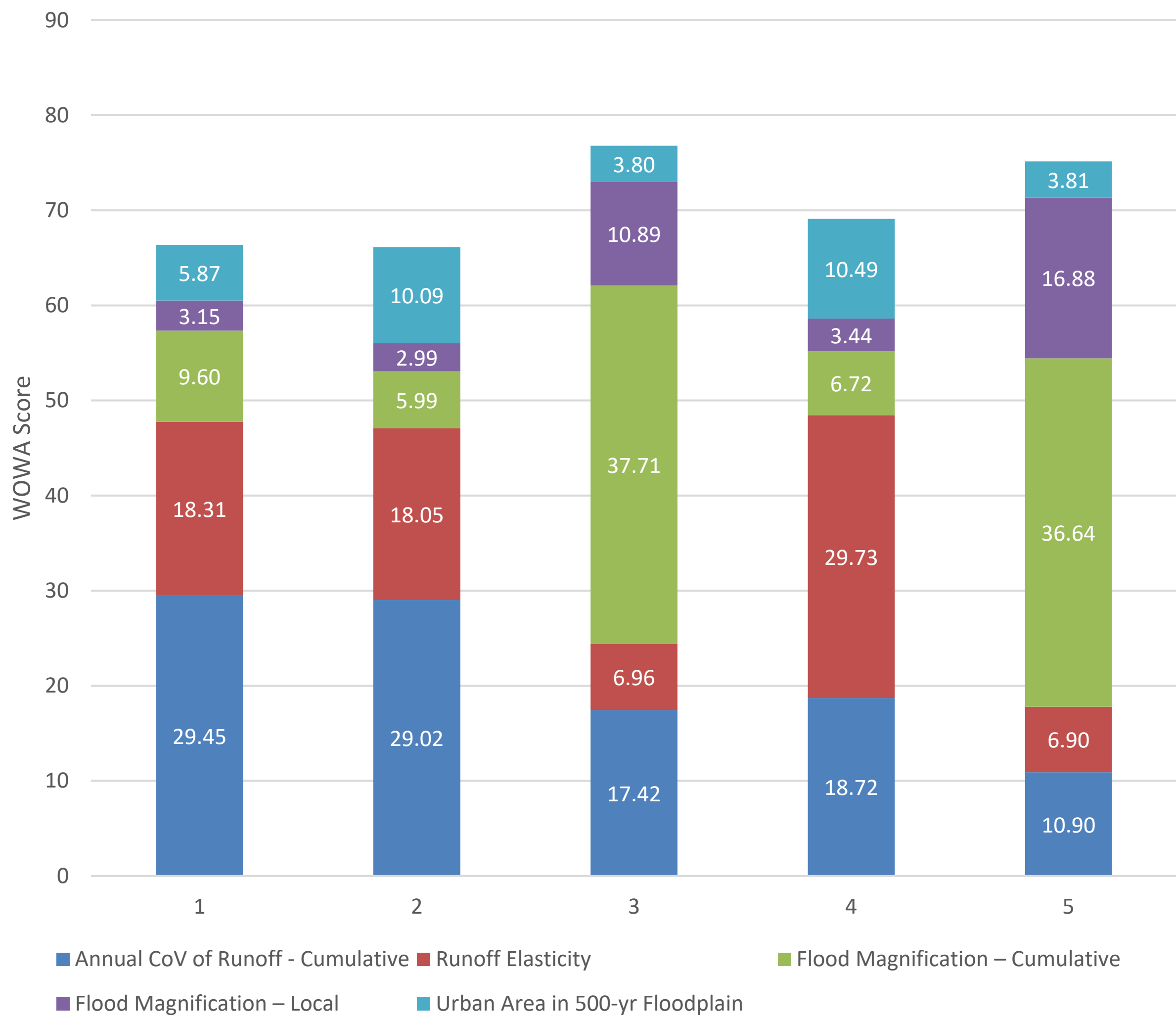


Figure 84: Flood Risk Reduction Vulnerability Scores by Indicator, Lower Kansas River Basin (HUC 1027)

4.3. Recreation

Vulnerability indicators for the Recreation business line include drought severity, the two flood magnification factors (local and cumulative), the 90% duration exceedance low flow, change in low runoff, short term variability in hydrology, sensitivity of the basin runoff to increased precipitation (runoff elasticity), flood runoff, and projected change in sediment load. Figure 85 depicts the vulnerability scores for the three HUC-4's. Table 14 lists the total vulnerability scores for each HUC-4 by epoch and scenario. Figure 86 through Figure 88 present the WOWA scores for each indicator. As for the Flood Risk Reduction business line, the vulnerability scores for the Republican and Smoky Hill basins do not greatly increase for the future dry scenarios. Under the wet scenarios, however, the total scores increased more than 10 points. For the Republican and Smoky Hill basins, the cumulative flood magnification score increased greatly for the future epochs under wet conditions, but the large increases were somewhat offset by decreases in the low runoff vulnerability indicator. Drought severity also increased significantly for the 2085 epoch under both dry and wet scenarios in these basins. Results were similar for the Lower Kansas HUC-4, but the overall increase in vulnerability score was not as pronounced. All three HUC-4's are within the top 20% nationwide for vulnerability for both epochs and scenarios. Overall, future recreation in the Kansas River basin may be threatened by both increases in flooding or changes in low flow conditions and/or drought effects.

Recommendations by the watershed study for any recreation measures should consider the vulnerabilities identified, particularly the possible increases in flood flows in the Kansas River Basin. Some of the recreation measures being considered for recommendation in the study are wetland construction/maintenance, harmful algal bloom research/management, lake level management, new public access points along the Kansas River, improve/construct new boat ramps, improved management of invasive species, habitat development, and water craft inspection/decontamination. For example, new boat ramp construction or extension efforts should consider a range of elevations to build at based on projected changes to low or high stream levels. If the wet projections come to fruition, vulnerability due to low runoff and change in low runoff will be reduced.

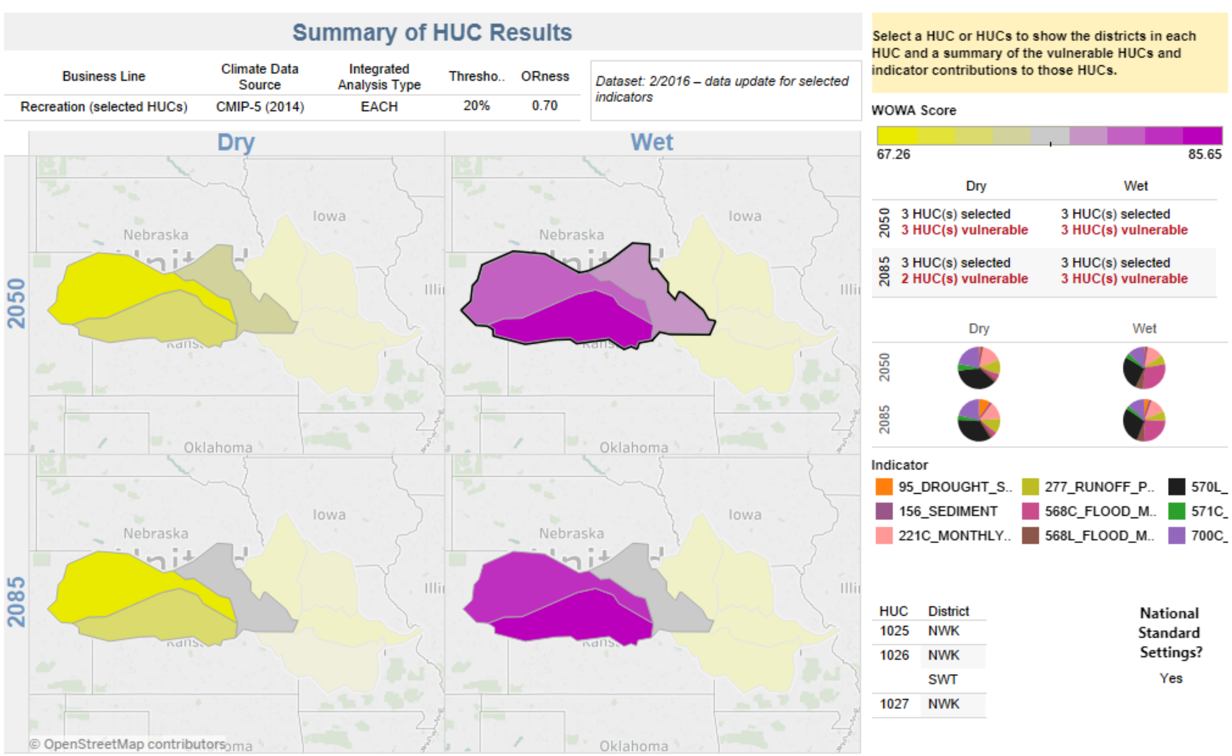


Figure 85: Screening-Level Climate Vulnerability Assessment Tool results for Recreation

Table 14: Recreation Projected Vulnerability for Kansas River Basin

Business Line	HUC-4 Watershed	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Recreation	Republican (1025)	67.45	68.96	80.14	68.46	81.67
Recreation	Smoky Hill (1026)	70.45	72.25	85.65	72.67	83.62
Recreation	Kansas (1027)	71.75	74.39	77.90	75.74	77.34

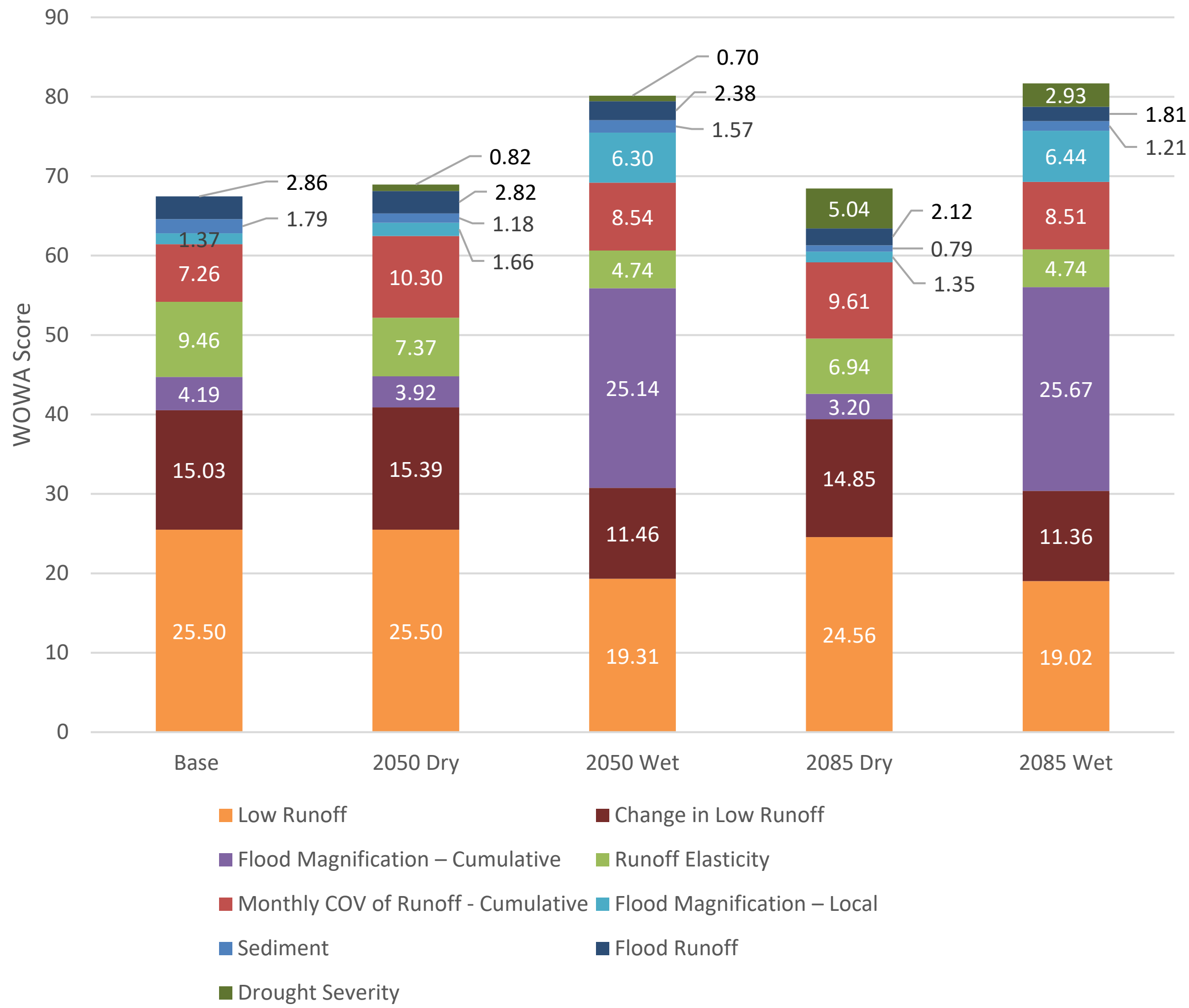


Figure 86: Recreation Vulnerability Scores by Indicator, Republican River Basin (HUC 1025)

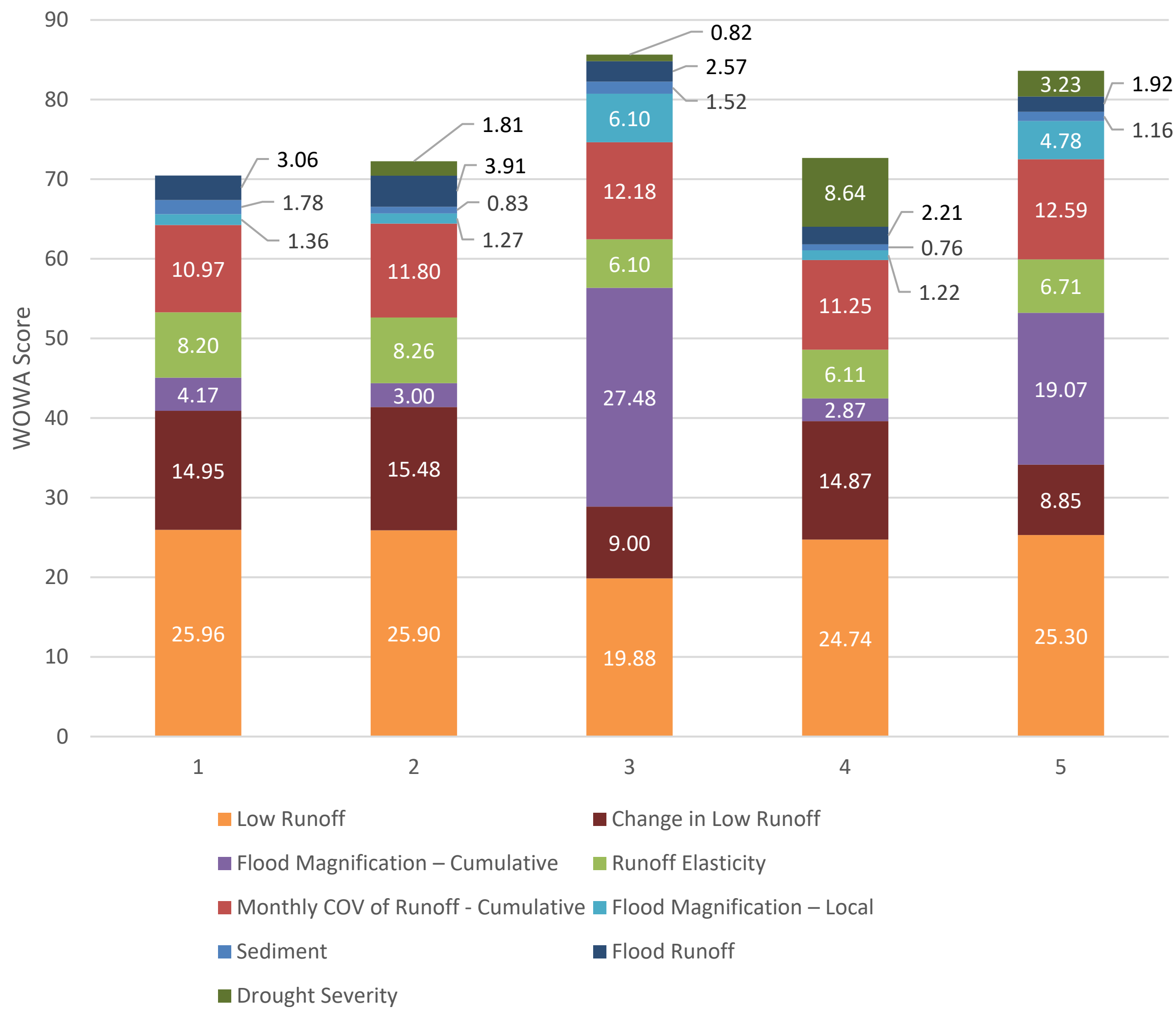


Figure 87: Recreation Vulnerability Scores by Indicator, Smoky Hill River Basin (HUC 1026)

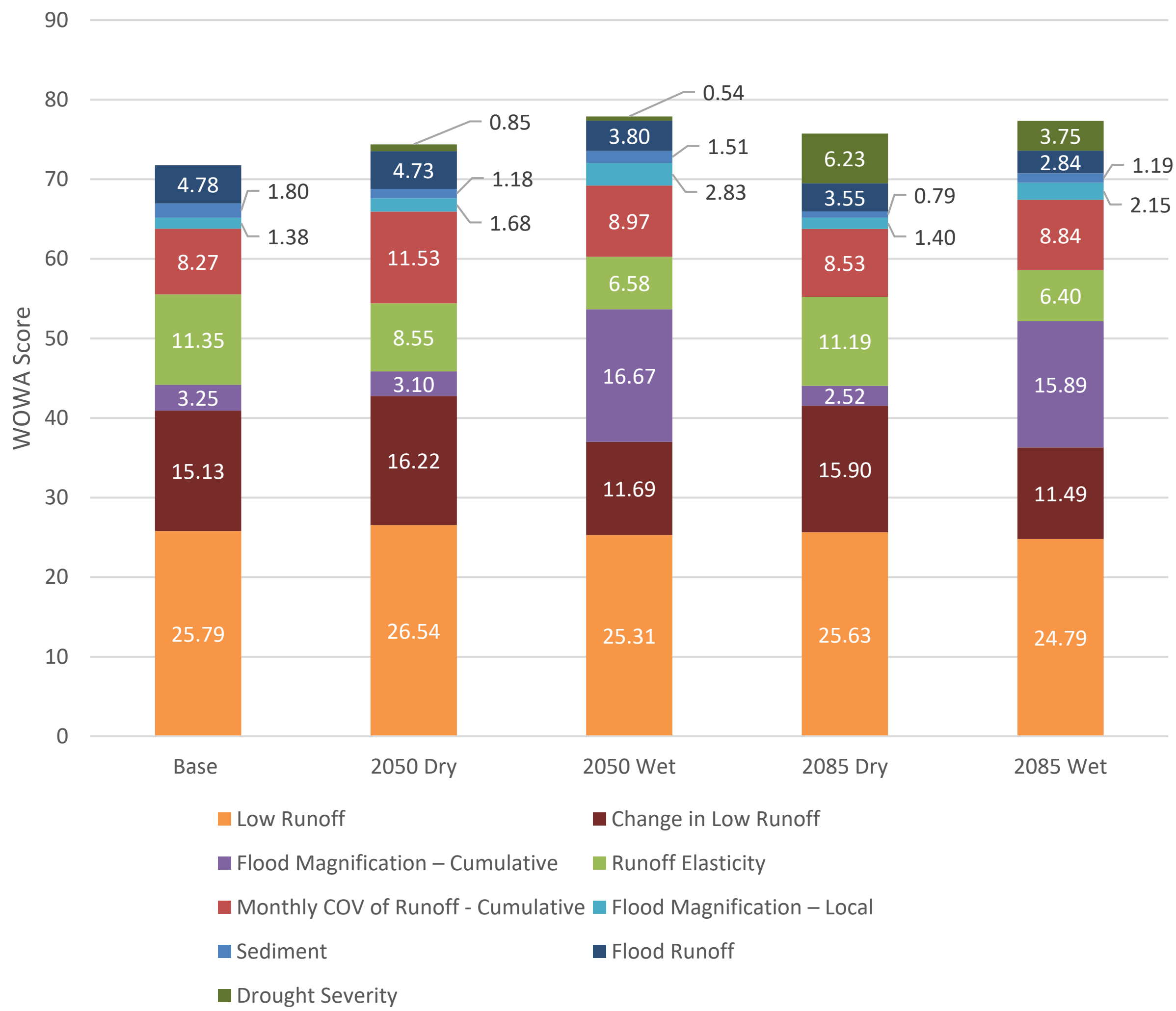


Figure 88: Recreation Vulnerability Scores by Indicator, Lower Kansas River Basin (HUC 1027)

4.4. Water Supply

Vulnerability indicators for the Water Supply business line include sediment load, drought severity, short and long term variability in hydrology, and sensitivity of the basin runoff to increased precipitation (runoff elasticity). Figure 89 depicts the three HUC-4's vulnerability scores for the Water Supply business line. All three HUC's are in the top 20% of watersheds analyzed by the tool. Table 15 lists the total vulnerability scores for the three watersheds for each epoch and scenario. Figure 90 through Figure 92 present the indicator scores and total vulnerability for each of the basins. For the Republican River Basin, the Water Supply vulnerability is projected to increase for all future epochs/scenarios. Vulnerability due to sedimentation increases for the wet scenarios, likely due to increased sediment deposition in water supply reservoirs. For the dry scenarios in the Republican River Basin, vulnerability due to sediment decreases, but total vulnerability increases due to runoff elasticity, long-term variability of runoff, or drought severity. For the Smoky Hill Basin, vulnerability of Water Supply is projected to decrease in the dry scenarios, again due to decreases in sediment and long-term runoff variability; however, drought severity is projected to increase somewhat. For the wet scenarios, increases in sediment and some drought severity lead to somewhat higher overall vulnerability. For the Lower Kansas Basin, overall vulnerability scores are nearly constant except for the 2085 Wet scenario. Generally, similar trends in the individual indicators are present as in the upstream basins, namely increases in sediment in wet scenarios, coupled with decreases in runoff elasticity and long-term runoff variability. For the dry scenarios in the Lower Kansas, increases in drought severity offset decreases in sediment and short-term runoff variability.

Recommendations by the watershed study for any water supply measures should consider the vulnerabilities identified, particularly the potential increase in sedimentation under the wet scenarios. Some of the water supply measures being considered for recommendation in the study are sediment management measures, reallocations, low flow target modifications, drought contingency planning, harmful algal bloom research/management, new reservoir construction, and drought forecasting. For example, all sediment management measures should consider the potential for sediment loading at the reservoirs to increase under future climate projections. This obviously applies to new reservoir construction also. All measures should take into account expected changes in hydrology, as increases in stream flow could make water supply infrastructure more resilient, but increasing drought conditions, as projected for all scenarios compared to the baseline can lead to failure of water supplies. Decreases in sedimentation could benefit the basin if future hydrology ends up on the dry side of the projected flows instead of the wet by reducing storage loss at reservoirs.

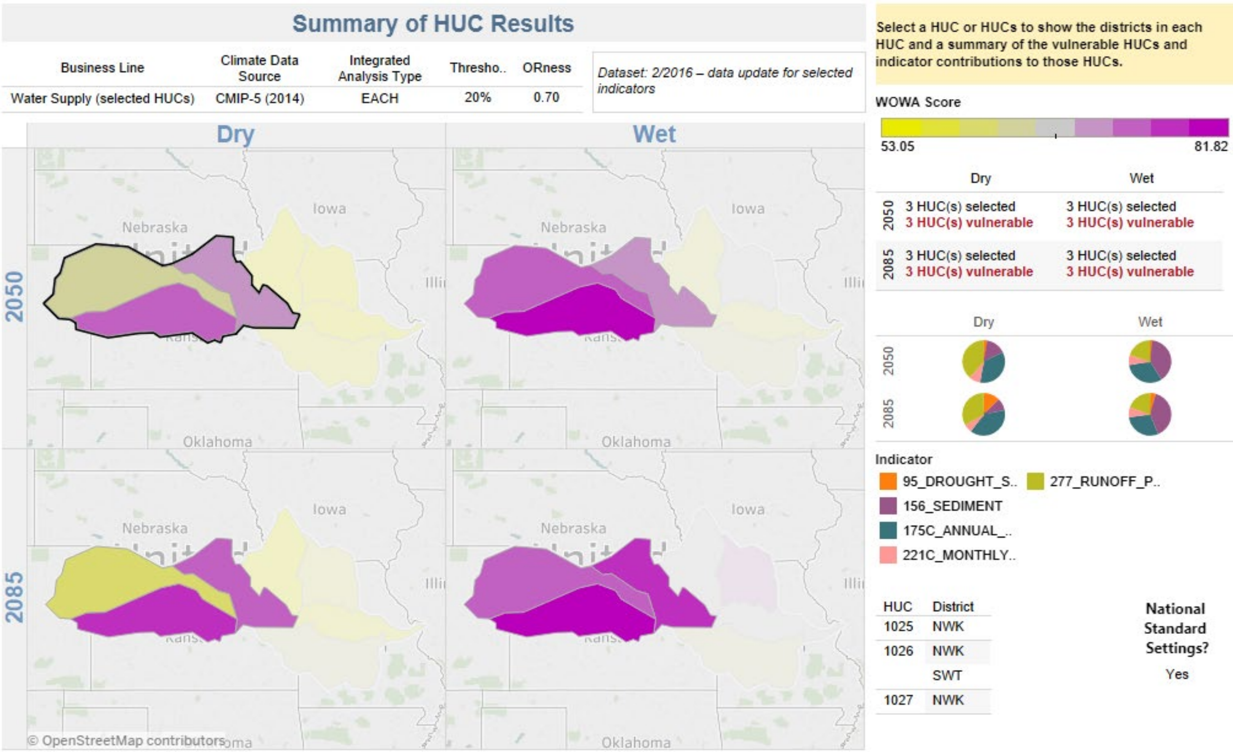


Figure 89: Screening-Level Climate Vulnerability Assessment Tool results for Water Supply

Table 15: Water Supply Projected Vulnerability for Kansas River Basin

Business Line	HUC-4 Watershed	Base	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Water Supply	Republican (1025)	60.79	64.06	73.55	61.54	74.23
Water Supply	Smoky Hill (1026)	77.98	73.54	80.34	77.75	81.82
Water Supply	Kansas (1027)	72.66	71.61	71.84	72.40	75.74

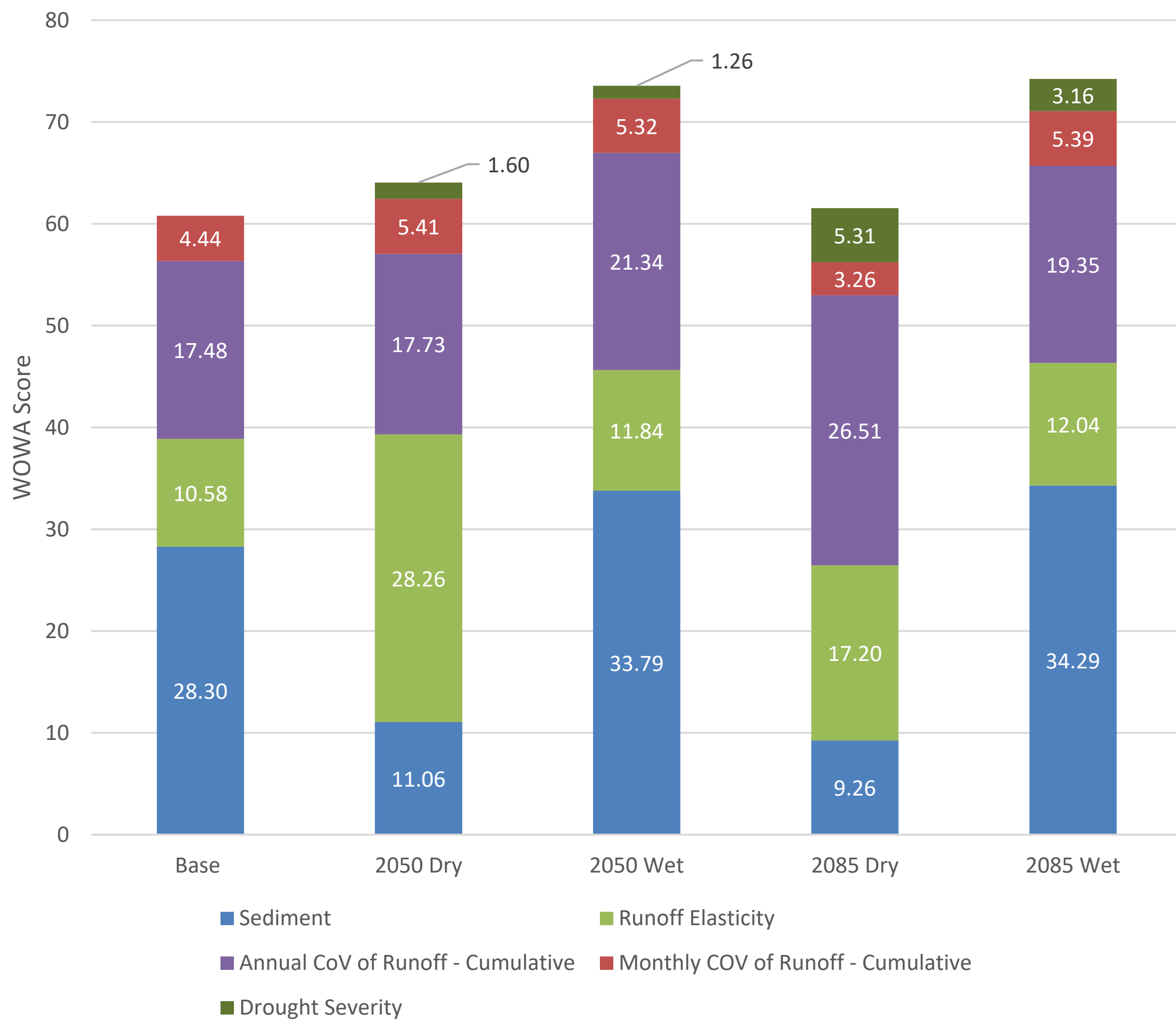


Figure 90: Water Supply Vulnerability Scores by Indicator, Republican River Basin (HUC 1025)

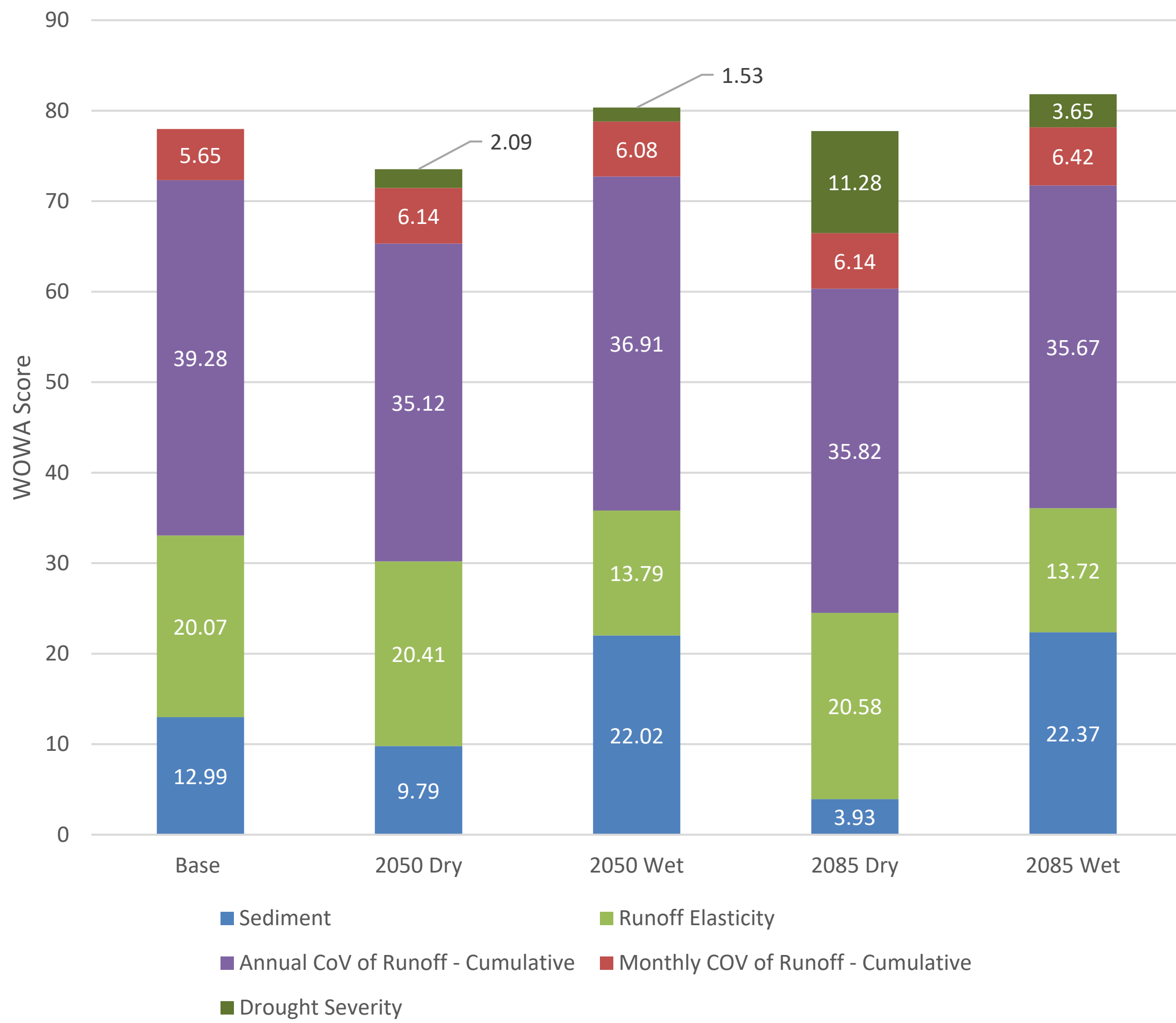


Figure 91: Water Supply Vulnerability Scores by Indicator, Smoky Hill River Basin (HUC 1026)

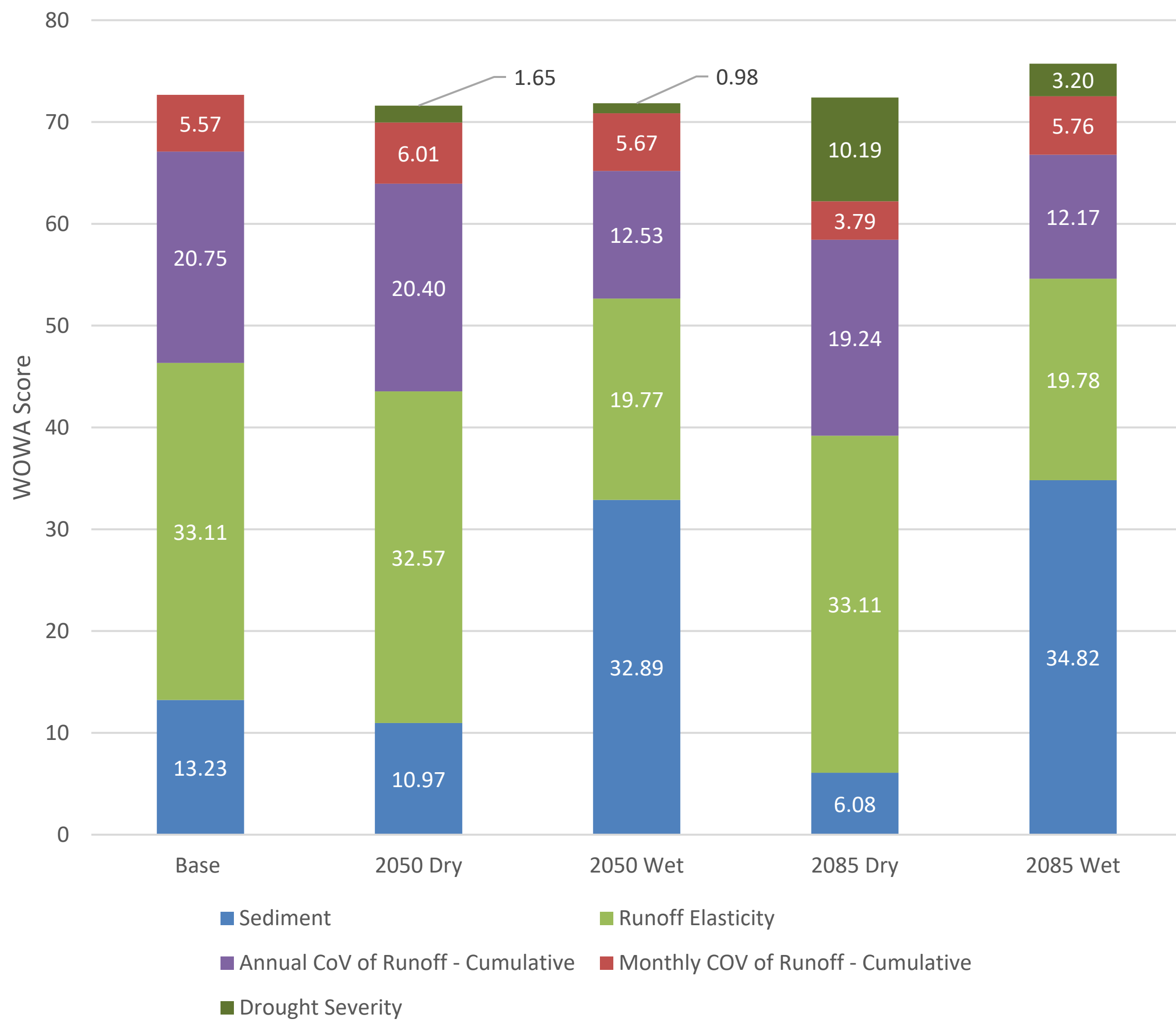


Figure 92: Water Supply Vulnerability Scores by Indicator, Lower Kansas River Basin (HUC 1027)

5. Conclusions

Overall, significant trends in several relevant climate variables are expected based on this qualitative analysis, but direct impacts to streamflow remain uncertain. The strongest consensus amongst the literature supports a trend of increasing temperatures and precipitation in the region resulting in increased frequency in the occurrence of extreme storm events. Extremes in climate will also magnify periods of wet and dry weather resulting in longer more severe droughts and larger more extensive storms. The literature is conflicted as to projected streamflow peak magnitude, duration, and volume of extreme events with the uncertainty being largely attributed to the uncertainty of the climate models themselves.

Based on this assessment, the recommendation is to constrain periods of analysis for flow frequency based on the results of non-stationarity detection and trend analysis. The mainstem Kansas River gaging stations analyzed indicate that the period of 1941-2019 may be considered stationary. For the reservoir inflow data analyzed, all reservoirs except Harlan County, may be considered stationary, as no strong non-stationarities or statistically significant trends were found. There may be other indicators of climate change, such as changes in biotic communities, but this analysis is focused on climate changes as they relate to hydrology and hydraulics. Methods of translating qualitative climate change impact uncertainty for an engineering-based analysis do not currently exist.

Results of the Climate Hydrology Assessment Tool (CHAT) indicate that increases in streamflow in the Kansas River basin are likely, and projections contain significant trends for the Republican River Basin and the Lower Kansas Basin. These trends, while indicative of increasing flows over time, are relatively small in magnitude. Four business lines pertinent to the Kansas River Flood and Sediment Study were analyzed using the USACE Screening Level Vulnerability Assessment Tool. The analyzed business lines included Ecosystem Restoration, Flood Risk Reduction, Recreation, and Water Supply. The tool indicates that for all four business lines, the three HUC-4's analyzed (1025, 1026, 1027) are in the top 20% most vulnerable basins in the CONUS, except for the Republican River Basin for Recreation in the 2085 Dry scenario. Primary vulnerability indicators for Ecosystem Restoration include at risk freshwater plants, runoff elasticity, and short-term variability in hydrology for all three HUC-4's. For Flood Risk Reduction, long-term variability of the hydrology and runoff elasticity drive the vulnerability for the Dry scenarios, while cumulative and local Flood Magnification drive the vulnerability for the Wet scenarios. Recreation vulnerability in the Kansas River Basin is driven by both increases in flooding or changes in low flow conditions and/or drought effects. For the Water Supply business line, sediment, runoff elasticity, and long-term variability in flows drive the vulnerability in the Kansas River Basin.

Specific resiliency measures were not identified for the watershed study, but any brainstorming effort to conceptualize measures should consider results from this assessment. Some examples of potential impacts of the projected changes on proposed measures were considered, such as increased/decreased sedimentation at reservoirs under wetter/drier conditions, potential for higher/lower water levels at recreation facilities, impacts of potentially greater flood flows on flood risk management infrastructure, and the potential for increased hydrologic variability on ecosystem restoration projects. Table 16 summarizes potential impacts of the expected or possible results of climate change on the currently proposed measures as of the Shared Vision Milestone.

Table 16: Climate Risks for Shared Vision Milestone Proposed Measures

Measure	**Trigger**	**Hazard**	**Harm/ Benefit**	**Qualitative Likelihood**
Flood Risk Management				
Operational Measures/ Dam and Reservoir Upgrades (Water Control Manual Updates, New Reservoir/Dam or Detention Basins Construction)	Larger flood volumes in future years	Higher pool elevations at existing/ proposed reservoirs.	Inability to contain flood events, more frequent occurrence of surcharge releases and uncontrolled flows.	Likely
Levee Upgrades (New or Modified Levees/ Dikes/Floodwalls)	Larger flood peaks in future years; Increased flood durations	Higher water surface elevations; Longer loading duration	Higher probability of overtopping; Greater likelihood of levee breach	Likely
Flow Improvements (Channel Modifications, High Flow Diversions)	Larger flood peaks in future years; Increased flood durations	Higher water surface elevations; Longer loading duration	Higher probability of exceeding capacity; Greater likelihood of erosion	Likely
Floodplain Improvements (Authority for Land Acquisition or Easement Purchase for Flood Control, Floodplain Management Plans)	Larger flood peaks in future years; Increased flood durations	Greater flood extents in non-leveed areas	Larger floodplain areas that require management or purchase	Likely

Measure	Trigger	Hazard	Harm/ Benefit	Qualitative Likelihood
Non-Structural Measures (Climate Plan/Extreme Event Planning, Kansas Flood Center/ Flood Information System, Floodplain Regulations, Flood Forecasting, Flood Warning/ Emergency Plans, Floodplain Mapping)	Larger flood peaks and volumes in future years; Increased flood durations	More frequent and larger floods	More frequent activation of flood forecasting/ warning systems, frequent updates of plans.	Likely
Water Availability and Sustainment				
Operational Measures, New Water Storage, Resiliency Planning	Increased Drought/ Decreased low inflows to reservoirs	Lack of water available to support reservoir releases/ withdrawals	Water users in basin won't have adequate supply	Likely
Incoming Sediment Reduction, Sediment Removal from Reservoirs	Increased frequency of extreme precipitation and stream flow events	Increased sediment loading from watershed	Loss of additional storage from increased sediment load	Likely
Ecosystem Restoration and Management				
Reservoir Habitat Improvements, In-channel Habitat Improvements, Off-channel/ Upper Watershed Improvements	Decreased streamflows/ increased drought frequency	Not enough water in streams/ reservoirs to allow use of habitat	Decreased fish/wildlife populations	Likely
	Increased flood flows	Damage to habitat improvements, reduction to habitat	Decreased fish/wildlife populations	Likely (Low Confidence)
	Increased Floodplain inundation	Improved habitat conditions/ availability	Increased fish/wildlife populations	Likely (Low Confidence)

Measure	**Trigger**	**Hazard**	**Harm/ Benefit**	**Qualitative Likelihood**
Invasive Species Management	Decreased streamflows/ increased drought frequency Increased stream flooding and longer duration flooding	Changed habitat conditions Increased likelihood of invasive species spread	Better conditions for invasive species, Decrease in suitable conditions for native species	Likely Likely (Low Confidence)
Water Quality				
Nutrient and Sediment Reduction	Decreased streamflows/ increased drought frequency	Decreased water volume could lead to increased nutrient concentrations	Increased water quality problems	Likely
Water Management	Decreased streamflows/ increased drought frequency	Lower reservoir storage volumes	Decreased ability to maintain water quality reservoir releases	Likely
Harmful Algal Blooms (HABs)	Decreased streamflows/ increased drought frequency	Increased reservoir nutrient concentrations	Increased frequency and intensity of HABs	Likely

Measure	Trigger	Hazard	Harm/ Benefit	Qualitative Likelihood
		Recreation		
Reservoir Recreation	Decreased reservoir inflows due to increased drought	Lower reservoir levels	Inadequate reservoir depths to support traditional recreation	Likely
	Increased reservoir inflow volumes due to increasing flood frequency	Higher reservoir levels	Flooding damage to recreation facilities, Closure of facilities for floods	Likely (Low Confidence)
Riverine Recreation	Decreased streamflows/ increased drought frequency	Lower stream water levels	Decreased recreational opportunities	Likely
	Increased stream flooding and longer duration flooding	High stream water levels make recreation too dangerous		Likely (Low Confidence)

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