Appendix F
Long-term Assessment of Hydrometeorological Conditions

FY: 2024
Project Title: Beattyville, KY FRM Project
Project No.: 498982
Location: Lee County, Kentucky

TABLE OF CONTENTS

Table of Tables

Table of Figures

1 GENERAL

This qualitative assessment of long-term hydrometeorological conditions is required by U.S. Army Corps of Engineers (USACE, "the Corps") Engineering and Construction Bulletin (ECB) 2018-14, "Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects." This is a screening-level assessment that documents the qualitative effects of long-term hydrometeorological conditions on hydrology in the region and informs the Beattyville, KY General Investigation of the potential impacts and risks drivers which can potentially be attributed to hydrometeorological vulnerabilities.

USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural hydrometeorological variability over their operating life spans. However, recent scientific evidence shows that in some places and for some impacts relevant to USACE operations, the hydrometeorological baseline may be changing. This is relevant to 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 the hydrometeorological parameters, which are important in hydrologic assessments for flood risk management in watersheds such as the Kentucky River Basin.

The Beattyville GI study is a flood risk mitigation study where flood risk in Beattyville is mainly driven by intense rainfall events. The flood-risk reduction business line will be considered in this long-term hydrometeorological assessment and the discussion will be focused on temperature, precipitation, and streamflow.

Beattyville, KY has had major flooding in the past couple years. Due to the flooding impacts, alternatives are being assessed to determine the best flood risk management projects. Some of the structural alternatives that are being considered are constructing levees or floodwalls that incorporate pump stations or pressure pipes to keep flooding out of the protected area. Non-structural alternatives are relocating structures, acquiring structures, wet/dry floodproofing, and raising structures. The final alternatives involve Flood Warning Emergency Evacuation Plans (FWEEP), determining the extent of inundation, evacuation planning, floodplain management plan, flood sensors/gages, and flood sirens. These are the alternatives being considered to help mitigate the flood risk in Beattyville, KY. This assessment will be used to verify and determine which alternatives will be most resilient to long-term changes in hydrometeorological conditions or improve community resilience.

The North Fork Kentucky River, Middle Fork Kentucky River, and South Fork Kentucky River join in Beattyville, KY to form the Kentucky River. The Kentucky River lies completely within the State of Kentucky and flows into the Ohio River. The Kentucky River Basin has a total watershed area of 7,000 square miles. The Kentucky River flows in the general Northwest direction for 255 river miles to its junction with the Ohio River at Carrollton, Kentucky. North Fork, Middle Fork, and South Fork join to form the Kentucky River draining 1,220, 1,130, and 1,262 square miles, respectively, of the total basin. The headwaters lie on the Appalachian Plateau and the lower portion of the basin consists of relatively wide valleys and gentle, rounded hills. The Kentucky River Basin falls within the U.S. Geologic Survey (USGS) region 05 and makes up approximately 73% of the area in the 4-digit Hydrologic Unit Code (HUC) 0510. The rest of the HUC-4 region consists of the Licking Basin, as seen in Figure 1.

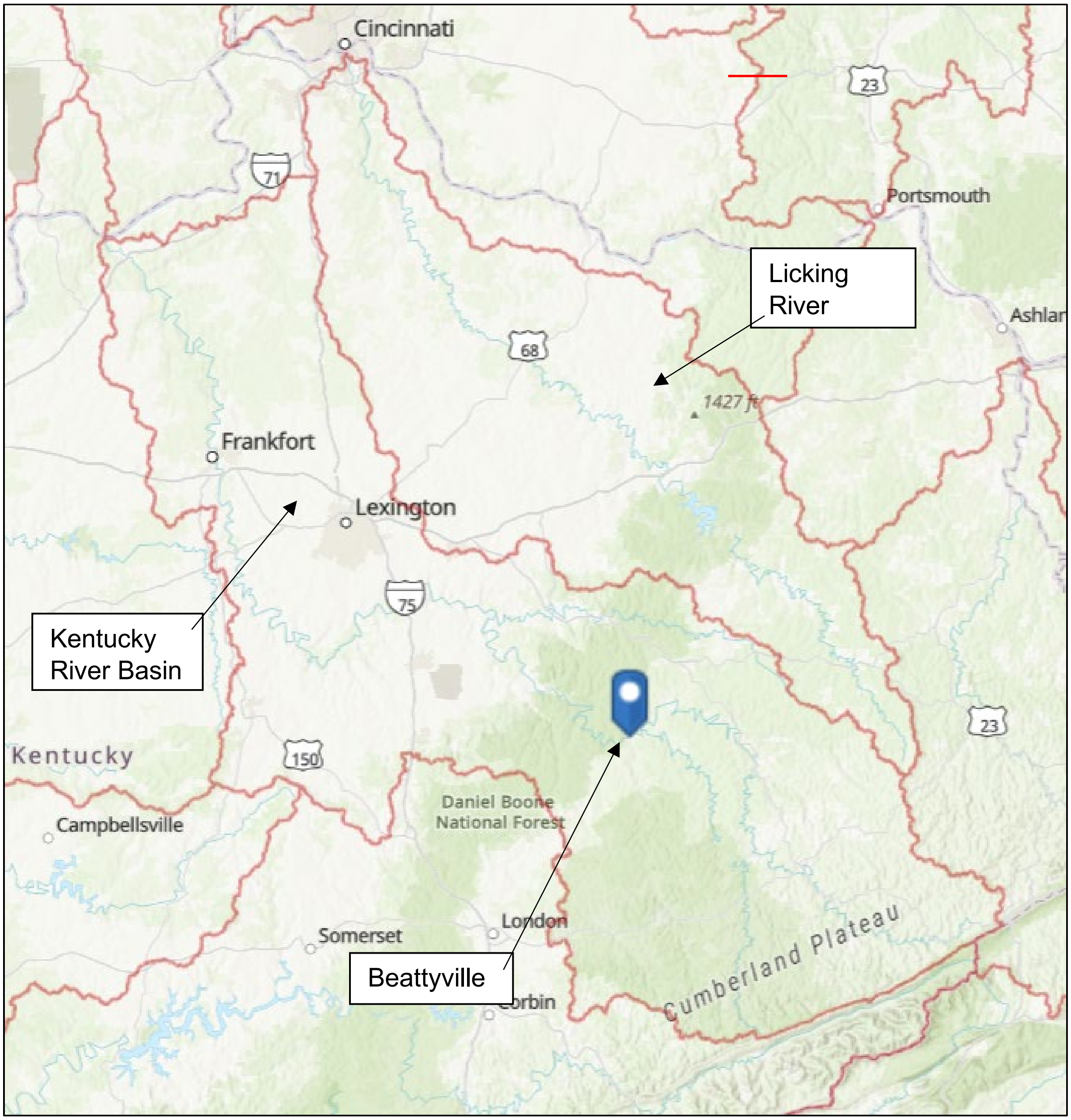


Figure 1 Map of the Kentucky River HUC-4 0510 region

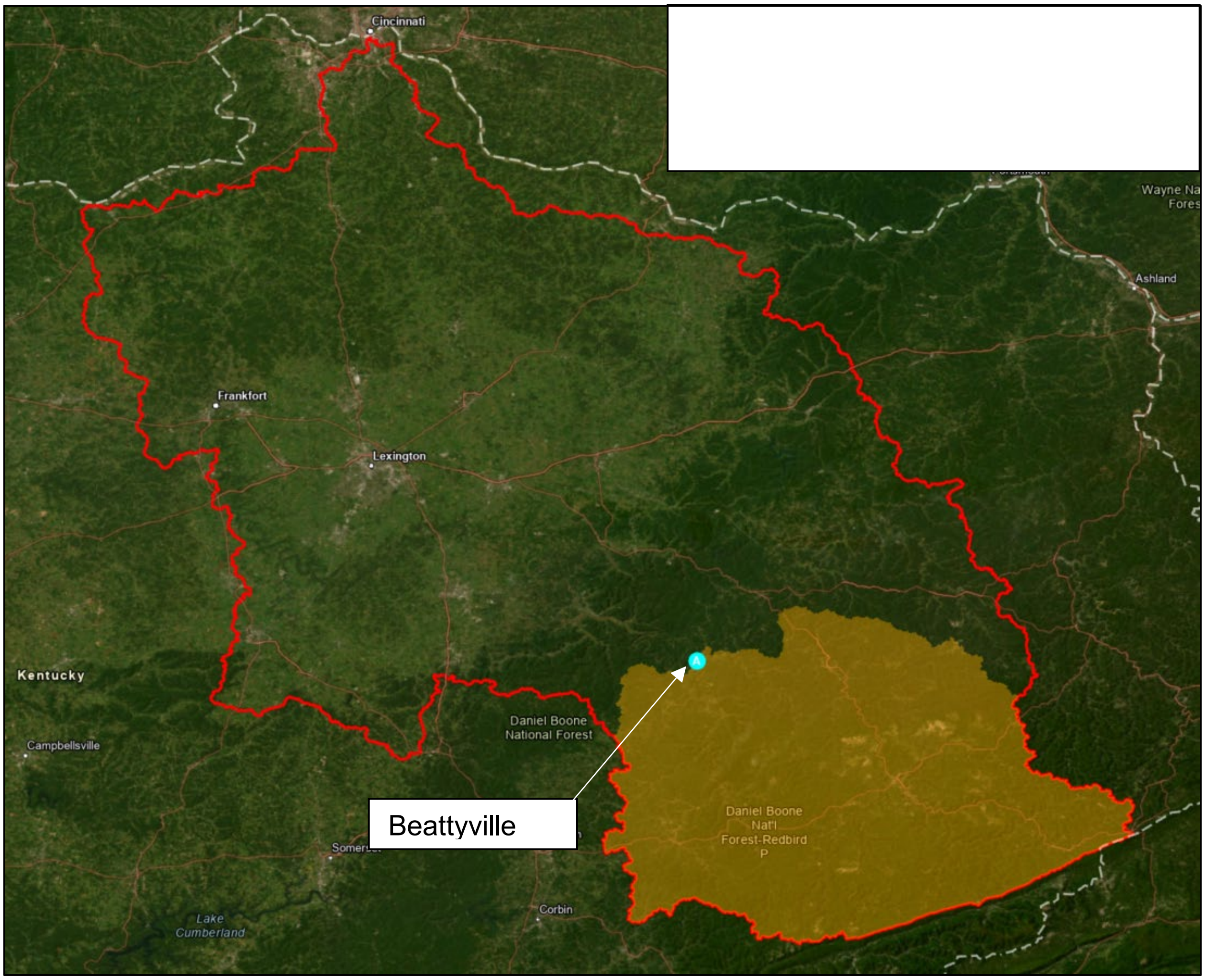


Figure 2 Map of the Kentucky River HUC-4 0510 region

Beattyville, KY, is located in the Kentucky River Basin at the confluence of the North Fork, Middle Fork, and South Fork Rivers which are all headwaters of the Kentucky River. Approximately 2,164 square miles of the Kentucky River Basin Watershed are upstream of Beattyville, KY, as can be seen in Figure 2 shaded in orange.

The U.S. Army Corps of Engineers operates Flood Risk Management (FRM) projects within the Kentucky River Basin upstream of Beattyville, KY, including Carr Creek Dam and Buckhorn Dam. These projects serve a primary function of flood risk management, as well as other congressionally authorized purposes such as irrigation, water supply, water quality, fish and wildlife conservation, forest resources conservation, and recreation. Buckhorn Dam is on the headwaters of the Middle Fork Kentucky River. Construction on Buckhorn Dam began in October 1956 and was placed in operation in December 1961. Buckhorn Dam has a drainage area of 408 square miles. Carr Creek Dam is on the headwaters of the North Fork Kentucky River. Construction on Carr Creek Dam was completed in December 1975, with filling complete in January 1976. Carr Creek Dam has a drainage area of 58.2 square miles. The two FRM reservoirs constitute 17.5% of the drainage area being regulated in the Kentucky River Basin Watershed upstream of Beattyville shown as the orange shaded area in Figure 2.. In addition to the two

USACE dam and reservoir projects within the Kentucky River Basin, there are 14 USACE lock and dam projects. The lock and dams were built prior to the reservoirs as a means of navigation to transport goods along the Kentucky River.

In total, there are 13 active stream gages distributed throughout the South Fork, Middle Fork, and North Fork of the Kentucky River Basin watershed: 2 gages on the South Fork, 6 on the Middle Fork, and 5 on the North Fork. The gage that is the main subject of this study is located in Heidelberg, KY on the Kentucky River about three air miles downstream of Beattyville (USGS 03282000). The gage has a drainage area of 2,657 square miles, as shown in Figure 3.

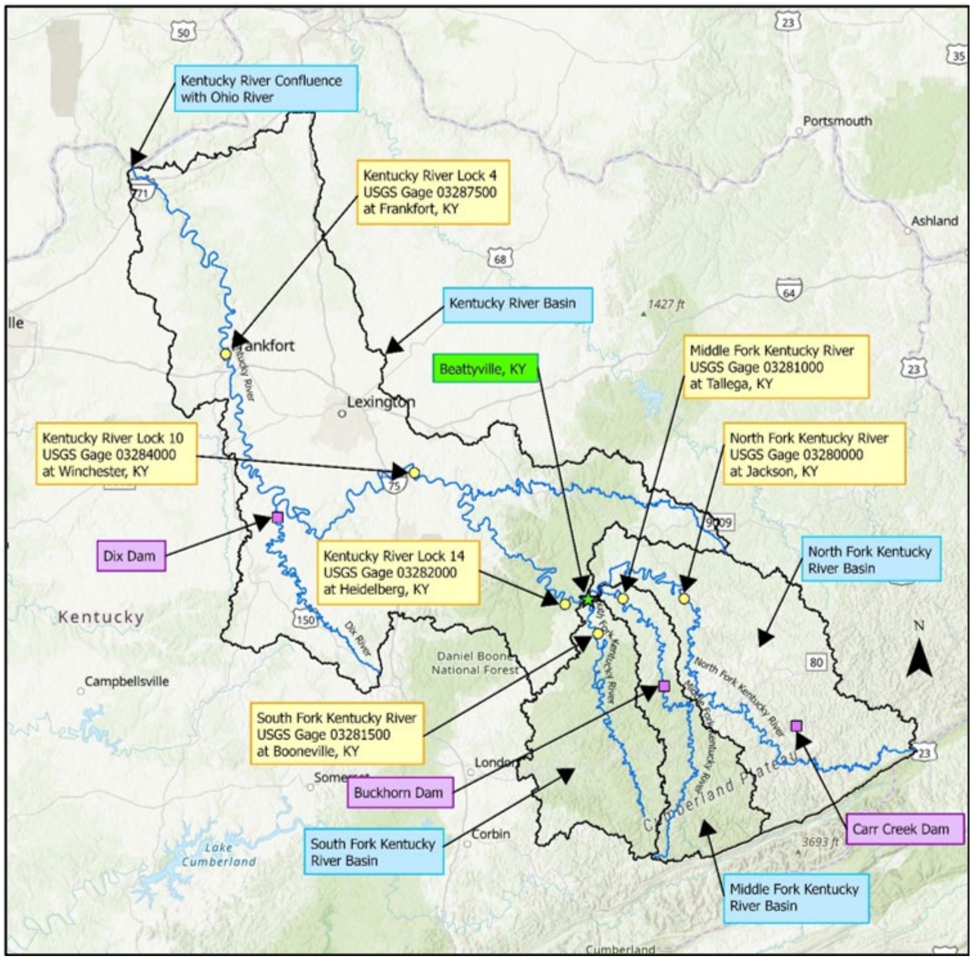


Figure 3 Kentucky River Basin Gages

The other gage considered is upstream of Beattyville. The majority of the closest gages to Beattyville are regulated by the two USACE reservoirs with the exception of the two gages on the South Fork. The South Fork gages are unregulated since there are no USACE reservoirs along this headwater nor are there any local levees. In order to separate out the hydrologic influence of observed hydrometeorological change from other significant anthropogenic impacts, such as upstream regulation, an effort was made to identify a relatively "pristine" gage which was largely free of the effects of watershed modification. The USGS gage on the South Fork Kentucky River at Booneville (USGS 03281500) is representative of natural run-of-the-river morphologic conditions, allowing for greater insight into the impacts which may have been caused by hydrometeorological factors. While the pristine gage chosen for analysis was selected primarily because of the lack of regulation within its upstream watershed, preference was also given to the site with lengthy annual peak streamflow period of record and to the site with relatively large drainage areas. Land-use change over time, such as urbanization and changing forestry practices, were not considered when selecting the pristine gage, which may have some impact on nonstationarity analysis.

Both analyzed gages and relevant parameters such as drainage area, peak streamflow, and period of record (POR) are in Table 1. It should be noted that reservoir operation was assumed to be consistent and uniform across the period of regulation. While there have been numerous deviations from the authorized water control plan, these changes were assumed to be relatively minor from a statistical and operational perspective.

Table 1. Relevant Gages used in Qualitative Analysis

USGS Gage #	USGS Site Name	Period of Record	Air Miles from Beattyville	# of Observations	Drainage Area (square miles)	Regulation
03282000	Kentucky River at Lock 14 at Heidelberg, Ky	1926 - 2023	3	97	2,657	Regulated Since 1960
03281500	South Fork Kentucky River at Booneville, Ky	1925 - 2022	7	98	722	Pristine

1.1 Historic Conditions within the Kentucky River Basin

Two FRM projects upstream of Beattyville discharge into the Kentucky River Basin: Buckhorn Reservoir and Carr Creek Reservoir. The local hydrometeorology is continental in nature which is characterized by large annual and daily ranges of temperature. These reservoirs lie near the average path of moisture-bearing cyclones that move in a general easterly direction across the United States. Annual precipitation is well distributed with peaks in early spring and summer. Snowfall occurrence varies from year to year but is common from November through April (*Reservoir Regulation Plan - Carr Fork Lake*, 1980; *Water Control Plan - Buckhorn Lake*, 1995).

Temperature. Temperatures in the Kentucky River Basin area are generally highest during July and lowest during January. The expected mean annual temperature for the area is in the upper 50 degrees Fahrenheit. Extreme summer temperatures usually exceed 100 degrees Fahrenheit and minimum temperatures of zero or lower can be expected during the winter at the forementioned reservoirs in the basin (*Reservoir Regulation Plan - Carr Fork Lake*, 1980; *Water Control Plan - Buckhorn Lake*, 1995).

Precipitation. Most of the precipitation over the Kentucky River Basin results from general storms which move easterly to northeasterly across the basin. These storms vary considerably in frequency and character, producing a wide variation in precipitation for individual months and years. These storms are well-distributed throughout the year with the most severe ones occurring from mid-winter to early spring. Winter and summer-type storms have separate and distinct characteristics (*Reservoir Regulation Plan - Carr Fork Lake*, 1980; *Water Control Plan - Buckhorn Lake*, 1995).

An assessment of observed trends in historic temperature and precipitation was conducted using local data in Beattyville and Heidelberg available from the National Oceanic and Atmospheric Administration (NOAA). Since the Beattyville gage had data only from 2002-2023, data from the Heidelberg gage was used in conjunction with the data from Beattyville's gage to best portray the area's historical temperature and precipitation trends. The Heidelberg gage is 3 air miles from Beattyville and had a large range of data- 1934-2011. Therefore, the dataset from the Heidelberg gage was used for observed historic trends prior to 2002. It was deemed important to include more recent large precipitation events that were captured by the Beattyville gage starting at the beginning of its data availability. Although the combined data and Heidelberg's individual data do not portray the exact same slope in their trendlines (see Figure 4 and Figure 5), both are increasing or decreasing at just a slightly different rate or have approximately no slope dependent on the data in question. In the figures below, data points and trendlines in red and yellow are from Heidelberg's data only. Meanwhile, data points in blue and green are from Beattyville's data only. Trendlines in purple and orange are based on the combined dataset for the Heidelburg and Beattyville gages (Heidelberg's data ranges from 1934 to 2002 and Beattyville's data ranges from 2002 to 2023).

Before combination, both data sets were plotted and analyzed separately to determine if statistically significant trends occurred in either dataset individually. Data analyzed includes monthly average temperature and monthly total precipitation. These monthly values were used to calculate annual average temperatures and annual total precipitation for 1934-2023. This dataset, associated trends, and statistical significance values are displayed in

Figure 5. Trends in Annual and Maximum Monthly Precipitation in Beattyville for both gages as well as for Heidelberg individually. The annual average temperature as well as the highest monthly average temperature for each year are displayed in Figure 4. The total annual precipitation and maximum monthly precipitation for each year are displayed in

No statistically significant trends (p-value < 0.05) were identified in Beattyville's individual dataset when analyzed at a 95% confidence level. However, in Heidelberg's individual dataset, the following statistically significant decreasing trends were identified with the same evaluation criteria: annual average temperature and maximum monthly temperature. In the gages' combined dataset, the same datasets- annual average temperature and maximum monthly temperature- were identified as having statistically significant decreasing trends while total annual precipitation was identified as having a statistically significant increasing trend. Discussion of regional temperature and precipitation trends is discussed in more detail within the literature review below.

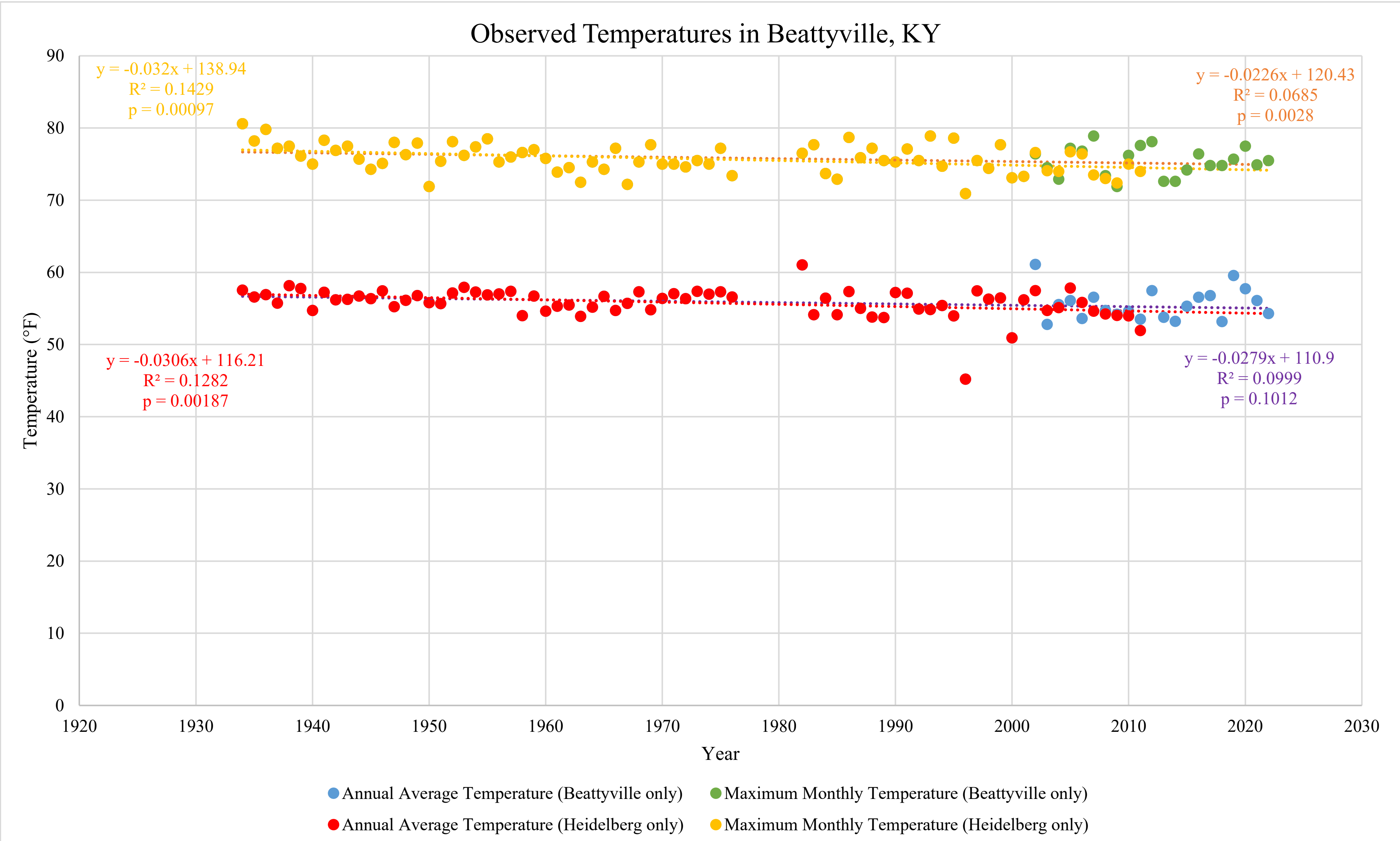


Figure 4. Trends in Annual and Maximum Monthly Temperature in Beattyville

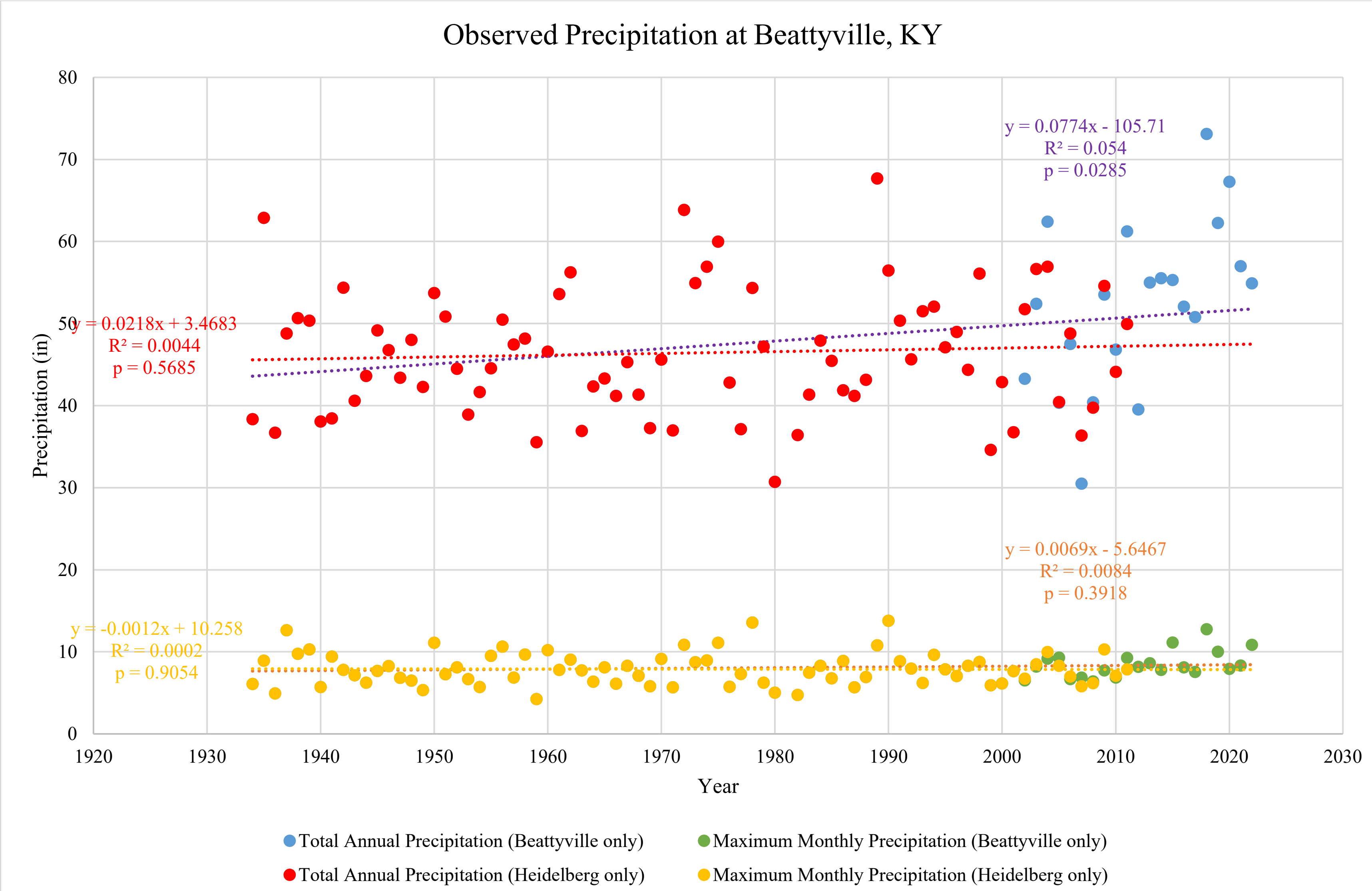


Figure 5. Trends in Annual and Maximum Monthly Precipitation in Beattyville

2 OBSERVED TRENDS IN HYDROMETEOROLOGICAL CONDITIONS

2.1 LITERATURE REVIEW

2.1.1 USACE Civil Works Technical Report Literature Synthesis

A January 2015 report conducted by the USACE Institute of Water Resources summarizes the available peer reviewed literature related to trends in both observed and projected hydrometeorological variables for the Ohio Region (HUC-0205), which includes the Ohio River Valley. The Kentucky River Basin is located in the southeast portion of the region. Figure 6 shows a summary of observed and future hydrometeorological trends and literary consensus from the syntheses. It should be noted that Figure 6 was created in 2015 and does not include any publications since that date. It should also be noted that the hydrometeorological characteristics of the Kentucky River Basin may not necessarily match the trends of the Ohio River Valley region as a whole.

Temperature. The 2015 USACE Literature Synthesis found a general consensus that the region spans a transition zone between a century-long warming trend toward the north and a cooling trend toward the south. However, the extent and seasonality of the warming and cooling zones vary between studies. In most studies, the Kentucky River Basin has less drastic, or sometimes opposite, changes in temperature than the rest of the Ohio Region.

Precipitation. According to the USACE Literature Synthesis: "A mild increasing trend in precipitation in the study region, in terms of both annual totals and occurrence of storm events, has been identified by multiple authors but a clear consensus is lacking. Results show increases in precipitation in some portions of the Ohio Region and show decreases in other portions. Recent reports indicate that rainfall may be concentrated more in larger events now than in the past." In most evaluated studies, the Kentucky River Basin is within areas of little-to-no increase or a decrease in precipitation.

Observed Precipitation

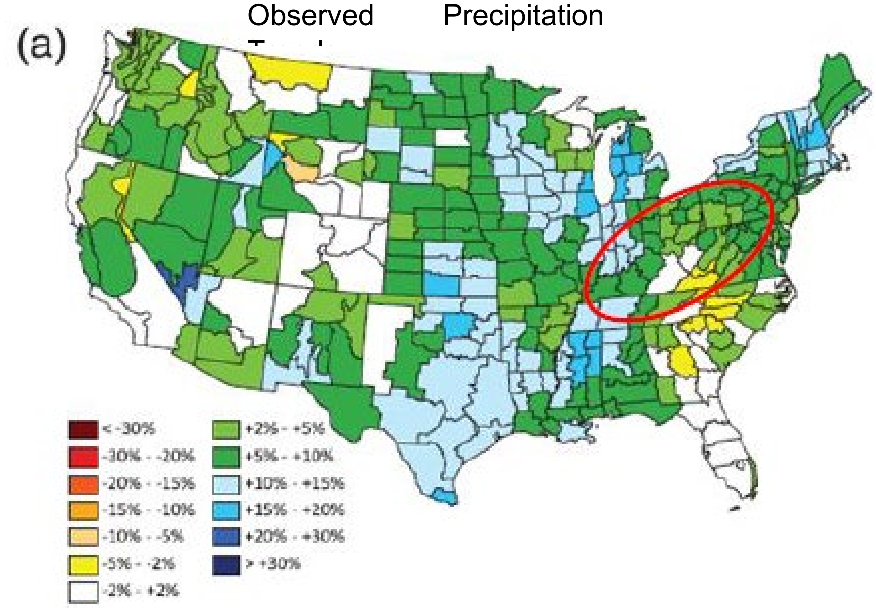


Figure 6 Linear trends in annual precipitation, 1895 - 2009, percent change per century

Hydrology / Streamflow. The 2015 USACE Literature Synthesis found split conclusions about streamflow trends in the Ohio Region; however, more literature supported an upward trend in streamflow.

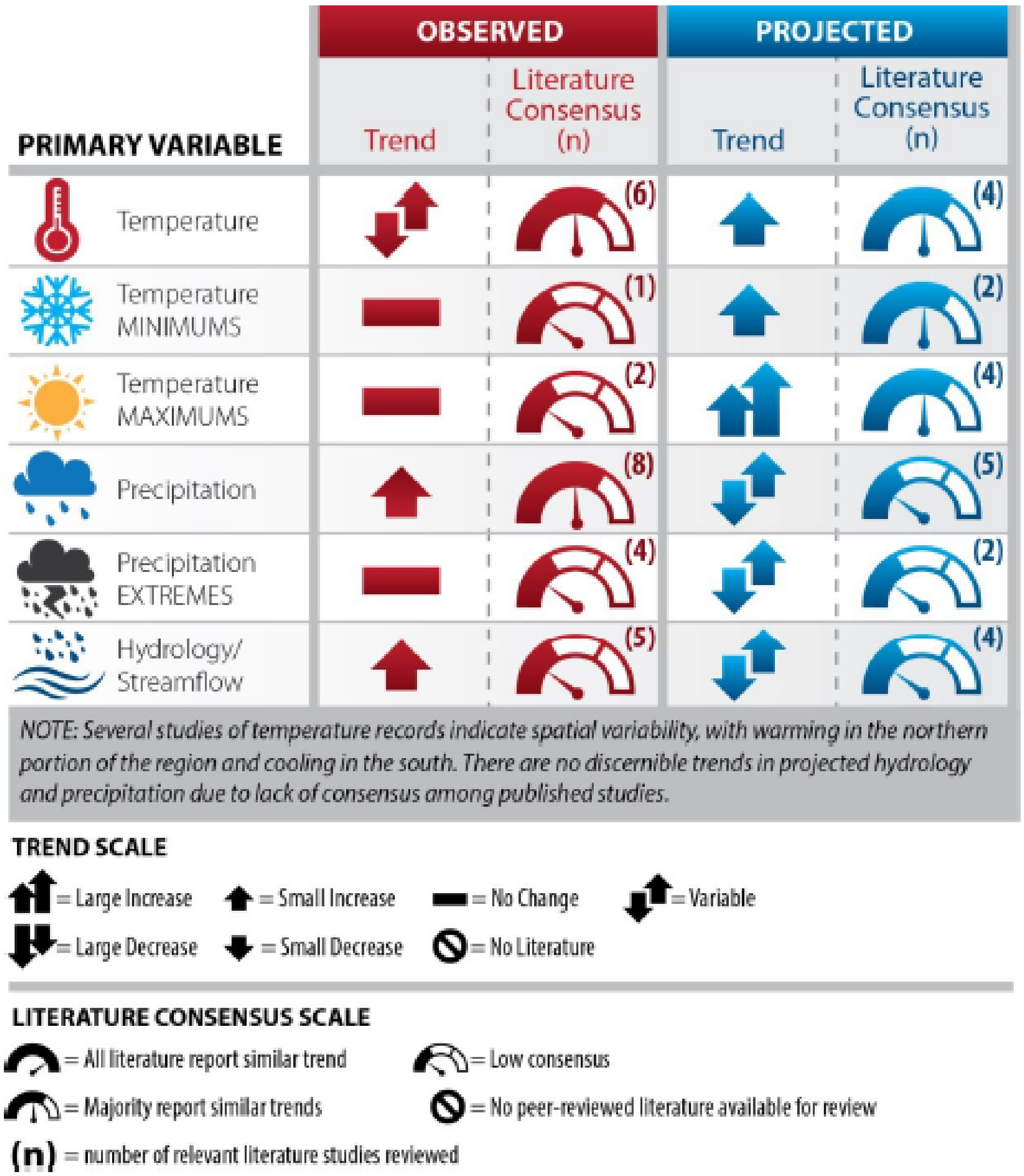


Figure 7 Summary of Findings from 2015 USACE Literature Synthesis, Ohio Region 05

2.1.2 Fifth National Climate Assessment (NCA5)

The NCA5, released in 2023, draws on science described in NCA4 Volume II and focuses on 10 regions and 18 national topics. Particular attention is paid to observed and projected risks, impacts, consideration of risk reduction, and implications under different mitigation pathways. Of specific interest to this qualitative analysis are the chapters regarding changing hydrometeorological trends, water, and the Southeast region, which includes Virginia, Kentucky, Tennessee, Arkansas, Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina, and North Carolina. The Kentucky River Basin is entirely located in the Southeast region. Additionally, the entirety of the area that drains through Beattyville, KY is included in this region.

Temperature. Temperatures in the contiguous United States have risen by 2.5°F since 1970. While average temperatures have increased, warming trends are not consistent across seasons as can be seen in Figure 8. Winter is warming twice as fast as summer in many northern states. In Beattyville, KY winter temperatures have increased between 0°F and 0.5°F while summer temperatures have remained the same of decreased between 0°F and 0.5°F. The approximate study area is circled in the following figures.

While heatwaves are becoming more frequent globally, the number of very hot days (days over 95°F) for the central and eastern United States has decreased. Additionally, cold days has increased by 3 days (days below 32°F) and warm nights (number of nights bellow 70°F) have increased by 7.9 days, as seen in Figure 9.

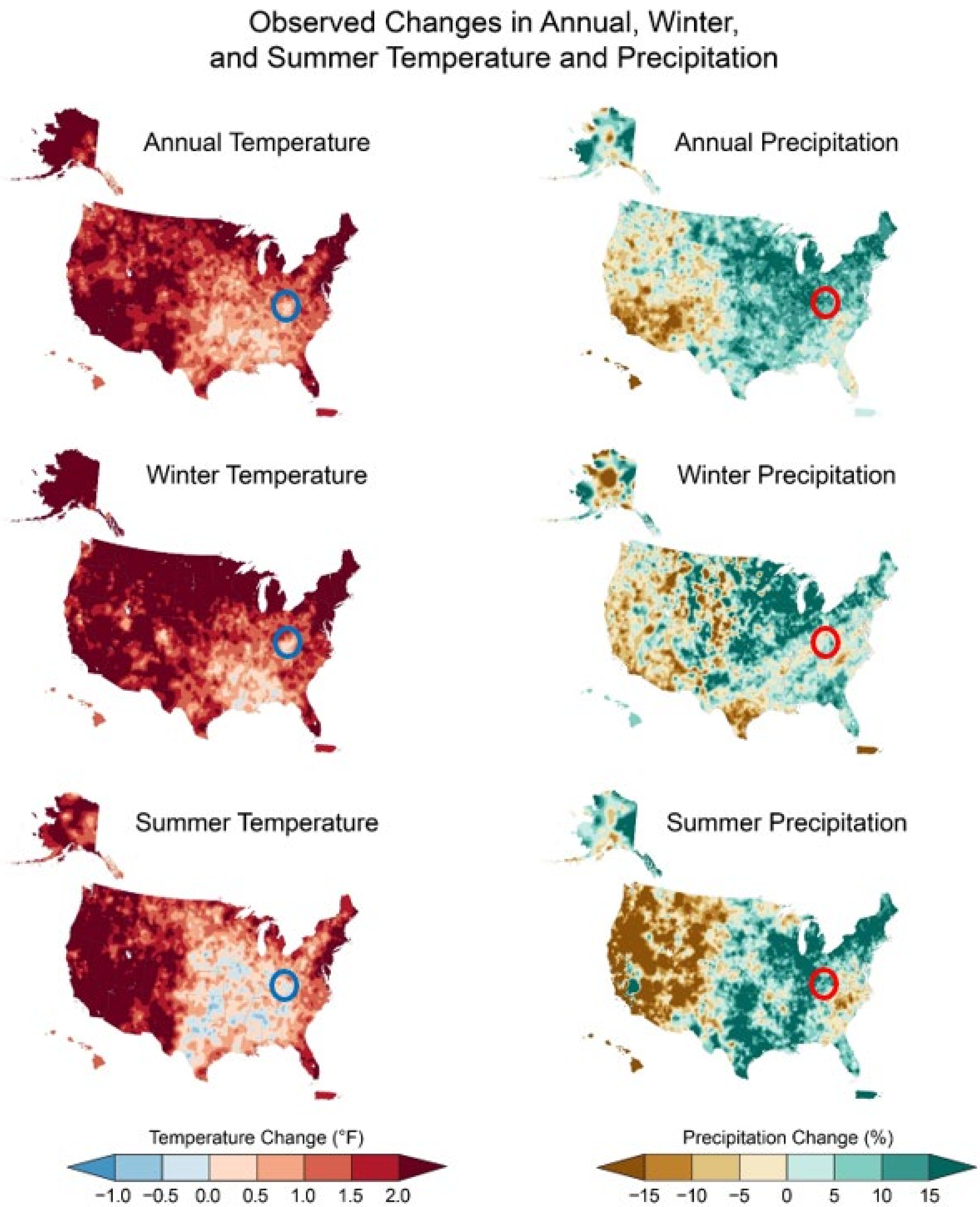


Figure 8. Observed Changes in Annual, Winter, and Summer Temperature and Precipitation

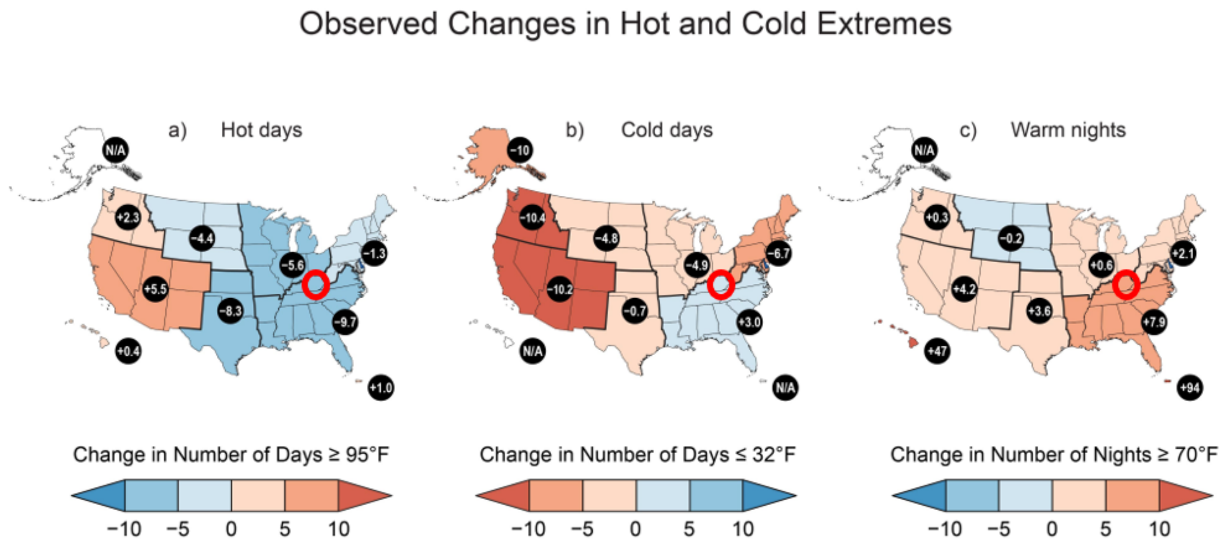


Figure 9. Observed Changes in Hot and Cold Extreme

Precipitation. The average annual precipitation from 2002-2021 is 5-15% higher than the 1901-1960 average for the central and eastern US. The Southeast has experienced more precipitation in the fall and drier conditions in the spring and summer. Figure 8 shows the observed changes in annual precipitation, winter precipitation, and summer precipitation. Beattyville, KY, part of the Southeast region, has experienced a 0-5% increase in precipitation in winter and a 10-15% increase in precipitation in summer.

Since the 1950s an increasing trend in heavy precipitation has been experienced across the US. The increasing trend is a result of more frequent precipitation extremes with smaller changes in the intensity of the extreme precipitation events. Figure 10 displays the percentage change in observed total precipitation on heaviest 1% of days, five-year maximum daily precipitation, and the annual maximum daily precipitation. For all three of the observed changes an increase was found for the Southeast with the total precipitation on heaviest 1% of days having the largest increase of 37%.

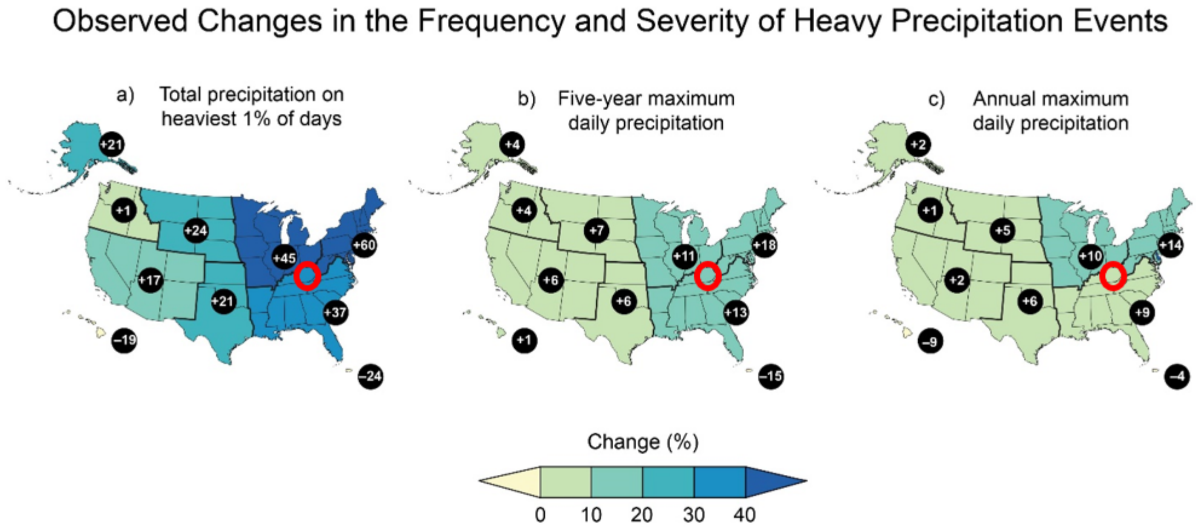


Figure 10. Observed Changes in the Frequency and Severity of Heavy Precipitation Events

2.1.3 National Centers for Environmental Information

The National Centers for Environmental Information (NCEI) produces summaries for individual states. The Kentucky summary, published in 2022, offers a review of observed and future hydrometeorological trends for the state of Kentucky as a whole. The entirety of the Kentucky River Basin lies within the state, but it should be noted that the portion of Kentucky within the Appalachian Mountains- the southeastern half of the Kentucky River Basin- experiences different hydrometeorological effects than the rest of the state.

Temperature. While the United States as a whole has warmed by about 1.5°F since 1900, the summary states: “Temperatures in Kentucky have risen by 0.6°F, less than half of the warming for the contiguous United States, since the beginning of the 20th century, but the warmest consecutive 5-year interval was 2016-2020.” The summary also notes that since 1955, the number of extremely hot days and number of extremely cold events has been below average.

Precipitation. “Total annual precipitation in Kentucky exhibits an overall upward trend and has averaged 7.4 inches above the long-term (1895-2020) average since 2011.” Also, the overall number of extreme precipitation events, while highly variable, has an upward trend.

2.1.4 Appalachian Region Vulnerability Assessments

In December 2015, NatureServe reported the results of vulnerability assessments upon the Appalachian Landscape Conservation Cooperative Region (Sneddon et. al). A portion of the Kentucky River Basin lies in the Appalachian Mountain region, as identified by this report. The report states the following regarding the Appalachian region’s historical hydrometeorological conditions: “The Appalachian LCC region saw temperatures ranging from no change in portions of eastern Kentucky to a 1.5°F increase in the Central Appalachians between 1895 and 2011, and a 71% increase in extreme precipitation in the northeast (defined as the heaviest 1% of all daily events), and 27% increase between 1958 and 2010.”

2.2 NONSTATIONARITY DETECTION

The USACE Time Series Toolbox nonstationary detection tool (TST NSD) was used to assess whether the assumption of stationarity- which is the assumption that the statistical characteristics of a time-series dataset are constant over the period of record- is valid for a given hydrologic time-series dataset. Nonstationarities are detected through the use of 12 different statistical tests which examine how the statistical characteristics of the dataset change with time (Engineering Technical Letter (ETL) 1100-2-3, *Guidance for Detection of Nonstationarities in Annual Maximum Discharges*; *Nonstationarity Detection Tool User Manual*, version 1.2).

The TST NSD Tool was applied to the same stream gage sites listed previously in Table 1, and the same observed period of record was analyzed. A nonstationarity can be considered “strong” when it exhibits consensus among multiple nonstationarity detection methods, robustness in detection of changes in statistical properties, and a relatively large change in the magnitude of a dataset’s statistical properties. Many of the statistical tests used to detect nonstationarities rely on statistical change points. These are points within the time series data where there is a break in the statistical properties of the data such that data before and after the change point cannot be described by the same statistical characteristics. Similar to nonstationarities, change points must exhibit consensus, robustness, and a significant magnitude of change.

Figure 11 displays the nonstationary detection tool output for the complete period of record (minus historic flows with large data gaps) for the Kentucky River at Lock 14 at Heidelberg, KY gage. Note that there are multiple nonstationarities change-point tests triggered in the period of record. Most notably is the strong nonstationarity detected around the end of the 1970s. This strong nonstationartiy can be attributed to a significant decrease in mean annual peak flow as Carr Fork Lake began regulating streamflow upstream of the gage in the 1970s (USGS, 2024). This nonstationarity shows both consensus and robustness as it was detected by multiple statistical tests targeting different statistical properties (mean, variance, and overall distribution) all around the same time. The timing of this strong nonstationarity aligns with the construction and impoundment of Carr Creek Reservoir, whose primary intent is to lower peak flows. Therefore, this nonstationarity can be attributed to the upstream regulation of Carr Creek and Buckhorn Reservoirs.

The hydrologic and hydraulic (H&H) analysis for the Beattyville, KY general investigation developed an unregulated dataset for Kentucky River at Lock 14 at Heidelberg. The unregulated dataset for the gage was analyzed in TST NSD which concluded no nonstationarities were detected, so it is a plausible unregulated dataset for the gage, Kentucky River at Lock 14 at Heidelberg.

Figure 12 displays the nonstationary detection tool results for the gage on the South Fork Kentucky River in Booneville, KY. It was deemed to be “pristine” and largely free of influence from the type of upstream regulation affecting the Kentucky River at Lock 14 at Heidelberg gage. The South Fork gage was expected not to have strong nonstationaries, but multiple tests detected changes in stream flow in the 1980s. The change point detected around 1985 had consensus and change in magnitude of the statistics (mean, variance, and standard deviation) but it lacked the robustness of having multiple tests triggering for the same change in statistic.

Given that the South Fork Kentucky River at Boonville gage was one test short of having a strong nonstationarity, more data were analyzed. First, aerial imagery was analyzed to see if there were any reservoirs, logging efforts, or strip-mining scars that would have caused a nonstationarity;

nothing of significance was noted. Second, active and inactive gages near and on the South Fork were explored. Many of the gages started recording in the 1990's, excluding the 1980's which is the time frame that needed to be analyzed. There was another gage upstream on the South Fork Kentucky River on Goose Creek, a headwater of the South Fork. Goose Creek at Manchester, KY gage had no strong nonstationarities detected because there was no consensus or robustness in the detection (Figure 13).

Since there was no consensus for the nonstationarity after looking at the aerial imagery and other gages, precipitation was analyzed with TST. Multiple sources were analyzed to find precipitation for the South Fork. The earliest precipitation record found for South Fork Kentucky River at Booneville, KY was in 2007, so a similar location with 1980's records was used to analyze the precipitation. Hourly precipitation data was pulled from NOAA for Buckhorn Lake, on the Middle Fork. The dataset was used to calculate the Annual Max 1-Day and Annual Max 3-Day Precipitation. In the NSD Tool, no nonstationaries were detected for the precipitation. Overall, no similarities were found in the nonstationaries of the datasets analyzed for the South Fork Kentucky River at Booneville, KY gage. This indicates that the multiple tests triggered on the South Fork gage were in response to a localized change and likely not part of a larger regional trend.

Both stream gages had negative trends that were not statistically significant (p-value > 0.05). Considering these related lines of evidence, it can be assumed that long-term natural hydrometeorological trends, land use/land cover, and/or dam construction changes are significantly undermining the stationarity of the historically, observed, peak streamflow records on Kentucky River at Lock 14 at Heidelberg, KY and South Fork Kentucky River at Booneville, KY in the Kentucky River Basin.

Note that for all outputs generated from the TST, the following abbreviations apply for the statistical nonstationarity detection tests. CPM indicates a change point method.

Table 2. Nonstationary Detection Test Abbreviations

Method Abbreviations	Statistical Test Name
CVM	Cramer-Von-Mises (CPM)
KS	Kolmogorov-Smirnov (CPM)
LP	LePage (CPM)
END	Energy Divisive Method
LW	Lombard Wilcoxon
PT	Pettitt
MW	Mann-Whitney (CPM)
BAY	Bayesian
LM	Lombard Mood
MD	Mood (CPM)
SLM	Smooth Lombard Wilcoxon
SLW	Smooth Lombard Mood

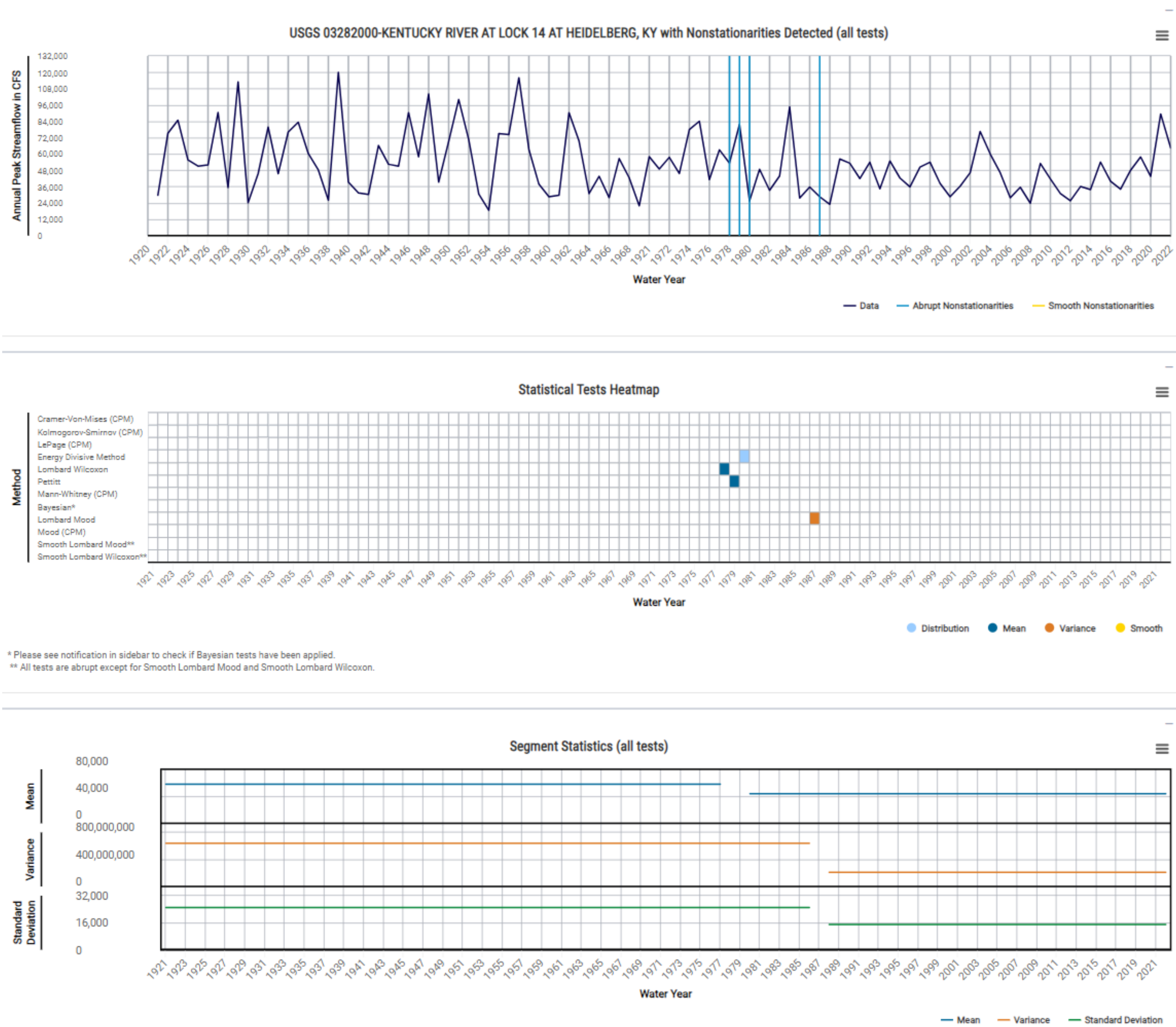


Figure 11. Nonstationarity Detection for Kentucky River at Lock 14 at Heidelberg, KY. Complete Period of Record. 1921-2022.

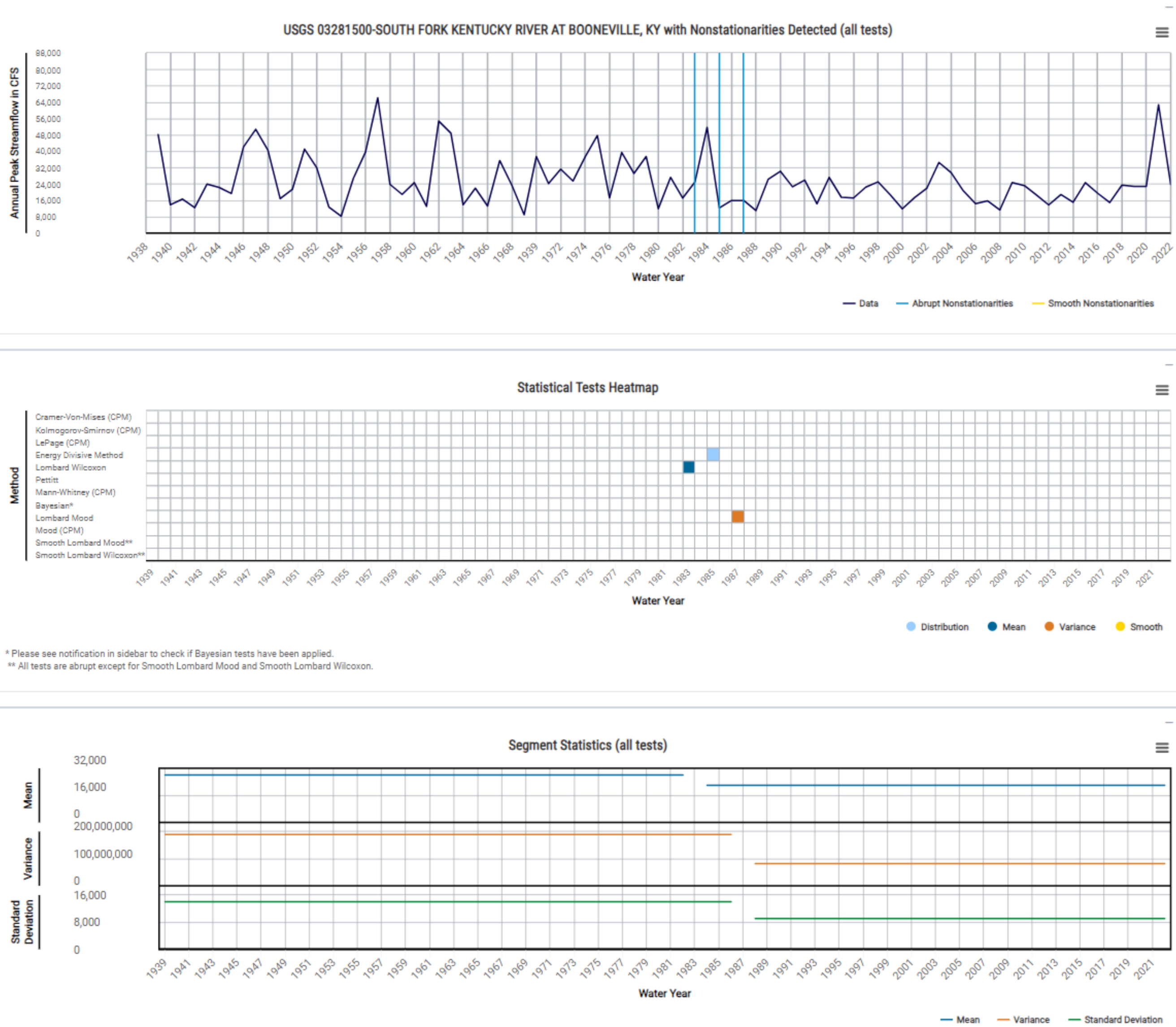


Figure 12. Nonstationarity Detection for South Fork Kentucky River at Booneville, KY. Period of Record. 1926-2012.

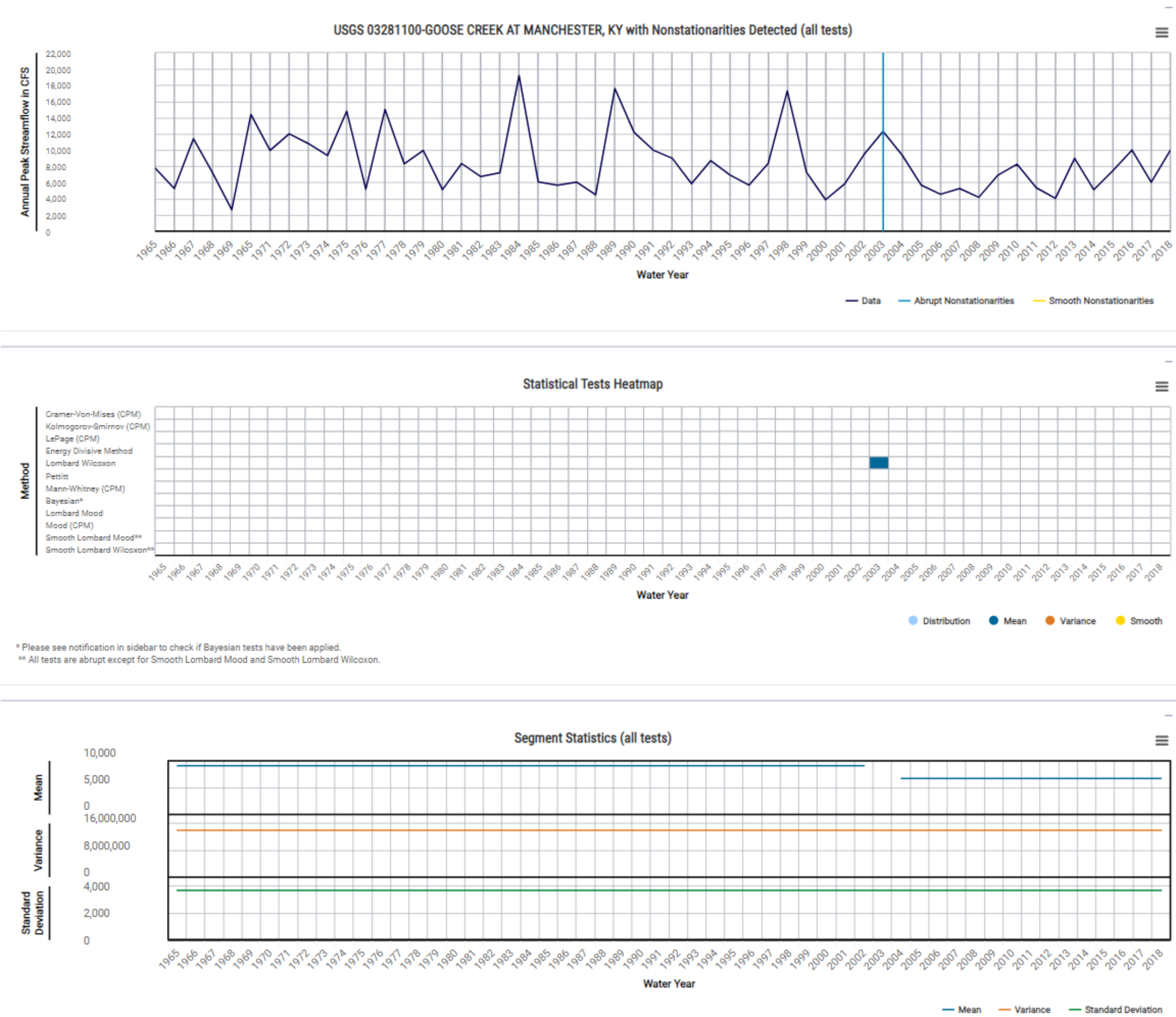


Figure 13. Nonstationarity Detection for Goose Creek at Manchester, KY. Complete Period of Record. 1965-2018.

2.2.1 Time Series Toolbox (TST)

The Time Series Toolbox (TST) developed by USACE was utilized to examine trends in observed annual peak streamflow for the various gage locations shown in Table 1. The TST tool is used to fit a linear regression to the peak streamflow data in addition to providing a p-value indicating the statistical significance of a given trend. Many of the gages selected for TST analysis have been heavily impacted by regulation over different periods of time. For gages where the observed period of record includes the effects of regulation, the annual peak streamflow dataset cannot be considered homogeneous, and it is difficult to draw conclusions based upon the trends identified within these datasets. In addition to assessing the entire period of record at regulated gage sites, subsets of data prior to and after reservoir construction were also analyzed.

The gage on Kentucky River at Lock 14 at Heidelberg, KY can be used to illustrate how periods of reservoir regulation influence trends in streamflow. Peak annual flow for this gage is available on a continuous basis from 1921 until 2022 in the TST. The annual peak data from 1921-1978 represents a pre-regulation dataset. Buckhorn reservoir began impounding water upstream in 1960, however, as shown through the data, the impoundment did not have a large impact on the annual peak data. Carr Creek began impounding water in 1975, and coincidingly, there was a noticeable change in the annual peak data. The time period of 1978–1980 represents an era of dam building and reservoir filling upstream of Heidelberg, KY; this period disrupts the homogeneity and homoscedasticity of the streamflow dataset. After 1980, reservoir operations became established, and once again the period of record can roughly be considered homogeneous in terms of reservoir operation. For these reasons, the period of record for the Kentucky River at Lock 14 at Heidelberg, KY was analyzed over 3 time periods: (1) complete heterogeneous period of record, (2) pre-regulation period, and (3) post-regulation period. The complete heterogeneous period of record has a negative trend that is statistically significant, see Figure 14. When the data was divided into pre-regulation and post-regulation periods the trends were negative with no statistical significance (p-value > 0.05).

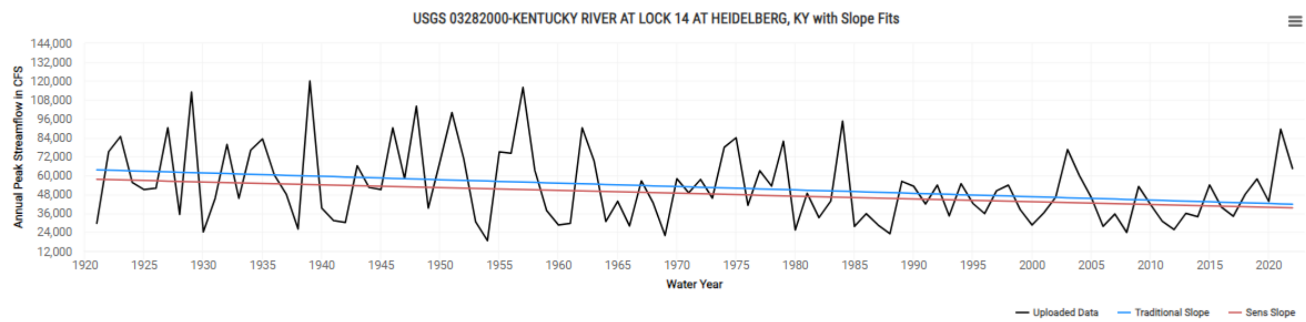
When dividing the Kentucky River at Lock 14 at Heidelberg's period of record into different intervals of regulation for each gage, consideration was given to ensure that the shortened record length remained adequate for trend analysis. Of the gage whose record was divided based on regulation, the shortest record length was the post-regulation record length of 40 years. This shortened length may impact the linear regression analysis and the statistical significance of the data analyzed. Additionally, there is uncertainty regarding whether the post-regulation period of record reflects homogenous reservoir operation since reservoir regulation is not always consistent and operational deviations are common. However, for the purposes of this analysis, reservoir operations were assumed to be consistent, and the impacts of changes in regulation and deviations from typical operation were considered to be minor. Nonstationarity detection results offer further insight into the homogeneity of the peak streamflow dataset and are discussed below.

Unregulated dataset for Kentucky River at Lock 14 at Heidelberg developed by the H&H analysis for the Beattyville, KY general investigation was analyzed in the TST. The TST concluded the unregulated data has no specific trend, the traditional slope calculated a positive trend and Sen's slope calculated a negative trend, with no statistical significance (p-value > 0.05). The South Fork Kentucky River Booneville, KY gage (USGS 03281500), with a period of record from 1926-2022, was also analyzed in the TST to represent unregulated conditions within the Kentucky River Basin. Although considered pristine the gage did trigger several nonstationarity tests around 1985 but not enough to be considered a strong nonstationarity in Section 2.2. The stream gage was analyzed over 3 time periods: (1) complete heterogeneous period of record, (2) pre-detection period, and (3) post-detection period. No statistical significance (p-value > 0.05) was detected over the 3 separate time periods in the streamflow data. The model analysis calculated three different trends over the analyzed time periods: (1) negative, (2) positive, and (3) positive.

Precipitation was also analyzed for trends in this basin due to the South Fork gage having several tests triggered around 1985. The earliest precipitation record found for South Fork Kentucky River Booneville, KY was 2007. Given the short period of data, it wasn't used to analyze nonstationary of the precipitation in Booneville. A close area with a greater range of data, Buckhorn Lake on the Middle Fork, was used. The hourly precipitation dataset was compiled and analyzed from NOAA for Buckhorn Lake. The dataset was used to calculate the Annual Max 1-Day and Annual Max 3-Day precipitation. No statistical significance (p-value > 0.05) was detected in the precipitation data, but the analysis showed a negative trend.

Individual graphical output for each gage and period of record were analyzed. Note that only the complete period of record for streamflow at Beattyville, KY had a strong statistically significant trend (p-value << 0.05) detected. This trend was in the negative direction and was found when looking at the entire period of recorded flows at sites impacted by regulation. This is to be expected because the primary function of flood risk management regulation is to reduce peak flows. Thus, relative to the pre-regulation period, the post-regulation period consists of lower flood peaks resulting in the observed downward trend. When these same gages were examined either by limiting the period of record to pre-regulation or post-regulation, the trends were not statistically significant.

The agreement across the watershed and through various time periods indicates that the only statistically significant trend is likely due to the influence of upstream regulation and likely not due to climatic shifts driving changes in hydrology. There were no statistically significant trends detected in any homogeneous period of record that would indicate changes in streamflow due to sources other than regulation.



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-216	478541
Sen's Slope	Negative	-179	402309

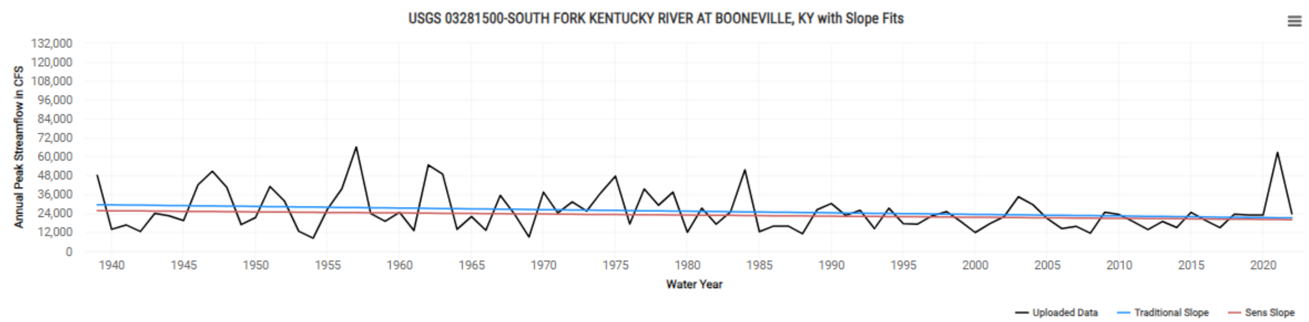
Trend Hypothesis Test

Test	P-Value
t-Test	0.0045094
Mann-Kendall	0.017601
Spearman Rank-Orde	0.016422

Test	P-value
t-Test	0.004509
Kann-Kenn	0.017601
Spearman Rank-Order	0.016422

- A statistically significant trend (at the alpha = .05 level) was detected by the t-Test.
- 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 14. Kentucky River at Lock 14 at Heidelberg, KY. Complete POR 1921 – 2022. Regulated.



Trend Line Coefficients

Method	Directionality	Slope	Intercept
Traditional Slope	Negative	-101	225233
Sen's Slope	Negative	-69	158514

Trend Hypothesis Test

Test	P-Value
t-Test	0.070909
Mann-Kendall	0.12797
Spearman Rank-Order	0.15316

Test	P-value
t-Test	0.070909
Kann-Kenn	0.12797
Spearman Rank-Order	0.15316

- A statistically significant trend (at the alpha = .05 level) was NOT detected by the t-Test.
- 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 15. South Fork Kentucky River at Booneville, KY. Complete POR 1926-2022. Pristine.

2.2.2 Comprehensive Hydrology Assessment Tool (CHAT): Historical Trends

The USACE Comprehensive Hydrology Assessment Tool (CHAT) was used to assess hindsight projected trends within the Upper Kentucky River Basin, HUC-05100204 stream segment ID 05000135. Since the focus of this tool is on the predicted trends, the figures of the results will be presented in the Projected Trends section. The tool displays the range of projected streamflow, precipitation, and temperature variables from 1951-2099, with the projections from 1951-2005 representing hindcast projections and 2006-2099 representing forecasted projections. The annual maximum of mean monthly streamflow and annual maximum 1-day precipitation were considered in this review. The 2006-2099 forecasted streamflow and precipitation is discussed in a later section.

Figure 21 through Figure 24 show the range in simulated results from the 32 combinations of CMIP5 general circulation models (GCMs) with representative concentration pathway (RCPs) 4.5 and 8.5 scenarios for streamflow and precipitation variables produced using Localized Constructed Analogs (LOCA) statistical downscaling. RCP 4.5 and 8.5 represent different emissions scenarios and are used for the simulated future projections discussed later.

The streamflows are simulated using an unregulated Variable Infiltration Capacity (VIC) hydrologic model for the stream segment (ID: 05000135) of the Upper Kentucky River (HUC 05100204) where the South Fork of the Kentucky River meets the North Fork of the Kentucky River directly downstream of Beattyville, Kentucky. It should be noted that the hindcast projections do not replicate historically observed precipitation or streamflow and should therefore not be compared directly with historical observations. This is in part because observed streamflows are impacted by regulation, while the VIC model used to produce the results displayed in Figure 21 through Figure 24 are representative of the unregulated condition.

Upon examination of Figure 21 through Figure 24, the historic simulated range in projections lower range of results are steady while the higher projections show more variability. A wide range of results are produced from the 32 combinations of CMIP5 GCM due to the sources of variation and the significant uncertainty associated with these models including the boundary conditions applied to the GCMs, as well as variation between GCMs and selection of RCPs applied. Each GCM and RCP independently incorporate significant assumptions regarding future conditions, thus introducing more uncertainty into the future hydrologic conditions. Model downscaling and a limited temporal resolution further contribute to the uncertainty associated with CHAT results. There is also uncertainty associated with the hydrologic models. The large spread of results shown in Figure 21 through Figure 24 highlights current climatic and hydrologic modeling limitations and associated uncertainty.

Figure 25 through Figure 28 show the mean of the range of model results. A linear regression was fitted to the mean of the results of the 32 GCM historical simulated projects for the annual maximum of mean monthly streamflow. The slope was found to be 5.3252 cfs/yr. While the slope suggests an increasing streamflow, the statistical test performed by CHAT shows the trend to not be statistically significant. The three statistically significant test performed by the CHAT resulted in a p-value greater than 0.05. A p-value less than 0.05 would indicate a statistically significate trend. The results of statistics test can be seen in Table 3.

The slope of the mean historical simulated projections for the annual maximum 1-day precipitation scenario was found to be 7e-04 in/yr. In addition to the insignificant increasing slope, the statistics test shows the trend to be statistically insignificant as can be seen in Table 3. The models show no historic simulated increase in precipitation.

Table 3. P-values for GCM historic simulated projections for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204.

Test	P-value	
	Streamflow	Precipitation
t-Test	0.343	0.24
Mann-Kendall	0.309	0.211
Spearman Rank-Order	0.285	0.192

The outputs of the simulated historic projections quantitatively suggest no increase in the annual maximum of mean monthly streamflow and the annual maximum 1-day precipitation from 1951 - 2005. The results from CHAT are simulated and do not measure historic streamflow or precipitation. Streamflow results cannot be compared to historic measurements as the CHAT results are unregulated. The results show no increases in flow or precipitation as compared to the simulated future projects discussed latter.

2.2.3 Summary of Observed Trends in Hydrometeorological Conditions

Based on the literature review and the first order statistical analysis carried out in support of the study, there is little evidence or consensus regarding significant temperature or precipitation changes in the Kentucky River Basin Region. This is likely due to the region being a "transition zone" within the Appalachian Mountain region, where the northern and southern Appalachian regions are being impacted by hydrometeorological factors in different, almost opposite, ways. Additionally, no statistically significant trends were observed in precipitation or temperature in the historic record.

Based on the results of the linear regression analysis performed with the TST and the nonstationarity analysis, there is little observed evidence of statistically significant increasing or decreasing trends or nonstationarities within the basin that can be attributed to hydrometeorological change. There are statistically significant decreasing trends and nonstationarities in observed, peak streamflow that can be directly attributed to the construction of flood risk management project.

The literature review and first order statistical analyses' results are compiled in the table below:

Table 4. Summary of Observed Hydrometeorological Trends in Beattyville, KY with Used Methods/Tools

Analysis Method/Tool	Significant Temperature Changes	Significant Precipitation Changes	Significant Streamflow Changes
Literature Review	Inconclusive Trend	Slightly increasing trend in volume/frequency	Increasing Trend
Time Series Toolbox Nonstationary Detection tool (TST NSD)	Not Analyzed	Slightly increasing trend but **not** statistically significant[1]	Decreasing Trend but **not** statistically significant
Comprehensive Hydrology Assessment Tool (CHAT)	Not Analyzed	Increasing trend but **not** statistically significant	Increasing trend but **not** statistically significant

3 PROJECTED TRENDS IN HYDROMETEOROLOGICAL CONDITIONS

3.1 LITERATURE REVIEW

3.1.1 USACE Civil Works Technical Report Literature Synthesis

In addition to the observed trends discussed previously, the 2015 USACE Literature Synthesis for the Ohio Region 5 also summarizes available literature for projected future trends in various

[1] Excel analysis was performed in place of the TST NSD (Figure 11)

hydrometeorological variables. These variables are projected using a variety of statistical methods in conjunction with global circulation models (GCMs). Figure 16 summarizes the findings of the literature synthesis regarding projected climatic trends. Additional discussion is provided in the following paragraphs.

Temperature. The 2015 USACE Literature Synthesis found strong consensus in the literature that average and extreme temperatures in the Ohio Region show an increasing trend over the next century. Temperatures are projected to change across all months, however there is no consensus on the predicted amount of change. The intensity, duration, and frequency of extreme heat waves are projected to increase in the vicinity of the Kentucky River Basin.

Precipitation. The USACE Literature Synthesis states: “Although precipitation is projected to increase in most studies surveyed, there are no clear trends in the literature indicating the magnitude or geographic distribution of future changes to average or extreme precipitation.” Compared to the rest of the Ohio Region, the Kentucky River Basin is projected to have lower increases in precipitation.

Hydrology / Streamflow. Low consensus exists amongst the literature with regards to projected changes in hydrology for the region. Large variability in the projected hydrologic parameters (e.g., runoff, streamflow, SWE) exist across the literature and varied with location, hydrologic modeling approach, GCM used, and adopted emission scenario.

3.1.2 Fifth National Climate Assessment (NCA5)

In addition to the observed trends discussed previously, the NCA5 offers some insight into future climatic projections, as well as the implications of these projections on risk, infrastructure, engineering, and human health.

Temperature. The NCA5 reported on temperature trends based on warming levels (GWL). GWL is the global average temperature change in degrees Celsius relative to preindustrial temperatures. Figure 16 shows the expected temperature changes for the US for GWL of 1.5°C, 2°C, 3°C, and 4°C. Expected increases in temperatures are not uniform across the globe. Most of the US is expected to have larger increases in temperature with respect to the global average with the northern and western portions of the country experiencing largest levels of warming. At a GWL of 2°C (3.6 °F) the US experiences an average increase between 4.4°F to 5.6°F degrees of warming. At a GWL of 2°C (3.6 °F) Beattyville, KY experiences 4°F to 5°F of warming. As can be seen in Figure 16, Beattyville, KY experiences middle levels of warming for each of the GWL.

Note that in general, increases in projected temperature are greater in higher latitudes and lessen farther south in the country. Coastal states are largely projected to experience less warming than interior regions. The Kentucky River Basin, circled in the figures below, is in a transition zone between the coastal and interior regions. Regardless of spatial variation, temperature increases are projected for the entire country under all GWLs.

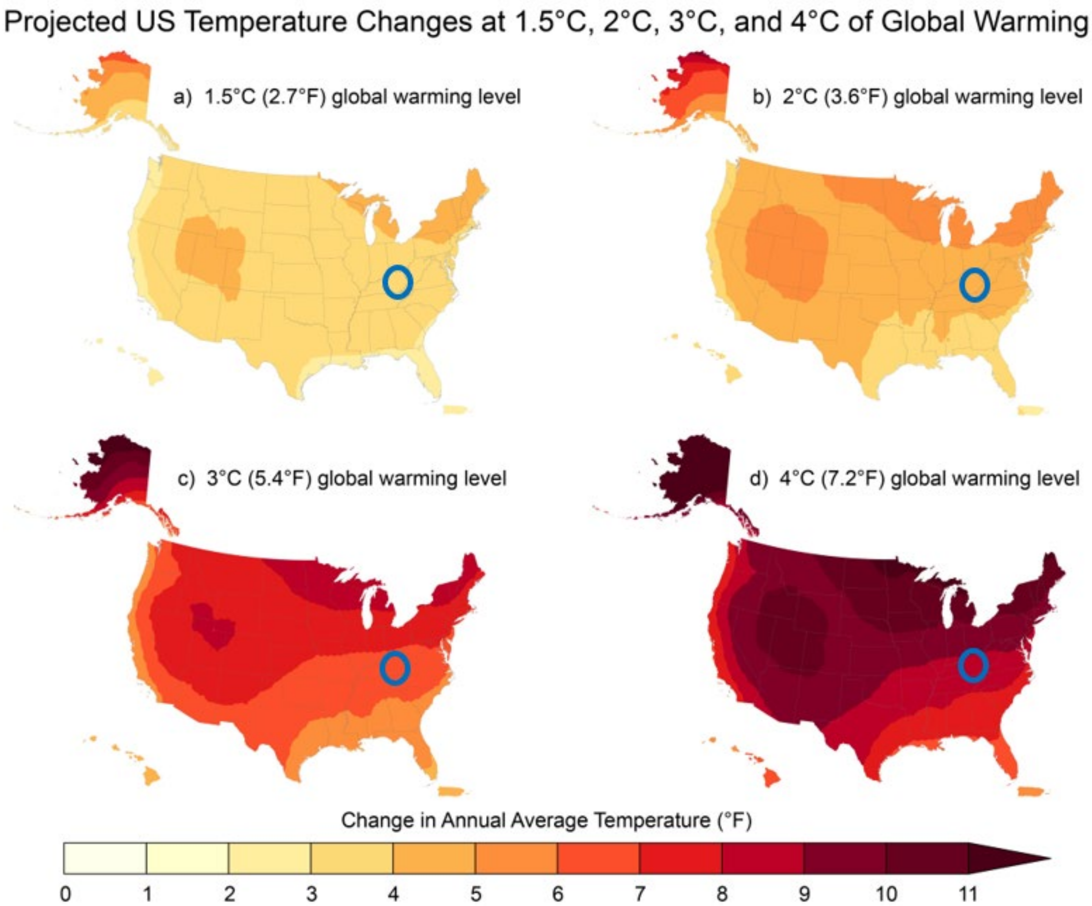


Figure 16. Projected US Temperature Changes at 1.5°C, 2°C, 3°C, and 4°C of Warming

As average temperatures increase the risk of extreme temperatures increase. Figure 17 shows the projected changes to hot and cold extremes for three metrics at 2°C of warming relative to the period 1991-2020: number of days ≥ 95°F (hot days), days ≤ 32°F (cold days), and day ≥ 70°F (warm nights). As shown in Figure 17, Beattyville, KY is expected to see in increase in around 10 to 15 hot days, a decrease of about 15 to 20 cold days, and increase in around 15 to 20 warm nights.

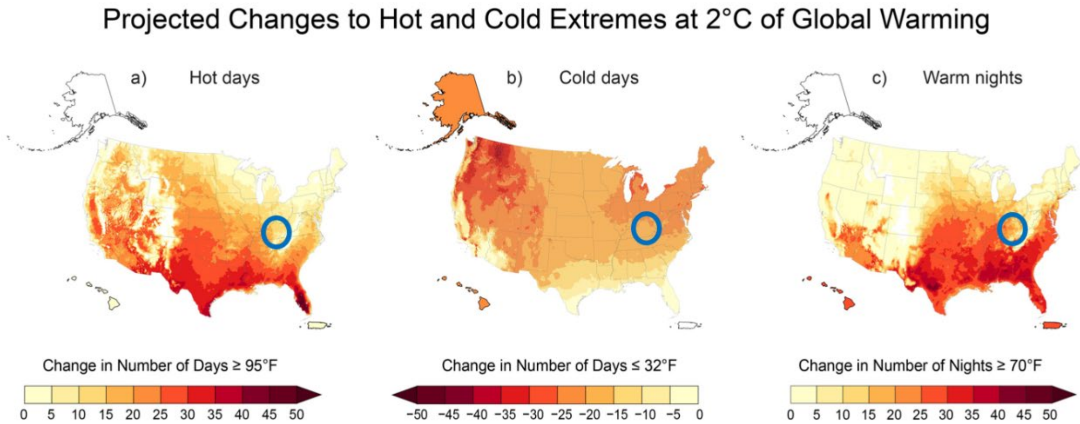


Figure 17. Projected Changes to Hot and Cold Extremes at 2°C of Warming

Precipitation. The NCA5 noted precipitation changes are less certain than temperature changes. For the eastern US annual average precipitation is very likely to increase as global temperatures increase. Figure 18 shows the projected changes in average annual precipitation for different GWL. Areas with hatching indicate where 80% or more of models agree on the sign of the change. As temperatures increase average annual precipitation increases for Beattyville, KY in all of the global warm levels. For the three higher GWL, Beattyville's average annual precipitation are located in areas with hatching. The precipitation for the 2°C (3.6°F) GWL in the Kentucky River Basin is projected to increase by 0-10%.

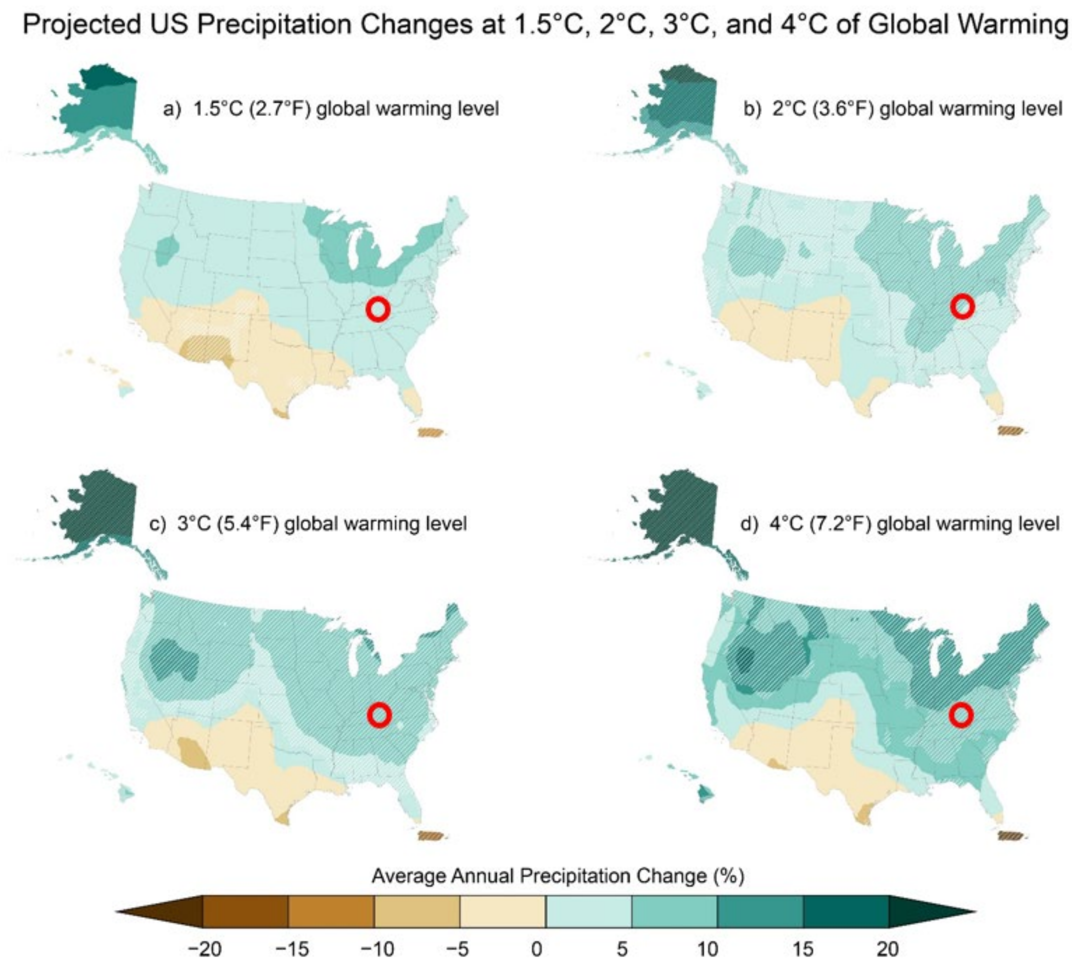


Figure 18. Projected US Precipitation Changes at 1.5°C, 2°C, 3°C, and 4°C of Warming

Recent trends in the frequency, severity, and amount of extreme precipitation are expected to continue across the US. Figure 18 displays projected changes in extreme precipitation for GWL of 2°C to the period 1991-2020. Figure 19 includes three metrics to portray projected percentage change in extreme precipitation: total precipitation on heaviest 1% of days, five-year maximum daily precipitation, and annual maximum daily precipitation. Additionally, the NCA5 noted changes in extreme precipitation events differ seasonally. Projected increases in extreme precipitation are larger for spring and winter months which are the typical flood season. Extreme precipitation is likely to increase by 20% to 40% for the Total precipitation on heaviest 1% of days in the Kentucky River Basin. Projected changes for the summer season are more uncertain.

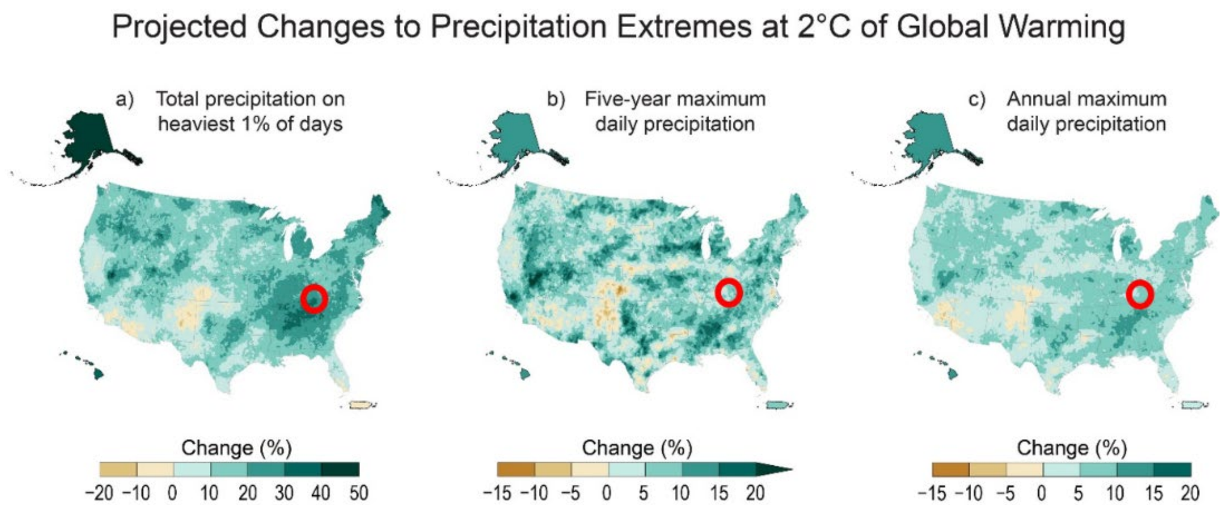


Figure 19. Projected Changes to Precipitation Extremes at 2°C of Warming

There is potential for changes in hydrometeorological conditions to increase stress on infrastructure and water supply within the Kentucky River Basin. More frequent and intense extreme weather and hydrometeorological-related events are expected to damage infrastructure, ecosystems, and social systems. Increasing temperatures and changes in precipitation are intensifying droughts, which can impact water supply. Heavy precipitation events are also expected to occur more frequently, making current infrastructure that is designed for historical hydrometeorological conditions more vulnerable for future events.

The NCA5 goes on to qualitatively discuss some of the risks associated with projected, future hydrometeorological conditions. The NCA5 report emphasizes that the likelihood of hydrometeorological phenomena like droughts, extreme storms and flood events may be misrepresented when defined using historic records that are limited in length (approximately 10-100 years). Selected points from this discussion relevant to the Kentucky River Basin include:

- Extreme precipitation events are projected to increase as temperatures increase and may lead to more severe rainfall-driven floods and a greater risk of infrastructure failure.
- Long-lasting droughts and warm spells can compromise earthen dams and levees as a result of soil cracking due to drying, resulting in a reduction of soil strength, erosion, and land subsidence.
- The procedures used to design water resources infrastructure, estimations of probability of failure, and risk assessments for infrastructure typically rely on 10-100 years of observed data to define flood and rainfall intensity, frequency, and duration. This approach assumes that frequency and severity of extremes do not change significantly with time. However, numerous studies suggest that the severity and frequency of climatic extremes, such as precipitation and heat waves, have in fact been changing due to human-driven hydrometeorological changes. These changes represent a regionally variable risk of increased frequency and severity of floods and drought. Additionally, tree ring-based reconstructions of hydrometeorological conditions over the past 500 years for the U.S. illustrates a much wider range of hydrometeorological variability than does the instrumental record (beginning around 1900). This historic variability includes wet and dry periods with statistics very different from

those of the 20th century. Infrastructure design that uses recent historic data may underrepresent the risk seen from the paleo record, even without considering future hydrometeorological conditions.

- Statistical methods have been developed for defining future hydrometeorological risk and frequency analysis that incorporate observed and/or projected changes in extremes. However, these methods have not yet been widely incorporated into infrastructure design codes, risk assessments, or operational guidelines.
- Future hydrometeorological conditions are expected to increase the frequency and/or intensity of many extreme events that affect infrastructure. Available vulnerability assessments for infrastructure show the prominent role that future extremes play. Since much of the existing infrastructure was designed and is managed for an unchanging hydrometeorological condition, changes in the frequency and intensity of flooding, drought, wildfire, and heat waves affect the reliability of water, transportation, and energy services.

Streamflow. Extreme flood events and runoff (surface water flow) are difficult to predict due to complex interactions of precipitation amount and timing, soil moisture, snowpack, and land cover. Increases in precipitation do not always translate directly into increases in runoff or river flooding due in part to the many processes at the land surface. Figure 20 shows projected changes in annual runoff by midcentury for 2036 – 2065 relative to 1992-2020. The average of all available projections found an increase of 0.1-inch to 0.5-inch in the Kentucky River Basin. Additionally, Figure 20 displays the average of wettest 20% and average of driest 20% of projections which displays an increase of 0.1-inch to 1-inch difference and a decrease of 0-inch to 0.1-inch difference, respectively.

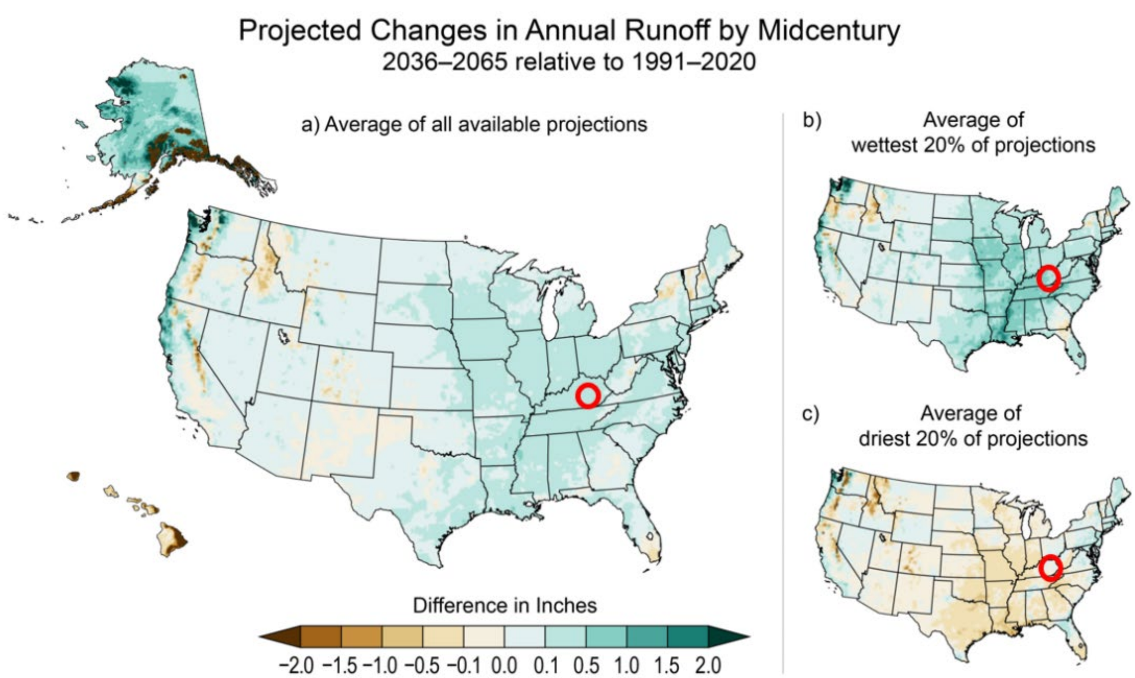


Figure 20. Projected Changes in Annual Runoff by Midcentury

3.1.3 National Centers for Environmental Information

In addition to the observed trends previously discussed, the NCEI Kentucky summary also analyzed future hydrometeorological conditions. Trends were extrapolated under both higher and lower RCPs.

Temperature. Temperatures in Kentucky are projected to exceed historical levels by the mid-21st century under both the higher and lower emissions pathways. Heat waves are projected to be more intense while cold waves are projects to be less intense.

Precipitation. Precipitation in Kentucky is projected to increase in the winter and spring under the higher emissions pathway. Changes in fall and summer precipitation are uncertain. The number and intensity of extreme precipitation events are also expected to increase in the future, following the recent observed trends.

The NCEI summary also projects that future droughts and floods may be more intense in the region due to temperature-caused increases in evaporation and increased extreme precipitation events.

3.2 Comprehensive Hydrology Assessment Tool (CHAT): Projected Trends

The USACE CHAT was used to assess projected future trends within the Upper Kentucky River Basin, HUC-05100204 stream segment ID 05000135. Forecasted annual maximum of mean monthly streamflows and the annual maximum 1-day precipitation projections from 2006-2099 are analyzed in this review. The 1951-2005 hindsight projections were previously discussed.

Figure 21 through Figure 24 displays the range of forecasted projections for 32 combinations of CMIP5 GCMs with RCPs 4.5 and 8.5 scenarios for streamflow and precipitation variables produced using LOCA statistical downscaling. Upon examination of the range of model results, there is no clear increasing trend in the higher projections for the RCP 4.5 scenario for the annual maximum of mean monthly streamflow variable. There is an increase trend for the RCP 4.5 annual maximum 1-day precipitation scenario and both the RCP 8.5 scenario variables. The lower projections appear to be relatively stable and unchanging through time for all scenarios and variables. The spread of the model results for the RCP 4.5 precipitation scenario and both RCP 8.5 scenario variables also increases with time which is expected as uncertainty in future projections increase as time moves away from the model initiation point.

Figure 25 through Figure 28 display only the mean result of the range of the 32 projections of future, hydrometeorological conditions. The full range of outputs are shown in Figure 21 through Figure 24. A linear regression line was fit to this mean and displayed an increasing trend. The CHAT tool uses three statistical significances test: the Student t-test, Mann-Kendall, and Spearman Rank Order. The results of the statistic test for all RCP scenarios and variables are shown in Table 5. A p-value of less than 0.05 indicates that the trend should be considered as statistically significant. The RCP 4.5 scenario has no significant p-values. As such, the linear regression trend for the RCP 4.5 scenario is not considered statistically significant. The RCP 8.5 scenario has a p-value less than 0.05 for both the Mann-Kendall and Spearman Rank Order while the student t-test was slightly larger than 0.05, making it statistically significant. The majority suggests there is a statistically significant increasing trend for the RCP 8.5 scenario.

The linear regression line fit to the mean of the annual maximum 1-day precipitation for the modeled RCP 4.5 and RCP 8.5 scenarios were found to have an increasing slope. The statistical significance tests for both the precipitation RCP 4.5 and RCP 8.5 scenarios were found to be less than 0.05. This indicates a statistically significant increasing trend for both emission scenarios.

Table 5. P-values for GCM projections for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204.

Test	P-value			
	Annual-Maximum of Mean Monthly Streamflow		1-Day Precipitation	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
t-Test	0.825	0.0538	6.3e-10	2.07e-12
Mann-Kendall	0.774	0.0154	< 2.2e-16	< 2.2e-16
Spearman Rank-Order	0.735	0.0364	6.26e-10	4.14e-12

These outputs from the CHAT qualitatively suggest that the annual maximum of the mean monthly flows for the RCP 4.5 scenario are not expected to increase in the future. The CHAT outputs suggest that the annual maximum of the mean monthly flows for the RCP 8.5 scenario, the annual maximum 1-day precipitation for the RCP 4.5, and the annual maximum 1-day precipitation for the RCP 8.5 are expected to increase in the future relative to the current time. The CHAT indicates a slight increase in the RCP 8.5 scenario streamflow while the tool shows a larger increase for both precipitation scenarios. An important caveat is that the CHAT tool is simulating an unregulated watershed. Reservoir operations can be expected to decrease the variance of flows shown in the CHAT, as well as decrease the magnitude of their peaks. It is important to consider that the CHAT results do not assess peak stream flow which is more significant to flood infrastructure in the region. While the results indicated by the CHAT suggest an increase in streamflow for the RCP 8.5 scenario, there was no consensus in the literature review pertaining to the projected future streamflow. While the literature does not find consensus in magnitude and location of precipitation changes, the CHAT does reflect the trend of increasing precipitation found in the literature.

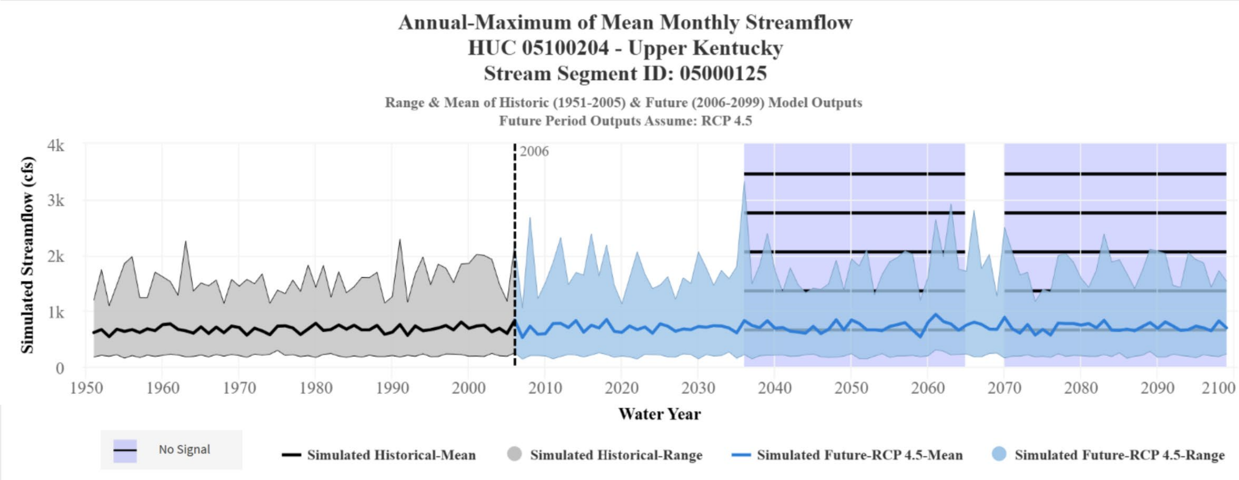


Figure 21. Range of GCM projections for an RCP 4.5 scenario for the Annual Maximum of Mean Monthly Streamflow for Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

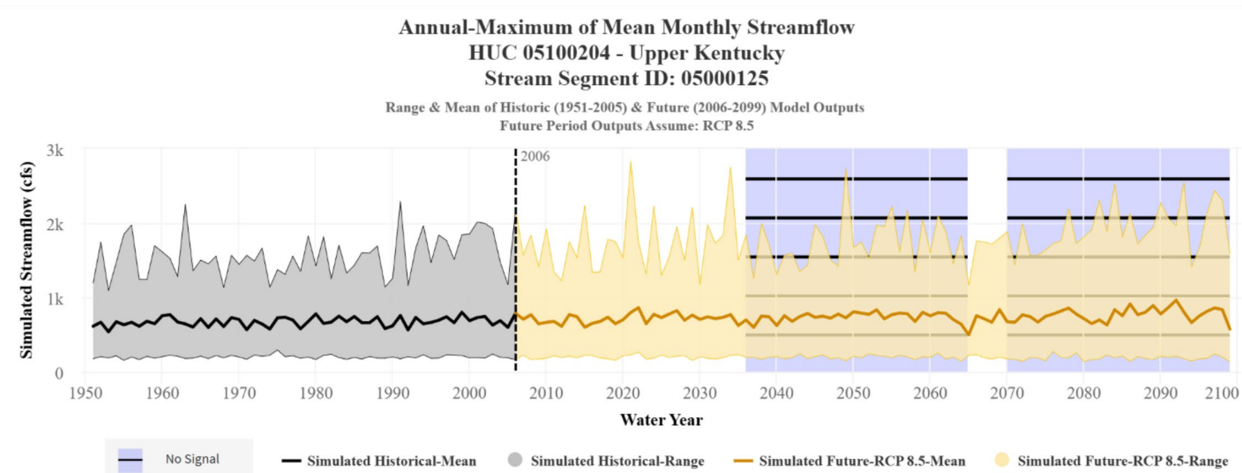


Figure 22. Range of GCM projections for an RCP 8.5 scenario for the Annual Maximum of Mean Monthly Streamflow for Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

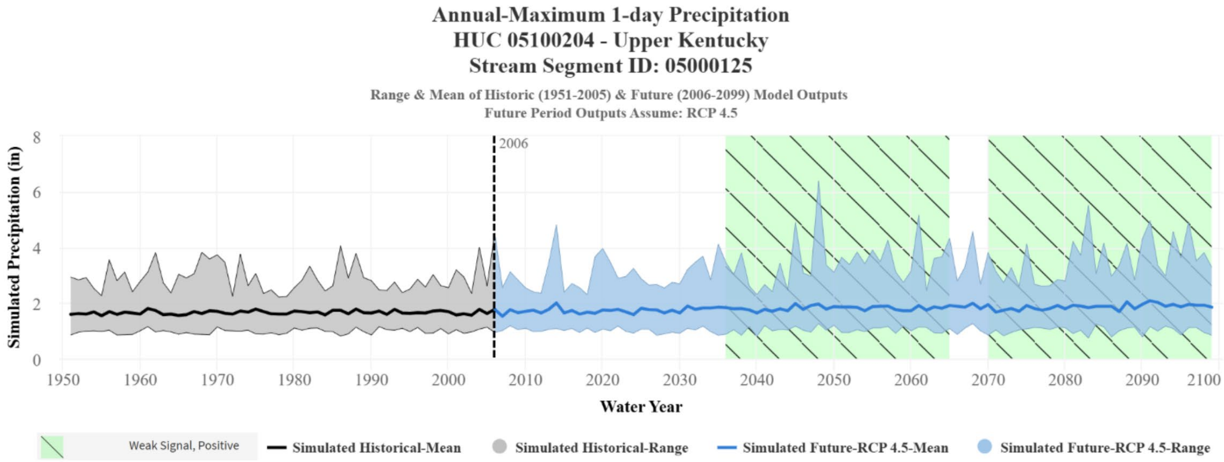


Figure 23. Range of GCM projections for the Annual Maximum 1-day Precipitation RCP 4.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

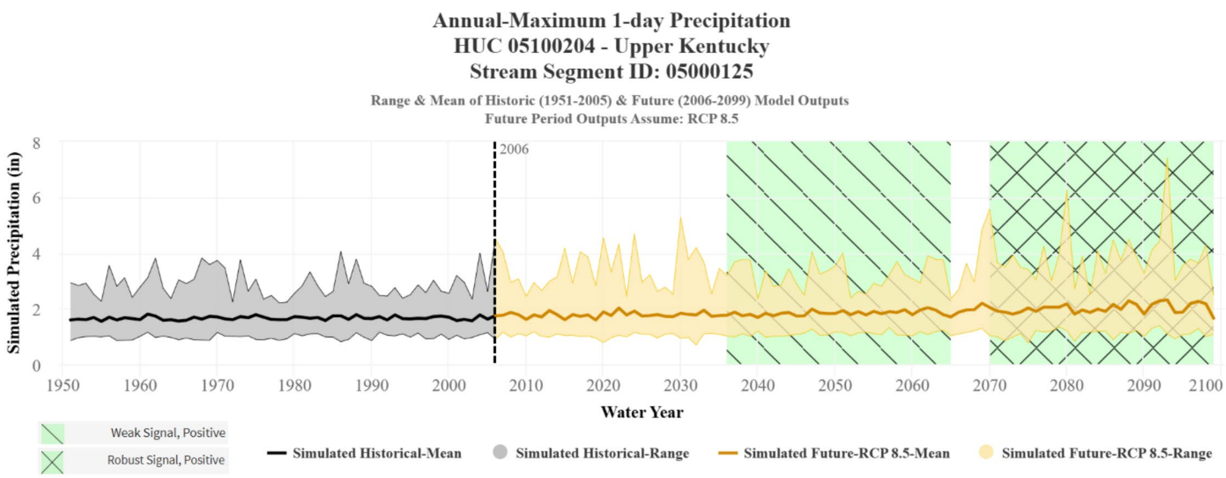


Figure 24. Range of GCM projections for the Annual Maximum 1-day Precipitation RCP 8.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

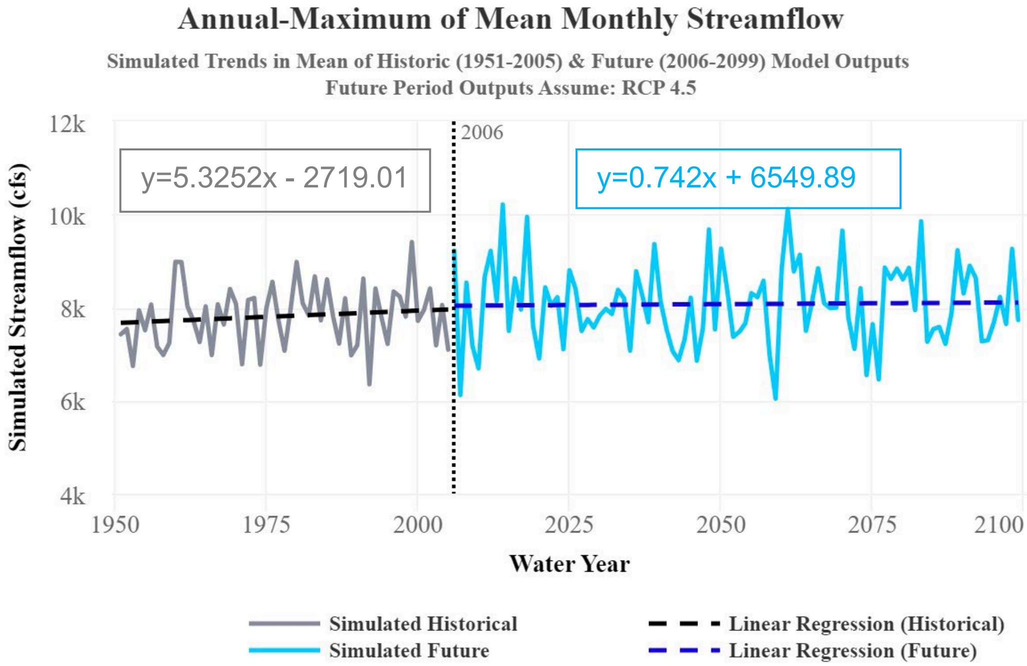


Figure 25. Mean of GCM projections for the Annual Maximum of Mean Monthly Streamflow RCP 4.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

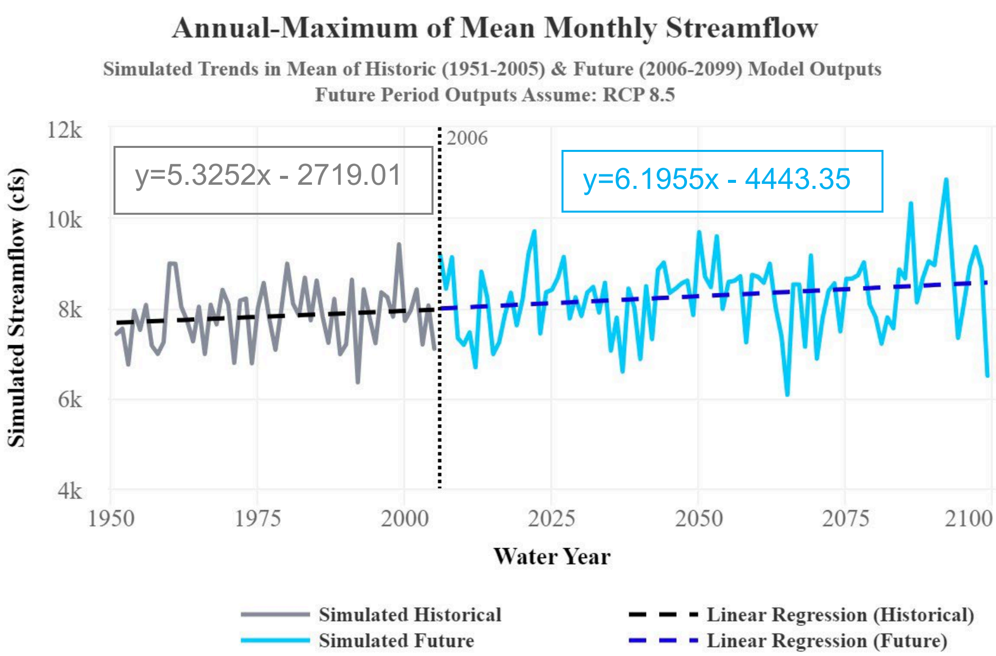


Figure 26. Mean of GCM projections for the Annual Maximum of Mean Monthly Streamflow RCP 8.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

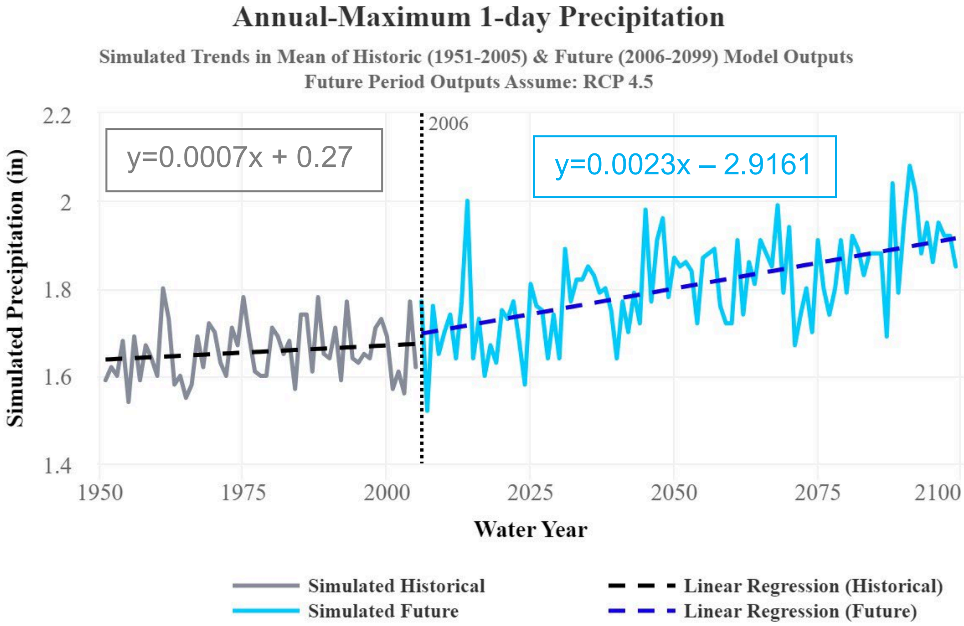


Figure 27. Mean of GCM projections for the Annual Maximum 1-day Precipitation RCP 4.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

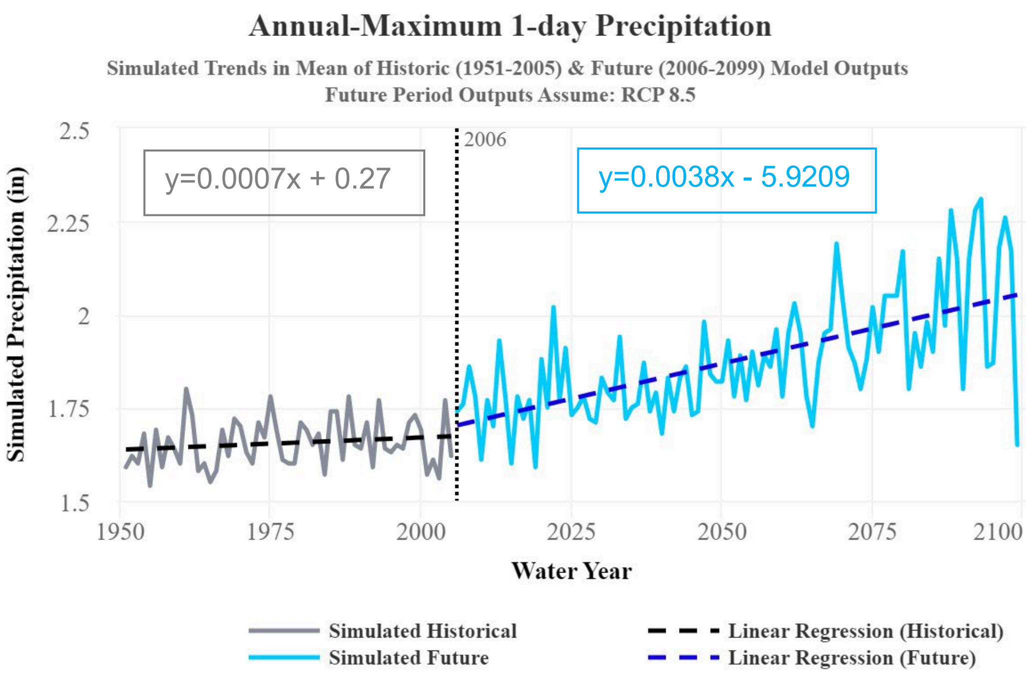


Figure 28. Mean of GCM projections for the Annual Maximum 1-day Precipitation RCP 8.5 scenario for the Stream Segment ID: 05000125 of the Upper Kentucky River, HUC-05100204

3.3 VULNERABILITY ASSESSMENT

The USACE Civil Works Vulnerability Assessment Tool (VA Tool) facilitates a screening level, comparative assessment of how vulnerable a given HUC-4 watershed is to the impacts of changes in hydrometeorological conditions 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 “Flood Risk Reduction” or “Navigation” to future hydrometeorological conditions. Assessments using this tool help to identify and characterize specific hydrometeorological 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 is to changes in hydrometeorological conditions specific to a given business line. The HUC-4 watersheds with the top 20% of WOWA scores are flagged as being vulnerable. It should be noted that although a watershed may not be deemed vulnerable, this does not mean that future hydrometeorological conditions will not impact the study area, but rather that it is anticipated to impact this region less than other regions in the United States for a particular business line.

When assessing future risk, the VA Tool makes an assessment for two 30-year epochs of analysis centered in 2050 and 2085. These two periods were selected to be consistent with many of the other national and international analyses. The VA tool assesses how vulnerable a given HUC-4 watershed is to the impacts of hydrometeorological change for a given business line using future hydrology based on a combination of projected hydrometeorological 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) macro-scale hydrologic model. For this assessment, the default National Standards Settings are used to carry out the vulnerability assessment.

Business lines included in the VA tool include ecosystem restoration, emergency management, flood risk reduction, hydropower, navigation, recreation, regulatory, and water supply. All business lines were evaluated for the Kentucky-Licking Basin. The basin was not considered vulnerable to future hydrometeorological impacts for any of the forementioned business lines within a threshold of 20%, meaning that its business lines’ vulnerability did not score in the top 20% of the most vulnerable for any of its business lines. For this project, flood risk reduction is the most relevant business line and the output for this business line from the VA tool is discussed more in-depth below.

Table 6 displays the overall vulnerability scores for the flood risk reduction business line. The scores are shown for both wet and dry scenarios and for both epochs. The indicators driving the residual vulnerability for the flood risk reduction business line are shown in Figure 29. Table 7 displays the indicators contributing to vulnerability within the Kentucky-Licking Basin for the flood risk reduction business lines; the table is generally sorted from largest to smallest average indicator contribution to vulnerability. Additionally, the tables display the indicator code, name, and a brief description of the indicator’s meaning.

Regarding the Flood Risk Reduction business line, the primary indicators driving vulnerability within the watershed are flood magnification (indicator 568C) and the runoff-precipitation elasticity index (indicator 277). The flood magnification factor represents how the monthly flow exceeded

10% of the time is predicted to change in the future; a value greater than 1 indicates flood flow is predicted to increase. For all epochs and scenarios within HUC 0510, the flood magnification factor is slightly greater than 1 and ranges between 1.04 and 1.37. This agrees with the literature reviews which indicate there will be increasing amounts of extreme rainfall events in the future. The runoff-precipitation elasticity index is defined as the percent change in runoff divided by the percent change in precipitation. The values for HUC 0510 are 2.07-2.20, meaning for every 1% increase in monthly precipitation, there is a 2.07-2.20% increase in monthly runoff. With the projected increases in precipitation, the region will produce even more runoff that could cause flooding and stress on flood-control infrastructure.

Note that some of the indicators contain a suffix of "L" (local) or "C" (cumulative). Indicators with an "L" suffix reflect flow generated within only one HUC-4 watershed, whereas indicators with a "C" suffix reflect flow generated within a HUC-4 watershed and any upstream watersheds. In the case of the Kentucky-Licking (HUC 0510), there is a substantial drainage area upstream of the 4-digit HUC- approximately 3,612 square miles of the Kentucky River Basin Watershed (U.S. Army Corps of Engineers, 2016).

It is important to note the variability displayed in the VA tool's results highlights some of the uncertainty associated with the projected hydrometeorological data used as an input to the VA tool. Because the wet and dry scenarios each represent an average of 50% of the GCM outputs, the variability between the wet and dry scenarios underestimates the larger variability between all the underlying projected hydrology estimates. This variability can also be seen between the 2050 and 2085 epochs, as well as various other analysis within this report, such as output from the CHAT (Figure 21 and Figure 22).

Table 6. Overall Vulnerability Scores for all Epochs and Scenarios

	Flood Risk Reduction	
Epoch	2050	2085
Dry	47.09	45.44
Wet	50.54	54.09

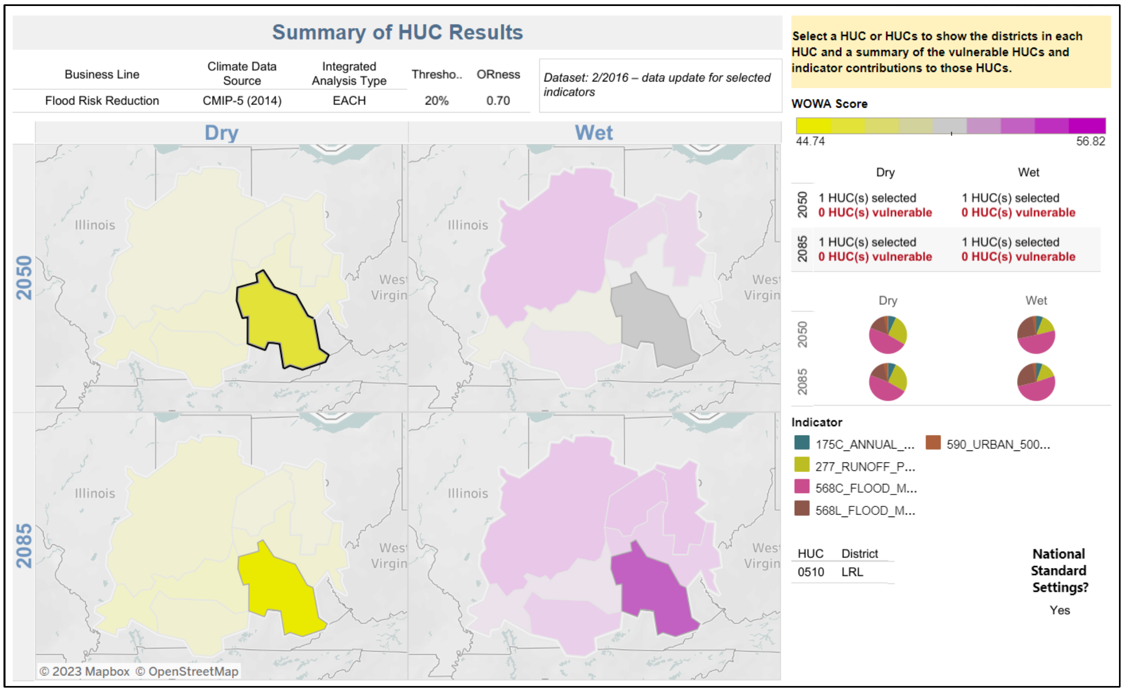


Figure 29. VA Tool Summary of HUC 0510 Results for Flood Risk Reduction Business Line

Table 7. Vulnerability Indicators for Flood Risk Reduction Business Line. Sorted by highest to lowest indicator contribution to vulnerability.

Flood Risk Reduction Business Line			2050	2050	2085	2085
Indicator Code	Indicator Name	Description	Dry	Wet	Dry	Wet
568C	Flood Magnification	Change in flood runoff: ratio of indicator 571C (monthly runoff exceeded 10% of the time, including upstream freshwater inputs) to 571C in base period.	47.81%	50.48%	47.73%	51.47%
277	Runoff-Precipitation Elasticity	Median of: deviation of runoff from monthly mean times average monthly runoff divided by deviation of precipitation from monthly mean times average monthly precipitation.	26.44%	15.22%	26.42%	14.35%
568L	Flood Magnification	Change in flood runoff: ratio of indicator 571L (monthly runoff exceeded 10% of the time, excluding upstream freshwater inputs) to 571L in base period.	15.69%	25.51%	15.67%	26.00%
175C	Annual Covariance of Runoff	Long-term variability in hydrology: ratio of the standard deviation of annual runoff to the annual runoff mean. Includes upstream freshwater inputs (cumulative).	6.86%	5.87%	6.79%	5.39%

590	Urban 500-year Floodplain	Acres of urban area within the 500-year floodplain.	3.20%	2.91%	3.40%	2.79%

3.4 Summary of Projected Trends in Hydrometeorological Conditions

Across the range of literature reviewed in this analysis, there is conflicting evidence regarding the hydrologic trends which can be expected in the future. In general, the following statements represent the probable hydrologic future that can be expected within the Kentucky River Basin:

- Winter and spring precipitation could potentially increase while trends in summer and fall precipitation are uncertain. Projected increases in precipitation fall during the typical flood season, which is likely to further increase peak streamflow and reservoir levels. This projection emphasizes the continued need for flood risk management projects into the future. The associated increases in flows on the rivers in the Kentucky River Basin may lead to more frequent and higher loading of levees and other flood infrastructure in the region during the winter and spring flood season.
- The frequency and intensity of extreme precipitation events could potentially increase, making current infrastructure that is designed for historical hydrometeorological conditions more vulnerable to future events.
- Projected future temperatures are anticipated to increase moderately over historic norms. This has various hydrologic implications including increased atmospheric moisture, evapotranspiration rates, frequency of droughts, and water supply demand.

Data analyzed in the CHAT for precipitation displayed similar results to the literature review. While the CHAT found increasing stream flows for the higher emissions scenario, the literature review did not find a consensus for hydrologic trends. For the projected Annual-Maximum of Mean Monthly Streamflow with scenario RCP 4.5, the slope was trending slightly upward, but the trend was not statistically significant. For the projected Annual-Maximum of Mean Monthly Streamflow with scenario RCP 8.5, the slope was trending upward. Out of the three statistically significant tests run, two noted the upward trend as significant, meaning it is a probable trend. For the projected annual maximum 1-day precipitation with scenario RCP 4.5 and RCP 8.5, the slope was trending upwards, and all statistically significant test were found to be significant. Overall, scenario RCP 4.5 will not have an increase in mean monthly streamflow while scenario RCP 8.5 will have a slight increase in mean monthly streamflow. While precipitation can be expected to increase for both scenarios, a large increase in precipitation can be expected for the RCP 8.5 scenario. It is also important to note that CHAT is simulating an unregulated watershed when considering the results.

For the Beattyville, KY General Investigation, flood risk reduction is the most relevant business line. The Kentucky-Licking Basin was not within the threshold of the top 20% of HUC's for this business lines in the VA tool. Despite not being within the top 20% of HUC's for the flood risk reduction business line, the VA tool results agree with the literature review's which indicate there will be increasing amounts of extreme rainfall and runoff events. However, it should be noted that there is uncertainty associated with the projected hydrometeorological data due to the variability seen in the VA tool results.

The literature review and tool analyses' results are compiled in the table below:

Table 8. Summary of Projected Hydrometeorological Trends in Beattyville, KY with Used Methods/Tools

Analysis Method/Tool	Significant Temperature Changes	Significant Precipitation Changes	Significant Streamflow Changes
Literature Review	Increasing Trend	Slightly increasing trend in volume/frequency	Inconclusive Trend
Comprehensive Hydrology Assessment Tool (CHAT)	Not Analyzed	For both RCP 4.5 and 8.5, there **is** a statistically significant increasing trend	For RCP 4.5, there is **not** a statistically significant increasing trend For RCP 8.5, there **is** a statistically significant increasing trend
Vulnerability Assessment Tool (VAT)	Not Analyzed	Slightly increasing trend in volume/frequency	Increasing Trend

4 SUMMARY AND CONCLUSION

The Kentucky River Basin flood risk management reservoirs and this related Beattyville, KY General Investigation operate to reduce risks and associated damages of flooding for Beattyville, Kentucky. Based on the literature review and the first order statistical analysis carried out in support of the study, there is little evidence or consensus of significant observed temperature or precipitation changes in the Kentucky River Basin Region. This is likely due to the region being a “transition zone” within the Appalachian Mountain region, where the northern and southern Appalachian regions are being impacted by hydrometeorological changes in different, almost opposite, ways. An assessment of observed peak annual streamflow by the CHAT and TST revealed little evidence of statistically significant increasing or decreasing trends or nonstationarities within the basin that can be attributed to changes in hydrometeorological conditions. There are statistically significant decreasing trends and nonstationarities in observed peak streamflow at the Heidelberg gage that can be directly attributed to the construction of flood risk management projects within the basin. The nonstationary found on the “pristine” gage on the South Fork Kentucky River Booneville, KY, determined that there are no statistically significant trends in precipitation or streamflow meaning the nonstationary is localized and not likely part of a larger regional trend.

Regarding projected trends, there is literature supporting increasing temperatures, precipitation, and streamflow. However, trends in projected streamflow are weaker and were not strongly supported in the analysis of the historic and observed data and the literature review of projected hydrometeorological trends offered little consensus. While trends for typical streamflow were inconclusive, more consensuses exist for increases in extreme precipitation events. Therefore, project features impacted from extreme precipitation such as interior drainage structures may expect increase in the future. While project features impacted from increases in streamflow can be assumed to not be significantly impacted during its lifecycle. It should be noted that substantial uncertainty exists within future hydrometeorological projections, this uncertainty is effectively illustrated by the range of GCM peak annual streamflow projections shown in Figure 21 though Figure 22. At this time, each of the 32 hydrometeorological model projections included in this figure’s range can be considered equally likely to occur.

The HUC-4 region is not considered to be within the threshold of the top 20% of HUCs for the flood risk reduction business line compared to other HUC regions throughout the United States, however this does not mean that future hydrometeorological conditions will not impact the region. Beattyville’s flood risk is currently reduced by two USACE flood protection reservoirs located upstream within the Kentucky River Basin.

Table 9 displays the residual risk table required by ECB 2018-14. This table lists potential climatic triggers, hazards, harms, and approximate qualitative likelihood of occurrence. The table is primarily focused on the business line of interest, flood risk reduction, however that is not to say that other USACE business lines will not be impacted by future hydrometeorological conditions. Because this qualitative analysis is focused on the Beattyville, KY General Investigation as a whole, only generic project features of consideration have been identified within the table.

It is recommended that stage-frequency, flow-frequency, and precipitation-frequency for Kentucky River and South Fork Kentucky River be reevaluated periodically in the future to determine how projected trends manifest themselves in future observations. Depending on the results of these future analyses, additional flood risk reduction measures may be required.

Based on this assessment, it is recommended that the potential long-term changes in hydrometeorological conditions be treated as occurring within the uncertainty range calculated for the current hydrologic analysis. If this assumption proves to be inadequate when future observations or more refined projections become available, then a quantitative evaluation and revision of these results may be required.

Table 9. Residual Risk Table for the Beattyville, KY General Investigation

Feature of Measure	**Trigger**	**Hazard**	**Harm**	**Qualitative Likelihood (Frequent, Occasional, Likely, Seldom, Unlikely)**	**Consequence (Catastrophic, Critical, Marginal, Negligible)**	**Adaptation**
Levee/Floodwall (Structural)	Increased streamflow from precipitation	Levee/Flood wall have a greater probability of overtopping	Levee/floodwall is overtopped leading to loss of structure and protected side of the levee/floodwall gets inundated	Likely or Seldom (Depends on conservatism in crest design height)	Earthen Levee – Catastrophic Floodwall - Marginal	Increase crest design height for projected streamflow increase
Interior Drainage (Structural)	Increased precipitation	Pump and pipes are undersized	Low lying structures would be inundated from interior ponding	Likely or Seldom (Depends on conservatism in interior drainage design)	Pump Station - Marginal Gravity Drains - Negligible	Design for larger pump and pipe sizes
Relocation/ Acquisition (Non-Structural)	Increased streamflow from precipitation	Increased 100-year inundation extents and depths	Structures that are near but not in the current 100-year floodplain may be at a higher risk of flooding in the future but may not be relocated or acquired during this project	Likely or Seldom (Depends on sensitivity of structure inundation near the 100-year floodplain extents)	Critical to Negligible (Depends on sensitivity of structure inundation near the 100-year floodplain extents)	Buyout structures at an increased floodplain extent
Floodproofing Wet/Dry (Non-Structural)	Increased streamflow from precipitation	Increased 100-year inundation extents and depths	Floodproofing efforts are not done to a high enough elevation	Likely or Seldom (Depends on conservatism in floodproofing design height)	Marginal	Increase floodproofing elevation

FWEEP (Inundation Mapping, Evacuation Planning, Flood Plain Manageme nt Plan)	Increased precipitation intensity (rate of inundation depth rise)	Inundation rises at a quicker rate than existing conditions	Warning times are reduced leading to individuals not evacuating in time	Seldom	Critical or Marginal (Depends on sensitivity of warning times)	Earlier warning notification in FWEEP, triggered with lower elevations
Floodway Acquisition Ecosystem Restoration Features	Increase in extreme temperature s	Increase in droughts frequency and extreme heat waves	Increase in temperature and drought stresses ecosystem restoration features	Likely	Critical of Marginal (Depends on design of ecosystem restoration features)	Include vegetation which is more resilient to drought and extreme temperatures.
Floodway Acquisition Recreation al Features	Increased magnitude and frequency of extreme precipitation	Increases in localized flooding	Drainage features in recreation features are not capable of resulting in minimal flooding	Likely (Depends on selected project features and location)	Marginal to Negligible (Depends on recreation features)	Add recreational features which are resilient to extreme events

Note: Likelihood and Consequence ratings are based on Risk Register Criteria

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