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APPENDIX A2: CHANGING CONDITIONS

WACCAMAW RIVER,

HORRY COUNTY, SOUTH CAROLINA

FLOOD RISK MANAGEMENT STUDY INTEGRATED FEASIBILITY REPORT AND ENVIRONMENTAL ASSESSMENT

MAY 2026

MAIN REPORT SUMMARY

The Integrated Feasibility Report and Environmental Assessment (FR/EA), that this appendix addresses, details a collaborative study by the U.S. Army Corps of Engineers (USACE) and Horry County, South Carolina. It is aimed at reducing existing and future flood risks to communities and transportation infrastructure within the Waccamaw River Basin, with a focus on Horry County. The study identifies four key flood impact areas: Longs & Red Bluff, Conway, Bucksport, and Socastee.

The flood impacts in each of these areas were independent of each other, so solutions could be evaluated self-reliantly, making any proposed alternative plans separable. The study considered a range of structural, non-structural, and nature-based solutions while incorporating public feedback gathered during meetings. An environmental analysis was completed, and a Finding of No Significant Impact is included within the main report. The document completed a public review and comment period while also undergoing internal agency reviews and adapted to those concerns and suggestions. In addition to historical flooding, the report acknowledges the flooding event caused by Hurricane Debby in August 2024 during this study, and its impact was assessed to further inform the study's conclusions.

The Recommended Plan, based on an evaluation of alternatives, includes two separable elements that are incrementally justified: Relief Bridges (cross drains) in the Conway flood impact area and Barrier Removal in the Socastee flood impact area. The Recommended Plan is classified as the National Economic Development Plan and is also the plan that maximizes net comprehensive benefits. No alternatives were justified for Federal investment for the Longs & Red Bluff and Bucksport flood impact areas. This Appendix provides detailed changing conditions information to support these recommendations.

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A INTRODUCTION - INLAND CLIMATE FACTORS FOR THE WACCAMAW RIVER WATERSHED

A.1 Introduction and Background

This is an evaluation of potential vulnerabilities to long-term changes in hydrometeorological conditions facing the Waccamaw River Watershed. This assessment was performed to highlight existing and future challenges facing the project's ability to mitigate flood risk in response to past and future changes, in accordance with the guidance in Engineering Construction Bulletin (ECB) 2018-14, revised 19 Aug 2022 and its replacement, ECB 2026-1. Background information on the project can be found in the main report, and background information on dynamic weather-driven risks to projects and assessments thereof can be found in the ECB 2026-1.

USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural variability over their operating life spans. However, recent scientific evidence shows that in some places and for some impacts relevant to USACE operations, changing conditions are shifting the baseline about which that natural hydrometeorologic variability occurs and may be changing the range of that variability as well. This is relevant to USACE because the assumptions of stationary hydrometeorologic conditions and a fixed range of natural variability, as captured in the historic hydrologic record may no longer apply. Consequently, historic hydrologic records may no longer be appropriately applied to carry out hydrologic assessments for flood risk management in watersheds such as the Waccamaw Basin.

A.2 Waccamaw River Watershed Description

The Waccamaw River is a 140-mile-long river, located in southeastern North Carolina and eastern South Carolina in the flat Coastal Plain. It drains an area of approximately 1,110 square miles (2,886 km^2) in the coastal plain along the eastern border between the two states into the Atlantic Ocean. Along its upper course, it is a slow-moving, blackwater river surrounded by vast wetlands, passable only by shallow-draft watercraft such as canoe. Along its lower course, it is lined by sandy banks and old plantation houses, providing an important navigation channel with a unique geography, flowing roughly parallel to the coast.

It enters South Carolina and flows southwest across Horry County, past Conway. Near Burgess, it is joined from the northwest by the Great Pee Dee River, which rises in north central North Carolina. It continues southwest, separated from the ocean by only five miles (8 km) in a long tidal estuary. The long narrow point of land along the ocean formed by the lower river is called Waccamaw Neck. At Georgetown it receives the Black River (South Carolina) from the north, then turns sharply to the southeast and enters the ocean at Winyah Bay, approximately five miles (8 km) north along the coast from the mouth of the Santee River. Inland communities across the state are at risk from flooding due to extreme precipitation throughout the entire year. The Waccamaw River basin has a temperate climate with moderate winters and warm humid summers. Rainfall is well distributed throughout the year; however, rainfall is greatest near the coast and decreases as the terrain transitions from Coastal Plain to Piedmont regions. The average annual precipitation over the Waccamaw River basin ranges from about 48 inches near Longs, SC up to 54 inches near Bucksport, SC. This difference is due to local factors like elevation, proximity to water bodies, and microclimates, which can impact rainfall. Such variations are important for water resource management, as they affect soil moisture, vegetation, and flood risks across the basin. Rainfall is generally well-distributed throughout the year, though it is greatest during the late spring to early fall when heavy localized rainfall and hurricanes are the most prevalent. The maximum monthly rainfall averages about 7 inches and occurs during July, whereas the driest month is November with an average rainfall of 3.1 inches (NACSE, 2021).

B OBSERVED TRENDS FROM LITERATURE REVIEW

The Waccamaw River is in Water Resource Region (i.e., HUC-8 watershed) number 0304, the Pee Dee Region. A January 2015 report conducted by the USACE Institute for Water Resources (USACE 2015b) summarizes the available changing conditions literature for this region, covering both observed and future changes. These include Temperature, Precipitation and Hydrology.

B.1.1 Temperature

This report synthesizes findings from various studies investigating historical temperature trends, incorporating research on both national scales, which includes data relevant to Water Resources Region 03, and more focused regional analyses specific to this area. The subsequent discussion outlines insights from these studies.

In 2009, Wang et al. conducted a study on historical temperature patterns across the continental United States, utilizing gridded mean monthly data (0.5 degrees x 0.5 degrees) from 1950 to 2000. Their research aimed to explore the relationship between the seasonality and regionality of temperature trends and variations in sea surface temperatures. The study found broadly positive, statistically significant trends in average air temperature across most of the U.S. (as illustrated in Figure B-1). Within the South Atlantic-Gulf Region, the findings were more nuanced: the spring and summer months showed a general, albeit slight, warming trend across much of the region. However, during autumn, the southern part of the region experienced warming, while a slight cooling trend was observed in the north. Winter months revealed a more distinct east-west split, with the eastern part warming and the western part cooling. These findings were slightly contradicted by a subsequent study from Westby et al. (2013), which analyzed data from 1949 to 2011 and indicated a general trend of winter cooling across the region. The Third National Climate Assessment (NCA) report by Carter et al. (2014) analyzes historical average annual temperatures in the Southeast U.S., revealing a complex pattern of mild warming in the early 20th century, followed by mid-century cooling and recent warming. Despite these fluctuations, the report indicates an overall absence of a clear long-term trend in mean annual temperature over the last century.

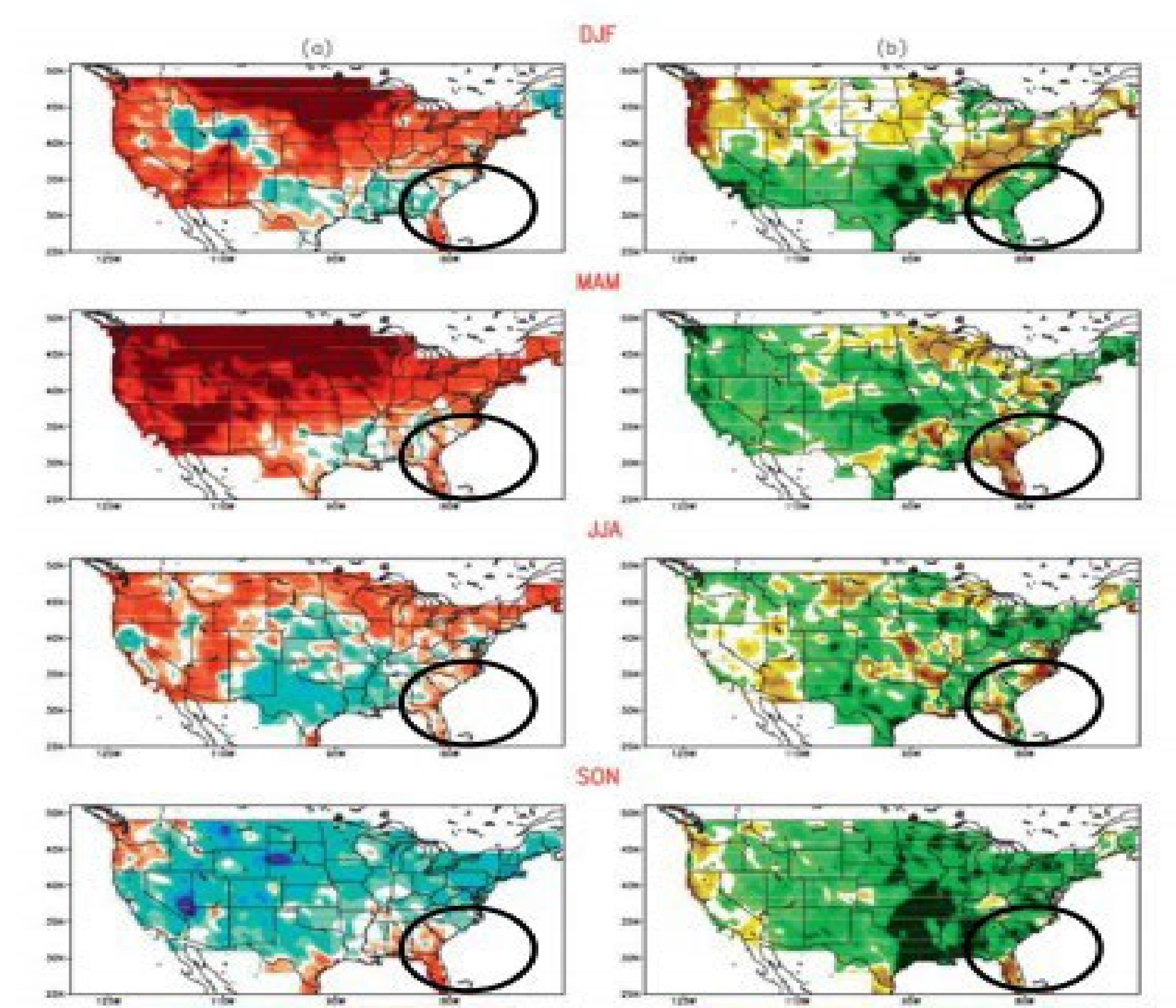


Figure B-1: Linear trends in surface air temperature (a) and precipitation (b) over the United States, 1950 – 2000 (DJF= December, January, February; MAM= March, April, May; JJA= June, July, August; SON= September, October, November)

A 2012 study by Patterson et al. focused exclusively on historical weather and streamflow trends in the South Atlantic region. Monthly and annual trends were analyzed for several stations distributed throughout the South Atlantic-Gulf Region for the period 1934 – 2005. Results (Figure B-2) identified a largely cooling trend for the first half of the historical period and the period as a whole. However, the second half of the study period (1970 – 2005) exhibits a clear warming trend with nearly half of the stations showing statistically significant warming over the period (average increase of 0.7 ºC). The circa 1970 “transition” point for temperature and streamflow in the U.S. has been noted elsewhere, including Carter et al. (2014). Trends in overnight minimum temperatures (Tmin) and daily maximum (Tmax) temperatures for the southeast U.S. were the subject of a study by Misra et al. (2012). Their study region encompasses nearly the full extent of the South Atlantic-Gulf Region and used data from 1948 to 2010. Results of this study show increasing trends in both Tmin and Tmax throughout most of the study region.

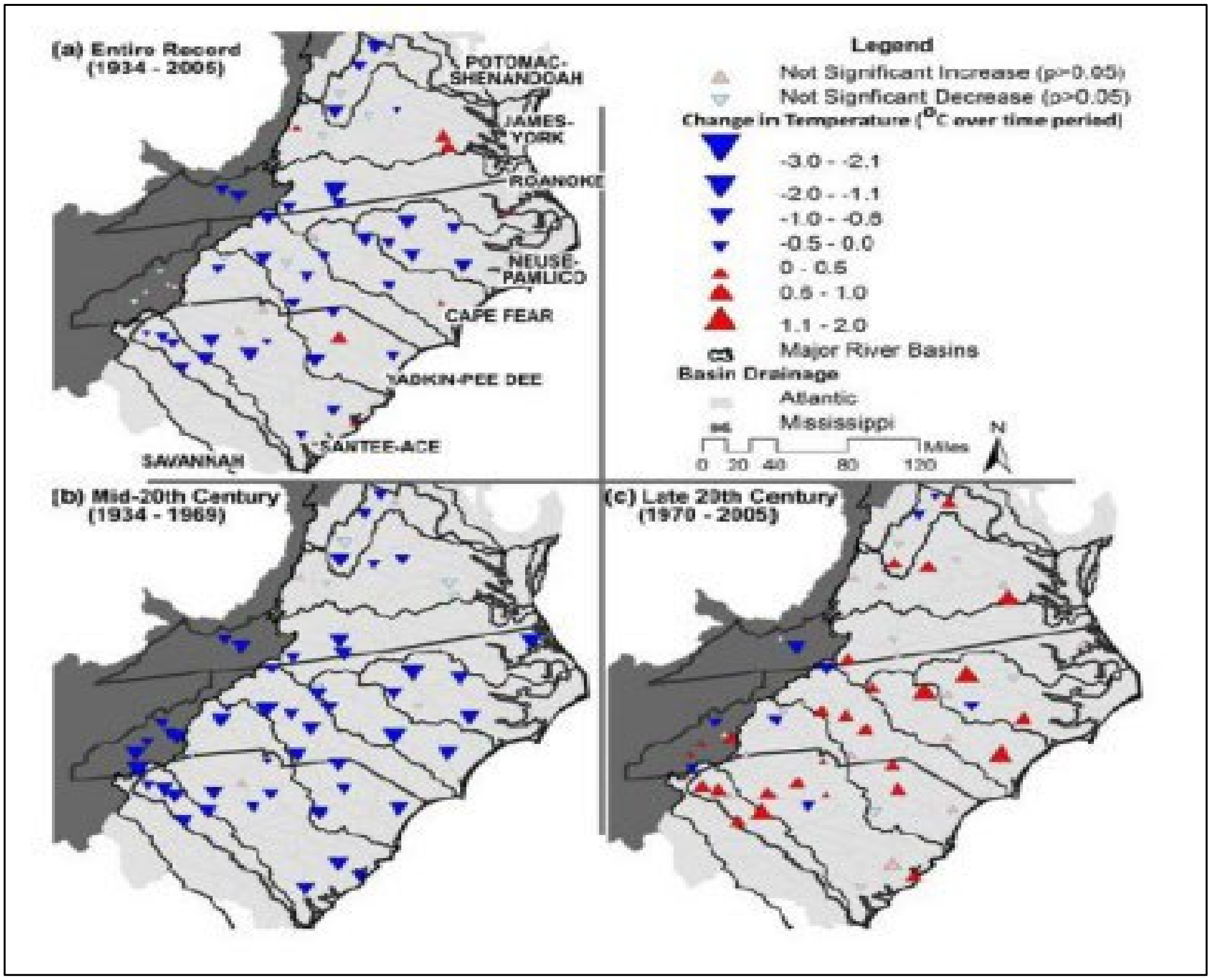


Figure B-2: Historical annual temperature trends for the South Atlantic Region, 1934 – 2005. Triangles point in the direction of the trend, size reflects the magnitude of the change. Blue indicates a decreasing temperature trend. Red indicates an increasing temperature trend (Patterson et al., 2012)

In South Carolina specifically the temperatures have risen more than 1.2ºC since the beginning of the 20th century. Winter average temperatures have been increasing with the 2015-2020 period exceeding the levels of the 1930s and 1950s. Summer average temperatures in the 2005-2020 period have been the warmest on record. Most of North Carolina has warmed 0.6-1.2 degrees Fahrenheit in the last 100 years. The southeastern United States has warmed less than most of the nation. Also of note is that from 1901 through 2020, global sea surface temperature rose at an average rate of 0.14°F per decade (NOAA 2021; see Figure B-3).

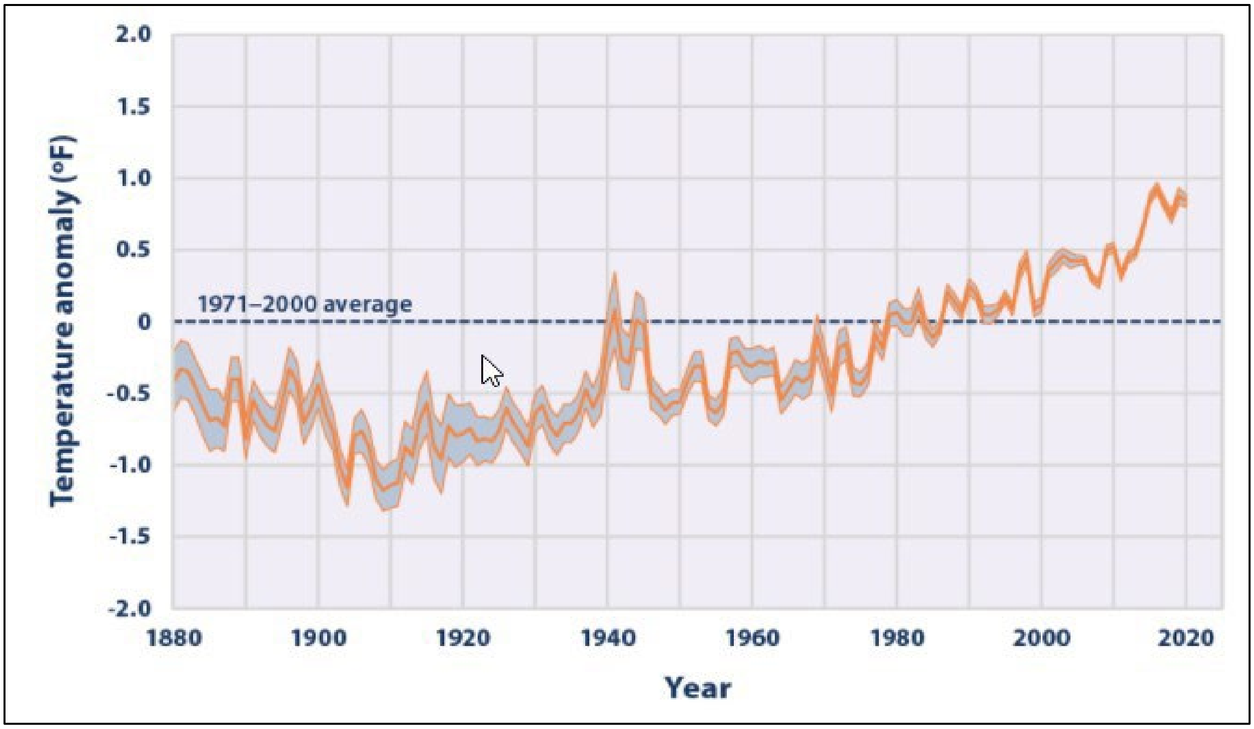


Figure B-3: Average Global Sea Surface Temperature Change, 1881-2020. (NOAA, 2021)

B.1.2 Precipitation

In their 2005 study, Palecki et al. analyzed historical rainfall records from the continental United States, focusing on the period between 1972 and 2002. They leveraged NCDC's 15-minute precipitation data to identify trends in rainfall patterns. Their findings highlighted significant upticks in the intensity of winter storms (measured in millimeters per hour) and the overall precipitation during autumn in the lower areas of the South Atlantic-Gulf Region. On the flip side, a notable decrease in the intensity of summer storms was observed in the upper portions of this region.

McRoberts and Nielsen-Gammon, in their 2011 research, utilized a novel, consistent dataset to examine precipitation trends across various sub-basins in the United States, covering a lengthy period from 1895 to 2009. This extensive study uncovered generally upward trends in yearly precipitation across most of the United States, as depicted in Figure B-4. Within the South Atlantic-Gulf Region, however, the trends were less consistent, with some areas experiencing minor drops in rainfall while others saw slight increases, leading to an inconclusive overall trend for the region based on this study.

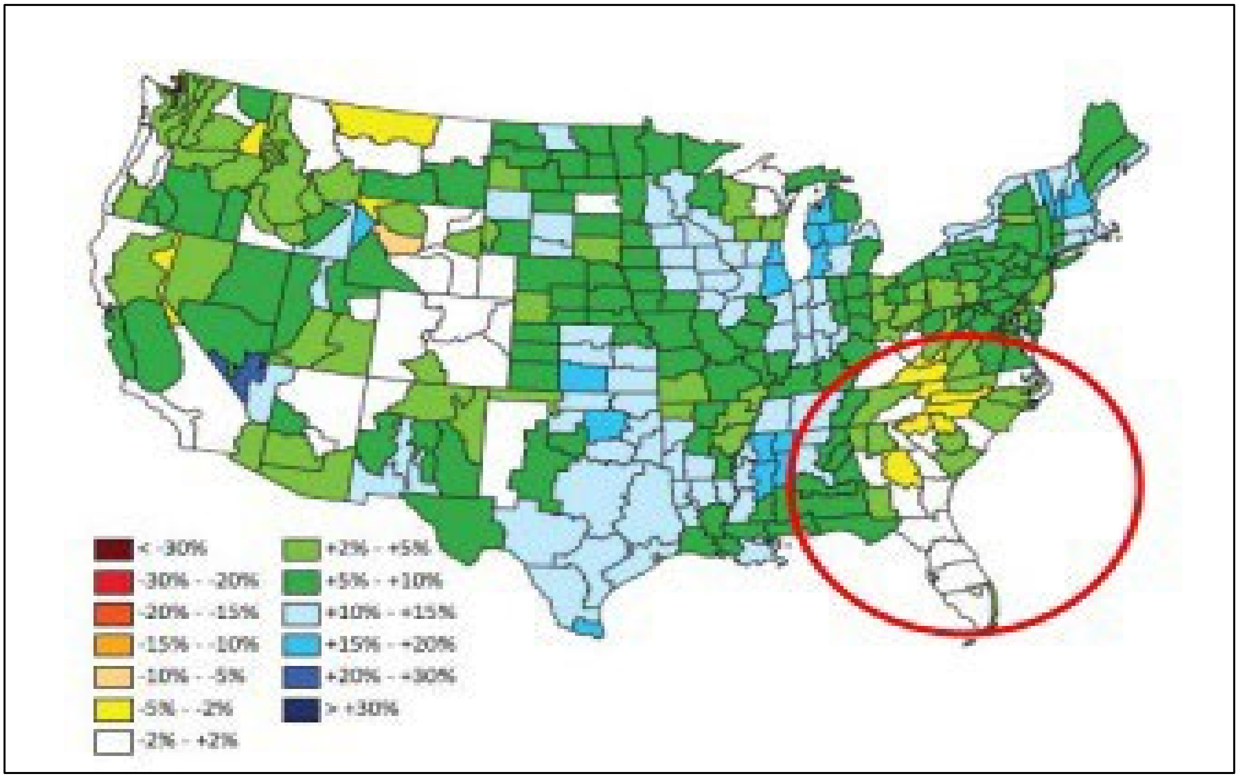
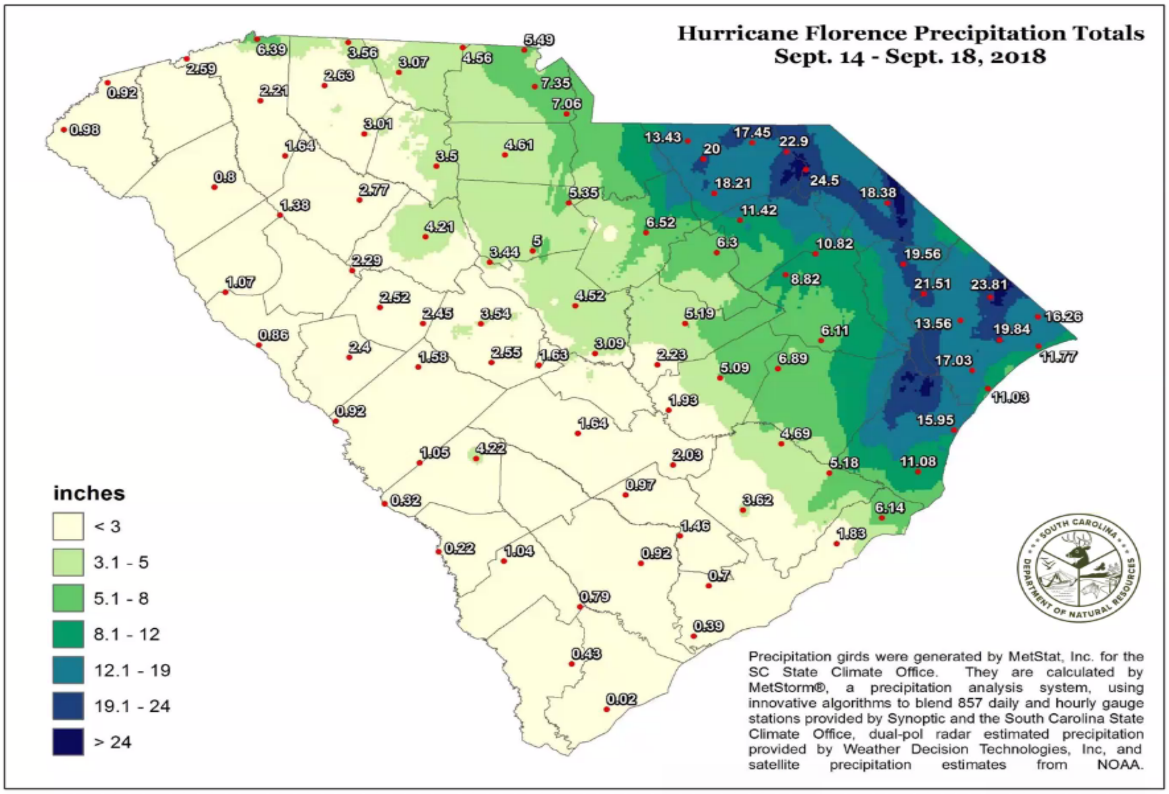


Figure B-4: Linear trends in annual precipitation, 1895 – 2009, percent change per century. The South Atlantic-Gulf Region is within the red oval (McRoberts and Nielsen-Gammon, 2011)

A number of research initiatives have centered on analyzing variations in extreme precipitation events using updated historical records. These studies have scrutinized the severity, frequency, and duration of such weather phenomena. In their 2008 investigation, Wang and Zhang harnessed both recent historical data and downscaled precipitation output from Coupled Model Intercomparison Project Phase 3 (CMIP3) to probe into shifts in extreme precipitation across North America, with a specific focus on the alteration in the occurrence rate of the maximal daily precipitation event expected once every 20 years. Their examination spanned historical trends and future trends.

The research highlighted a statistically marked increase in the occurrence of these two-decade storm events within the southern and central United States, observed in both the historical records and future model-based outputs. Particularly in the South Atlantic-Gulf Region, a significant shift was observed in the frequency of these storms between the two periods of 1977–1999 and 1949–1976, indicating an increase in frequency ranging from 25% to 50%. Depiction of the rainfall totals from Hurricane Florence is shown in Figure B-5, generated by MetStat for SC State Climate office.


Hurricane Florence Precipitation Totals
Sept. 14 - Sept. 18, 2018

Precipitation girds were generated by MetStat, Inc. for the SC State Climate Office. They are calculated by MetStorm®, a precipitation analysis system, using innovative algorithms to blend 857 daily and hourly gauge stations provided by Synoptic and the South Carolina State Climate Office, dual-pol radar estimated precipitation provided by Weather Decision Technologies, Inc, and satellite precipitation estimates from NOAA.

Figure B-5: Precipitation Totals Hurricane Florence (SCDNR, 2022)

Despite these findings, the study reported a varied pattern in overall precipitation changes across the region during the studied interval. Some locations noted uptrends in precipitation, while others observed downtrends. Looking at the entire time span of the study, a greater number of sites showed slight increases in precipitation compared to decreases. Specifically, in North and South Carolina, there was no clear trend in yearly precipitation, though there was a general observation that rainfall tends to be higher during the summer months, according to a 2022 report by the National Centers for Environmental Information (NCEI).

Heavy precipitation events have increased in both frequency and intensity across the United States and are projected to continue increasing with warming temperatures. In the Southeast, the amount of precipitation falling during the heaviest events has increased by approximately 27 percent since 1958 (Walsh, J. et al 2014). Warmer atmospheric conditions are expected to further increase rainfall rates during tropical storms and hurricanes, potentially exacerbating flood risk in coastal areas (Carter et al., 2018.

However, while heavy precipitation has increased across most of the southeastern United States, trends specific to South Carolina are less clear. Most long-term precipitation records evaluated in South Carolina do not exhibit significant long-term trends in 1-day precipitation events for the 50%, 10%, or 1% AEP events (SCOR 2023). The meteorological station at Conway, however, does indicate a statistically significant increase in heavy precipitation. The 10% AEP (10-year) event defined using 1930-1979 precipitation data is equivalent to a 20% AEP (5-year) event when 1970-2019 data is evaluated (SCOR 2023).

B.1.3 Streamflow

In their 2008 study, Kalra et al. reported consistent declines in both the yearly and seasonal flow of streams across a wide array of measuring stations in the South Atlantic-Gulf Region, spanning the historical timeline from 1952 to 2001. This research also highlighted a notable shift during the mid-1970s, which coincides with a temperature warming phase discussed in the temperature section (2.1). A similar conclusion was reached by Small et al. (2006), who analyzed HCDN data from 1948 to 1997, revealing significant downward trends in the annual minimum flow rates at several locations throughout the same region, although many sites showed no discernible trend either way.

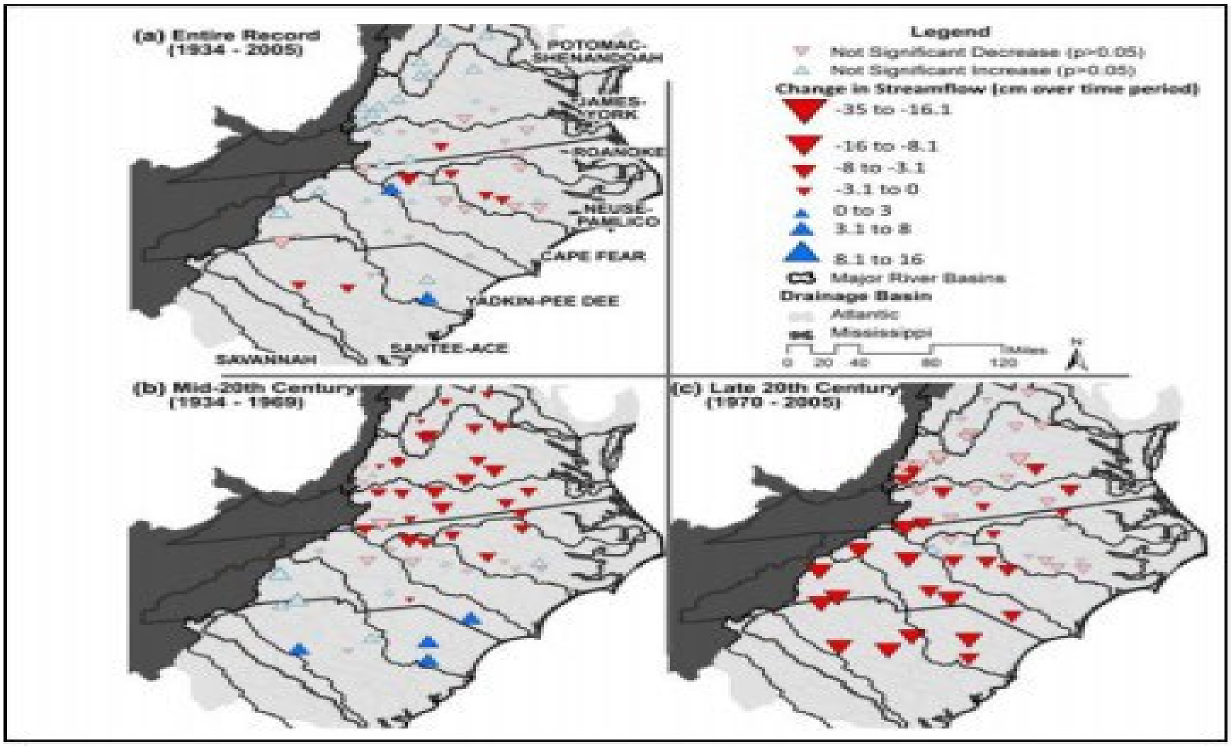


Figure B-6: Observed changes in annual streamflow, South Atlantic Region, 1934 – 2005. Triangles point in the direction of the trend, size reflects the magnitude of the change. Blue indicates a decreasing streamflow trend. Red indicates an increasing streamflow trend. (Patterson et al., 2012)

Patterson et al. (2012) further identified a pivotal "transition" around 1970, along with marked decreases in streamflow in the South Atlantic-Gulf Region for the years 1970 to 2005, as depicted in Figure B-6. The findings for the preceding years, from 1934 to 1969, were varied, with streamflows at some locations decreasing and at others increasing. These studies collectively emphasize the critical transition period of the 1970s in the context of regional streamflow variations.

B.1.4 Summary of Historic Trends Literature Review

The literature review indicates distinct hydrometeorological trends over different periods. Initially, the temperature data shows a cooling trend for the first half of the historical period, while the second half

(1970–2005) reveals a significant warming trend, with nearly half of the monitoring stations reporting an average increase of 0.7 ºC.

Regarding precipitation, McRoberts and Nielsen-Gammon (2011) analyzed a comprehensive dataset from 1895 to 2009, finding general upward trends in yearly precipitation across much of the United States. In terms of hydrology, Kalra et al. (2008) reported consistent declines in both yearly and seasonal stream flows in the South Atlantic-Gulf Region from 1952 to 2001, highlighting a notable shift in the mid-1970s that aligns with the observed environment warming.

Kossin, J. P., et al. (2017) states "A global increase in the intensity of tropical cyclones," storm occurrences in the Waccamaw River basin are typically in the form of thunderstorms, northeasters, and hurricanes. The most severe floods of record over the basin have been associated with hurricanes. South Carolina lies in the path of tropical hurricanes as they move northerly from their origin north of the Equator in the Atlantic Ocean. These hurricanes usually occur in the late summer and autumn and have caused the heaviest rainfall and largest floods through the basin. These extreme hurricane events are characterized by heavy and prolonged precipitation.

Flooding in the project area primarily results from:

- Extensive rainfall throughout the year;
- Multi-day rainstorms leading to saturated soils;
- Warm Atlantic Ocean which is getting warmer contributing to the increased rainfall; and
- Increase in intensity and frequency of hurricanes.

These hydrometeorological factors are the main contributors to flooding that damages infrastructure in the project area, forming the basis of this climate hazard analysis. To assess existing conditions, we incorporated these factors into the FWOP (Future Without Project) scenario using 96-hour rainfall events, as multi-day storms have been observed in the region. The synthetic rainfall events included a secondary peak, reflecting the intense storm activity typical in the area. Additionally, we employed a rain-on-grid approach in the hydraulic model to comprehensively simulate the vast watershed area. Land use was not altered from the Existing Conditions (EC) to the FWOP, since we lacked certainty that any particular development would happen for FWOP, therefore, there was basically no change between EC and FWOP for the study area in regard to the land use.

C FUTURE TRENDS FROM LITERATURE REVIEW

Within the literature there is not a great deal of consensus indicating that average annual precipitation will change in South Carolina throughout this century (NOAA, 2022). Analysis reviewed by the South Carolina Office of Resilience (SCOR) indicates that when an ensemble of climate model results are considered, the inter-model mean increases by 5-10%, but wetter models can indicate an increase of over 40% and drier models can point to swings of 40% lower than current average conditions (SCOR, 2023).

Current hydrometeorological literature demonstrates a clear consensus that the Southeastern United States, including the Waccamaw River Basin, is subject to warming atmospheric temperatures which will exponentially increase moisture-holding capacity (Trenberth, 2011). However, it is also important to note that increasing temperatures will result in higher evaporation rates (SCOR, 2023). Model-based results indicate that temperatures in South Carolina will increase by 5-10 degrees Fahrenheit by the end of the

21st century and the number of days where state-averaged maximum temperature exceeds 95 degrees Fahrenheit will increase (SCOR 2023).

At least in part because of this thermodynamic shift, models project an increase in the frequency and intensity of short-duration, extreme precipitation events, even if changes in mean annual precipitation remain variable (Pfahl et al., 2017). The USACE 2015 literature synthesis also indicates that there is reasonable consensus that the intensity and frequency of extreme storms events will increase in the future for the South Atlantic-Gulf Region.

Furthermore, recent basin-specific ecohydrological modeling and broader regional analyses indicate that amplified climate variability will drive more extreme seasonal flooding events and increased mid-century streamflow (Q) in coastal Carolina rivers, specifically including the Waccamaw River (Olaniyi et al., 2026; NOAA, 2025, SCOR, 2023). The intense rainfall events are expected to increase in magnitude and frequency as well as the number of multi-day rainfall events, which exacerbate the flooding issues in this region. If rainfall is delivered in short duration, high intensity bursts more precipitation will run off from the land surface (SCOR, 2023).

Projected increase in tropical cyclone rainfall intensity are a major concern for the Waccamaw River Watershed. Heavy precipitation associated with hurricanes and other storm systems is expected to increase because of warming atmospheric conditions and higher sea surface temperatures, which enhance moisture availability and rainfall rates (USGCRP, 2017). Sea surface temperatures are projected to increase in the future, and these warmer temperatures are expected to contribute to increasing precipitation intensity in the project area.

Projected increases in the frequency and intensity of precipitation events will result in increasing flood risk (Walsh, 2016, Carter, 2018). These increases have the potential to disrupt activities and place additional stress on existing flood risk management infrastructure. Increasing inland flooding associated with extreme precipitation is also expected to contribute to greater economical and agricultural losses. (Carter, 2018).

D CRITICAL HYDROMETEROLOGCAL CONDITIONS FLOOD RISK

Large rainfall events can occur at any time of year and are a primary driver of flooding in the project area. Most recently, in 2024, a new record was observed at the Conway Municipal Airport for the average annual maximum 1-day precipitation (NWS Wilmington, 2024). The updated value of 2.34 inches exceeds the previous record of 2.07 inches set in 2009, representing a 33 percent increase.

Not only is the rainfall throughout the entire year a great concern, but the multiday storms also exacerbate the flooding issues within this region. Multi-day storms saturate soils, exacerbating flood risk by increasing the share of precipitation that runs off once the soil is saturated. The saturated soils from the multiday storms only worsen the flooding in this area, because the rainfall cannot be absorbed into the soil, thus causing a larger and faster runoff.

The warmer Atlantic Ocean leads to an increase in moisture in the environment, thus more rainfall events. Changing conditions are likely causing parts of the water cycle to speed up as warming global temperatures increase the rate of evaporation worldwide. With more evaporation, there is more water in the air so storms can produce more intense rainfall events in some areas. This can cause flooding – a risk to the environment and human health.

Hurricanes are another source of flood risk in the project area. Communities along the Waccamaw River have experienced major flooding events over the past 25 years, with Floyd (1999), Joaquin (2015), Matthew (2016) and Florence (2018) all ranking among the most destructive storms in state history (Kunkle et al. 2020). The damage from these storms was due primarily to flooding that resulted from the widespread heavy rains that accompanied the storms.

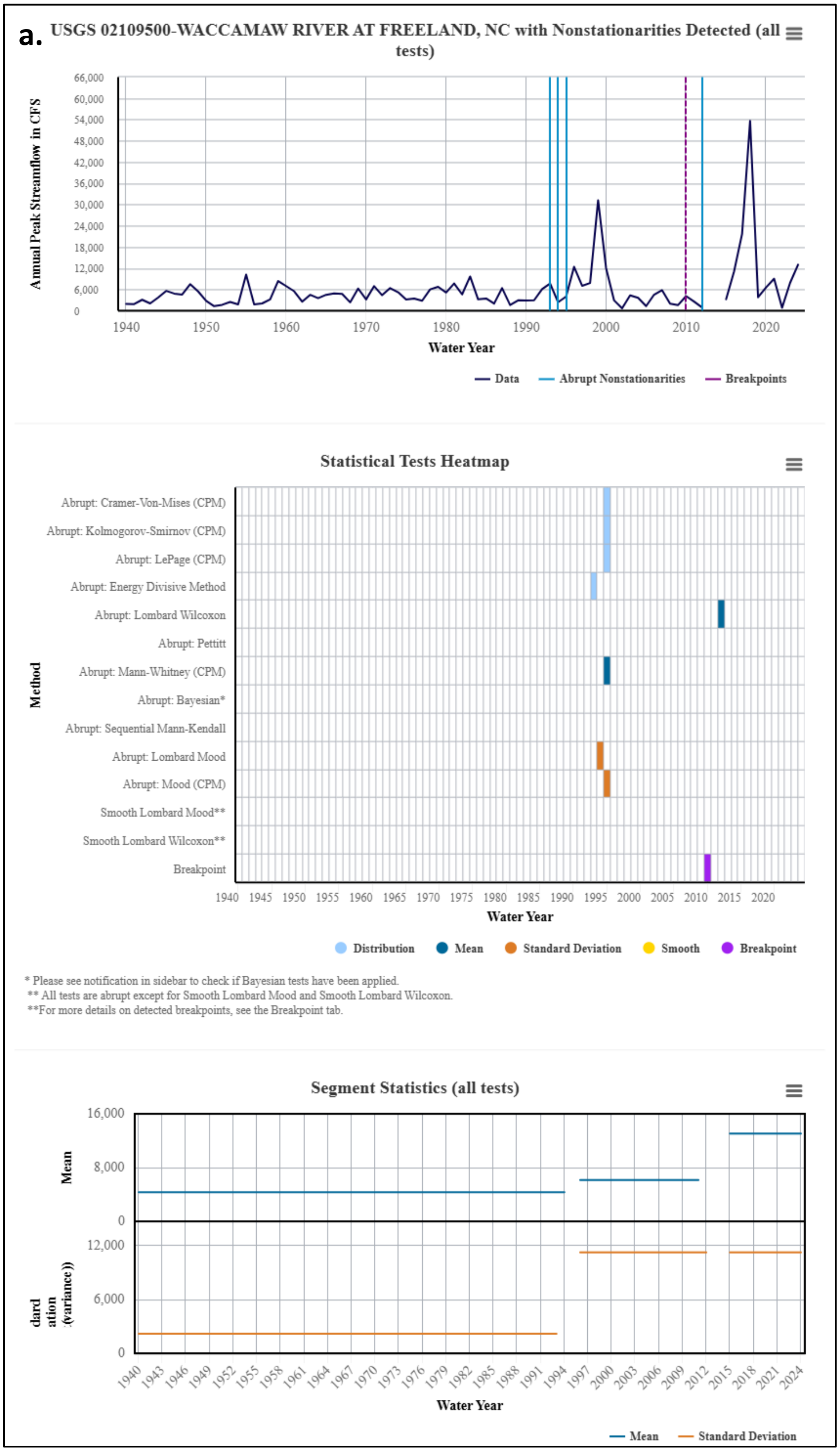
Flooding puts people and infrastructure at risk. Energy infrastructure located along inland watersheds is vulnerable to flooding during heavy precipitation events. Heavy precipitation from more intense and frequent storms can cause significant damage to public and private structures such as homes, roads, utility services, etc. Vulnerable populations are most at risk from flooding and may have difficulty evacuating when necessary. Flooding poses a threat to archaeological and historic sites on floodplains across all three physiographic regions and within every river basin in the state. Increased or more frequent flooding may inundate and potentially destroy more cultural resources.

The intensity of the strongest rainfall is likely to increase with warming of the oceans and atmosphere, leading to greater damage to people, communities, our economy and natural resources from more intense hurricanes and accompanying flooding and precipitation. Sea surface temperature increased during the 20th century and continues to rise, enhancing precipitation in the project area. More frequent flooding will impact inland habitats, fisheries, and the protective services that natural areas provide to local communities. Modeled, future trends toward intensifying, short-duration extreme precipitation and elevated streamflow provide strong empirical justification for the precipitation sensitivity analysis and validate the hydrologic assumptions applied throughout this report.

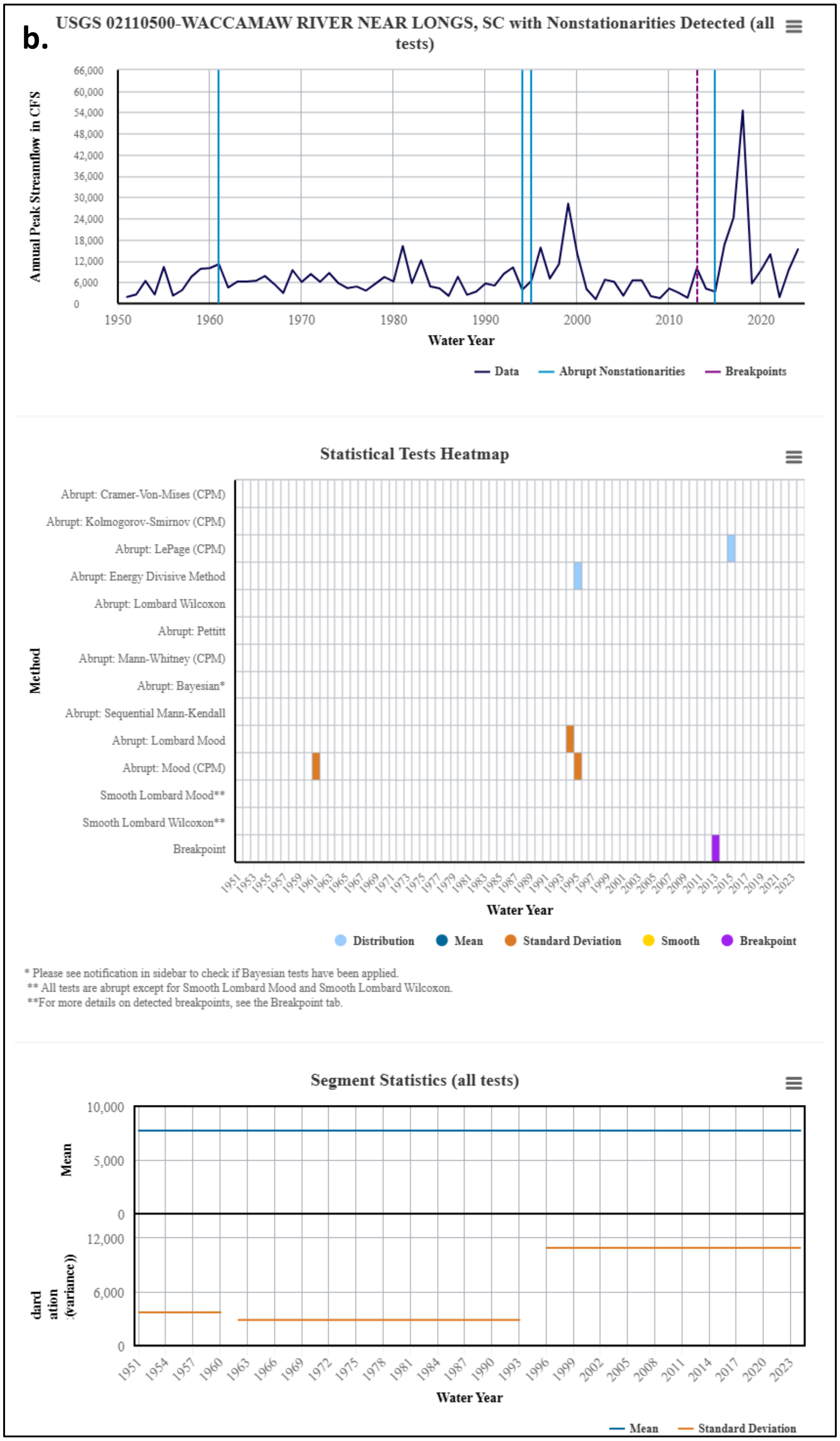
E HISTORIC ANALYSIS-NONSTATIONARITY DETECTION

In addition to future trends, the evaluation of observed historical time series within the Waccamaw River basin was conducted to detect evidence of nonstationarity. Recognizing that the assumption of hydrologic stationarity is no longer a default standard, historical streamflow and precipitation gauges were assessed for statistically significant shifts or trends over time. When combined with project-specific trends derived from the updated Comprehensive Hydrology Assessment Tool (CHAT), the data indicates that both observed records and modeled future hydrometeorology point toward increased variability. This evidence of nonstationarity directly informs the subsequent residual risk evaluation by establishing a baseline that accounts for shifting hydrological extremes.

The assumption that discharge datasets are stationary (their statistical characteristics are unchanging) in time underlies many traditional hydrologic analyses. Statistical tests can be used to test this assumption using techniques incorporated into the USACE Time Series Toolbox (TST) and described in ECB 2026-1. The TST is a web-based tool to perform these tests on hydrometeorological datasets including annual peak streamflow at U.S. Geological Survey (USGS) stream gages. The primary objective of this study is to evaluate flood control operations, so the focus of this investigation is the high flow regime that is best represented by annual instantaneous peak flows.



* Please see notification in sidebar to check if Bayesian tests have been applied.
** All tests are abrupt except for Smooth Lombard Mood and Smooth Lombard Wilcoxon.
**For more details on detected breakpoints, see the Breakpoint tab.



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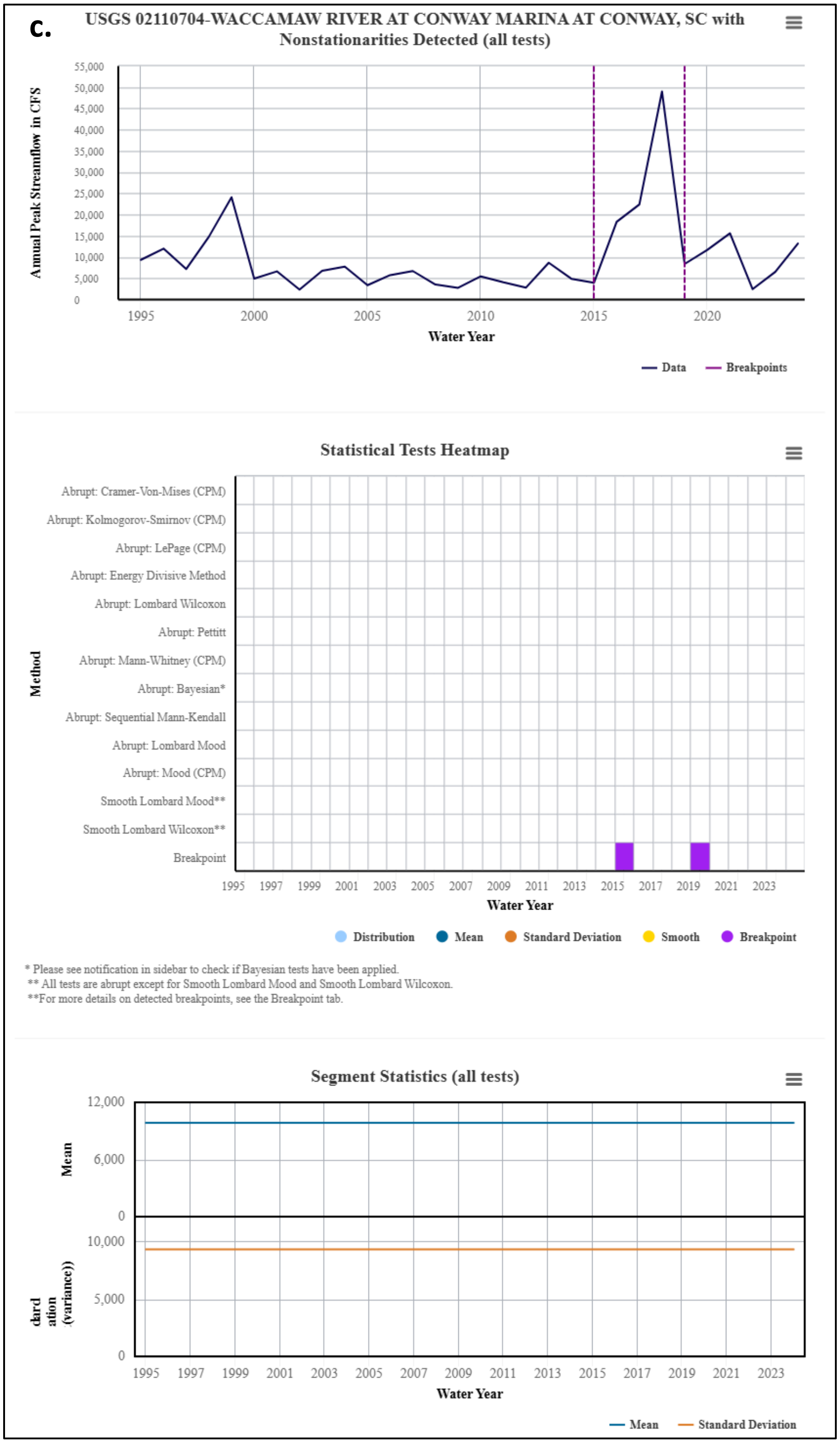
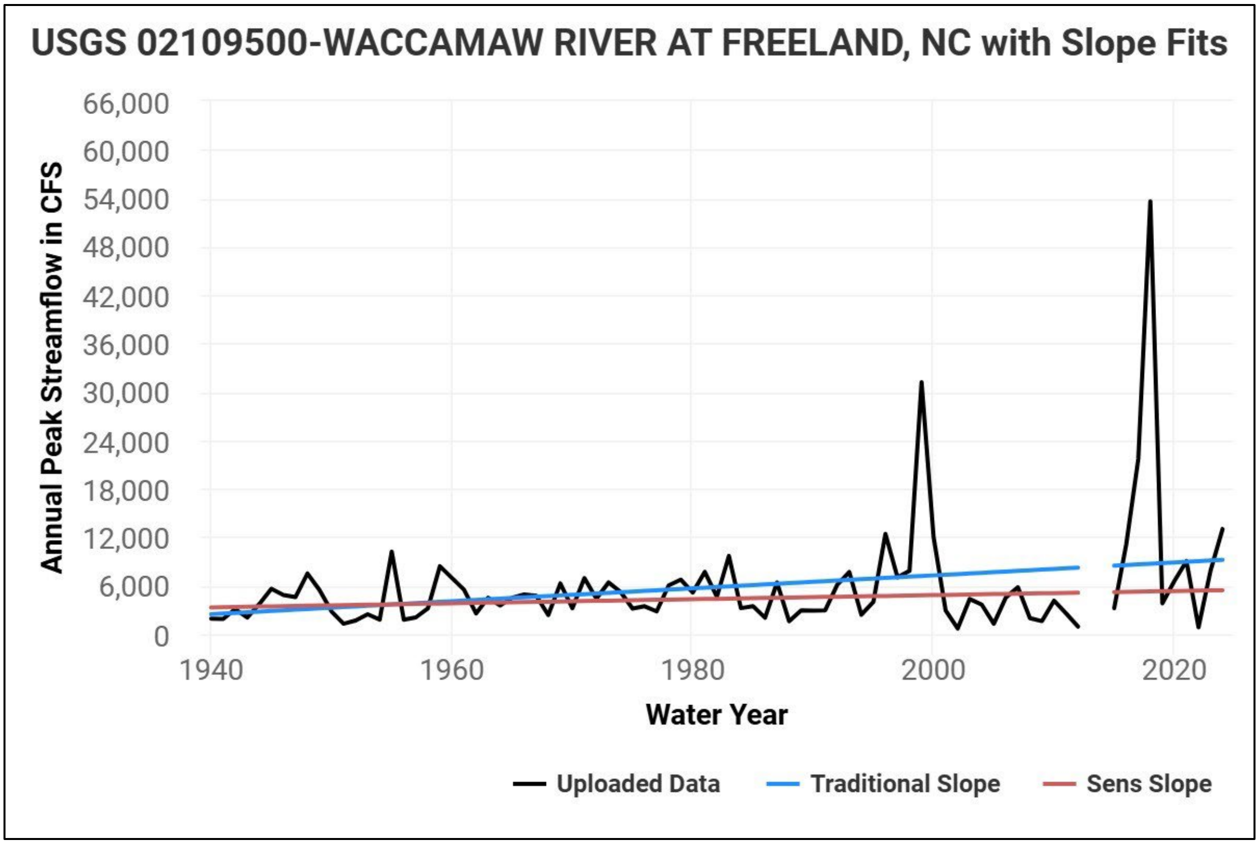


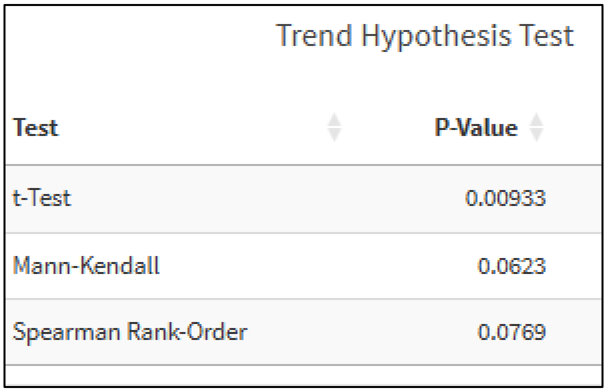
Figure E-1: Time Serries Toolbox Changepoint Analysis- (a) USGS 02109500 Waccamaw River at Freeland, NC, (b) USGS 02110500 Waccamaw River near Longs, SC (c) USGS 0211704 Waccamaw River at Conway Marina

Figure E-1 shows results for USGS gage 02109500 Waccamaw River gage at Freeland, NC, USGS Gage 02110500 Waccamaw River at Longs, SC and USGS 0211704 Waccamaw River at Conway Marina with the changepoints detected and the segment statistics from the data. This annual peak streamflow dataset span is evaluated from 1940-2024, 1951-2024, and 1995-2024, respectively and consists of 83, 74, and 30 data points. The gages capture 680, 1,110, and 1,440 square miles of drainage area, respectively, of the Waccamaw River. This evaluated portion of the Waccamaw River watershed is generally unregulated.

Evidence of 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 evidence of nonstationarity 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.

The Waccamaw River at Freeland record is missing two years of consecutive data between 2013-2014. For the Waccamaw River at Freeland there is strong evidence of nonstationarity in 1995 with six methods pointing to evidence of change in overall statistical distribution, mean, and standard deviation. Both the mean and variance increase substantially when the portions of the record pre-1995 and post-1995 are compared. The mean increases from about 5,300 cfs to 8,700 cfs and the standard deviation increases from about 2,200 cfs to 11,300 cfs. When the annual peak record at Freeland is evaluated for evidence of monotonic trends there is only moderate evidence (p-values are less than 0.01) of an increasing trend regardless of whether the full period of record or the period of record prior to 1995 is evaluated. This is illustrated by Figure E-2.





Trend Hypothesis Test

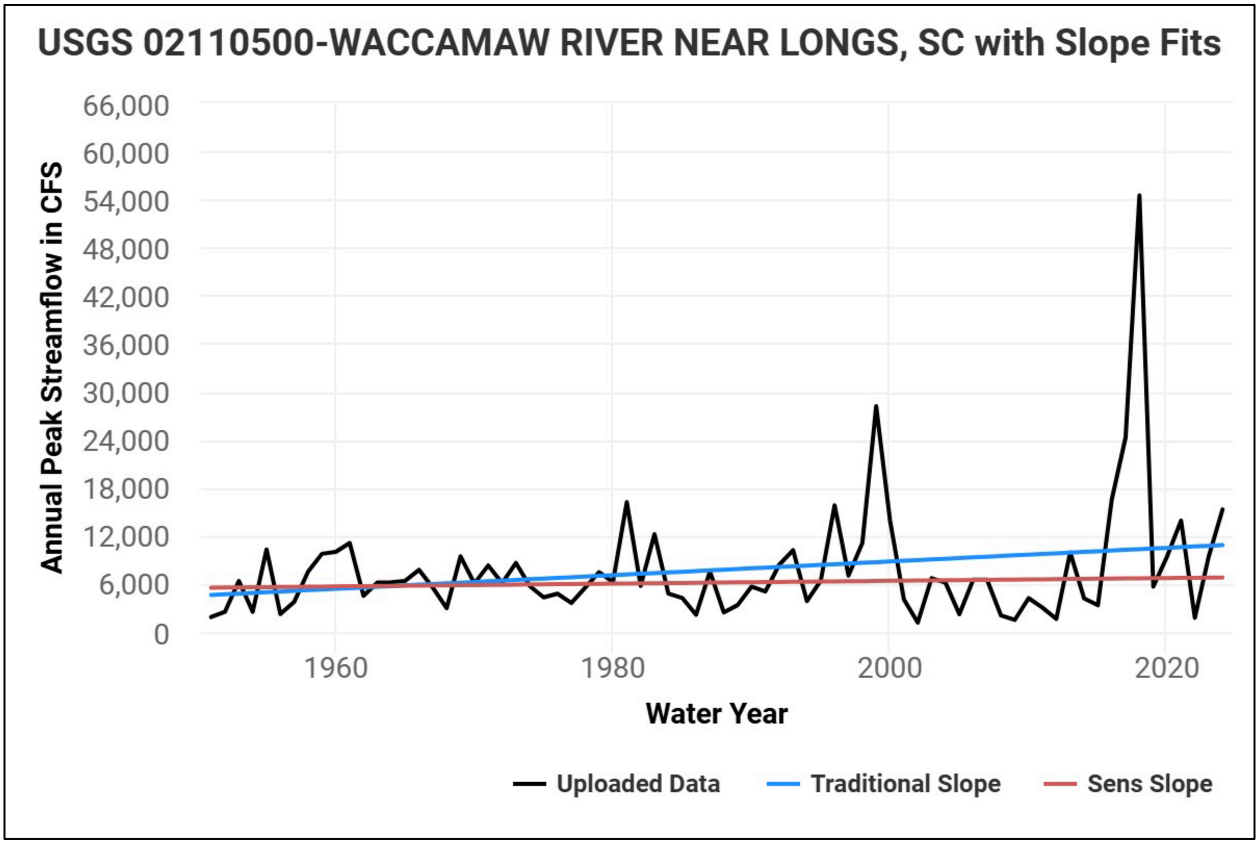
Test	P-Value
t-Test	0.00933
Mann-Kendall	0.0623
Spearman Rank-Order	0.0769

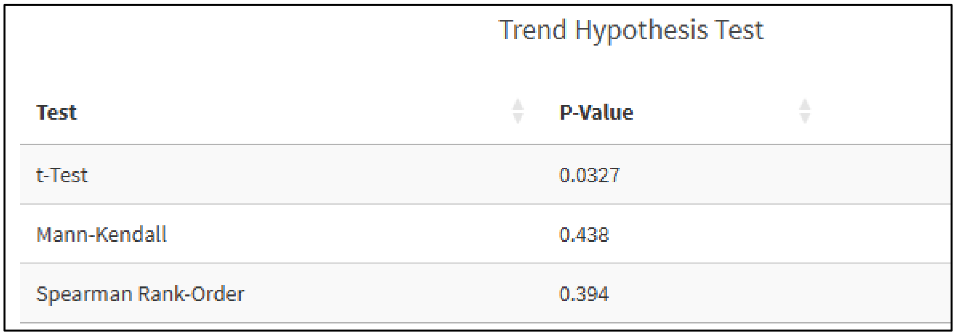
Figure E-2: Time Serries Toolbox Trend Analysis- USGS 02109500 Waccamaw River at Freeland, NC

Similarly, an evaluation of the stationarity assumption at USGS gage 02110500 Waccamaw River near Longs, SC was conducted using the TST. The watershed is unregulated upstream of Longs, SC. A few of the peak streamflow measurements at this site are denoted as estimates (e.g., 1951, 1982, and 2006). There is consensus between test pointing to evidence of a change in standard deviation circa 1995 with three methods pointing to abrupt changepoints. The standard deviation of the record increases from about 2,900 cfs to 10,900 cfs.

A monotonic trend analysis on the entire Period of Record (POR) (1951-2024) detected a statistically significant increasing trend using the t-Test (p-value=0.03), however the other two trend tests provide for insufficient evidence of a statistically significant trend (Mann-Kendall Test p-value=0.44 and the Spearman

Rank-Order p-value=0.39) . There is no evidence of a statistically significant trend when only the portion of the data pre-1995 is analyzed. Based on this evaluation evidence of nonstationarity is moderately robust.





Trend Hypothesis Test

Test	P-Value
t-Test	0.0327
Mann-Kendall	0.438
Spearman Rank-Order	0.394

Figure E-3: Time Series Toolbox Trend Analysis- USGS 02110500 Waccamaw River near Longs, SC

Figure E-1(c) shows TST nonstationarity analysis results for the Waccamaw River at Conway Marina at Conway, SC. There is no consensus between methods pointing to evidence of change. Only the breakpoint test points a shift in the dataset in 2015 and 2019. There is no evidence of a statistically significant trend in the dataset (p-values associated with the t-test, Mann-Kendall, and Spearman Rank-Order tests are greater than 0.33). This could be in part driven by the limited record length. Only 30-years of data is available (1995-2024), which is the minimum suitable amount for application of these statistical methods. Ideally this approach should be applied to long-term records with 50-years of record or more.

Evidence of change in streamflows along the Waccamaw River is driven by changing hydrometeorological conditions, land use alterations, and human activities. These changes likely result, at least in part from the synergy between shifting hydrometeorological patterns and rapid urbanization, which reduces natural infiltration through increased impervious surfaces. This "hardened" watershed creates a flashier hydrologic response, where human activities and land-use alterations amplify the impacts of extreme precipitation and elevate future residual risk.

F COMPREHENSIVE HYDROLOGY ASSESSMENT TOOL

The Comprehensive Hydrology Assessment Tool (CHAT) was used to assess future changes to hydrometeorology in the watershed. In CHAT, temperature and precipitation outputs are available at an 8-digit HUC watershed scale. Flows presented in the CHAT are available at a stream segment scale and were generated using an unregulated Variable Infiltration Capacity (VIC) model and routed using the MizuRoute method. Future streamflow, temperature, and precipitation are derived from statistically downscaled (using LOCA) outputs derived from 32 Coupled Model Intercomparison Project Phase 5 (CMIP5) designated models. CHAT output should not be directly compared to observations.

The tool displays the ensemble range of CMIP model-based outputs for water years 1951-2099 and includes robustness metrics which gives users insight into the inter-model agreement and the robustness of the change signal modeled for a selected variable relative to historic variability. Outputs are presented for two assumed scenarios representing pathways to a moderate (RCP 4.5) and high (RCP 8.5) increase in radiative forcings by the end of the century. Trend evaluation is performed on the annual, inter-model means for both a historic period (water years 1951-2005) and a future period (water years 2006-2099). Additionally, the tool provides a visualization of epoch-based differences in simulated monthly and annual historic versus future period streamflow, precipitation, and temperature model outputs.

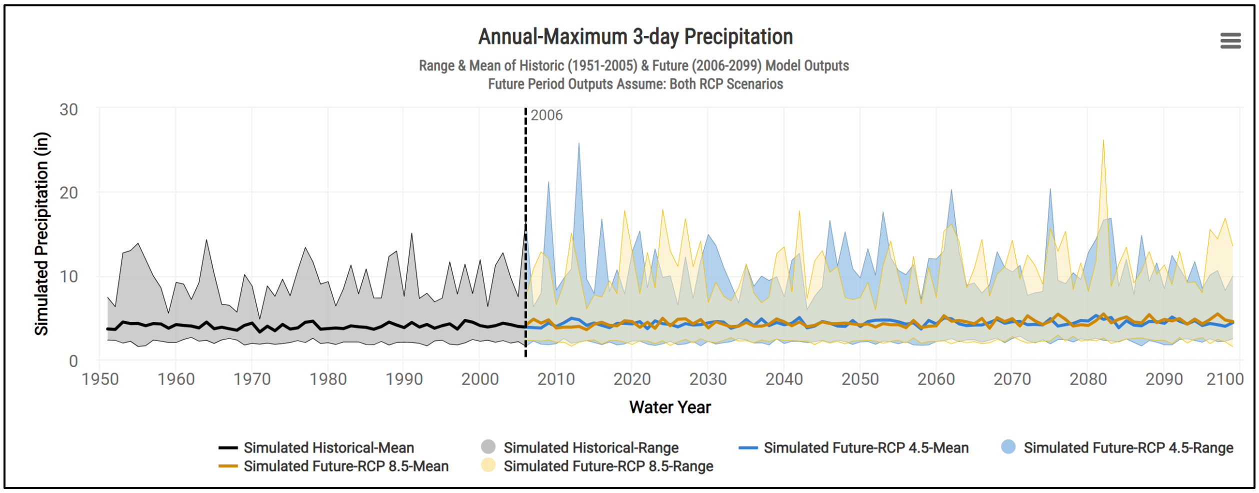
The Waccamaw River is in 4-digit HUC 0304 the Pee Dee watershed. Streamflow is evaluated for two portions of the watershed using the CHAT: the portion encompassing the USGS located near Longs, SC and the gage located at Conway Marina at Conway, SC. Figure F-1a shows the range of maximum 3-day precipitation and annual average temperature output (inter-model spread shaded area) presented in the CHAT for HUC 03040206. Figure F-2 displays annual maximum monthly streamflow output for Waccamaw stream segment ID: 03002007 near Longs, SC. Figure F-3 displays annual maximum monthly streamflow output for Waccamaw stream segment ID: 03002020 at Conway, SC. Different color schemes are applied to differentiate between the different time periods and scenarios (RCPs) being modeled.

CHAT is used to evaluate whether there is an indication of whether there is agreement between CMIP5 models in terms of the directionality of change and whether the signal of change emerges from the historic variability at both mid-century and end of century. CHAT is also used to evaluate the inter-model means for evidence of a statistically significant trend.

There is not a strong change signal in annual maximum 3-day precipitation when RCP 4.5 is evaluated. When RCP 8.5 is assumed, there is a weak increasing signal towards end of century. For the future period, 2006 to 2099, there is a statistically significant increasing trend (p-value<0.05) regardless of which scenario is evaluated. There is a strong increasing signal in annual-mean 1-day temperature regardless of which scenario or time horizon is analyzed. For the future period, 2006 to 2099, there is a statistically significant increasing trend (p-value<0.05) regardless of which scenario is evaluated.

For stream segment 03002007 near Longs, SC, when RCP 4.5 is evaluated, there is a weak increasing signal in streamflow at mid-century but no signal towards the end of the century. When RCP 8.5 is evaluated, there is no signal in streamflow at mid-century but a weak increasing signal towards the end of the century. For the future period, 2006 to 2099, there is no trend (p-values>0.05) in the inter-model mean of annual-maximum mean monthly streamflow when RCP 4.5 is assumed. There is a statistically significant increasing trend when RCP 8.5 is assumed.

For stream segment 03002020 near Conway, SC, when RCP 4.5 is evaluated, there is a weak increasing signal in streamflow at mid-century but no signal towards the end of the century. When RCP 8.5 is evaluated, there is no signal in streamflow at mid-century but a weak increasing signal towards the end of the century. For the future period, 2006 to 2099, there is no trend (p-values>0.05) in the inter-model mean of annual-maximum of mean monthly streamflow when RCP 4.5 is assumed. There is a statistically significant increasing trend when RCP 8.5 is assumed.



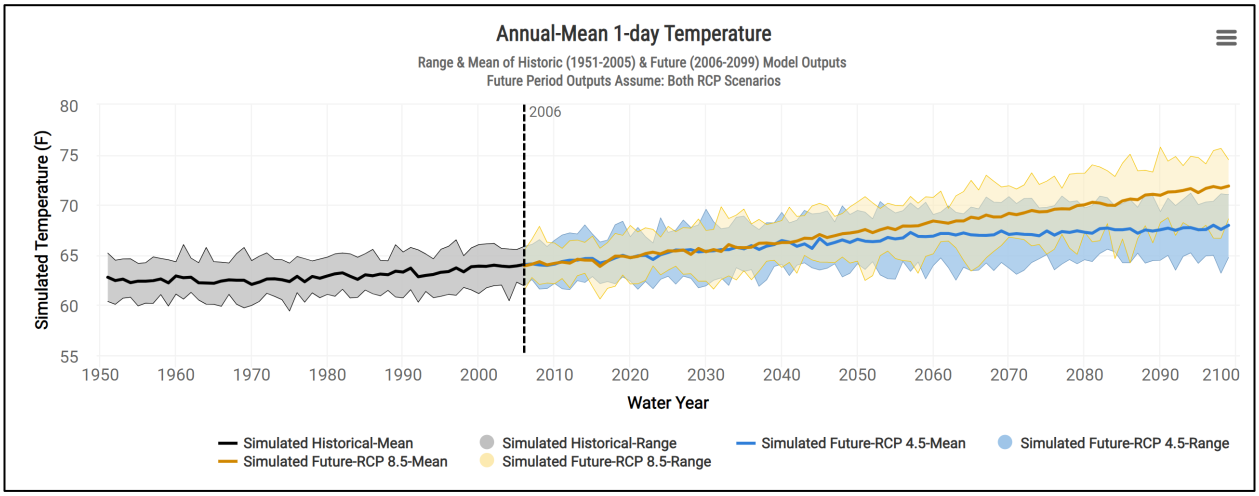


Figure F-1: (a) Annual Maximum 3-day precipitation and (b) Mean 1 Day temperature. 8-digit HUC 03040206 Waccamaw

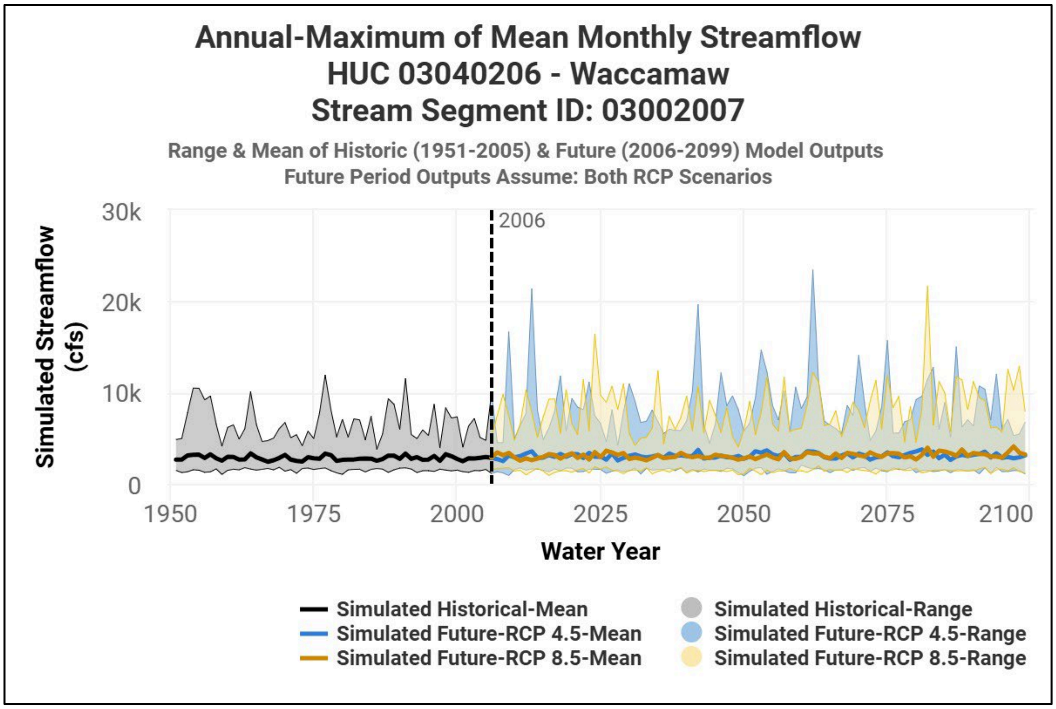


Figure F-2: Annual-Maximum of Mean Monthly Streamflow for Stream Segment 03002007 Waccamaw River near Longs, SC

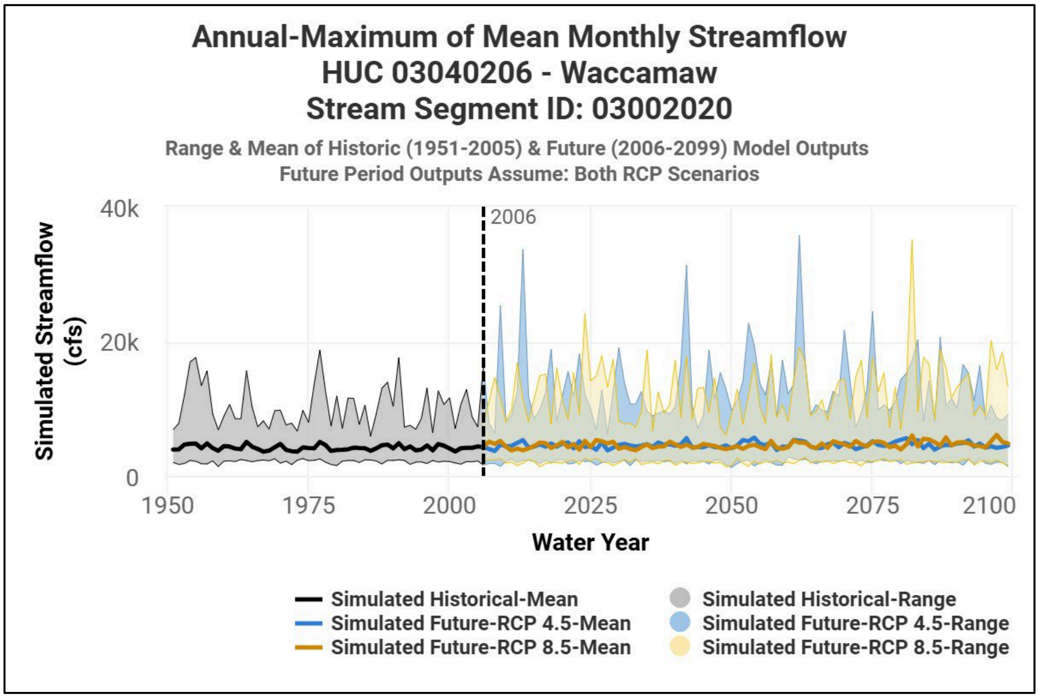


Figure F-3: Annual Maximum Streamflow for segment 03002020 Waccamaw River at Conway, SC

Figure F-1 (a, b, and c) illustrates modeled projections of streamflow and precipitation events for the Waccamaw stream segment (HUC 03040206, Stream ID: 03002020) near Longs, SC, highlighting the

Overall, these findings suggest that continued high emissions could lead to more frequent and intense hydrological extremes by the end of the 21st century, emphasizing the need for proactive planning in flood mitigation and water resource management.

The CHAT analysis indicates a robust increasing signal and indicates a statistically significant increase in mean temperatures throughout the 21st century regardless of RCP evaluated. Within future annual maximum 3-day precipitation output less than 80% of the CMIP5 models evaluated agree on the sign of the change and less than 66% of the models show change greater than variability over the historic period. There is however a statistically significant increasing trend (p-value <0.05) detected in the inter-model mean between 2006 and 2100 for both RCPs.

For both stream segments evaluated there is a weak increasing signal in streamflow circa mid-century (2050) when RCP 4.5 is assumed and a weak increasing signal towards the end-of-century (2085) when RCP 8.5 is assumed. Otherwise, there is no signal indicating a lack of both divergence from historic variability and model agreement. While the inter-model mean of future streamflow outputs exhibit only weak evidence (p-values ~0.2-0.3) of a trend in the RCP 4.5 scenario, both evaluated stream segments demonstrate a statistically significant (p-values<0.05) increasing trend in annual maximum streamflow under the higher-emission RCP 8.5 scenario.

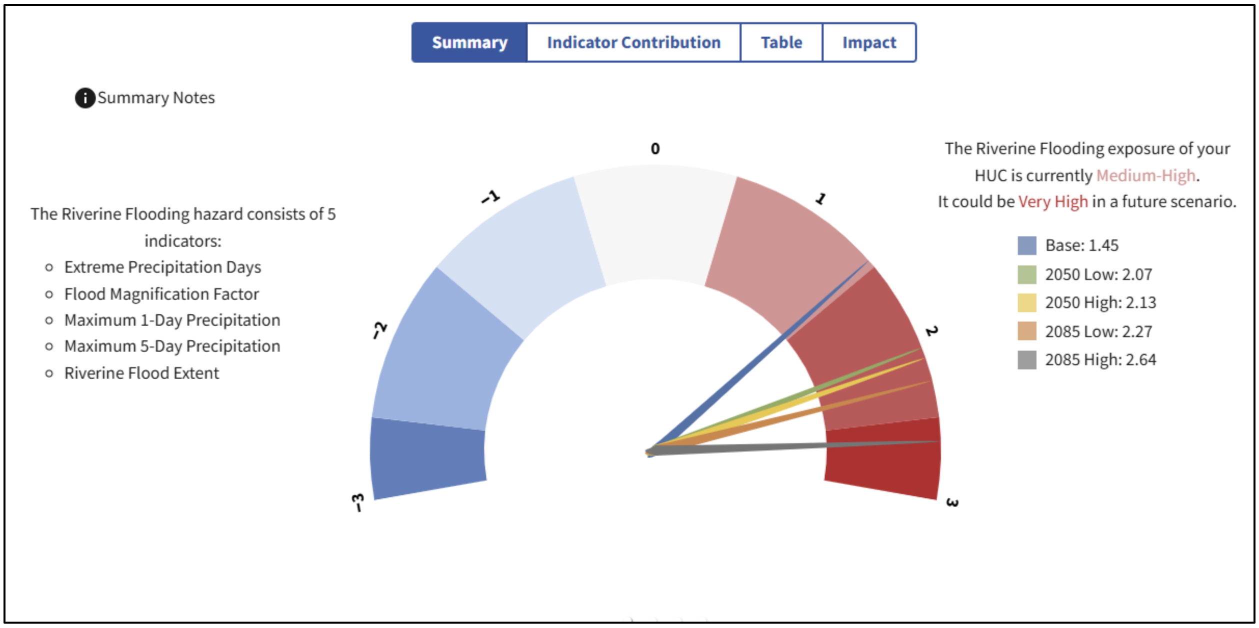
Ultimately, these results indicate that temperatures are likely to increase over the next century relative to historic conditions. However, changes in precipitation extremes and streamflow response are less certain. There is some evidence that both maximum annual precipitation and streamflow will increase in the future.

G VULNERABILITY ASSESSMENT

USACE Screening-Level Civil Works Vulnerability Assessment Tool (CWVAT) is applied to assess relative exposure and sensitivity of the project area to current and future natural hazards. Based on the purpose and relevant hydrometeorological factors for the project, the selected hazard category analyzed for this project is Riverine Flooding, and the indicators analyzed for this project are Flood Magnification, Extreme Precipitation Days, and Maximum 1-day Precipitation.

CWVAT measures the exposure for a selected 8-digit HUC watershed by using a "z-score." This score shows how much the exposure to a hazard (e.g., Riverine Flooding) in one watershed differs from the median of all HUC-8 watersheds across the U.S. Each hazard in CWVAT is assessed using a combination of indicators variables (e.g., Extreme Precipitation Days).

The tool computes indicator variable output and hazard scores for two future epochs, defined as 30-year periods centered on either 2050 or 2085. The 2050 epoch is consistent with medium-range planning (mid-century), while the 2085 epoch is used for long-range planning (late-century). The tool also contains a Base epoch (1950-2005) representing historical information as a baseline. In addition to presenting exposure scores and indicator variable output by epoch, the tool also features two scenarios (low and high) to capture the range of potential future conditions that projects might experience. For most indicator variables, CWVAT defines the low and high scenarios based on RCP 4.5 and 8.5 CMIP5 hydrometeorology products, representing pathways to a given change in radiative forcing by the end of the century.



The Riverine Flooding hazard consists of 5 indicators:

- Extreme Precipitation Days
- Flood Magnification Factor
- Maximum 1-Day Precipitation
- Maximum 5-Day Precipitation
- Riverine Flood Extent

The Riverine Flooding exposure of your HUC is currently Medium-High. It could be Very High in a future scenario.

Figure G-1: Riverine flooding Exposure Score change over time for the Waccamaw watershed

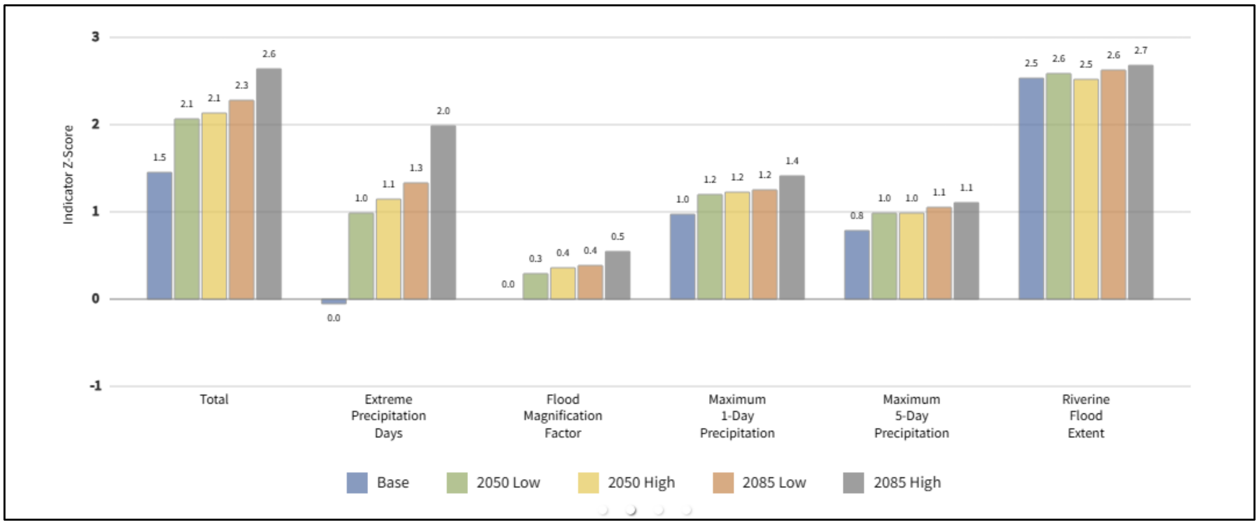


Figure G-2: Riverine Flooding indicator variable contributions over time - Waccamaw watershed

As shown in Figure G-1, the Waccamaw Watershed (HUC 03040206) currently has a medium-high exposure rating to riverine flooding and has a very high exposure rating for the 2085 high scenario. Thus, it is considered relatively vulnerable to changing conditions impacts for the flood risk reduction business line. The primary driver of this flood risk vulnerability for all scenarios and epochs is the riverine flood extent. Flood Extent is the area in acres of the watershed area that may be inundated during the 1% annual exceedance probability (AEP) riverine flood event. Other important contributors at this location include changes in maximum 1- and 5- day precipitation and the number of extreme precipitation days. Notably the number of extreme precipitation days increases by 6% when the 2085 low scenario is compared to the baseline and by 14% when the 2085 high scenario is compared to the baseline.

H CONCLUSIONS

There is strong consensus within the peer-reviewed literature that air temperatures will increase throughout the next century (USACE 2015). Evaluation of modeled future temperature output using the CHAT supports this finding. There is a lack of consensus with respect to potential future changes in annual precipitation; however, there is consensus that the intensity and frequency of extreme storm events will increase within the South Atlantic-Gulf Region throughout the 21st century. The CHAT indicates some evidence pointing to an increasing trend in future, modeled 3-day maximum precipitation coinciding with a weak increasing signal towards the end of the century, when RCP 8.5 is assumed.

Clear consensus is lacking in literature on how future changes in temperature and precipitation will alter future hydrology within the region. Evaluation of observed peak streamflow times series in the study area for evidence of an observed increase in flood flows also pointed to mixed results. Despite this lack of consensus, evidence pointing to increases in the frequency and intensity of extreme storm events have important implications for flood risk management within the Waccamaw River basin.

I SENSITIVITY ANALYSIS

I.1.1 Climate Trends and Literature Basis

Observed and projected climate trends indicate increasing precipitation intensity across the southeastern United States. The U.S. Global Change Research Program Fourth National Climate Assessment documents that heavy precipitation events have increased in frequency and intensity and are expected to continue increasing with warming temperatures. Regional summaries from National Oceanic and Atmospheric Administration (NOAA) and the state of South Carolina similarly indicate upward trends in extreme rainfall and associated flood risk in the Carolinas. In addition, the U.S. Army Corps of Engineers (2015) Climate Change Literature Synthesis identifies increasing precipitation intensity and hydrologic variability as key considerations for long-term water resources planning. These sources collectively support the use of a sensitivity-based approach to evaluate how increased rainfall may affect watershed response and project performance (Majidzadeh et al., 2017).

I.1.2 Sensitivity Analysis Methodology

The precipitation change factor used in this sensitivity analysis was obtained from the North Carolina Institute for Climate Studies (NCICS) climate data portal, developed under research supported by the Strategic Environmental Research and Development Program (SERDP) and the National Oceanic and Atmospheric Administration (NOAA). The tool seeks to transform precipitation intensity-frequency-duration (IDF) values analogous to those typically used for design (i.e., NOAA Atlas 14 IDF relationships) into relationships that account for nonstationary climate conditions with varying degrees of climate change (Kunkel et al., 2020).

This tool provides location-specific projections of extreme precipitation defined using two approaches. The first approach applies Localized Constructed Analogs (LOCA) statistically downscaled, Coupled Model Intercomparison Project Phase 5(CMIP5) global climate model (GCM) precipitation outputs. This approach “uses a statistical method known as generalized extreme value (GEV) applied to the downscaled precipitation dataset, where changes in extreme precipitation rates, both historically and from global climate models, are calculated and used to project changes in IDF values by modifying existing IDF values based on a stationary climate (Kunkel et al., 2020)." The second method makes use of meteorologic co-variates calculated from GCM simulations of past and future climate known to contribute to extreme precipitation rates (i.e., precipitable water and large-scale weather systems). These co-variates were used to transform IDF values from stationary to non-stationary estimates. The tool provides output for a moderate and high emission scenario (RCP 4.5 and RCMP 8.5, respectively) and seven future, 30-year target periods centered on 2025, 2035, 2045, 2055, 2065, 2075, and 2085.

For this study, data were extracted directly from a central location (Latitude 33.85559, Longitude -78.9368) within the Waccamaw River Watershed near Conway, SC, allowing the analysis to reflect regional climate characteristics of the coastal Carolinas rather than relying on broad national-scale averages. The NCICS methodology evaluates changes in precipitation IDF statistics (e.g., 96-hour, 1% AEP events) relative to NOAA Atlas 14 baseline, precipitation Intensity-Duration-Frequency (IDF) design values. This enables a consistent comparison between historical observations and future conditions. While the tool is intended for research and screening-level applications, it provides a scientifically grounded and regionally appropriate basis for evaluating potential changes in extreme precipitation relevant to watershed-scale hydrologic response.

For this analysis, the RCP 4.5 scenario centered on approximately 2075 was selected to represent a moderate emissions pathway. The NCICS dataset indicates an approximate 14.6% increase in the 96-hour, 1% annual exceedance probability (AEP) precipitation event relative to NOAA Atlas 14 values. This corresponds to an increase from approximately 12.68 inches to 14.53 inches. This increase was applied uniformly as a scaling factor to the NOAA Atlas 14 precipitation input within the HEC-HMS model to evaluate watershed response under elevated rainfall conditions. With a 14.6% increase in the 1% AEP rainfall event the water surface profile rises two feet which would be enough to exceed the culvert's freeboard of 1.5 feet.

I.1.3 Assumptions and Limitations

This sensitivity analysis is subject to several simplifying assumptions and sources of uncertainty including:

- The applied precipitation change factor represents a single scenario and does not capture the full range of potential future climate conditions (e.g., higher-end scenarios such as RCP 8.5).
- The NCICS projections are derived from downscaled GCM ensembles, which introduce uncertainty related to model selection, emissions pathways, and downscaling methodology. This is particularly significant in coastal regions where model performance may be more variable.
- The analysis assumes a uniform scaling of precipitation, which does not account for potential changes in storm temporal distribution, spatial variability, or temperature driven changes in watershed antecedent conditions (e.g., increases in evapotranspiration).
- The reported 90% confidence intervals associated with both Atlas 14 and NCICS future precipitation values primarily reflect statistical uncertainty in precipitation frequency estimation and do not fully capture the broader climate modeling uncertainty across the climate modeling chain.

Given these factors, results should be interpreted as screening-level indicators of sensitivity, rather than predictive outcomes.

For the Waccamaw River, these changing conditions act as compounding stressors. Studies show that heavier rainfall events significantly increase the flushing of stormwater runoff and organic matter into the main river stem (Majidzadeh et al., 2017). Simultaneously, rising temperatures accelerate biological decay and reduce dissolved oxygen solubility, elevating the risk of hypoxia. Ultimately, these peer-reviewed findings validate the necessity of this sensitivity analysis to evaluate alternative hydraulic and economic robustness under future elevated rainfall scenarios, reinforcing resilience without altering the selection of the NED plan.

I.1.4 Results and Implications

Model results indicate that increased precipitation intensity could lead to notable increases in peak water surface elevations, with simulated increases exceeding approximately two feet at Conway, South Carolina under the evaluated scenario. These findings suggest that:

- Project features may experience reduced levels of service under higher rainfall conditions, particularly during extreme events;
- Floodplain extents and conveyance capacity could be more frequently exceeded, increasing residual risk; and
- System performance is sensitive to precipitation assumptions, reinforcing the importance of adaptive and resilient design considerations.

However, because this analysis represents a single sensitivity scenario with substantial uncertainty, results were not used to modify alternative formulation, economic evaluation, or NED plan selection. Instead, they are used to qualitatively inform risk considerations, as discussed subsequently in Section J.

J RESIDUAL RISK

Residual risk for the Waccamaw River FRM project reflects the potential for project features to experience reduced performance under future conditions, including increased precipitation intensity and variability, consistent with U.S. Army Corps of Engineers guidance in ECB 2018-14. Risk is evaluated as a function of both likelihood of occurrence and consequence of non-performance, and categorized as low, moderate, or high based on the combined effect of these factors.

The recommended plan is based on the performance target criteria established at a stage corresponding to damages equal to five percent of those associated with the 1% (100-year) AEP event. With unavoidable uncertainties for estimating flood risk, the recommended plan is expected to handle more common floods, those that have about a 64–68% chance of happening in any given year with a high level of confidence (90%). However, the project is anticipated to be exceeded at least once during any 10-, 30-, or 50-year period. Furthermore, while the project provides flood reduction benefits, the project is not expected to prevent damage during flood events corresponding to the 10%, 4%, 2%, 1%, 0.4%, or 0.2% AEP levels.

Increased frequency and intensity of extreme rainfall events may elevate peak flows and flood volumes beyond those represented in the design conditions, potentially exceeding the hydraulic capacity of certain conveyance features such as cross drains and relief structures.

For the proposed cross drains, the likelihood of these conditions exceeding conveyance capacity more frequently in the future is characterized as moderate. Reduced conveyance capacity will result in negative impacts such as localized increases in flood stage, duration, and extent. As a result, residual risk for the cross-drain features is also characterized as moderate, reflecting the potential for performance degradation overtime in response to extreme events without resulting in system-wide failure. Culvert design is conservative. The current capacity of the culvert is designed to 1.5' of freeboard during a 1% AEP (100-year) flood event. This is half a foot freeboard than is recommended by the South Carolina Department of Transportation (SCDOT) and offers a degree of resilience against long-term hydrometeorological change. However, based on sensitivity analysis conducted using a climate-informed IDF relationship there is evidence that future 1% AEP (100-year) water surface profiles could exceed the culvert's design capacity in the future.

For weir removal, the project is expected to reduce residual risk relative to the without-project condition. Removal of hydraulic control structures increases conveyance efficiency and improves flow continuity, which reduces upstream backwater effects and allows the system to better accommodate higher flows under future conditions. Therefore, the likelihood of adverse impacts associated with weir removal is considered low, and the overall residual risk is low, with the action providing adaptive capacity under a range of future hydrologic conditions.

While changes in tailwater conditions associated with sea level rise could influence downstream water surface elevations, these effects are not expected to significantly alter the hydraulic performance of the upstream proposed features during storm-driven events. For the USACE High SLC scenario plus HAT at year 2085 the water surface profile associated with the 1% (100-year) AEP river profile at a cross-section downstream of proposed features is only 0.05 feet higher relative to baseline conditions. The change in water surface profile would be higher during a moderate riverine event and would also be notably higher at the end of the 100-year adaptation horizon if the high SLC materializes. However, even during these scenarios where SLC impacts would be amplified, the resulting change in water surface profile would still be relatively minimal and substantially less than available freeboard included in the culvert design.

Table J-1 summarizes the residual risk assessment for key project features, including the interaction between projected hydrometeorological and coastal changes and system performance. In general, while increased precipitation may elevate residual risk for some conveyance elements, the recommended plan does not increase flood risk relative to the without-project condition and, in the case of weir removal, is expected to improve system resilience. No features were identified as having high residual risk; therefore, additional structural modifications are not warranted at this stage. However, the results support consideration of adaptive management strategies, such as monitoring and future culvert capacity enhancements, should conditions evolve beyond those designed for.

Table J-1: Residual Risk Assessment for Recommended Plan.

Measure	Trigger	Hazard	Harm	Likelihood	Risk Rating
Weir Removal	Increased precipitation from larger, slower moving storms	Future flood volumes may be larger than at present Large flood volumes may occur more frequently	Improved conveyance reduces upstream flooding potential relative to without project condition	Not Likely	Low
	Projected Relative Sea Level Change (RSLC)	Increased Tailwater elevations at system outfalls	Minor influence on storm driven hydraulics; no meaningful reduction in performance; system remains more susceptible to fluvial flooding	Not Likely	Low
Cross Drains	Increased precipitation from larger, slower moving storms	Future flood volumes may be larger than at present Large flood volumes may occur more frequently	Potential for culvert capacity exceedance leading to localized flooding Conservative culvert design (1.5’ of freeboard at the 1% AEP event)	Moderate Likelihood	Moderate
	Projected Relative Sea Level Change (RSLC)	Higher tidal elevations /backwater at drainage outlets	Limited impact relative to storm-driven flows; system remains more susceptible to fluvial flooding Conservative culvert design (1.5’ of freeboard at the 1% AEP event)	Not Likely	Low

K SEA LEVEL CHANGE ASSESSMENT

Sea level change (SLC) at the Waccamaw River was evaluated following the guidelines presented in USACE Engineer Pamphlet EP 1100-2-1 “Procedures to Evaluate Sea Level Change: Impacts, Responses and Adaptation” (30 Jun 2019). The purpose of the EP was to provide instructional and procedural guidance to analyze and adapt to the direct and indirect physical and ecological effects of projected sea level change on USACE projects and systems of projects needed to implement Engineer Regulation (ER) 1100-2-8162.

ER 1100-2-8162 “Incorporating Sea Level Change in Civil Works Programs” (15 June 2019) provides both a methodology and a procedure for determining a range of SLC estimates based on global sea level change rates, the local historic sea level change rate, the construction (base) year of the project, and the design life of the project. Three estimates are required by the guidance, a Low (Baseline) estimate representing the minimum expected SLC, an Intermediate estimate, and a High estimate representing the maximum expected SLC. The guidance will be used to evaluate the future sea levels, the impacts to the Waccamaw River project during the 50-year period applied for economic analysis and the 100-year adaptation horizon (project life cycle evaluation), and to assess the risk associated with the SLC estimates.

The first step in evaluating sea level change was to identify a nearby NOAA water level gauge with a sufficiently long data record. The analysis was based on the NOAA tide gauge located in Springmaid Pier, Myrtle Beach, South Carolina (Station #8661070), seaward adjacent of Socastee (NOAA 2024b). The gauge is compliant and active with a historic record of 1976 to present, which includes a 2-month data gap in 1976, an 18-month data gap from September 1989 to April 1991, and a 10-month data gap in 2014. Datum information for this gauge is shown in Figure K-1 and Table K-1.

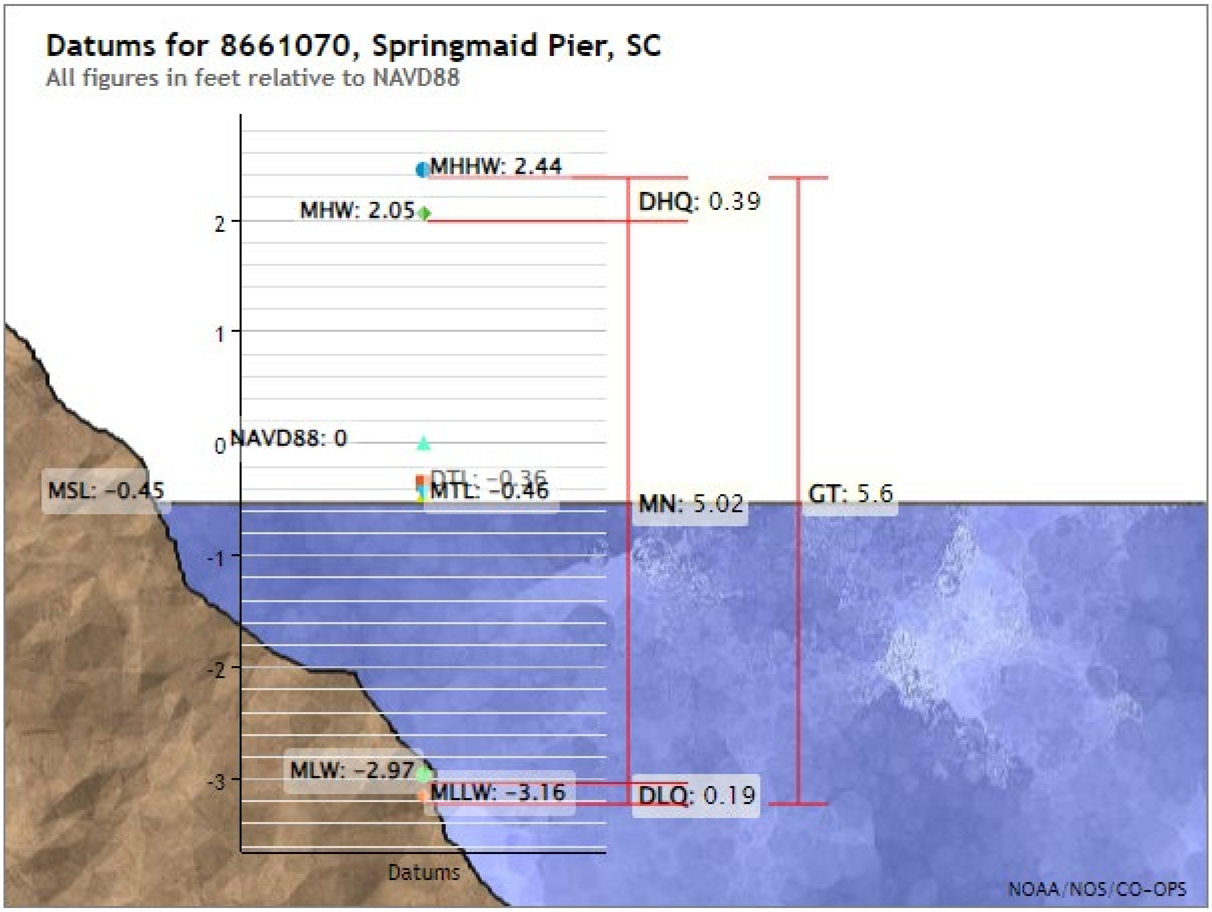


Figure K-1: Datum Information for NOAA Gauge 8661070

Table K-1: Datums for NOAA Gauge 8661070, in Feet Relative to NAVD88.

Datum	Value	Description
MHHW	2.44	Mean Higher-High Water
MHW	2.05	Mean High Water
MTL	-0.46	Mean Tide Level
MSL	-0.45	Mean Sea Level
DTL	-0.36	Mean Diurnal Tide Level
MLW	-2.97	Mean Low Water
MLLW	-3.16	Mean Lower-Low Water
NAVD88	0	North American Vertical Datum of 1988
STND	-32.45	Station Datum
GT	5.6	Great Diurnal Range
MN	5.02	Mean Range of Tide
DHQ	0.39	Mean Diurnal High Water Inequality
DLQ	0.19	Mean Diurnal Low Water Inequality
HWI	12.31	Greenwich High Water Interval (in hours)
LWI	6.17	Greenwich Low Water Interval (in hours)

Datum	Value	Description
Max Tide	7.3	Highest Observed Tide
Max Tide Date & Time	9/30/2022 21:30	Highest Observed Tide Date & Time
Min Tide	-7.05	Lowest Observed Tide
Min Tide Date & Time	3/14/1993 0:18	Lowest Observed Tide Date & Time
HAT	4.16	Highest Astronomical Tide
HAT Date & Time	10/27/2011 12:06	HAT Date and Time
LAT	-4.7	Lowest Astronomical Tide
LAT Date & Time	2/20/2019 6:36	LAT Date and Time

From Figure K-2 the linear relative sea level trend for this gauge is 3.29 mm/yr (0.0108 ft/yr) with a 95% confidence interval of +/- 0.480 mm/yr (0.00157 ft/yr) based on monthly mean sea level data collected from 1957 to 2024. For the 50-year analysis of 2035 to 2085 this is equivalent to an increase of 0.165 m (0.540 ft) in sea level. Regional sea level trends for stations on the central east coast are shown in Figure K-3. Stations directly to the north of the project location show a lower sea level trend, while stations directly to the south show a higher sea level trend. Coastal dynamics for the project location are closer to the dynamics at the Springmaid Pier, SC location. Note that the nearby NOAA gauges at Southport (8659084) and Wrightsville Beach (8658163) are non-compliant with less than 50-years of data and with interrupted records.

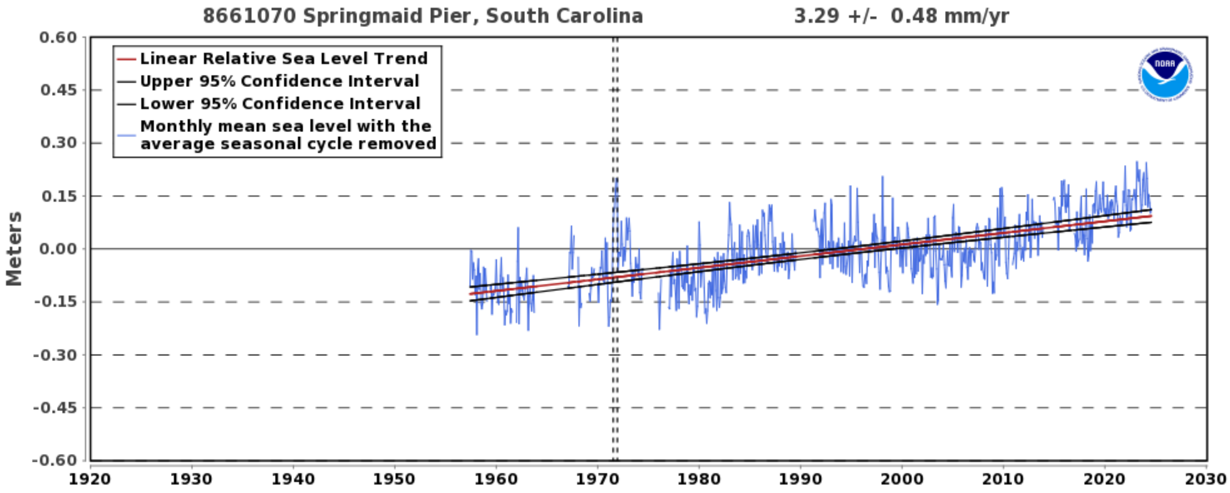


Figure K-2: Relative Sea Level Trend, NOAA Gauge 8661070

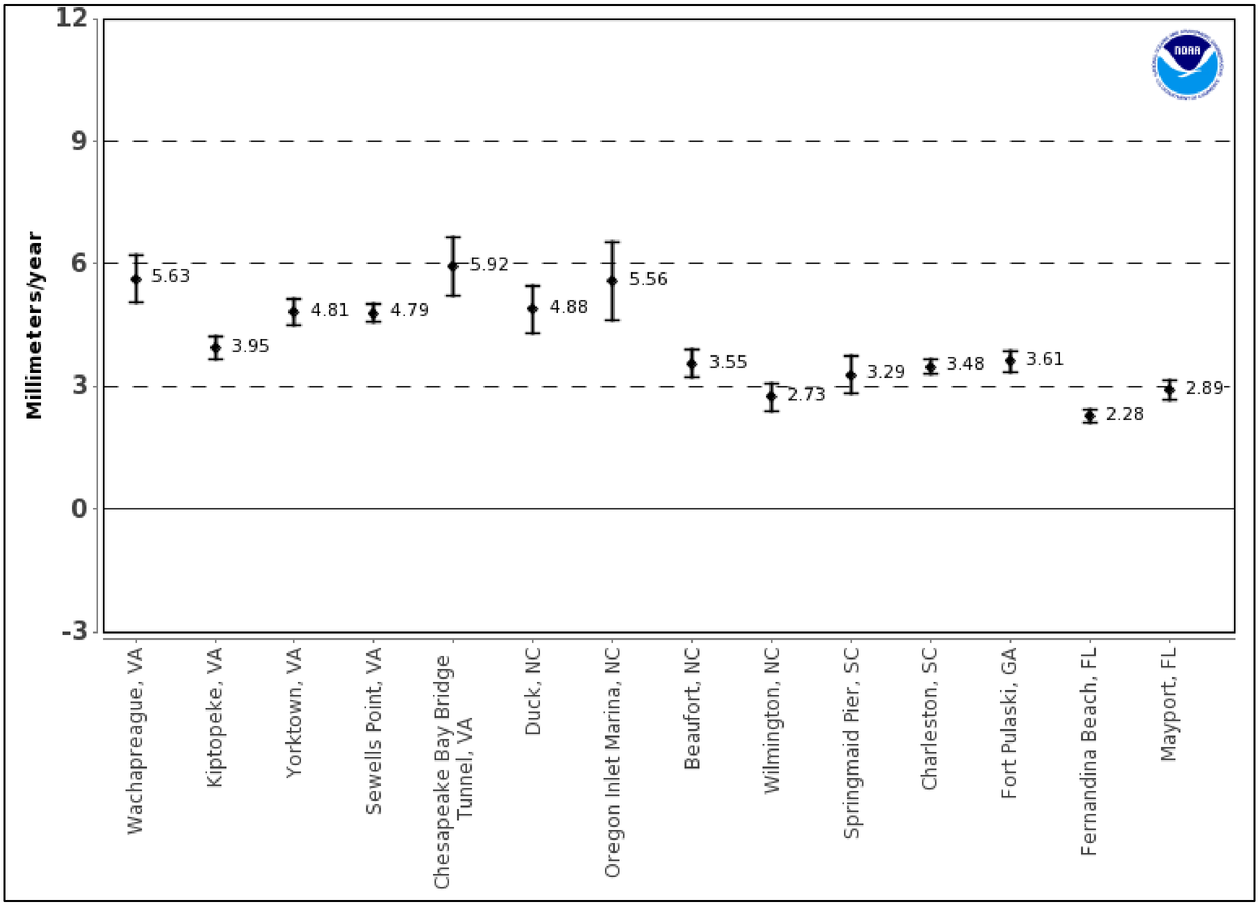


Figure K-3: Regional Sea Level Trends

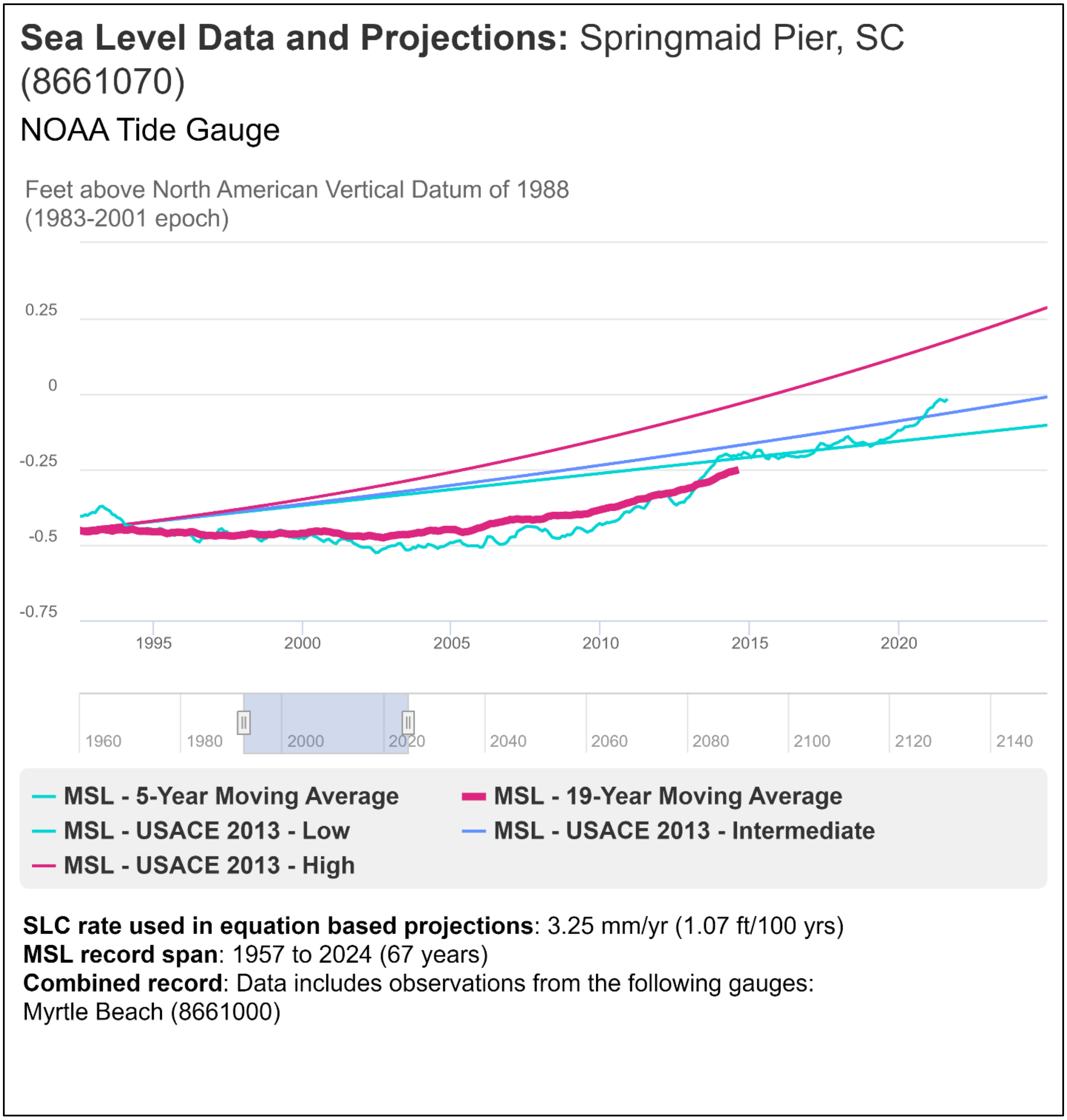
The second step in evaluating SLC was to assess future trends, mainly in determining whether the rate of sea level rise accelerates in the future. Any future increase or decrease in this long-term trend along with land subsidence and glacial rebound needs to be addressed throughout the 50-year period adopted for economic analysis and across the 100-year adaptation horizon (project lifecycle).

The USACE online Sea Level Analysis Tool (SLAT) was used to determine the current rate of SLC observed and the future trends in the rate of SLC. Extreme water levels (EWL) incorporated into the tool are based on statistical probabilities using recorded historic monthly extreme water level values. The SLAT is used to compare actual mean sea level (MSL) values and trends for specific NOAA tide gauges with the USACE SLC scenarios as described in ER 1100-2-8162 and EP 1100-2-1. The SLAT calculates the USACE Low, Intermediate, and High sea level change scenarios based on global and local change effects. Historical MSL is represented by either 19-year or 5-year midpoint moving averages. Guidance in using the SLAT and technical background is provided in USACE "Sea Level Analysis Tool (SLAT) – Technical Documentation."

The SLAT was used to evaluate the NOAA Springmaid Pier gauge data. The regionally corrected rate of 3.29 mm/yr (0.0108 ft/yr) was used as the rate of SLC and was sourced from Technical Report NOS CO-OPS 065 (Zervas et al., 2013) and accounts for vertical land motion. This regional rate is also the Low USACE estimated SLC rate.

Figure K-4 presents the results of the SLAT focused on trends between 1992 to 2024. The light blue line represents the 5-year moving average and the heavy dark pink line represents the 19-year moving average. The 19-year average is useful in that this represents the moon’s metonic cycle and the tidal datum epoch. These estimates are referenced to the midpoint of the latest National Tidal Datum Epoch (NTDE), 1992. The reader is referred to ER 1100-2-8162 for a detailed explanation of the procedure, equations employed, and variables included to account for the eustatic change as well as site specific uplift or subsidence to develop corrected rates. The red line is the High SLC prediction, the blue is the Intermediate and the green is the Low rate prediction.

From Figure K-4 it can be noted that the 19-year moving average is below the Low SLC curve and the 5-year moving average is above the Intermediate curve, but both are sloping upward.



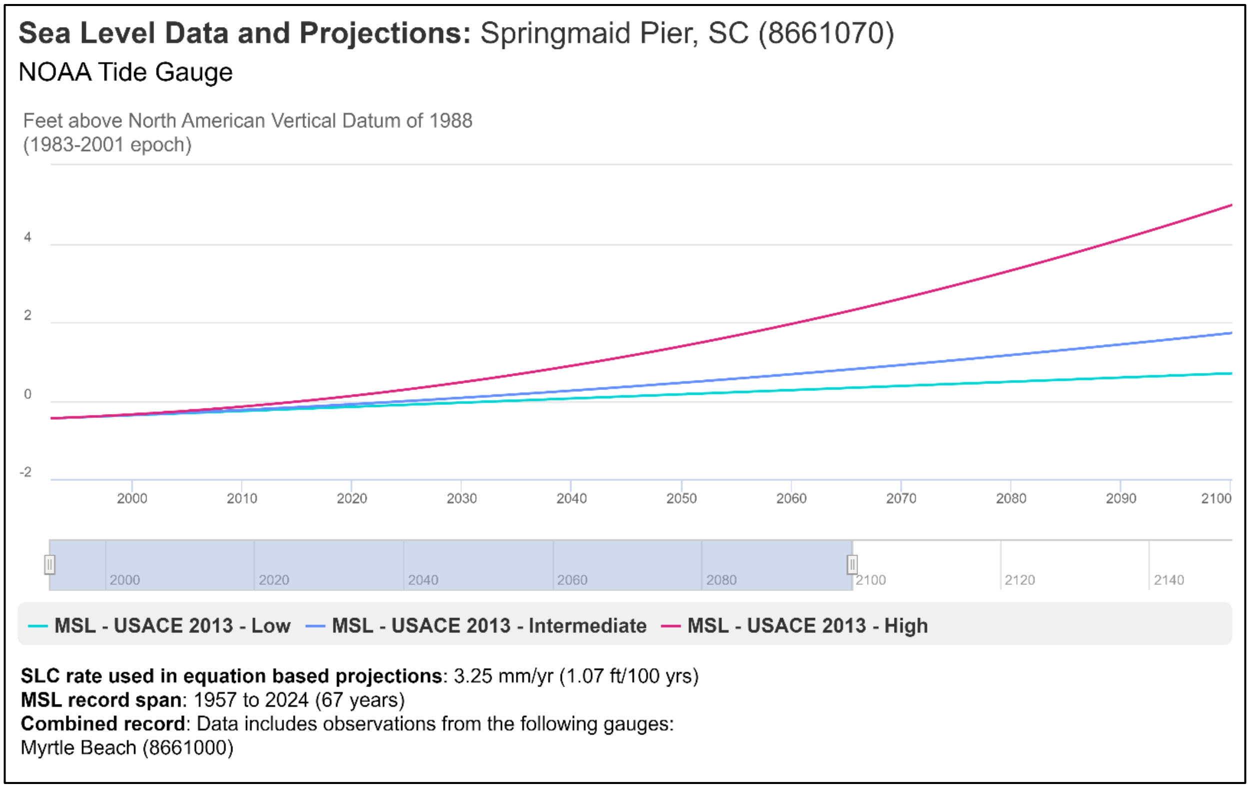
Sea Level Data and Projections: Springmaid Pier, SC (8661070)

NOAA Tide Gauge

SLC rate used in equation based projections: 3.25 mm/yr (1.07 ft/100 yrs)
MSL record span: 1957 to 2024 (67 years)
Combined record: Data includes observations from the following gauges:
Myrtle Beach (8661000)

Figure K-4: Springmaid Pier NOAA Gauge #8661070 SLC with 19-Year and 5-Year Moving Average

The future USACE sea level predictions for the Waccamaw River project based on the Springmaid Pier gauge are provided in Table K-2. For the 2035 to 2085 period the predicted change in sea level for the Low scenario (regional rate) is 0.54 ft, the Intermediate SLC increase was 1.14 ft and the High SLC increase was 3.06 ft. For the 2035 to 2135 period the predicted change is 1.07 ft, 2.72 ft, and 7.96 ft. The future SLC curves are shown in Figure K-5. For comparison, the regionalized NOAA estimates (NOAA et al., 2012) are also provided in Table K-2.



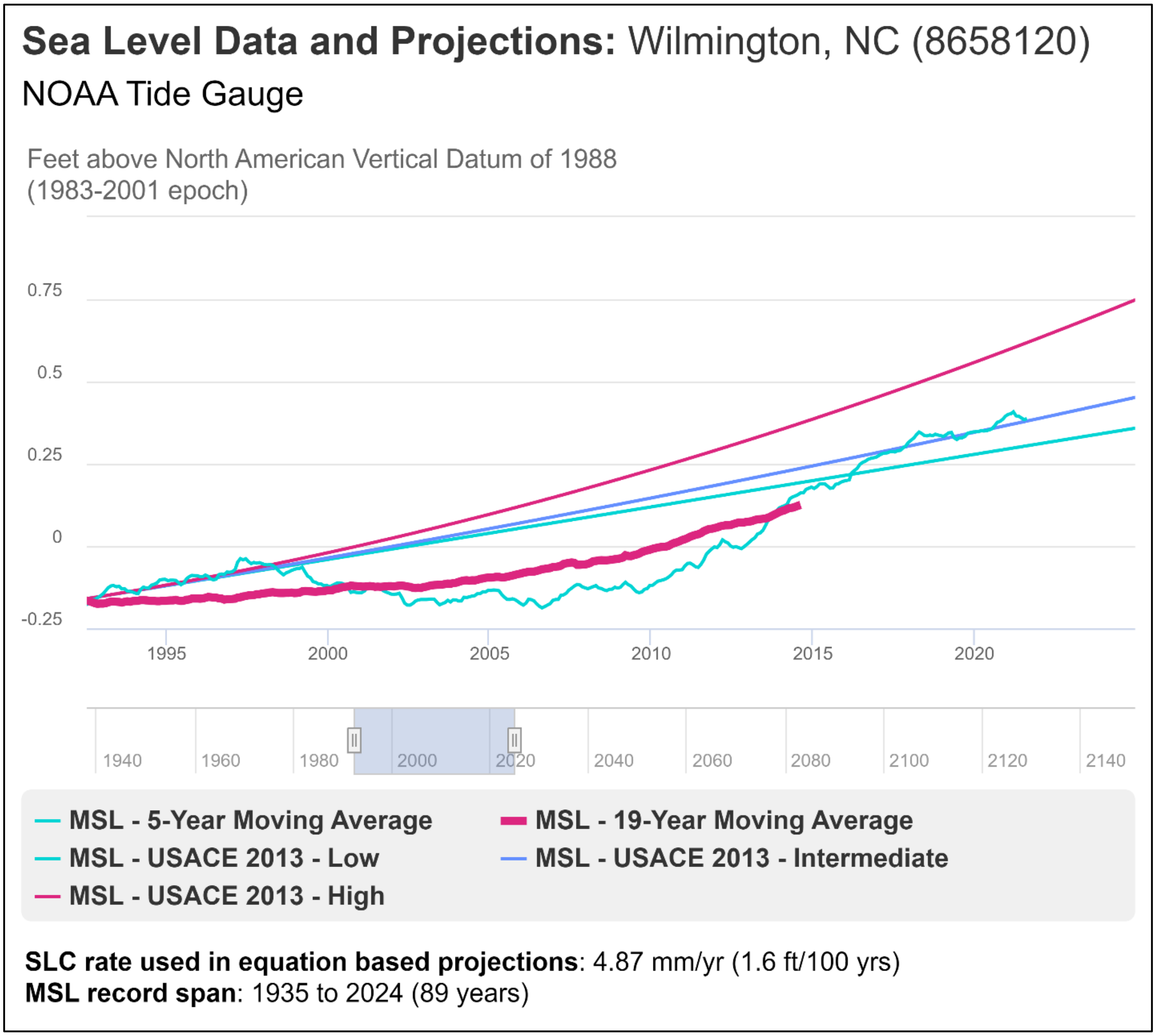
SLC rate used in equation based projections: 3.25 mm/yr (1.07 ft/100 yrs)
MSL record span: 1957 to 2024 (67 years)
Combined record: Data includes observations from the following gauges:
Myrtle Beach (8661000)

Figure K-5: Springmaid Pier Gauge USACE Sea Level Change Predictions, 1992 to 2100

Table K-2: USACE and NOAA 50-Year and 100-Year Sea Level Change Estimates (ft relative to NAVD88).

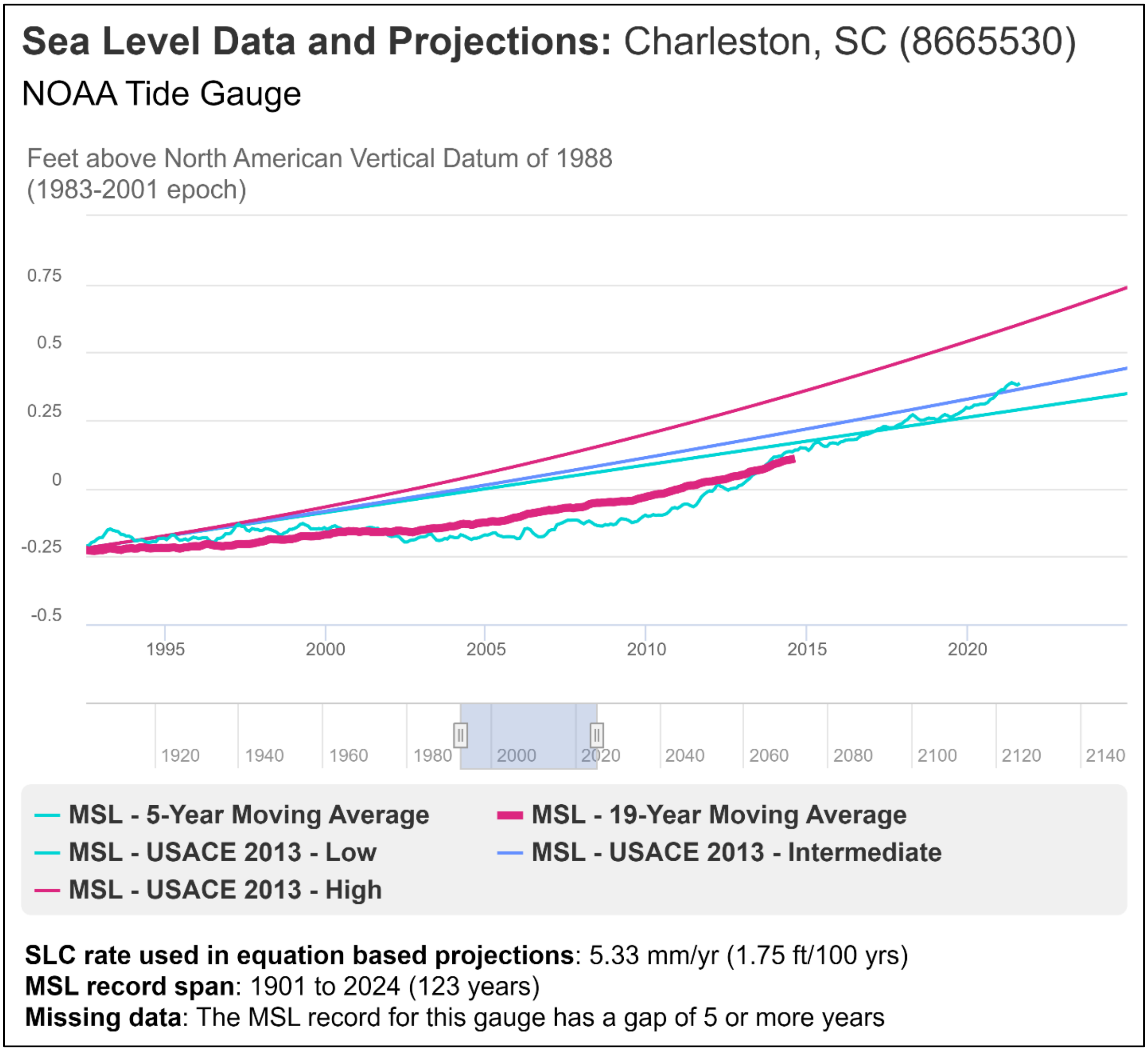
Project Year	Year	USACE			NOAA			
		Low	Int	High	Low	Int-Low	Int-High	High
Center of NTDE	1992	-0.45	-0.45	-0.45	-0.45	-0.45	-0.45	-0.45
Base	2024	-0.106	-0.016	0.28	-0.106	-0.016	0.19	0.426
	2030	-0.04	0.08	0.49	-0.04	0.08	0.37	0.69
Start	2035	0.01	0.175	0.705	0.01	0.175	0.545	0.965
	2040	0.06	0.27	0.92	0.06	0.27	0.72	1.24
	2050	0.17	0.47	1.42	0.17	0.47	1.13	1.89
	2060	0.28	0.69	1.99	0.28	0.69	1.6	2.64
	2070	0.38	0.92	2.64	0.38	0.92	2.12	3.5
	2080	0.49	1.18	3.36	0.49	1.18	2.7	4.45
End	2085	0.55	1.32	3.76	0.55	1.32	3.02	4.98
	2090	0.6	1.45	4.16	0.6	1.45	3.34	5.51
	2100	0.7	1.74	5.03	0.7	1.74	4.03	6.67
	2110	0.81	2.05	5.97	0.81	2.05	4.79	7.93
	2120	0.92	2.37	6.99	0.92	2.37	5.6	9.3
	2130	1.02	2.71	8.08	1.02	2.71	6.46	10.77
	2135	1.08	2.90	8.67	1.08	2.90	6.93	11.56
50-Year Increase =		0.54	1.14	3.06	0.54	1.14	2.48	4.02
100-Year Increase =		1.07	2.72	7.96	1.07	2.72	6.38	10.59

To compare the predicted Springmaid Pier USACE SLC trends with regional NOAA gauges, the tide gauges # 8658120 at Wilmington, NC (Figure -6) 80 miles to the north and # 8665520 at Charleston, SC (Figure -7) 85 miles to the south were reviewed. The 1992 to 2022 SLC trends with the 19-year and 5-year moving averages are provided in Figures K-6 and K-7. Both gauges are active and compliant with over 40-years of data. The Wilmington gauge shows a trend closer to the high rate for the 19-year moving average and above the high rate for the 5-year moving average. For the Charleston gauge the 19-year average is near the intermediate rate while the 5-year moving average is closer to the high rate.



SLC rate used in equation based projections: 4.87 mm/yr (1.6 ft/100 yrs)
MSL record span: 1935 to 2024 (89 years)

Figure K-6: Wilmington, NC NOAA Gauge # 8658120 SLC with 19-Year and 5-Year Moving Average



SLC rate used in equation based projections: 5.33 mm/yr (1.75 ft/100 yrs)
MSL record span: 1901 to 2024 (123 years)
Missing data: The MSL record for this gauge has a gap of 5 or more years

Figure K-7: Charleston, SC NOAA Gauge # 8665530 SLC with 19-Year and 5-Year Moving Average

The effect of SLC on overall hazard levels for the Waccamaw River project was analyzed using a sensitivity analysis. All three USACE curves were considered to account for possible SLC scenarios, in accordance with ER 1100-2-8162. Simulations were run with and without SLC and extreme, high tidal conditions at the downstream (coastal) boundary condition in HEC-RAS. SLC was simulated using each of the three USACE SLC curves relative to NAVD88 for the end year 2085. Each simulation was run using the same 1% AEP upstream boundary conditions, but with varying downstream boundary conditions for no SLC, with each of the three 2085 SLC conditions (change relative to the 1992 MSL datum), and with the highest astronomical tide (HAT, 4.16 ft) in addition to the 2085 SLC conditions. The 1% (100-year) AEP water surface level was applied as the upstream boundary condition. This event can be used to evaluate efficacy of culvert design because the culvert is designed to pass the 1% (100-year) AEP event plus 1.5 feet of freeboard. Cross-section plots of the maximum water surface elevations were created for each location in Figure -8 and presented in Appendix A1, Section 5.3.4. Project features are located upstream of the circled cross-section near Socastee and Conway.

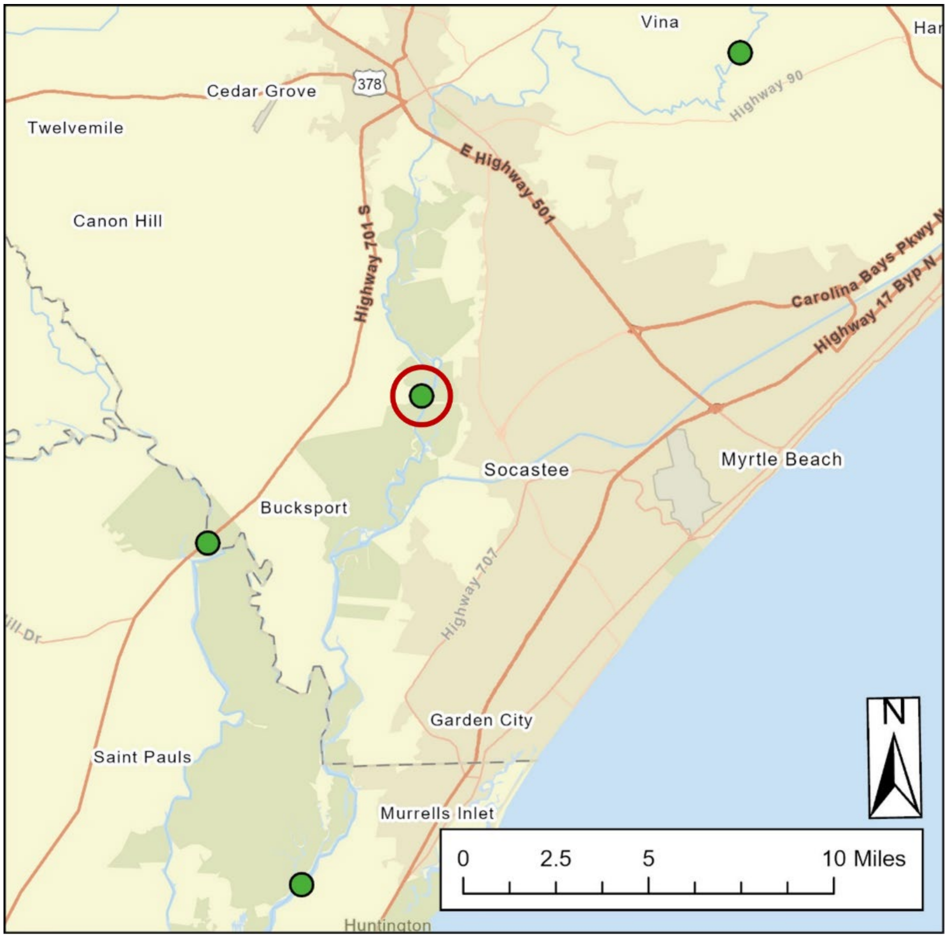


Figure K-8: Cross-Section Locations *(closest cross section downstream of project features circled)*.

The chosen plan of action was optimized for all SLC scenarios throughout the economic period of analysis (2035-2085). The analysis demonstrates that coastal influences and projected sea level change will not affect the performance of the proposed measures. Using the "High" estimate, which represents the maximum anticipated SLC anticipated through 2085, results indicate that high tides and SLC do not contribute to the overall water level and storm surge is dissipated prior to the arrival of the primary fluvial flooding. Notably, the change in sea level associated with the 2085 High SLC scenario is greater than the SLC projected across the project's adaptation horizon (2035-2135) when either the Low or Intermediate SLC scenario is assumed. At the downstream boundary of the study area (southernmost green circle in Figure -8), the maximum water levels at the center of the river were 6.88 ft for no SLC, 7.32 ft for with-SLC, and 8.32 ft for with-SLC and tides. This is a 1.44 ft difference. However, further upstream at the cross-section closest to study features, the change in water surface elevation is only 0.05 feet.

The effects of SLC and high tides would be more substantial during more moderate riverine conditions and would increase across the project's full adaptation horizon through year 2135. However, although this might result in increased flood risk throughout the study area relative to present-day conditions, SLC and tidal impacts will not be substantial enough to exceed the designed culvert capacity. The culvert is designed to the 1% (100-year) AEP flood event with 1.5' of freeboard. For all SLC scenarios, fluvial forces will remain the prominent driver of flood elevations and damages.

An analysis was also done for the nonlinearity of SLC related to surge-only annual exceedance frequencies (AEFs). Coastal Hazards System (CHS) wave and water level data for each of the three SLC values modeled in CHS (0 ft, 2.73 ft, and 7.35 ft) were gathered at each location of interest: Longs, Bucksport, Conway, Socastee, and the HEC-RAS model boundary (Figure -9). In CHS, the three SLC values represent “zero” sea level change (MSL datum referenced to 1992) and two higher SLC conditions relative to the same datum, which can be used in comparison with localized, project-specific values. For this study, 2.73 ft aligns with the USACE Intermediate curve for 2130 or the High curve for 2070 and 7.35 ft aligns with the USACE High curve for 2132. The nonlinear residual, or the water level increase in addition to storm surge and SLC, was calculated as the total water level AEF with surge and SLC, minus the original storm surge water level AEF without SLC, minus the SLC value for each AEF and displayed in Table K-3 below. It is important to note that these values are for residual from coastal effects only; the order of magnitude is much lower than that of fluvial events in the study location.

Table K-3 shows that estimating effects of SLC by linear addition will introduce minimal error in the accuracy of stillwater level (SWL) AEF estimates compared to overall changes in water levels from flooding. Therefore, the project delivery team concluded that a linear addition of SLC and surge to the total SWL is acceptable in analyzing model results. This allows modelers to estimate the total SWL for scenarios with SLC without having to run the model with each SLC option. Instead, a sensitivity analysis was run in HEC-RAS (Appendix A-1, Section E.3.4.6) to confirm these assumptions.

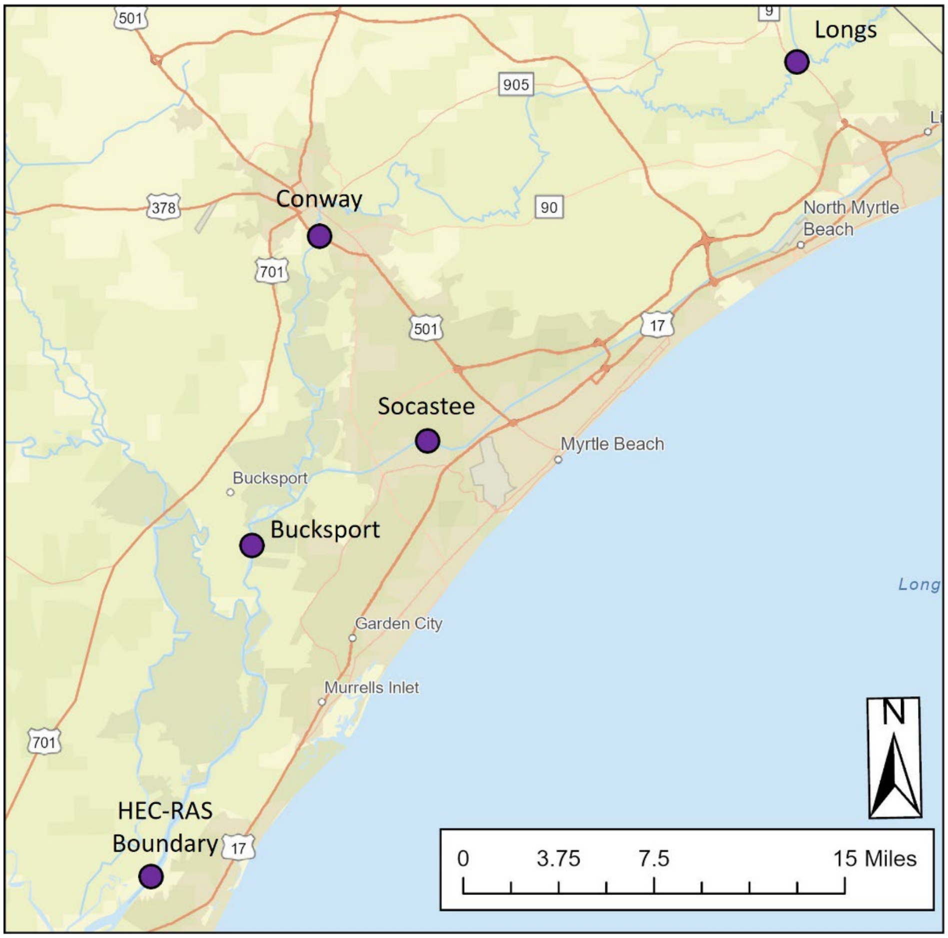


Figure K-9: CHS Point Locations

Table K-3: Nonlinear SWL Residual from Storm Surge.

Location	Annual Exceedance Frequency [Average Nonlinear SWL Residual in feet per foot SLC]						
	50%	20%	10%	5%	2%	1%	0.2%
Longs	0.18	0.13	0.07	0.06	0.06	0.07	0.07
Conway	-0.03	-0.02	-0.01	-0.01	-0.01	0.00	0.00
Socastee	0.09	0.11	0.11	0.11	0.11	0.12	0.16
Bucksport	-0.04	-0.03	-0.02	-0.02	-0.01	-0.01	0.00
HEC-RAS Boundary	-0.01	0.00	0.00	-0.01	-0.02	-0.04	-0.05

The EP 1100-2-1 guidance on how to plan and implement adaptation to changing sea level was used. Because focus areas in this study are far enough inland such that minimal effects of SLC are realized and damages are driven by fluvial flooding, future sea levels will thus have minimal impact on the adaptation plan.

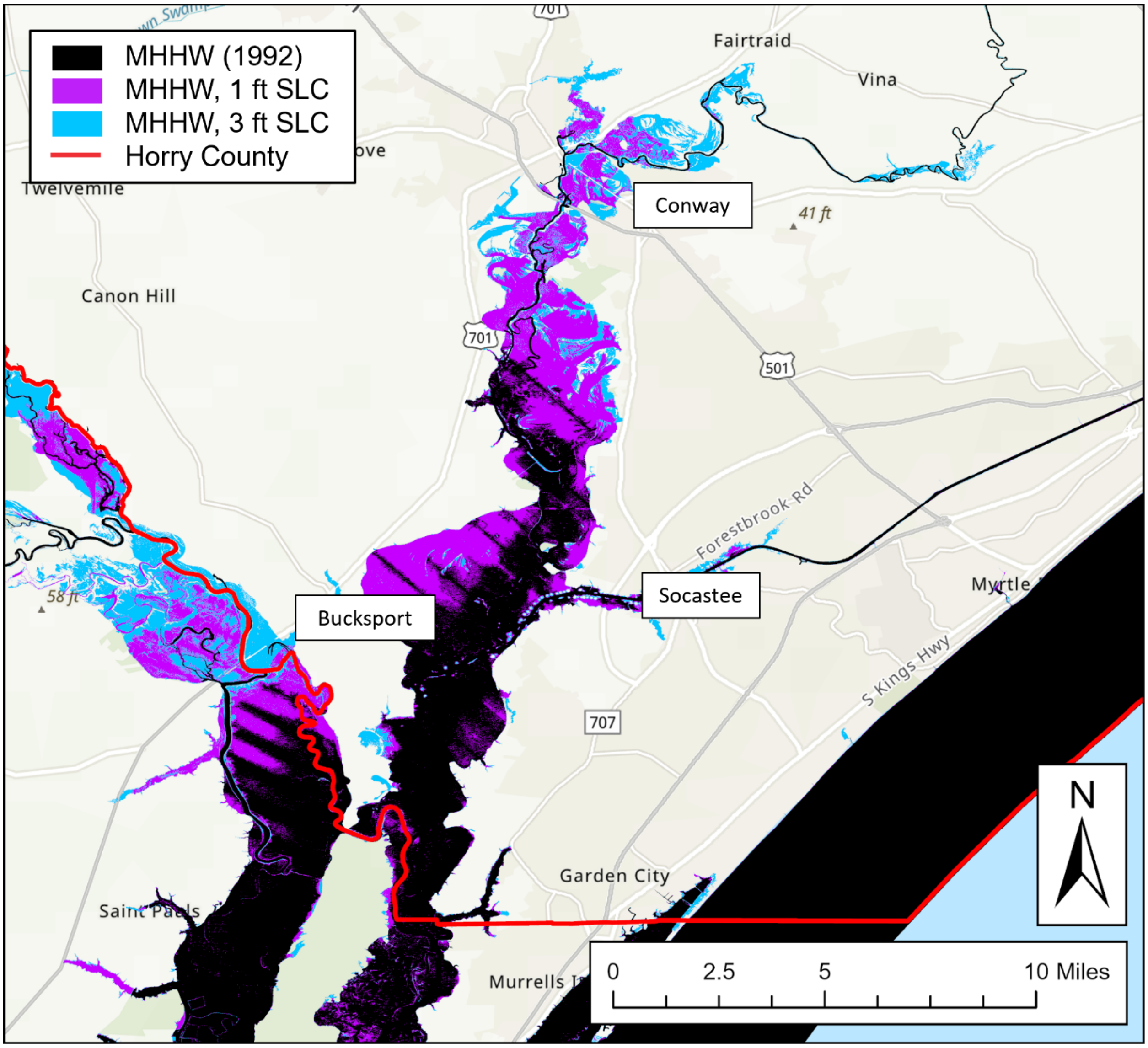


Figure K-10: NOAA Sea Level Rise Viewer

In addition to increased AEF water levels, SLC will cause land loss throughout topographically low-lying areas. As shown in Figure K-10, derived from the NOAA Sea Level Rise Viewer (NOAA 2024a), 1 ft of SLC at MHHW would cause a large portion of the tidal marshlands to drop below MSL. This amount of SLC is slightly less than the 50-year projected sea level increase of 1.14 ft (2035-2085), according to the USACE Intermediate curve. Figure K-10 also shows the MSL footprint at MHHW with 3 ft of SLC, which roughly corresponds to the 50-year (2035-2085), High curve increase (3.06 ft) or the 100-year (12035-2135), Intermediate curve increase (2.72ft). Although high levels of SLC across the 50-year period of analysis (2035-2085) will cause large areas of marsh to become submerged during high tides, this was proven in sensitivity analyses (Appendix A1, Section E.3.4.6) to have a negligible effect on the maximum flood elevations during low-frequency events, therefore having minimal impact on proposed features located at Socastee and Conway. However, across the 100-year adaptation horizon these impacts may be more significant.

The recommended plan is resilient across all Sea Level Change (SLC) scenarios through the 2135 adaptation horizon. Impacts to water surface elevations remain below 0.05 feet when either the Low or Intermediate SLC scenario is assumed. While, the change at the coastline will be significantly greater for the High SLC scenario, it will still not result in an operationally significant difference where project features are located. While coastal and tidal influences are projected to increase over time, fluvial forces remain the primary driver of flood elevations and damages during extreme events. The culvert design, which includes 1.5 feet of freeboard for the 1% AEP flood event, effectively accommodates these projected changes. Even under the USACE High SLC scenario of 7.96 feet, with-project conditions provide superior flood risk management compared to the Future Without Project (FWOP) condition, ensuring that infrastructure capacity is not exceeded by tidal or sea level impacts.

L CHANGING COASTAL AND HYDROMETEROLOGICAL CONDITIONS SUMMARY AND CONCLUSION

Flooding in the project area is due to extensive rainfall throughout the year, multi-day rainstorms leading to saturated soils. Stronger hurricanes coupled with extreme precipitation have the potential to destroy or damage public and private buildings and property. Increased inland flooding caused by extreme precipitation events could further increase economic and agricultural losses after an event. Vulnerable populations are most at risk of flooding impacts and may have difficulty evacuating when necessary.

The literature review indicates strong consensus that air temperatures will rise in the study area and across the country over the next century. Most studies forecast a rise in mean annual air temperature by about 5-10 degrees Fahrenheit by the second half of the 21st century for the South Carolina. A warmer Atlantic Ocean could contribute to increasing rainfall and an increase in intensity and frequency of hurricanes. Much of the literature and analysis of nonstationarity IDF relationships done by the NCICS point to increases in extreme rainfall over the next century. Predictions regarding changes in annual precipitation and streamflow response are more uncertain, with the studies reviewed showing an even split between anticipating increases and decreases in the future.

Analysis of the Climate Hydrology Assessment Tool's range of model results shows a distinct upward trend in future temperatures. There is a weak positive increasing signal in both maximum precipitation and streamflow variables evaluated towards the end of the century when RCP 8.5 is assumed. For all variables evaluated there is a wide range in output over the future period which is indicative of the uncertainty associated with model-future conditions. This uncertainty stems from various factors, including the initial conditions set for the GCMs, differences among GCMs themselves, and the choice of Representative Concentration Pathways (RCPs). Further uncertainties arise from the process of downscaling, limited temporal resolution, and the hydrologic models themselves, as evidenced by the broad range of results depicted in Figures E-2 to E-3.

Waccamaw's relative vulnerability to riverine flood hazard was evaluated using the CWVAT. Driven primarily by expanding 1% AEP flood extents and an increase in extreme precipitation days, the Waccamaw Watershed's vulnerability to riverine flooding is projected to escalate from medium-high today to very high by 2085 under high scenarios.

A rainfall sensitivity analysis was conducted increasing the intensity of 1% AEP rain event and found that the water surface elevations are sensitive to an increase in precipitation of that magnitude. A 14.6% increase in total rainfall for a 96-hour event produced a rise in water surface elevation of more than two feet for the Waccamaw River at Conway, SC. If water surface elevations were to increase two feet during the 1% AEP event in the future, project features would experience reduced levels of service and floodplain extents and conveyance capacity would be exceeded, increasing residual risk. These results were not used to choose the recommended plan and are not included in the Economics and Benefits analysis but were applied to help characterize residual risk. The results are provided in Appendix A-1 Hydrology and Hydraulics.

Sea level projections for the Waccamaw River basin, based on the USACE SLAT and data from the Springmaid Pier, SC NOAA station, predict substantial increases in sea level along the coast throughout the next 100-years. At the coast, by 2085, the Low-rate Sea level increase (from 2035) was 0.16 m (0.54 ft), the Intermediate sea level increase was 0.35 m (1.14 ft), and the High sea level increase was 0.93 m (3.06 ft). For predicted SLC through year 2135, the Low-rate sea level increase (from the start of the project in 2035 to 2135) was 0.33 m (1.07 ft), the Intermediate sea level increase was 0.83 m (2.72 ft), and the High sea level increase was 2.43 m (7.96 ft) underscoring the broad range of possible future sea level change.

Based on the sensitivity analysis conducted for all SLC scenarios, SLC will not substantially affect the performance of project features in a way that would necessitate adaptive action. During the 1% (100-year) event, a 3.06-foot increase in sea level at the coast only amounts to a 0.05-foot increase in water surface elevation in the vicinity of project features. This increase would be greater during more moderate events and if the high SLC scenario is realized by 2135 but would still be unlikely to result in significant reductions in project performance. However, during these conditions it is possible that SLC could result in increased flood risk across the study area in general.

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