Mississippi Valley Division
Regional Planning and Environmental Division South

Upper Barataria Basin, Louisiana Feasibility Report

Appendix A: Annex 8 – Relative Sea Level and Climate Change

December 2021

Annex 8 – Relative Sea Level and Climate Change

Part I: Sea Level Change

The Upper Barataria Basin (UBB) project is a coastal storm damage risk reduction (CSDR) project located in a coastal area subject rapid local sea level change. Therefore, changes in sea level are expected to affect project performance over time. By policy, USACE projects must perform as intended for their full project life, despite uncertainty about future conditions, including sea level and future climate. While the fact of sea level change is not uncertain, the rate of future change is unknown. USACE guidance, in the form of ER 1100-2-8162, requires sea level change to be considered in planning and design, and defines the range of reasonably plausible future sea level conditions using three scenarios, called Low, Intermediate, and High. For projects such as UBB, these scenarios can be used to address three main questions:

1) What is the reasonable extent of potential future climate change (particularly sea level change) in this area?

2) Is the selected plan the best alternative under all reasonable future climate scenarios?

3) How does the selected plan balance initial investment with adaptation cost to optimize performance in consideration of future climate change?

These three questions are addressed below.

1) The reasonable extent of future sea level change can be estimated by using the High sea level scenario in the year 2123, which is 100 years after the assumed construction date. Per ER 1110-2-8159, Life Cycle Performance and Design, major infrastructure such as levees are assumed to have a 100 year project life unless otherwise specified (note that this project life is distinct from the 50 year period of economic analysis that derives from discounting future costs and benefits to net present value). The closest tidegage to the UBB project is the USACE gage on Bayou Barataria at Barataria (MVN gage 82750), in Figure 1 below. The three USACE sea level scenarios are plotted for this gage in Figure 2, below.

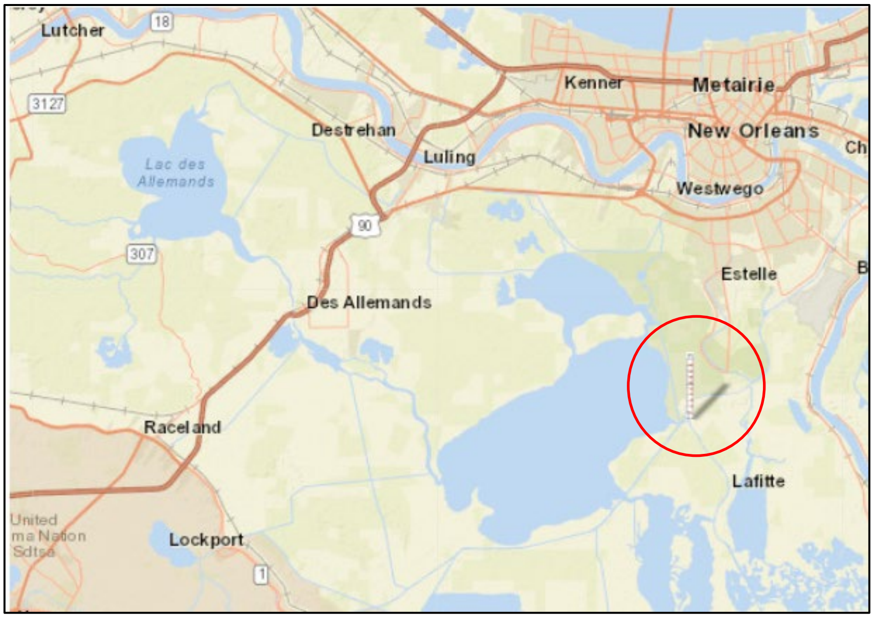


Figure 1: Location of Barataria gage relative to UBB project location

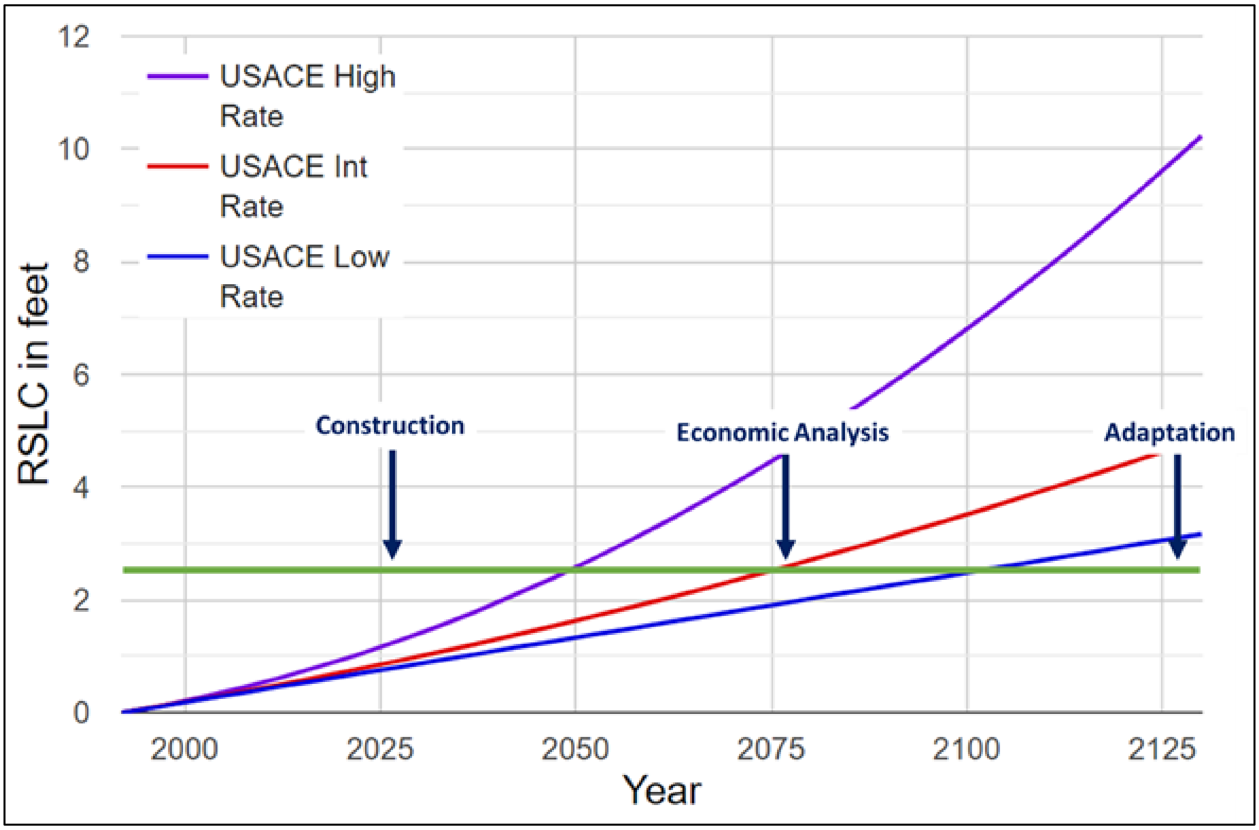


Figure 2: Sea level projections for Bayou Barataria at Barataria

The High scenario for relative sea level change at this gage is 9.37 ft relative to 1992, which is the midpoint of the most recent National Tidal Datum Epoch (NTDE) and thus represents presently published mean sea level. The extent of inundation at this sea level was visualized using the NOAA Sea Level Rise Viewer and is shown in Figure 3. It is no surprise that the UBB project area is largely covered by this degree of sea level change. This represents the maximum extent of potential impact for the project area and sets the strategic decision context for the project analysis of climate change.

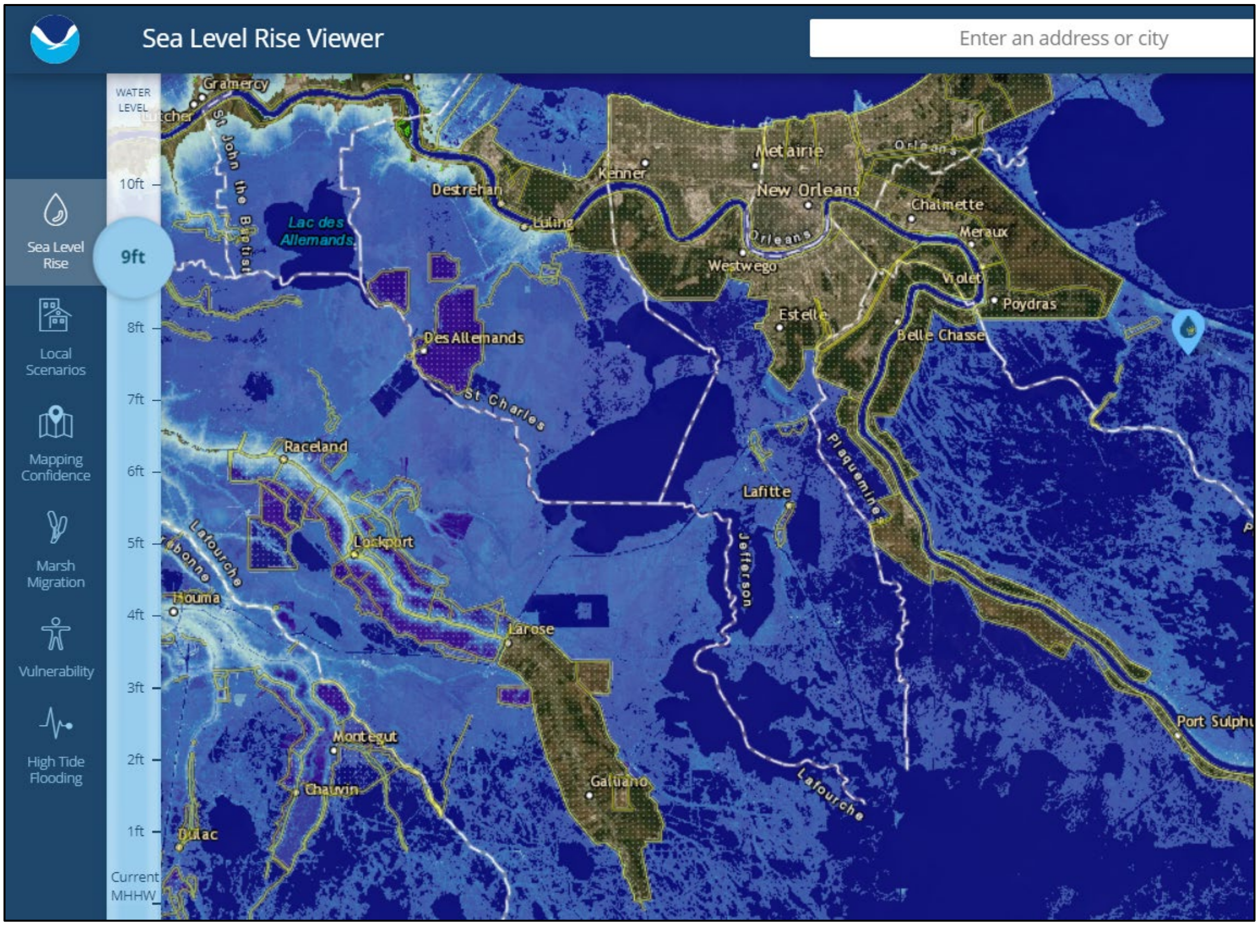


Figure 3: Inundation and mean sea level in the year 2123 under the USACE High sea level scenario. This represents the maximum plausible upper range of future conditions facing the UBB project.

2) USACE policy, outlined in ER 1100-2-8162, requires that sea level change be considered in project formulation. In particular, policy requires that alternatives be evaluated such that an alternative that performs best across the full range of plausible future conditions should generally be selected over an alternative that only performs well under one of the scenarios. At the TSP selection step, the team should demonstrate that uncertainty over future sea level conditions does not constitute uncertainty over which alternative will perform the best in the future. In the case of the UBB project, the TSP is the plan that ties into existing high ground and pre-existing levee systems without raising the elevation of those systems or the surrounding high ground. Alternative plans considered consisted of alternate levee alignments as well as nonstructural measures. Nonstructural measures (such as house raisings) were evaluated as a stand-alone alternative (limited to hot spots within the basin). This

alternative was subsequently eliminated from further consideration because it could not be economically justified. The elimination of this alternative is not sensitive to the uncertainty over sea level change since there is a low population density in the area, which results in low net benefits. However, the TSP can be enhanced with the inclusion of nonstructural measures, provided the implementation of these measures can be economically justified. Alternative levee alignments considered (see Hydraulic Levee Design Exterior Analysis for details) would be impacted by sea level similarly to the TSP alignment. Thus the choice of the TSP was not highly sensitive to sea level change uncertainty and the team is confident that the TSP is the best choice under all plausible future sea levels.

3) Performance of the selected plan over the project life can be assessed using future conditions model runs. The constraints of SMART planning, combined with the temporal urgency of projects funded under the Bipartisan Budget Act of 2018, did not allow for new model studies of future conditions for this project. Instead, the team leveraged analysis performed by the Coastal Protection and Restoration Authority of Louisiana for the 2017 Coastal Master Plan. This analysis modeled future conditions storm surge and waves for large areas of the Louisiana Coast using the ADCIRC storm surge model combined with the UnSWAN model for nearshore waves (model details are available at http://sonris-www.dnr.state.la.us/dnrservices/redirectUrl.jsp?dID=4734245). The CPRA analyzed several eustatic sea level scenarios; the one used for this study assumed approximately 1.5 feet of eustatic sea level rise beginning in the year 2017. Subsidence and accretion of topography and bathymetry in this analysis were spatially-varying based on the outputs of a geomorphic model; relative change in elevations is shown in Figure 4. The local land area around the UBB project shows net accretion of wetland over time (relative to NAVD88) but the bottoms of Lakes Salvador and Cataouatche are subsided approximately 0.5 feet. Thus this CPRA analysis is equivalent to approximately 2 feet of relative sea level rise.

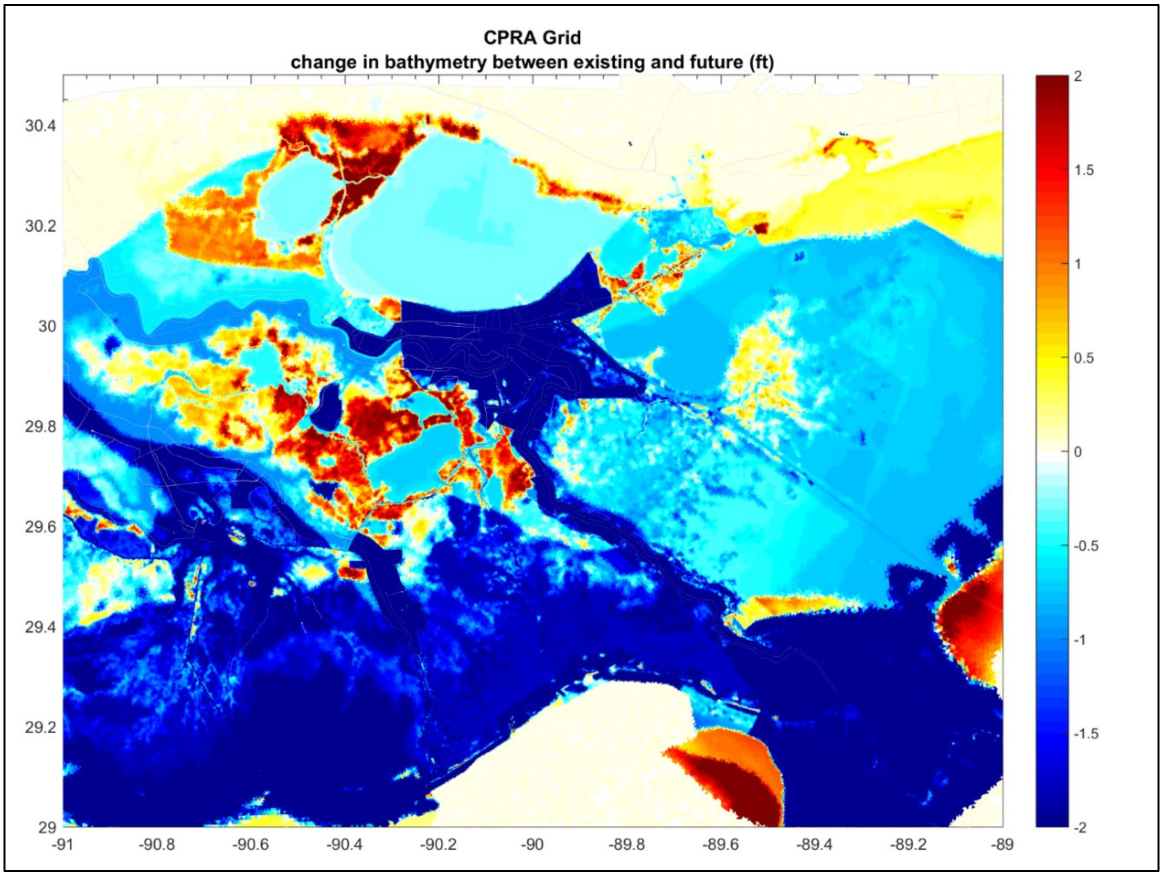


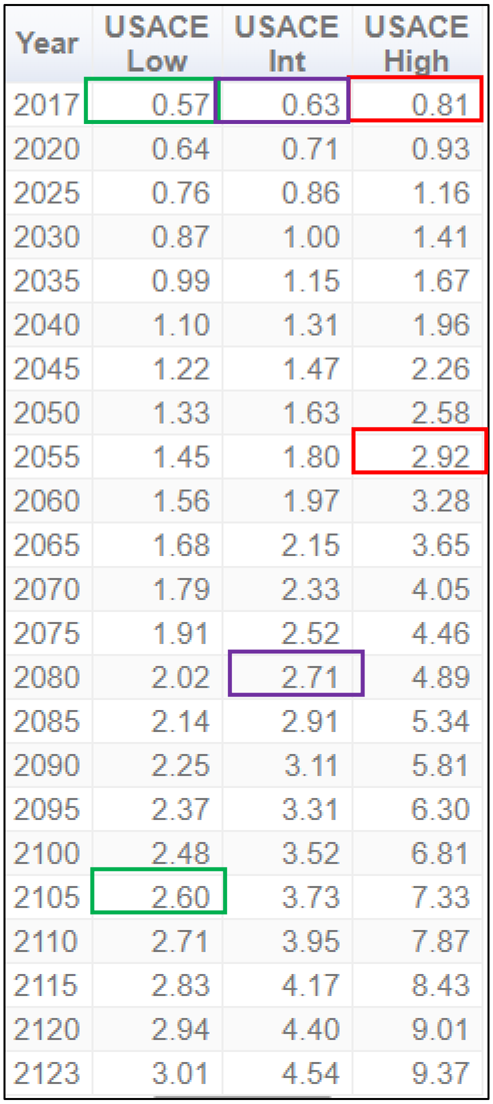
Figure 4: Relative change between CPRA 2017 and S13 future conditions ADCIRC model grids.

Mean sea level rise at the Barataria tidegage between 2017 and 2073 is approximately 1.8 feet under the Intermediate scenario, thus the CPRA analysis using scenario S13 for future conditions was considered reasonably similar, given the constraints of this study, to the Intermediate scenario at the end of the period of economic analysis. This was the sea level condition used to compute project economic benefits over the economic analysis period. While this assumption ignores the uncertainty in relative sea level in the year 2017, which may be 0.6-0.8 feet higher than 1992 at Barataria, the CPRA ADCIRC model uses a starting water surface elevation of 1.2 feet NAVD88 to account for factors such as thermosteric effect, despite the fact that mean sea level at the NOAA gage located on Bayou Gauche (gage 8762482) is only about 0.8 feet above NAVD88 (note also that this MSL is based on the NOAA modified 5 year NTDE used in high-subsidence areas which spans from 2012-2016, rather than the standard NTDE that spans from 1983-2001). For the purposes of this study, the 1.2 foot initial water surface elevation was considered sufficient to address sea level rise between 1992 and 2017.

It is critical to understand that the UBB TSP design is optimized for NED benefits, rather than to deliver a set quantity of residual risk to the project area. Furthermore, the design is dictated by the elevation and performance of the surrounding high ground and pre-existing levee systems into which the proposed levee will tie. This means that the project will reduce risk to a known level (approximately 2% AEP) when construction is complete, at which point risk will gradually increase over time at an unknown rate due to sea level rise and subsidence. Because the plan does not address adaptation of the existing high ground or pre-existing levee system, there is no opportunity to adapt this project in the future to maintain performance because such adaptations would not be marginally economically justified. The project sponsor and public must be aware of the increasing risk to the project area communities and take actions to manage this risk.

Adaptation to sea level is most effectively considered in a “when, not if” context. The fact of sea level rise is certain; only the rate is uncertain. In the case of UBB, there is no performance threshold where the plan suddenly no longer performs due to excessive sea level. Instead, performance gradually decreases over time. The 50-year, Intermediate sea level change scenario used for economic analysis and represented by the CPRA 2017 analysis may be considered a benchmark for assessing the TSP against the other two USACE sea level scenarios. Under the Low scenario, this 2 foot increase would not be expected until approximately the year 2105, after the end of the assumed project life. Under the High scenario, it would be expected as soon as the year 2053. Thus at some point between the year 2053 and the year 2105, the risk to the project area can be expected to equal the conditions described in the CPRA 2017 analysis in the with-project condition (see Upper Barataria Basin Hydraulic Levee Design Exterior Analysis for details of the future conditions flood frequency).

While residual risk to the project area will increase faster under the High sea level scenario (and slower under the Low scenario) than assumed under the Intermediate scenario, this does not mean that the project benefits will necessarily be lower than computed if sea level rises faster than assumed. In fact, economic benefits may actually be higher under the High scenario due to worsened conditions in the without-project condition, though this cannot be confirmed without detailed economic analysis.



Year	USACE Low	USACE Int	USACE High
2017	0.57	0.63	0.81
2020	0.64	0.71	0.93
2025	0.76	0.86	1.16
2030	0.87	1.00	1.41
2035	0.99	1.15	1.67
2040	1.10	1.31	1.96
2045	1.22	1.47	2.26
2050	1.33	1.63	2.58
2055	1.45	1.80	2.92
2060	1.56	1.97	3.28
2065	1.68	2.15	3.65
2070	1.79	2.33	4.05
2075	1.91	2.52	4.46
2080	2.02	2.71	4.89
2085	2.14	2.91	5.34
2090	2.25	3.11	5.81
2095	2.37	3.31	6.30
2100	2.48	3.52	6.81
2105	2.60	3.73	7.33
2110	2.71	3.95	7.87
2115	2.83	4.17	8.43
2120	2.94	4.40	9.01
2123	3.01	4.54	9.37

Table 1: Duration of assumed future conditions project performance under the three USACE sea level scenarios

Part II: Climate Change Impacts to Inland Hydrology

Introduction

USACE guidance for analyzing the impacts of climate change on inland hydrology is included in Engineering and Construction Bulletin (ECB) 2018-14, entitled *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects* (USACE 2018). The bulletin provides a framework for evaluating the effects of climate change on inland hydrology and related climate variables (including but not limited to temperature, precipitation, and evaporation), as well as the effects of climate change on non-climate variables affecting inland hydrology (for example, sedimentation). The analysis is intended to aid in reducing climate change-related vulnerabilities and enhancing the resilience of Corps projects, and can be used to inform decisions pertaining to project planning, engineering, operations, and maintenance. The focus of the analysis is the evaluation of observed and projected trends for project area air temperature, precipitation, and streamflow, based on literature review and USACE climate tools, which are described later in this section.

Literature Review

ECB 2018-14 specifies that the assessment of climate change impacts on inland hydrology includes a literature review summarizing observed and projected climate trends applicable to the project area, with an emphasis on the climate variables of air temperature, precipitation, and streamflow. Literature reviewed for the UBB study includes *Recent Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region* (USACE 2015), the *Louisiana State Climate Summary* (NOAA 2019), *Climate Change Indicators in the United States* (USEPA 2016), and volumes I and II of the *National Climate Assessment* (USGCRP 2017/2018). The following sections summarize literature review findings for observed and projected air temperature, precipitation, and streamflow trends.

Air Temperature

Observed Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Although there are no studies evaluating historical temperature trends specifically within the Lower Mississippi River Region, several studies are available evaluating historical temperature trends on a national scale, from which trends within the Lower Mississippi River Region can be ascertained. Findings from Wang et al. (2009) and Westby et al. (2013) suggest a slight cooling trend occurred in the region during the second half of the 20th century, while Liu et al. (2012) suggests a cooling trend occurred during the third quarter of the 20th century and was followed by a warming trend during the final quarter of the century. The third National Climate Assessment (Carter et al. 2014) also suggests the region experienced a cooling period near mid-century and has been warming since the latter

20th century. Despite their findings of overall slight cooling trends, Wang et al. (2009) and Carter et al. (2014) found no significant temperature trends in the region when evaluating each season individually.

Louisiana State Climate Summary: Temperatures in the state were historically warm in the early 20th century, and were cooler from the 1950s to 1970s. Since the 1970s, temperatures have warmed by about 2°F.

Climate Change Indicators in the United States: Since the beginning of the 20th century, temperatures in the project area have risen slightly (0-0.5°F/century). Nationwide, daily highs and lows have been increasing since the 1970s.

National Climate Assessment: Recent (1986-2016) temperatures in southeast Louisiana were slightly cooler compared to the first half of the 20th century.

Projected Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Several global climate models predict a future increase in air temperatures in the Lower Mississippi River region. Liu et al. (2013), Zhang et al. (2010), and Jayakody et al. (2013) predict increases ranging from 0.9-7.2°F by mid-21st century. Elguindi and Grundstein (2013) predict a shift to warmer climate types by mid-21st century. Liu et al. (2012), Scherer and Diffenbaugh (2014), and Carter et al. (2014) predict increases typically between 3.6-9°F by the end of the 21st century. Tebaldi (2006), Kunkel et al. (2010), and Gao et al. (2012) predict an increase in the number of heat wave days by the end of the 21st century. Jayakody et al. (2013) also predicts an extended summer weather period that will change from July-August to June-September.

Louisiana State Climate Summary: By the end of the 21st century, temperatures in Louisiana are expected to warm by approximately 1.5-12°F. Warming is predicted to increase heat wave intensities and decrease cold front intensities.

National Climate Assessment: Annual average air temperatures in the southeastern U.S. are predicted to increase by 3.4-4.3°F by the mid-21st century, and by 4.4-7.7°F by the late 21st century. By the mid-21st century, the coldest day of the year is predicted to be 5°F warmer than the recent (1976-2005) average, and the warmest day of the year is predicted to be 5.8°F warmer. The southeastern U.S. will experience about 40-50 more days per year with maximum temperatures above 90°F by the mid-21st century.

Precipitation

Observed Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Findings from Grundstein

(2009), Wang et al. (2009), McRoberts and Nielsen-Gammon (2011), Pryor et al. (2009), and Small et al. (2006) suggest an increasing trend in annual precipitation in the region occurred during the 20th century and the second half of the century. Wang and Zhang (2008) found that the frequency of extreme (20-year) rainfall events in the region increased by 25-50% during the last quarter of the 20th century compared to the third quarter, while Pryor et al. (2009) did not find an increase in extreme (annual 90th percentile) precipitation intensity during the 20th century. Li et al. (2011) and Villarini et al. (2013) found an increase in the frequency and magnitude of anomalous summer precipitation in the southeastern U.S. during the second half of the 20th century.

Louisiana State Climate Summary: The state has experienced variable precipitation since the early 20th century, with wetter periods in the 1940s, from the 1970s to the early 2000s, with the wettest period on record in the 2010s.

Climate Change Indicators in the United States: Since about the 1970s, the continental U.S. has experienced an increasing frequency of extreme precipitation events. Precipitation in the project area has increased slightly (2-10%) since the beginning of the 20th century.

National Climate Assessment: Recent (1986-2016) precipitation in southeast Louisiana was slightly (0-5%) greater compared to the first half of the 20th century. Seasonal precipitation was substantially higher (>15%) during the fall, slightly higher (0-5%) during the winter and summer, and lower (-5-0%) during the spring. The southeastern U.S. has experienced a large increase in extreme precipitation events.

Projected Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Projections of future precipitation in the region are generally lacking in consensus. Zhang et al. (2010) and Gao et al. (2012) predict an increase in precipitation in the coastal portion of the Lower Mississippi River region by the mid-21st century. Liu et al. (2012) predicts a slight (additional 10-50 mm/year) increase in annual precipitation by the end of the 21st century. Gao et al. (2012), Tebaldi et al. (2006), and Wang and Zhang (2008) predict an increase in frequency and intensity of extreme precipitation events by the end of the 21st century. Modeling by Joetzjer et al. (2013) suggests an increase in frequency and aerial extent of droughts in the region during the second half of the 21st century.

Louisiana State Climate Summary: Summer precipitation is predicted to decrease by between 5-10% in Louisiana by the mid-21st century. However, the predicted decrease is much smaller than the natural variability in rainfall in the state.

National Climate Assessment: Small changes in seasonal precipitation are predicted for southeast Louisiana by the end of the 21st century, including slight (0-10%) increases in the fall and winter and slight (-10-0%) decreases in the spring and summer. Recent increases in the frequency and intensity of extreme rainfall events, which are the result of increased atmospheric water vapor associated with higher air temperatures, are expected to continue. In the southeastern U.S., extreme precipitation events are predicted to increase in frequency by approximately 20-40% by the mid-21st century and 40-100% by the end of the 21st century. The intensity of extreme events is predicted to increase by 9-12% by the mid-21st century and by 13-21% by the end of the 21st century in the southeastern U.S.

Streamflow

Observed Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Studies of trends and nonstationarity in streamflows within the region over the past century generally suggest increasing streamflows. Xu et al. (2013) and Small et al. (2006) found increases in annual streamflow and baseflow for several streams within the region during the second half of the 20th century, while Kalra et al. (2008) found no trends in annual or seasonal flows for several streams within the region over a similar time period.

Louisiana State Climate Summary: In the southeastern U.S., the frequency and magnitude of flooding has generally decreased since the mid-1960s, although decreases were not statistically significant. Since the beginning of the 20th century, the continental U.S. has experienced several major drought periods including in the 1930s, 1950s, early 1960s, late 1980s, and 2000s, with wetter periods in the 1900s, 1940s, 1970s until the late 1980s, and the 1990s.

Projected Trends

Climate Change and Hydrology Literature Applicable to U.S. Army Corps of Engineers Missions – Lower Mississippi River Region: Projected changes in streamflow are based on global climate modeling and macro-scale hydrologic models. Döll and Zhang (2010) predict a small (10-20%) decrease in low flows and average annual flows in the region by mid-21st century, while Carter et al. (2014) also predicts a decrease in water availability by the end of the 21st century. Hagemann et al. (2013) predicts a 200 mm/year reduction in runoff by the late 21st century.

Summary

Since the 1970s, air temperatures in the southeastern U.S. and in Louisiana have warmed slightly. Air temperatures are projected to increase by 0.9-7.2°F by the mid-21st century and by 1.5-12°F by the end of the 21st century. Annual low and high temperatures are predicted to increase by approximately 5-6°F, and increases in the annual number of extremely hot days and the duration of summer weather are predicted. A slight increase in precipitation has occurred concurrent with increasing temperatures, which is associated with an increasing frequency and intensity of extreme rainfall events and greater seasonal rainfall during the fall. Although annual precipitation amount is not expected to change significantly in the future, the recent trends of increasing frequency and intensity of extreme rainfall events and greater seasonal rainfall are expected to continue, and droughts may become more common and widespread. There is a lack of consensus concerning historical streamflow trends, while streamflow modeling suggests slightly decreasing streamflow by both the middle and end of the 21st century.

Climate Tools

Vulnerability assessment also includes the use of USACE climate tools to provide information on observed and projected climate trends relevant to the project area. The Climate Hydrology Assessment Tool (CHAT), Nonstationarity Detection Tool (NSD), and Time Series Toolbox can be used to determine historical trends, while the CHAT and Vulnerability Assessment (VA) tools can be used to project future trends. Tools are available on the USACE Climate Preparedness and Resilience CoP Applications Portal (https://maps.crrel.usace.army.mil/projects/rcc/portal.html).

Because no long-term streamflow data is available within the project area, the NSD and CHAT tools could not be used. Instead, long-term daily precipitation data was evaluated using Time Series Toolbox. The Time Series Toolbox can be used to determine nonstationarity similarly to the NSD tool.

Time Series Toolbox

The Time-Series Toolbox was developed by the USACE to address the need for multiple types of analytical methods for time series data analysis. Climate-related data can come from a variety of sources (e.g., streamflow, water levels, tide gauge data, precipitation data) where some datasets are often very large. The Time-Series Toolbox provides automated data pre-processing and works to standardize and streamline common approaches to time series analysis by performing trend analysis and nonstationarity detection for user-supplied datasets. A common use for the Time-Series Toolbox is to use it in place of the NSD when a climate assessment is needed for a climate variable other than flow (e.g., precipitation), or if the NSD does not have a gauge in close proximity to the project area.

The toolbox was used to evaluate precipitation data for the Paradis 7 S and New Orleans Airport weather stations located in Bayou Gauche, LA and Kenner, LA, respectively (see Table 1 for site information). Precipitation data was acquired using the NOAA National Centers for Environmental Information (NCEI) mapping tool (NOAA 2020). Both sites are located outside of the project area. Paradis 7 S, located 3.5 miles southeast of the project area, has a longer precipitation data period of record (1911-2011), while at the New Orleans Airport site, located 10 miles northeast of the project area, data is still being collected (1948-2020). Because some of the tools within the Time Series Toolbox would not work with daily precipitation data, annual precipitation totals were used instead. The seasonality tool was therefore not able to be used. The

Time Series Toolbox includes tools for model-based analysis of trend, seasonality, nonstationarity detection, and time series.

Table 1: Precipitation data collection site information

Name	Paradis 7 S	New Orleans Airport
Site ID	USC00167096	USW00012916
Latitude	29.78920	29.99691
Longitude	-90.42860	-90.27751
Elevation (m)	1.5	1.2
Start	1911	1945
End	2011	2020
Coverage	96%	97%

Trend Analysis

The Trend Analysis Tool is used to measure trends in hydrologic data by fitting regression curves to the data and determining regression slopes. The tool uses both parametric (t-Test) and non-parametric (Spearman Rank-Order and Mann-Kendall) regression techniques to test the significance of the trend line slopes. The Trend Analysis Tool also computed a fitted trendline using Sen's slope, an approach that is more robust to outliers than a traditional least-squares regression. Sen's slope is the median of the slopes between every pair of datapoints.

Figures 1 and 2 provide trend analysis data and trendlines. At both sites, trendlines are positive, suggesting a slight increase in precipitation over the period of record. Table 2 provides p-values for t-test, Spearman rank-order, and Mann Kendall tests for the significance of the trend line slope. All p-values are greater than 0.05, and the only p-values less than 0.10 are for the New Orleans Airport site, for both the Spearman rank-order and Mann Kendall tests. Results suggest no strong trends, and a weak increasing trend in annual precipitation since the mid-twentieth century. Estimated slope magnitudes based on least-squares regression were approximately 0.1 in/yr and 0.06 in/yr of increased annual total precipitation at New Orleans Airport and Paradis, respectively. In addition to not being statistically significant at the $p < 0.05$ level, these increases are likely to be of little practical significance to the project.

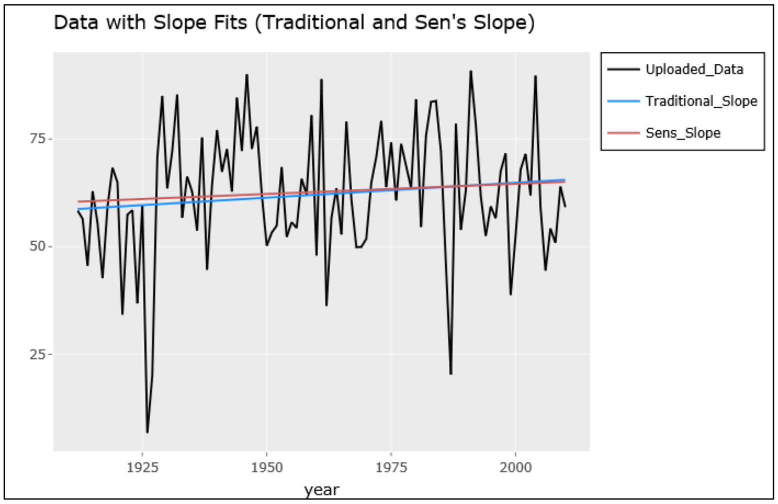


Figure 1: Paradis 7 S annual precipitation data and trendlines

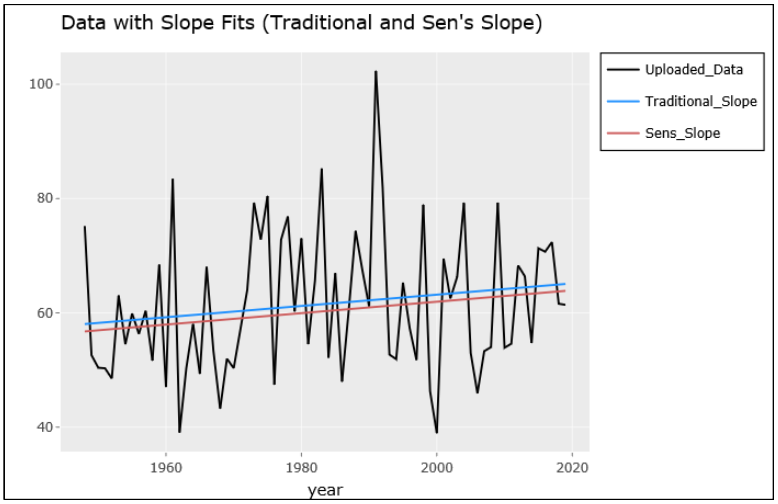


Figure 2: New Orleans Airport annual precipitation data and trendlines

Table 2: Trend test p-values

Test	*Paradis 7 S*	*New Orleans Airport*
t-Test	0.20	0.16
Spearman Rank-Order	0.39	0.09
Mann-Kendall	0.40	0.09

Nonstationarity Detection and Breakpoint Analysis

USACE projects, programs, missions, and operations have generally proven robust enough to accommodate the range of natural climate variability over their operational life. However, in some places and for some impacts relevant to USACE operations, climate change and modifications to watersheds are undermining the fundamental design assumption of stationarity (the statistical characteristics of hydrologic data are consistent with respect to time), an assumption has enabled the use of well-accepted statistical methods in water resources planning and design that rely primarily on the observed hydrologic data records. Nonstationarities are identified when the statistical characteristics of a hydrologic data series are not constant through time. USACE Engineering Technical Letter (ETL) 1100-2-3, entitled “Guidance for Detection of Nonstationarities in Annual Maximum Discharges” (USACE 2017), provides technical guidance on detecting nonstationarities in the hydrologic record which may continue to impact hydrology into the future and should be considered under future project conditions.

The Nonstationarity Detection Tab includes both the NSD Tool and Breakpoint Analysis. The NSD tool, which is based on ETL 1100-2-3, uses an array of statistical tests to detect the presence of nonstationarities in the data mean (Lombard Wilcoxon, Pettitt, Mann-Whitney, and Bayesian CPD), variance (Mood and Lombard Mood), or distribution (Cramer-Von-Mises, Kolmogorov-Smirnov, LePage, and Energy Divisive). The confirmation of nonstationarities by multiple tests provides robust evidence for nonstationarity. In combination with the NSD Tool, Breakpoint Analysis uses linear regression and the analysis of model errors with hypothesis testing to also identify points in the data that reflect sharp changes in behavior, suggesting the need for segmented analysis. In short, the Nonstationarity Analysis identifies when the statistical characteristics of the data have changed to the point that they may be considered two distinct datasets, while the Breakpoint Analysis identifies when the initial statistical model no longer fits the data and should be replaced with a new model.

Figures 3 and 4 depict NSD tool results for the Paradis 7 S and New Orleans Airport sites, respectively. For the Paradis 7 S site, the Cramer-Von-Mises (CVM) test suggests a change in the distribution of annual precipitation totals occurred in the late 1920s, while the Bayesian CPD test (BAY) suggests a change in the mean of annual precipitation totals occurred in the late 1920s and early 1980s, and the Mann-Whitney test (MW) also suggests a change in the mean of annual precipitation totals occurred in the late 1920s. For the New Orleans Airport site, the energy divisive test (END) suggests a change in the distribution of annual precipitation totals occurred around 1970, the Lombard-Wilcoxon test (LW) suggests a concurrent change in the mean, and the Smooth Lombard-Wilcoxon test (SLW) suggests a concurrent change in the distribution.

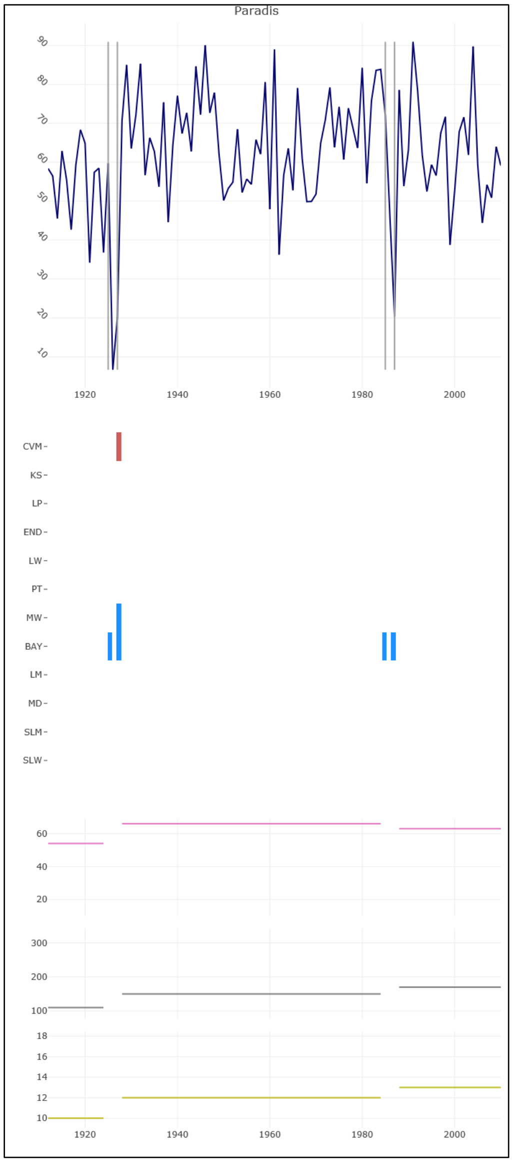


Figure 3: Nonstationarity Detection results for Paradis 7 S (Distribution-based tests: CVM=Cramer-Von-Mises, S=Kolmogorov-Smirnov, LP=LePage, END=Energy Divisive; Mean-based tests: LW=Lombard Wilcoxon, PT=Pettitt, MW=Mann-Whitney, BAY=Bayesian CPD; Variance-based tests: LM=Lombard Mood, MD=Mood SLM=Smooth Lombard Mood, SLW=Smooth Lombard-Wilcoxon)

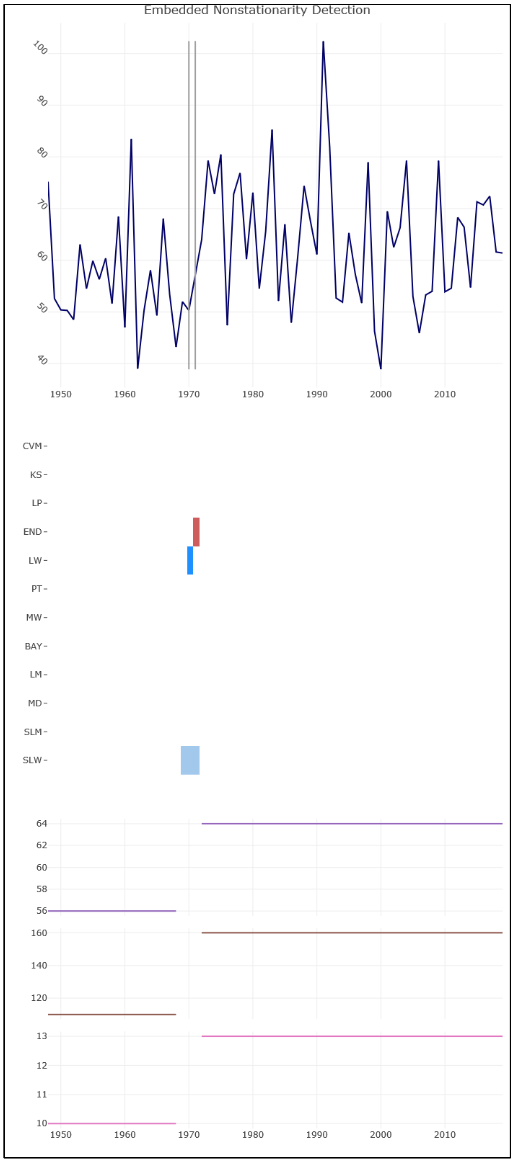


Figure 4: Nonstationarity Detection results for New Orleans Airport (Distribution-based tests: CVM=Cramer-Von-Mises, S=Kolmogorov-Smirnov, LP=LePage, END=Energy Divisive; Mean-based tests: LW=Lombard Wilcoxon, PT=Pettitt, MW=Mann-Whitney, BAY=Bayesian CPD; Variance-based tests: LM=Lombard Mood, MD=Mood SLM=Smooth Lombard Mood, SLW=Smooth Lombard-Wilcoxon)

Breakpoint analysis results include a breakpoint for the Paradis 7 S site in 1927, which corresponds to the strongest NSD findings (several tests suggest changes in the behavior of annual precipitation beginning around this time).

Time Series Analysis

Time Series Analysis includes the determination of the appropriate time series model by using techniques that control for seasonality, trend, and nonstationarities. This tool includes linear, Auto Regressive Integrating Moving Average (ARIMA), and Exponential

Smoothing (ETS) models. ARIMA and ETS models and diagnostic plots are included in Figures 5 - 12. The models do not suggest a significant trend or forecast; residuals do not appear to exhibit heteroscedasticity, and autocorrelation is generally highly variable. Linear modeling could not be performed within the Time Series Analysis using annual precipitation totals.

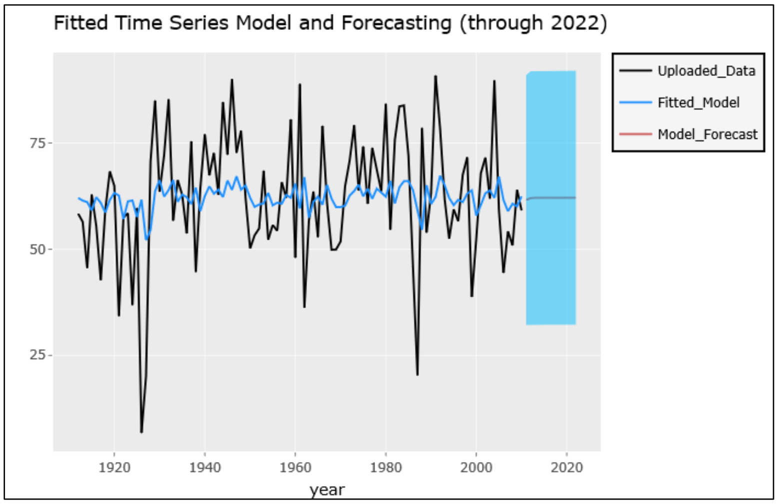


Figure 5: Paradis 7 S annual precipitation ARIMA model and forecast

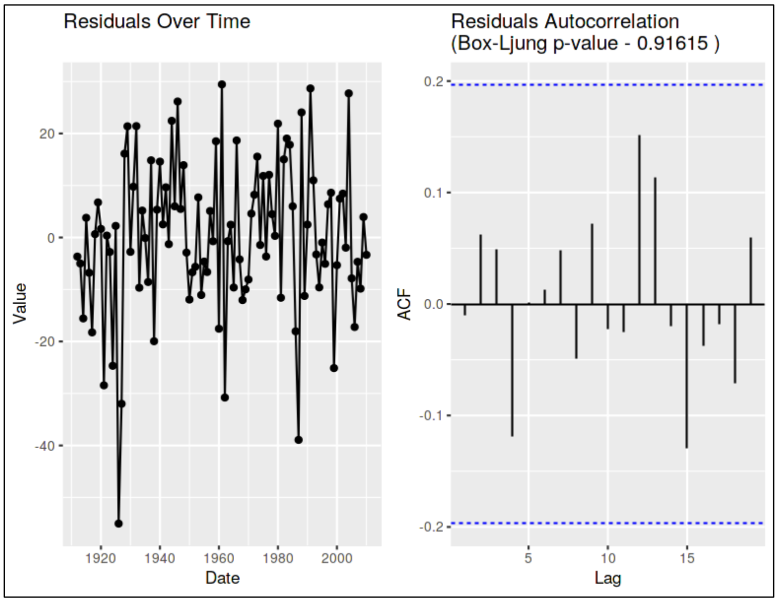


Figure 6: Paradis 7 S annual precipitation ARIMA residual plots

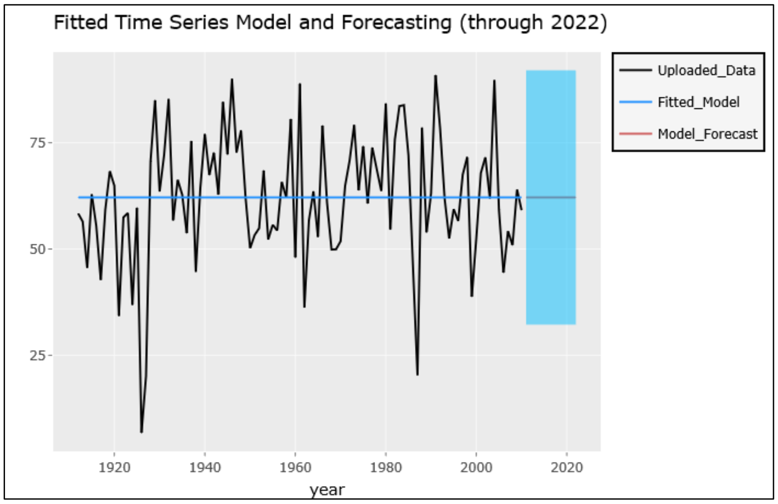


Figure 7: Paradis 7 S annual precipitation ETS model and forecast

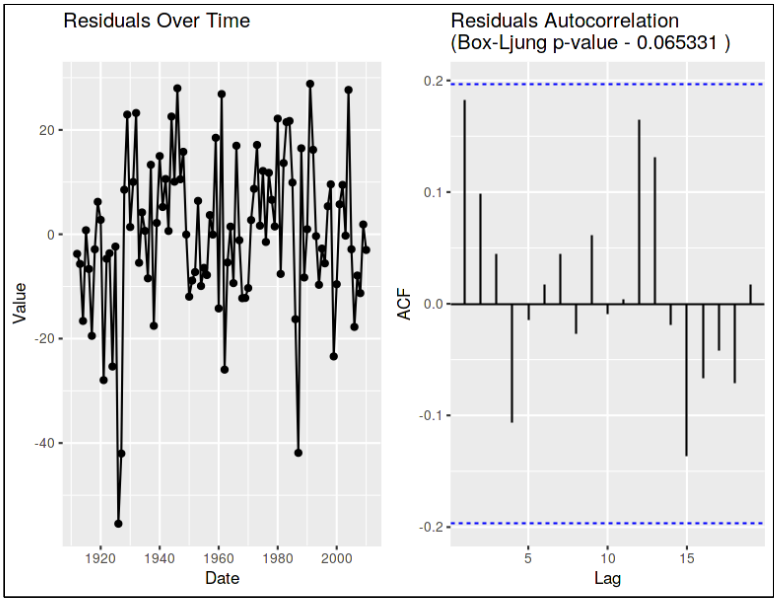


Figure 8: Paradis 7 S annual precipitation ETS residual plots

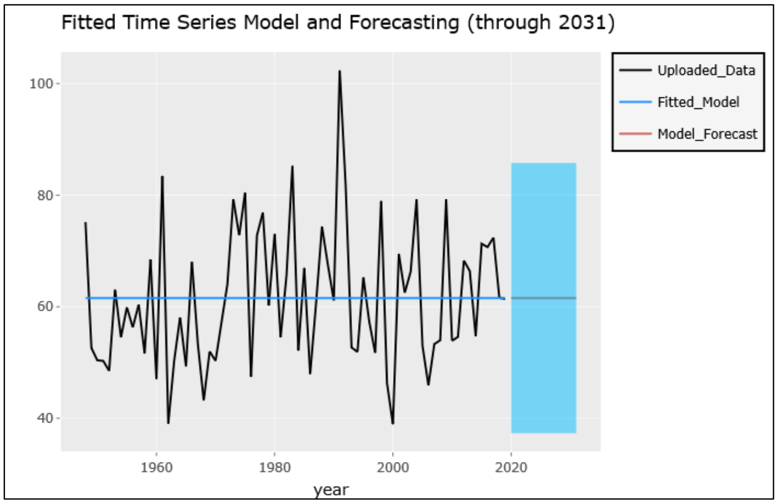


Figure 9: New Orleans Airport annual precipitation ARIMA model and forecast

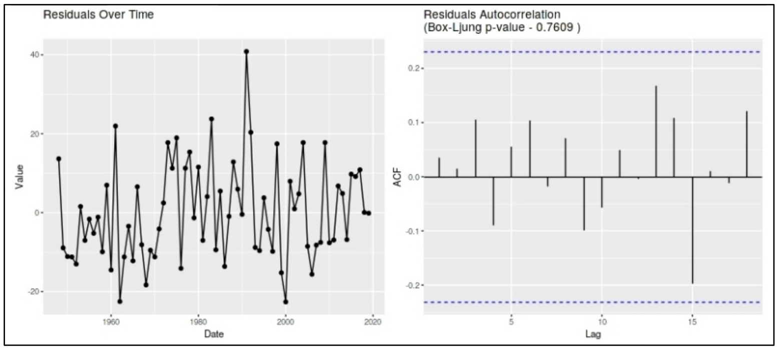


Figure 10: New Orleans Airport annual precipitation ARIMA residual plots

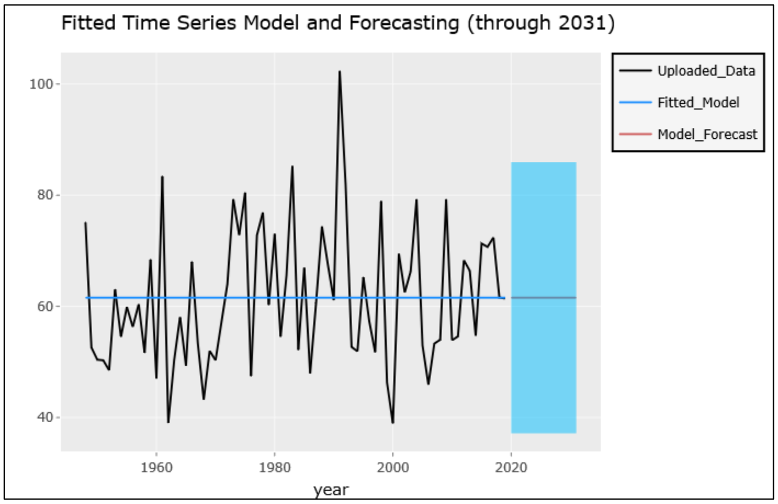


Figure 11: New Orleans Airport annual precipitation ETS model and forecast

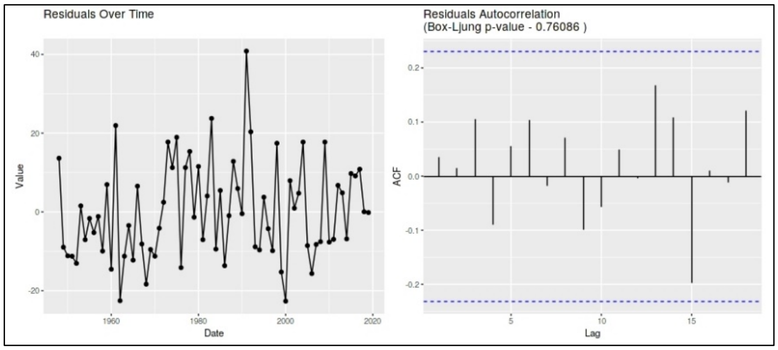


Figure 12: New Orleans Airport annual precipitation ETS residual plots

Overall, the results of the Nonstationarity and Breakpoint Analyses suggest that while there is some weak evidence for change in the precipitation data at Paradis in the late 1920's, these results exhibit insufficient consensus, robustness, or magnitude to justify censoring or re-regulating the record. The potential uncertainty related to changes in past precipitation are within the normal range of uncertainty for climatological and hydrological analysis, and do not necessitate a deviation from normal design procedures.

VA Tool

The USACE Watershed Vulnerability Assessment Tool provides a screening-level assessment of future climate change vulnerability with regards to USACE functions for each fourth level watershed (level 4 HUCs using USGS delineations) in the continental United States (USACE 2016). The tool assesses vulnerability for two future time periods: 2035-2064 and 2070-2099, which are labeled '2050' and '2085', respectively, based on the midpoint of each time period. The tool also assesses two climate change scenarios, labelled 'wet' and 'dry'. These scenarios are based on annual precipitation forecasts for a suite of general circulation models (GCMs) for each second level watershed (level 2 HUCs). GCMs with annual precipitation above the median of all GCMs in the years 2050 and 2085 are used for modeling the 'wet' scenario for each respective time period, while those with annual precipitation below the median are used for modeling the 'dry' scenario. A key point to remember is that these distinctions are relative to each other, not to present climate. A 'wet' scenario, for example, may be wetter or drier than present climate so long as it is wetter than the median of all scenarios.

The assessment is performed with respect to USACE functions known as 'business lines', which include flood risk reduction, ecosystem restoration, recreation, regulatory, navigation, hydropower, water supply, and emergency management. Each business line includes a suite of 'indicators' which are parameters used to determine business line vulnerability (see Table 3 for example). For each indicator within a business line, scores are determined based on the percentile of the rank among all fourth level watersheds of the difference between a future climate change scenario/time period combination as determined by GCMs and base conditions (the base conditions period of analysis varies by indicator), as well as indicator weight (which ranges between 1-2). The combined score of all indicators for a business line is the total score for that business line, known as a WOWA (Weighted Order Weighted Average) score. For a given future climate change scenario/time period/business line combination, watersheds with a WOWA score in the top 20th percentile are considered vulnerable to climate change.

Table 3: Example business line indicators

Business Line	Indicator Short Name	Importance Weight
Flood Risk Reduction	568C_FLOOD_MAGNIFICATION	1.8
	590_URBAN_500YRFLOODPLAIN_AREA	1.75
	568L_FLOOD_MAGNIFICATION	1.4
	175C_ANNUAL_COV	1.25
	277_RUNOFF_PRECIP	1

The assessment can also be performed using custom settings, which include the use of custom indicators and indicator weights, custom percentile thresholds for defining vulnerability, defining vulnerability based on the aggregate of all results (i.e., the top nth percentile of all combinations of watershed, climate change scenario, and time period), and by using a custom suite of watersheds. However, for the UBB study, the "National Standard View" (no custom settings) was used.

The UBB study is within the Lower Mississippi watershed (level 4 HUC 0809). Analysis of this HUC is complicated somewhat by the presence of the Mississippi River, which is contained within the HUC but does not influence the UBB project. For each combination of climate change scenario and future time period, at least one business line has a WOWA score in the top 20th percentile, and therefore may be vulnerable to climate change risks (Table 4). The business lines most vulnerable according to the assessment tool are the ecosystem restoration business line, which had WOWA scores within the top 20th percentile for every combination of climate change scenario and future time period, and the flood risk reduction business line, which had WOWA scores within the top 20th percentile for the dry climate change scenario for both time periods. The dry climate change scenario had three business lines with WOWA scores within the top 20th percentile for each future time period, while the wet scenario had only one for each future time period.

Table 4: Lower Mississippi watershed business line vulnerability summary

	2050	2085
Dry	Ecosystem Restoration, Emergency Management, Flood Risk Reduction	Ecosystem Restoration, Flood Risk Reduction, Recreation
Wet	Ecosystem Restoration	Ecosystem Restoration

Table 5 provides a summary of WOWA scores for each combination of business line, climate change scenario, and time period, while Table 6 provides details concerning indicator scores. WOWA scores in the top 20th percentile are highlighted in yellow.

The ecosystem restoration business line, which is vulnerable to climate change risks for all future climate change scenarios and future time periods, is most affected by indicator scores for 8_AT_RISK_FRESHWATER_PLANT (percent of freshwater plant communities at risk) and 297_MACROINVERTEBRATE (macroinvertebrate index for biotic condition), which are also the two most heavily weighted indicators for the business line. The indicator score for 297_MACROINVERTEBRATE is more than double the average for all HUCs for all climate change scenarios and future time periods, while the score for 8_AT_RISK_FRESHWATER_PLANT is less than 2 units greater than the average.

The flood risk reduction business line, which is vulnerable to climate change risks for the dry climate change scenario for both future time periods, is most affected by indicator scores for 590_URBAN_500YRFLOODPLAIN_AREA (acres of urban area within the 500-year floodplain) and 568C_FLOOD_MAGNIFICATION (flood magnification factor), which are also the two most heavily weighted indicators for the business line. The indicator score for 590_URBAN_500YRFLOODPLAIN_AREA is more than triple the average for all HUCs for the dry climate change scenario for both future time periods, while the scores for 568C_FLOOD_MAGNIFICATION are below the average by about 6-7 units.

For the emergency management business line, which was only found to be vulnerable to climate change risks for the dry climate change scenario for the 2050 time period, 130_FLOODPLAIN_POPULATION (population in the 500-year floodplain) provided the greatest contribution to the business line WOWA score, and was the most heavily weighted indicator for the business line. For the recreation business line, which was only found to be vulnerable to climate change risks for the dry climate change scenario for the 2085 time period, 95_DROUGHT_SEVERITY (drought severity index) provided the greatest contribution to the business line WOWA score, and was the most heavily weighted indicator for the business line.

Table 5: Lower Mississippi watershed WOWA scores with comparison to all level 2 HUCs (WOWA scores in the top 20th percentile are highlighted in yellow)

Business Line Name	Scenario	Epoch	WOWA Score	
			0809	All HUCs
Ecosystem Restoration	Dry	2050	75.8	55.9 - 81.7
		2085	75.5	55.8 - 81.9
	Wet	2050	76.5	55.6 - 89.8
		2085	76.6	54.7 - 89.4
Emergency Management	Dry	2050	68.5	58.3 - 75.0
		2085	69.8	57.0 - 77.4
	Wet	2050	66.8	56.6 - 79.4
		2085	67.8	56.6 - 75.9
Flood Risk Reduction	Dry	2050	51.9	35.1 - 70.1
		2085	52.7	35.7 - 69.1
	Wet	2050	54.3	39.8 - 92.8
		2085	56.0	40.9 - 86.7
Navigation	Dry	2050	61.5	54.9 - 75.2
		2085	64.6	55.2 - 77.5
	Wet	2050	66.4	56.4 - 84.3
		2085	67.4	57.9 - 84.4
Recreation	Dry	2050	67.4	57.1 - 74.4
		2085	74.1	57.4 - 82.2
	Wet	2050	68.0	57.7 - 85.6
		2085	66.3	56.7 - 83.6
Regulatory	Dry	2050	72.0	57.8 - 82.8
		2085	72.3	57.7 - 82.7
	Wet	2050	73.0	57.3 - 91.0
		2085	73.5	57.3 - 89.3

Table 6: Lower Mississippi watershed business line indicator scores with comparison to all level 2 HUCs

		WOWA Indicator Score								WOWA Indicator Percent of Business Line Total							
		HUC 0809						All HUCs		HUC 0809						All HUCs	
			Base	2050		2085					Base	2050		2085			
Business Line Name	Indicator Short Name	Average Score		Dry	Wet	Dry	Wet	Average Score	Range of Score	Average Score		Dry	Wet	Dry	Wet	Average Percent of Total	Range of Percent of Total
Ecosystem Restoration	8_AT_RISK_FRESHWATER_PLANT	28.3	28.4	28.1	28.5	28.5	28.1	26.7	17.7 - 30.0	37.3%	37.8%	37.6%	36.8%	37.8%	36.7%	38.5%	25.3 - 47.1%
	277_RUNOFF_PRECIP	11.0	10.9	10.9	11.4	11.0	10.9	11.0	2.1 - 20.1	14.5%	14.5%	15.0%	14.2%	14.5%	14.2%	15.8%	3.0 - 24.7%
	221C_MONTHLY_COV	6.2	5.8	6.2	6.3	6.3	6.3	9.4	1.3 - 20.4	8.1%	7.7%	8.3%	8.1%	8.3%	8.3%	13.5%	2.1 - 26.2%
	297_MACROINVERTEBRATE	18.8	18.8	18.6	18.9	18.9	18.6	8.8	3.2 - 30.0	24.7%	25.1%	24.9%	24.3%	25.0%	24.3%	12.6%	4.3 - 38.8%
	65L_MEAN_ANNUAL_RUNOFF	3.9	4.3	3.2	4.3	4.3	3.2	5.4	1.4 - 15.3	5.1%	5.7%	5.7%	4.2%	5.7%	4.2%	7.8%	2.1 - 21.6%
	568C_FLOOD_MAGNIFICATION	2.5	1.5	2.4	2.1	2.1	4.3	2.8	1.2 - 15.0	3.3%	2.0%	2.8%	3.1%	2.8%	5.6%	4.0%	1.6 - 20.3%
	700C_LOW_FLOW_REDUCTION	2.4	2.6	1.6	3.0	3.1	1.7	2.5	0.6 - 8.0	3.2%	3.5%	4.0%	2.1%	4.1%	2.2%	3.6%	0.9 - 12.0%
	156_SEDIMENT	1.9	2.0	4.4	0.3	0.2	2.4	2.0	0.0 - 17.3	2.5%	2.6%	0.4%	5.8%	0.3%	3.2%	2.8%	0.0 - 24.6%
	568L_FLOOD_MAGNIFICATION	1.0	0.8	1.0	1.1	1.1	1.0	0.9	0.6 - 3.1	1.3%	1.0%	1.4%	1.4%	1.5%	1.3%	1.4%	0.8 - 3.7%
Emergency Management	447_DISABLED	12.7	13.8	13.7	11.1	11.1	13.7	14.1	4.6 - 22.3	18.6%	19.9%	16.2%	20.5%	15.9%	20.2%	21.6%	6.4 - 32.7%
	700C_LOW_FLOW_REDUCTION	13.6	10.2	10.4	18.1	18.6	10.9	13.3	2.7 - 24.8	19.9%	14.7%	26.3%	15.5%	26.7%	16.0%	20.2%	4.6 - 32.1%
	130_FLOODPLAIN_POPULATION	17.1	21.7	17.6	14.3	14.2	17.5	8.9	0.0 - 26.4	25.0%	31.2%	20.9%	26.4%	20.4%	25.8%	13.4%	0.0 - 34.5%
	443_POVERTY_POPULATION	7.7	7.7	7.7	7.8	7.7	7.6	6.8	0.3 - 14.9	11.3%	11.1%	11.3%	11.5%	11.0%	11.3%	10.4%	0.4 - 20.5%
	700L_LOW_FLOW_REDUCTION	5.0	5.1	4.3	5.5	5.9	4.4	5.6	0.9 - 15.5	7.3%	7.4%	8.0%	6.4%	8.4%	6.4%	8.6%	1.5 - 20.1%
	448_PAST_EXPERIENCE	1.3	1.4	1.3	1.4	1.1	1.3	5.3	0.4 - 25.4	1.9%	2.0%	2.0%	2.0%	1.6%	2.0%	8.1%	0.5 - 35.8%
	568C_FLOOD_MAGNIFICATION	4.2	2.9	5.5	3.1	3.8	5.8	5.2	1.2 - 26.2	6.2%	4.2%	4.6%	8.2%	5.5%	8.5%	8.0%	1.6 - 33.0%
	277_RUNOFF_PRECIP	3.4	3.8	3.0	3.9	3.1	3.0	2.9	0.7 - 10.4	4.9%	5.5%	5.8%	4.6%	4.4%	4.5%	4.4%	1.0 - 14.9%
	450_FLOOD_INSURANCE_COMMUNITIES	2.1	2.1	2.1	2.2	2.1	2.1	1.9	0.2 - 10.6	3.1%	3.1%	3.1%	3.2%	3.1%	3.1%	2.8%	0.3 - 15.0%
	175C_ANNUAL_COV	0.6	0.7	0.7	0.7	0.6	0.6	1.3	0.4 - 18.2	0.9%	1.0%	1.0%	1.1%	0.8%	0.8%	1.9%	0.7 - 25.7%
	95_DROUGHT_SEVERITY	0.7	0.0	0.5	0.4	1.6	0.9	0.3	0.0 - 4.6	1.0%	0.0%	0.6%	0.7%	2.2%	1.3%	0.5%	0.0 - 6.2%
Flood Risk Reduction	568C_FLOOD_MAGNIFICATION	16.0	12.7	15.4	13.7	13.5	24.9	21.3	4.4 - 47.1	30.1%	25.5%	26.4%	28.3%	25.6%	44.6%	43.6%	6.5 - 57.6%
	568L_FLOOD_MAGNIFICATION	6.0	4.2	8.5	4.4	4.6	8.4	9.2	2.2 - 26.4	11.3%	8.4%	8.6%	15.7%	8.6%	15.0%	18.8%	3.3 - 43.3%
	277_RUNOFF_PRECIP	6.6	7.6	4.9	7.9	7.6	4.9	8.1	1.6 - 29.7	12.6%	15.3%	15.3%	9.1%	14.5%	8.7%	16.7%	2.8 - 47.3%
	590_URBAN_500YRFLOODPLAIN_AREA	22.6	23.7	23.8	24.2	25.4	16.2	6.8	0.0 - 43.5	43.0%	47.7%	46.6%	43.8%	48.1%	28.9%	12.8%	0.0 - 66.3%
	175C_ANNUAL_COV	1.6	1.6	1.7	1.7	1.7	1.6	4.2	1.2 - 37.3	3.1%	3.2%	3.2%	3.1%	3.2%	2.8%	8.2%	2.3 - 52.6%
Recreation	570L_90PERC_EXCEEDANCE	10.0	11.7	11.2	11.3	8.0	7.8	17.7	4.7 - 29.6	14.7%	17.7%	16.7%	16.5%	10.8%	11.8%	26.7%	7.9 - 43.8%
	700C_LOW_FLOW_REDUCTION	17.6	15.8	20.0	21.9	15.8	14.4	17.1	1.6 - 26.1	25.8%	24.0%	32.5%	29.4%	21.3%	21.8%	26.4%	2.6 - 39.6%
	221C_MONTHLY_COV	2.8	3.4	2.6	2.7	3.1	2.4	7.1	1.2 - 22.6	4.2%	5.1%	3.9%	3.9%	4.2%	3.7%	10.7%	2.1 - 31.5%
	571C_10PERC_EXCEEDANCE	14.4	20.6	15.3	15.1	10.6	10.6	6.7	1.4 - 20.6	21.3%	31.2%	22.4%	22.5%	14.3%	16.0%	10.4%	1.9 - 31.2%
	568C_FLOOD_MAGNIFICATION	4.4	4.4	6.7	3.5	2.4	4.9	5.3	1.8 - 27.5	6.5%	6.7%	5.2%	9.9%	3.2%	7.4%	8.0%	2.4 - 32.1%
	277_RUNOFF_PRECIP	5.3	6.8	5.0	6.7	4.5	3.5	4.8	1.2 - 12.7	7.8%	10.3%	10.0%	7.4%	6.1%	5.3%	7.3%	1.7 - 19.2%
	95_DROUGHT_SEVERITY	11.2	0.0	3.8	4.5	28.1	19.7	3.8	0.0 - 35.5	16.0%	0.0%	6.7%	5.6%	38.0%	29.7%	5.6%	0.0 - 46.1%
	568L_FLOOD_MAGNIFICATION	1.5	1.4	1.8	1.5	1.4	1.6	1.8	0.7 - 6.4	2.3%	2.2%	2.2%	2.7%	1.8%	2.5%	2.7%	1.1 - 7.9%
	156_SEDIMENT	1.0	1.9	1.4	0.3	0.2	1.2	1.4	0.0 - 20.8	1.5%	2.9%	0.4%	2.1%	0.2%	1.8%	2.2%	0.0 - 31.7%

Conclusion

Available academic literature is largely lacking in consensus about past trends in precipitation and temperature, with uneven cycles of warmer and cooler weather potentially obscuring longer-term changes, and natural variability in precipitation dominating changes in mean rainfall. Future changes described in the literature are expected to bring warmer temperatures but varied effects for rainfall frequency and intensity. Because the UBB project area does not include a river, there was no opportunity to test nonstationarity of river discharge or project changed river flow in the future. Instead, the timeseries toolbox was used to assess changes in precipitation over time at New Orleans Airport and the Paradis weather station. While there was some evidence possibly indicating a slow increase in annual rainfall over time and/or a potential change point in the early portion of the record, the detected trends were not statistically significant at the $p < 0.05$ level and the change points did not meet the criteria of consensus, robustness, and magnitude to justify a greater level of uncertainty than that normally associated with hydrologic analysis. Finally, the Vulnerability Assessment tool was used to assess potential project vulnerabilities based on projected future climate data. The results of this analysis indicate that that UBB project is located in a watershed that is among the 20% most vulnerable in the USACE portfolio for the Flood Risk Reduction business line, primarily as a result of the population within the 500 year floodplain and the cumulative projected runoff amplification. These results should be interpreted cautiously as the watershed that contains the UBB project also includes the Mississippi River and metro New Orleans, so these indicators may not be representative of the project site specifically. Nevertheless, the designers of the UBB project and the residents of the project area should be aware of the potential for increased vulnerability in the future due to more frequent rainfall flooding, along with other potential risks summarized in Table 7, below. Adaptation measures might include drainage structures proactively increased in size, pump houses (if any) sized to accommodate larger pumps in the future, and increased detention areas for storage of rainfall runoff. These considerations should be included in design and in operation and maintenance plans when detailed plans are produced during preconstruction engineering and design.

Table 7: Upper Barataria Basin Climate Risks

Feature	Trigger	Hazard	Harm	Qualitative Likelihood
Barge gate	Increased precipitation intensity	Future rainfall flood volumes could be greater than present	With the barge gate closed, rainfall trapped inside the project area may exceed available storage and lead to flooding	Low; little statistical evidence of increasing rainfall and designs use recent 30 years of rainfall data
Levee	Rapid sea level rise	Sea level rise may be faster than assumed	Residual risk of overtopping levee will be higher than planned. However, flood damage reduction compared to	Moderate; sea level rise may be faster or slower than the values used in design. Current policy considers all

			the without-project condition will also be higher.	USACE sea level scenarios equally likely.
Levee and barge gate	Tidal amplification	As sea levels rise, tidal range may also increase	Residual risk of flooding increased. Gate operational frequency may also increase.	Likely. However, magnitude of change is likely small compared to total water levels.
Levee and barge gate	Increase in storm frequency	More frequent hurricanes increase risk	Risk of overtopping levee is increased. Gate operational frequency may also increase.	Low; little scientific evidence for increased storm frequency at this time.
Project area	Sea level rise, increase in tide range, increase in rainfall	Increase in flood risk unrelated to coastal storm surge	When no storm is present and the gate is open, climate change may increase flood risk in ways the project does not address.	Likely. Sea level rise is certain, precipitation changes are more speculative. Project purpose is only coastal floods; other flood risk will likely continue to increase. Future adaptations (e.g. adding pumps) may help address these risks.

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