US-64 BRIDGE REPLACEMENT ALLIGATOR RIVER, NORTH CAROLINA

PROBABILISTIC SEA LEVEL RISE STUDY

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moffatt & nichol

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ABBREVIATIONS

Abbreviation	Definition
AEP	Annual Exceedance Probability
AIS	Antarctic Ice Sheet
AR5	5th Assessment Report (IPCC)
CMIP5	Coupled Model Intercomparison Project Phase 5
DA	Decision Analysis
DP16	SLR projections based on DeConto and Pollard (2016)
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
GIS	Greenland Ice Sheet
GMSL	Global Mean Sea Level
IPCC	Intergovernmental Panel on Climate Change
K14	SLR projections based on Kopp et al. (2014)
M&N	Moffatt & Nichol
MCS	Monte Carlo Simulation
MSL	Mean Sea Level
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
RSL	Relative Sea Level
SLR	Sea Level Rise
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate
USACE	United States Army Corps of Engineers

1.0 INTRODUCTION

Moffatt & Nichol (M&N) has been retained by the North Carolina Department of Transportation (NCDOT) to provide engineering services in support of the project to replace the US-64 bridge that spans the Alligator River. This report provides a review and analysis of sea level change and storm flooding considerations throughout the design life of the new bridge. To the extent possible, this study was performed as a probabilistic analysis, which illustrates the degree of uncertainty present in sea level change projections.

The existing US-64 bridge across the Alligator River (Figure 1-1) is approximately 15,000 feet long, spanning between Tyrrell and Dare counties. The existing bridge is aging and has had to close several times in recent years for repairs. Efforts are underway to design a new bridge that would fully replace the existing bridge.

Imagery Source: ESRI World Imagery.

Figure 1-1: Project Location

2.0 INPUTS

2.1 Sea Level Rise

2.1.1 Global Sea Level Change

The Intergovernmental Panel on Climate Change (IPCC) is currently in the Sixth Assessment cycle[1]. Although the full sixth Assessment Report (AR6) is not yet complete, the contribution from Working Group I was published[2] in August 2021 (IPCC 2021). This report contains updated global mean sea level rise projections based on the latest climate simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring, et al. 2016). Although the AR6/CMIP6 sea level change projections are not yet published in a format to support the probabilistic analysis presented in this study, the projections for global mean sea level change by 2100 are presented below for comparison with prior projections, providing a helpful perspective regarding how the science is progressing.

The Intergovernmental Panel on Climate Change (IPCC) published its most recent complete Assessment Report (AR5) in 2014 (IPCC 2014, Church, et al. 2013). This report serves as the basis for the projections reported in the North Carolina Sea Level Rise Assessment Report (Overton, et al. 2015). Since the publication of AR5, numerous papers have been published both interpreting and applying the science summarized in AR5 and further developing the underlying science. In late 2019, the IPCC published a *Special Report on the Ocean and Cryosphere in a Changing Climate* (SROCC) (Portner, et al. 2019), with the primary purpose to assess new knowledge since the publication of AR5.

As its name implies SROCC covers special topics related to climate change. Chapter 4 is entitled *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities* (Oppenheimer, et al. 2019) and surveys relevant advances in climate science related to sea level rise projections. Although the report provides an extensive summary of the new scientific knowledge, the underlying climate simulations are from CMIP5 (Taylor, Stouffer and Meehl 2012, Yin 2012). These are the same simulations that were used as the basis for AR5. As indicated above, although the CMIP6 simulation results have been summarized in the IPCC Working Group I report, they have not yet been published in a format suitable for this study.

Because the SROCC projections are based on the same global climate simulations studies as AR5, SROCC left many of the sea level rise components unchanged (e.g., thermal expansion, glacier melt, and the contribution of the Greenland Ice Sheet [GIS]). However, the Antarctic Ice Sheet (AIS) component of the projections was updated based on new research for probabilistic ice melt models of Antarctica in Golledge et al. (2015), Ritz et al. (2015), Levermann et al. (2014),

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[1] IPCC produces several documents in each assessment cycle. For the sixth cycle, three special reports have already been produced, along with a methodology report. In its final form, the Sixth Assessment Report (AR6) will consist of the contributions (reports) from three Working Groups along with a Synthesis Report to integrate the Working Group assessments with the special reports already published.

[2] In its current format, the Working Group I report is stamped with a note indicating "Do Not Cite, Quote or Distribute" and is subject to revisions following the approval of the Summary for Policy Makers, corrigenda, copy-editing, and layout.

Golledge et al. (2019), and Bulthuis et al. (2019). SROCC estimates the Antarctic contribution to GMSL rise by combining the results of these studies (the assumptions used to "combine" them are not discussed). The uncertainties of the different studies were combined using Monte Carlo simulation.

Including the updated Antarctic contribution, the updated GMSL rise prediction for Representative Concentration Pathway (RCP) 8.5 in 2100 is 0.84m [2.76ft] with a "likely" range of 0.61m-1.1m [2.00ft to 3.61ft] (refer to IPCC AR5 (IPCC 2014) for discussion and definition of RCP scenarios). The likely range is defined as one standard deviation from the mean estimate (or 17% - 83% confidence limits). This is 10cm [4 inches] higher than the estimate of 0.74m [2.43ft] (likely range 0.52m to 0.98m [1.71ft to 3.22ft]) published in AR5. A comparison between the overall GMSL projections from AR5 (Church, et al. 2013) and SROCC (Portner, et al. 2019) are summarized in Table 2-1. Note that these projections are not provided with reference to sea levels in a particular year. For AR5 projections (including SROCC), levels are relative to the sea levels between 1986 and 2005. For AR6 projections, levels are relative to sea levels between 1995 and 2014.

The GMSL projections of Kopp et al. (2017) that are discussed below are included for comparison, along with a recent study by Horton et al. (2020) that summarizes results of a survey of SLR experts (H20 survey). While the number of scientists subscribing to a particular SLR estimate is not necessarily an indication that the associated outcomes are more likely to materialize, it is informative to see where the current consensus lies in the scientific community. As can be seen in Table 2-1 [see Table 2-2 for units of feet], both the median and high end of the likely range based on the H20 survey results are higher than the values published by IPCC (AR5 and SROCC) and K14. As discussed in the SROCC, higher projections have been produced by many researchers based on ice melt models for GIS and AIS that have not been accepted by IPCC. These studies (e.g., DeConto and Pollard (2016)) would tend to skew the survey results higher.

Note that these projections are for changes in the global mean sea level. Consideration must be given to local effects, such as subsidence prior to applying these projections to a particular project.

Table 2-1: Global Mean Sea Level Rise Projections for 2100 (in meters)

Emissions Scenario	**Source**				
	AR5 *Church et al.* (2013)	SROCC *Portner et al.* (2019)	K14 *Kopp et al.* (2017)	*H20* *Horton et al.* (2020)	*AR6* *Fox-Kemper et al.* (2021)
RCP 2.6 / SSP1-2.6	0.44 *(0.28 to 0.61)*	0.43 *(0.29 to 0.59)*	*0.49* *(0.36 to 0.66)*	*0.45* *(0.30 to 0.65)*	*0.44* *(0.34 to 0.59)*
RCP 4.5 / SSP2-4.5	0.53 *(0.36 to 0.71)*	0.55 *(0.39 to 0.72)*	*0.59* *(0.44 to 0.78)*	-	*0.61* *(0.50 to 0.81)*
RCP 8.5 / SSP5-8.5	0.74 *(0.52 to 0.98)*	0.84 *(0.61 to 1.1)*	*0.79* *(0.61 to 1.01)*	*0.93* *(0.63 to 1.32)*	*0.81* *(0.68 to 1.05)*

Notes:

[a] "likely" ranges are shown in italics below the median estimate. The likely range is defined in IPCC reports as the 17% to 83% confidence limits (i.e., approximately one standard deviation from a central estimate, assuming a normal distribution).

[b] Comparing these projections is imprecise due to differences in the way the starting-date is assumed for each source. The K14 projections have a definite starting year of 2000 for these projections. AR5, SROCC and H20 follow the IPCC AR5 reference date range of 1986-2005 rather than a single starting year for their projections. AR6 projections are relative to a reference range of 1995-2014.

[c] AR6 uses different nomenclature for emissions scenarios, distinguishing between different Shared Socio-economic Pathways (SSPs) instead of Representative Concentration Pathways (RCPs). However, the nomenclature for SSPs is analogous to the RCPs (e.g., SSP1-2.6 corresponds with RCP 2.6, SSP2-4.5 Corresponds with RCP4.5, and SSP5-8.5 corresponds with RCP8.5). RCP nomenclature is maintained in this study due to reliance on AR5 projections.

Table 2-2: Global Mean Sea Level Rise Projections for 2100 (in feet)

Emissions Scenario	**Source**				
	AR5 *Church et al.* (2013)	SROCC *Portner et al.* (2019)	K14 *Kopp et al.* (2017)	*H20* *Horton et al.* (2020)	*AR6* *Fox-Kemper et al.* (2021)
RCP 2.6 / SSP1-2.6	1.44 *(0.92 to 2.00)*	1.41 *(0.95 to 1.94)*	*1.61* *(1.18 to 2.17)*	*1.48* *(0.98 to 2.13)*	*1.44* *(1.12 to 1.94*
RCP 4.5 / SSP2-4.5	1.74 *(1.18 to 2.33)*	1.80 *(1.28 to 2.36)*	*1.94* *(1.44 to 2.56)*	-	*2.00* *(1.64 to 2.66)*
RCP 8.5 / SSP5-8.5	2.43 *(1.71 to 3.22)*	2.76 *(2.00 to 3.61)*	*2.59* *(2.00 to 3.31)*	*3.05* *(2.07 to 4.33)*	*2.66* *(2.23 to 3.44)*

Notes: See notes for Table 2-1.

2.1.2 Local Sea Level Change

While considerable effort is focused on the underlying science for predicting changes in the global mean sea level, the work products produced by these studies are not always in a format that is useful for incorporating to coastal planning and design projects (Hinkel, et al. 2019). In particular, global estimates of mean sea level change are not directly applicable to any specific project; local effects such as vertical land motion can add or subtract from the global rate of sea level change.

Additionally, changes to the earth's gravitational field due to melting of polar ice results in significant variability in the distribution of the resulting sea level change; i.e., when ice melts, the sea level does not go up everywhere by the same amount [e.g., Bamber and Riva (2010), Mitrovica, et al. (2011), and Adhikari, et al. (2019)].

Because of the complexity in accounting for local effects, some sea level rise studies account only for the global mean sea level change and the local vertical land motion. That is the procedure followed by the North Carolina Sea Level Rise Assessment Report (Overton, et al. 2015). Some other recent studies have produced sea level rise projections that do include more of the local effects and present results in a very useful format. For example, in addition to producing probabilistic analyses for global mean sea level change, Kopp et al. (2014) and Kopp et al. (2017) provide detailed local probabilistic sea level rise projections for tide gauges (and other output points) throughout the world. These local projections can be used for planning and design, incorporating the local effects of subsidence as well as the expected variation in global sea level change.

Kopp et al. (2017) reports two separate sets of sea level projections, which differ in the assumptions made to characterize ice sheet melting.

- K14 – The projections labeled "K14" are based on Kopp et al. (2014), which relies on the expert elicitation work of Bamber and Aspinall (2013) for characterizing the contribution to sea level rise from ice sheets. The SROCC does note that Bamber and Aspinall (2013) has received some criticism regarding their approach for post-processing the expert elicitation data. However, the SROCC does not make any recommendations regarding a better source of probabilistic sea level rise projections.

- DP16 – The projections labeled "DP16" rely on the work of DeConto and Pollard (2016), which (as mentioned above) was specifically called out in the SROCC as being overly conservative. These projections were not used for this study because the DP16 ice melt model has not been widely accepted within the IPCC literature (e.g., criticism in SROCC report).

The likely ranges for the K14 projections published in Kopp et al. (2017) present comparable results to the AR5, SROCC, and AR6 projections (Table 2-1). Dr. Robert Kopp is one of the leading scientists contributing to 2017 NOAA Report on Sea Level Rise in the U.S. (Sweet, Kopp, et al. 2017). Although the K14 projections are based on the CMIP5 climate simulations, this work still represents best available scientific basis for estimating local sea level change at tide gauges around the country. Some states (e.g., Maryland, see Boesch et al. (2018)) have explicitly relied on the K14 results. Other states use the underlying science through reference to the NOAA report or through commission of other studies that use the same methodology (e.g., New York City Panel on Climate Change, see Horton et al. (2015) and Gornitz et al. (2019)). The K14 projections represent the best available projections for local sea level change in North Carolina and were used for this study. The K14 projections for relative sea level change for Duck, NC are shown in Figure 2-1 and Figure 2-2. Note that the K14 RCP8.5 projections include a small inflection at year 2100 which results from a change in the number of climate model simulations used for the periods before

2100 and after 2100. For the purposes of this analysis, the between 2100 and 2130 was smoothed to better fit the long-term trend.

The local sea level change at the Alligator River Bridge is taken as equal to the local sea level change at the Duck tide gauge. This is reasonable due to the structure of the underlying geologic framework, as outlined in Overton et al. (2015). Alligator River is in the Albemarle Embayment Zone which is the same zone as the Duck tide gauge (Zone 2, Figure 2-3). The Duck tide gauge is the only long-term tide gauge in this zone, as well as being the closest tide gauge to the project.

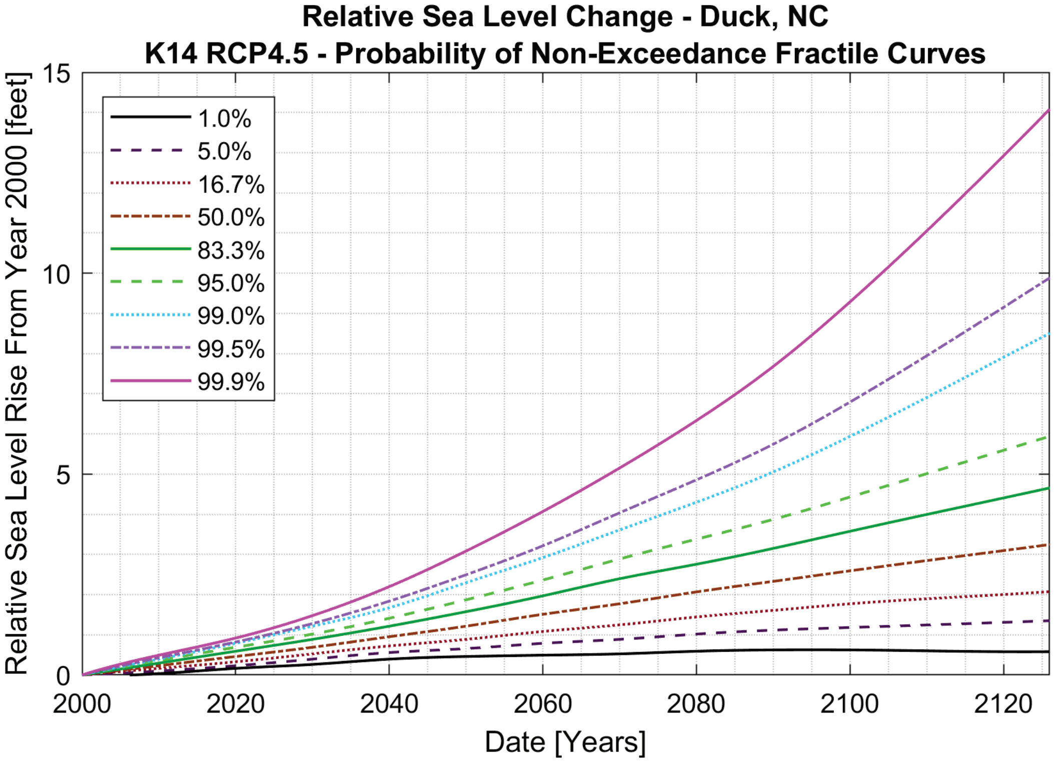


Figure 2-1: Relative Mean Sea Level Change – Duck, NC (K14 RCP4.5)

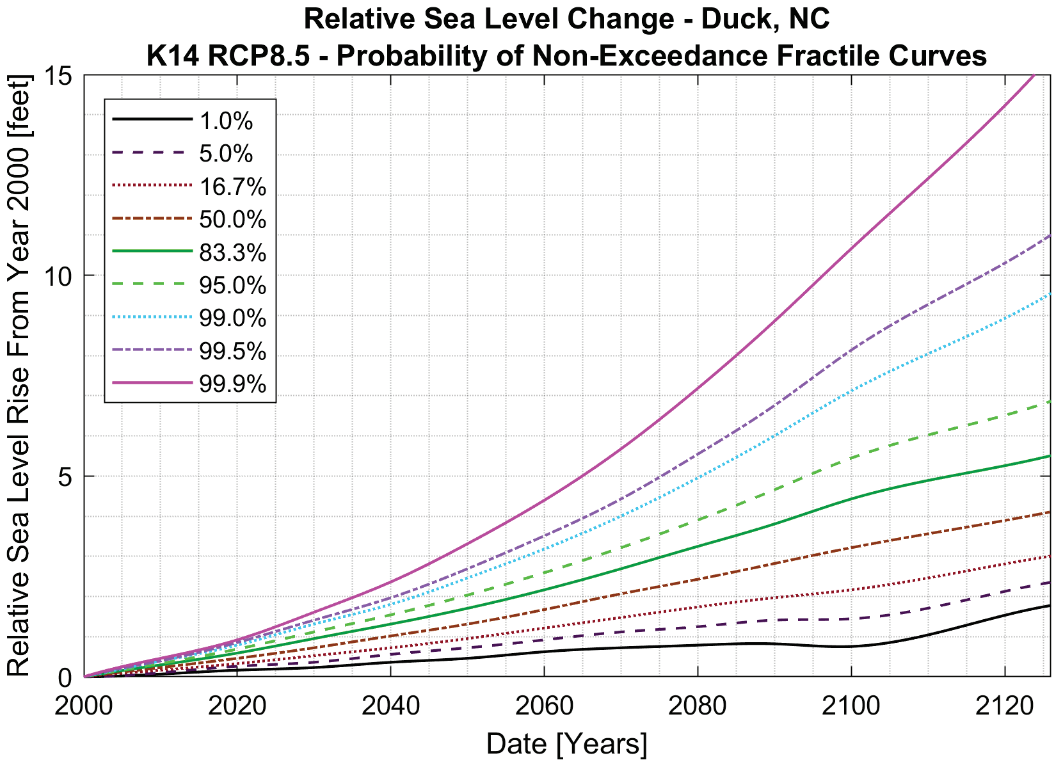


Figure 2-2: Relative Mean Sea Level Change – Duck, NC (K14 RCP8.5)

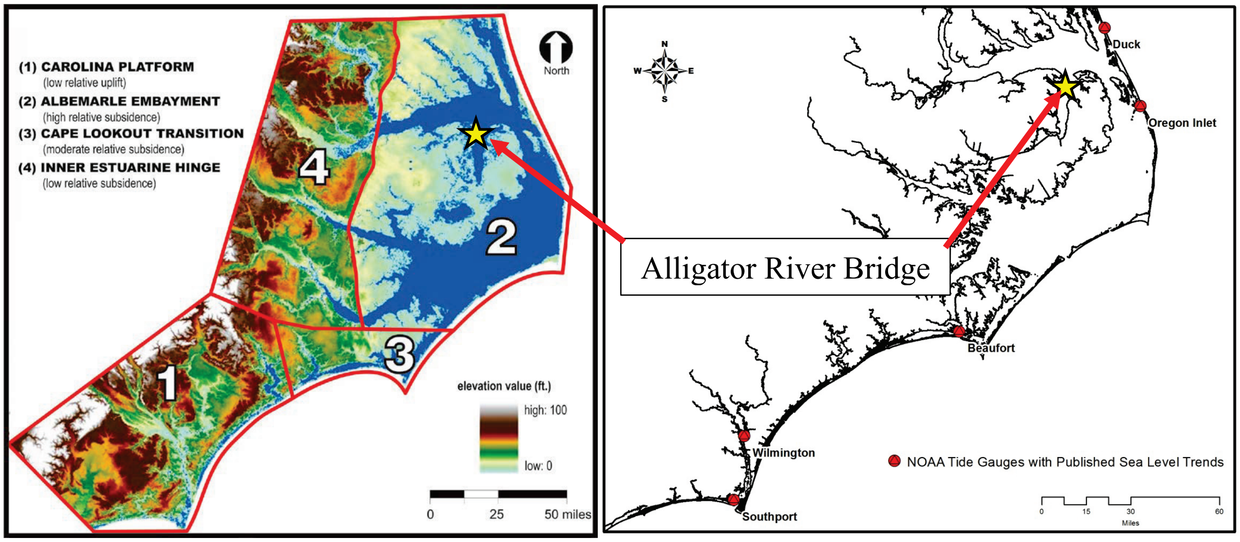


Figure 2-3: Location of the Alligator River Bridge relative to SLR reporting locations [figures from Overton et al. (2015)]

2.1.3 Working with Sea Level Rise Projections – "Deep" Uncertainty

Using SLR projections for planning or engineering design requires some reckoning with the uncertainty in the projections. The best approach for interpreting the uncertainty depends on the type of project, time frame of interest, risk tolerance, and/or other factors. Hinkel et al. (2019) discusses Decision Analysis (DA) approaches for incorporating sea level information, depending on the time horizon and the uncertainty tolerance of the user (e.g., the owner of a project). The authors break uncertainty down into two categories: *Deep* and *Shallow*.

- Deep uncertainty relates to questions that still have significant gaps or differing opinions in the scientific community such that a single probability distribution cannot be developed that summarizes the likelihood of future outcomes based on the consensus of the scientific community.

- Shallow uncertainty refers more to random processes when there is some understanding of the expected variability; therefore, there is some consensus on the likelihood of future outcomes (though still with uncertainty expressed as a single probability distribution function).

With this understanding, Hinkel et al. (2019) suggests that there is sufficient consensus regarding sea level rise probabilities out to about year 2050 to be considered "shallow" uncertainty. Beyond that there is deep uncertainty in the sea level rise estimates. For example, Figure 2-4 shows the relative sea level (RSL) projections published by Kopp et al. (2017) (K14) based on the DeConto and Pollard (2016) (DP16) ice melt model. The median estimate for RSL in 2100 based on DP16 is approximately 6.0ft, compared to approximately 4.0ft for K14 (see Figure 2-2). This difference reflects a fundamental difference in theory about how ice melting will proceed. While both of these studies represent possible outcomes from an RCP 8.5 climate scenario, they result in significant differences in RSL projection. The differences between the different RCP scenarios can also be considered deep uncertainty, since they cannot meaningfully be described by a probability distribution.

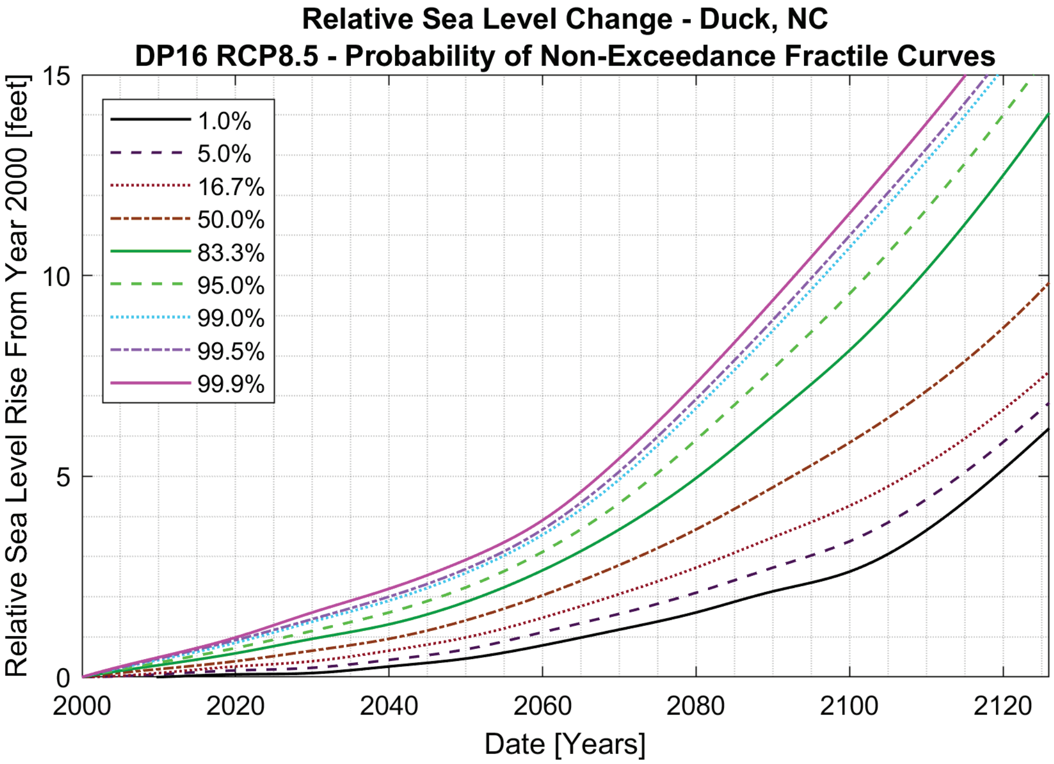


Figure 2-4: Relative Mean Sea Level Change – Duck, NC (DP16 RCP8.5)

When considering shallow uncertainty in planning and design, maximum expected utility (i.e., risk-based) analysis is suitable. With deep uncertainty, there are alternative approaches (e.g., Robust Decision Making [RDM]), which involve looking at a range of scenarios and identifying project alternatives that perform reasonably well (i.e., are *robust*) under a wide range of future states of the world (Hinkel, et al. 2019).

For the Alligator River bridge design project, the SLR projections will be reviewed out to year 2126, which provides for a 100-year design life of a bridge, beginning in 2026. RSL projections out to 2126 include a considerable amount of deep uncertainty, meaning that there is reason to consider using more advanced decision-making tools. This study does not consider a full RDM process. However, two different sea level rise scenarios (K14 RCP4.5 and K14 RCP8.5) are considered throughout the analysis. This study considers that a risk-based approach to SLR can still be appropriate for a 100-year design life if: 1) multiple SLR characterizations are considered to illustrate the sensitivity of results, and 2) if the final interpretation of results takes into consideration the range of predictions produced by the scenarios considered. This approach is consistent with the guidance in NCHRP 15-61 (Kilgore, et al. 2019), which recommends looking at a range of sea level rise scenarios rather than picking one.

For this study, SLR projections are used both for the nuisance flooding analysis and for consideration of storm-induced (i.e., extreme) floods. The K14 RCP4.5 and K14 RCP8.5 probabilistic models are used for this study. Note that the K14 SLR projections begin in year 2000. However, this study assumes historic rates of SLR up to 2010 (Section 2.2). Sea level changes based on K14 projections are used beyond 2010. E.g., the 95th percentile estimate for sea level in

2030 is taken as the sea level in 2010 (based on historic data) plus the change in sea level between 2010 and 2030 following the 95th percentile curve in the K14 projections.

2.2 Vertical Datums

The vertical datum for this study is the North American Vertical Datum of 1988 (NAVD88). Because this study considers Sea Level Rise (SLR) as a variable, the reference tidal datums (e.g., Mean Sea Level [MSL]) are not static. The tidal datums that are currently reported by NOAA for Duck, NC (NOAA Station 8651370) are generally not applicable for the project, considering that the project is substantially isolated from open ocean tides (due to limited flows through Oregon Inlet and the large size of Albemarle Sound, which absorbs any tidal flows with minimal water level change). However, the MSL reported for Duck, NC may be considered broadly indicative of the relative sea level in the vicinity of the project (see discussion in Section 2.1.2). The Duck tide gauge reports an MSL of -0.42 ft NAVD88, which corresponds to the 1983 to 2001 tidal epoch (i.e., approximately MSL in 1992). This study accounts for the change in sea level between 1992 and 2010 (reference starting year for RSL projections in this study) by assuming the average historic rate reported by NOAA (4.79 mm/year). This results in an increase in all water levels of 3.4 inches (or 0.28 ft) between 1992 and 2010.

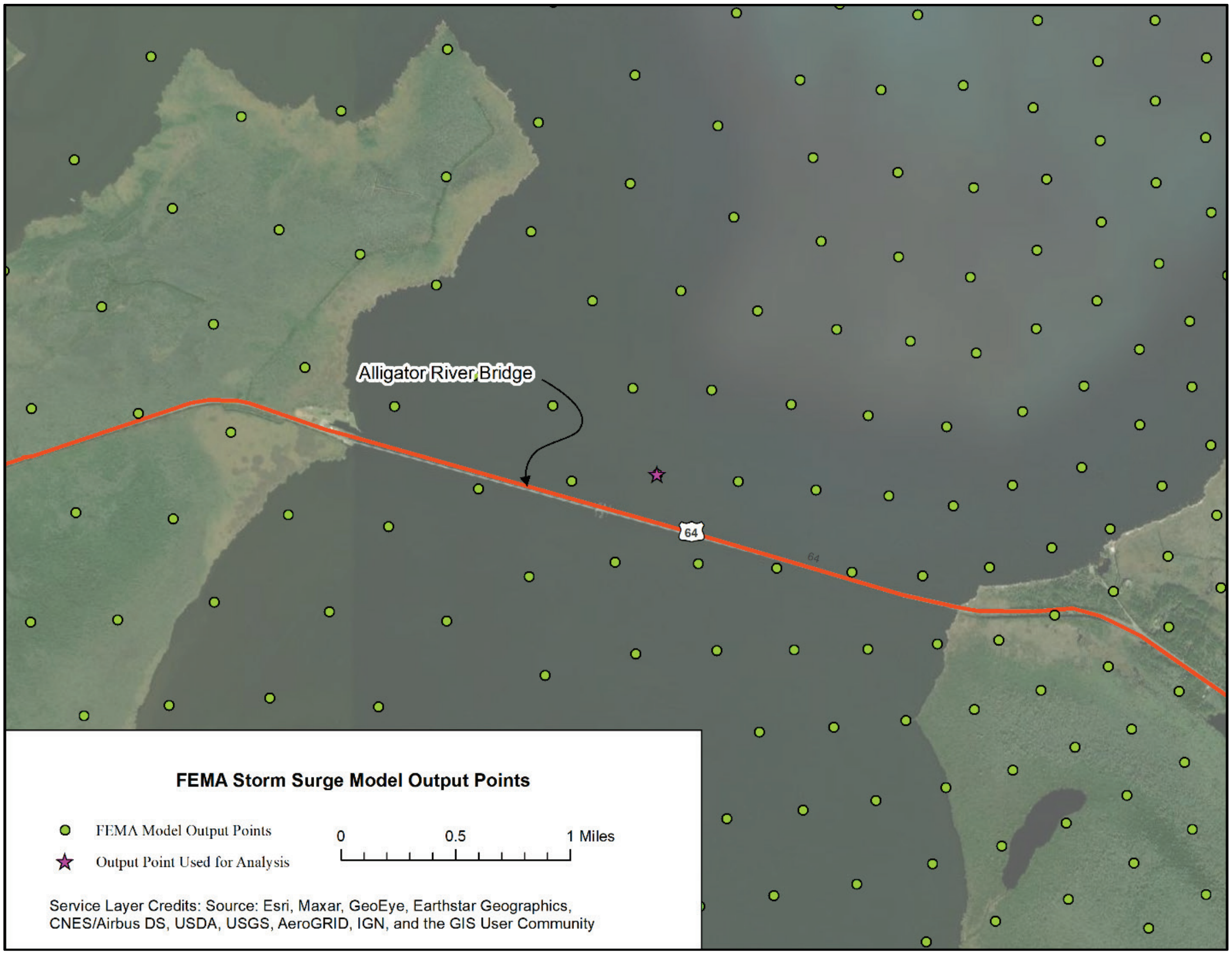
Note that a long-term/stable estimate of the present day (2021) sea level is not known precisely. That is why the year 2010 is used as the start year for RSL projections. It is reasonable to account for some uncertainty in our understanding of historic sea level trends. However, it would be overly conservative to completely disregard the past 21 years of tidal data and use the K14 projections starting in year 2000. For comparison, median estimate for SLR rate for both K14 RCP4.5 and RCP8.5 is approximately 7 mm/year [0.28 inches/year] between 2000 and 2020, which is approximately 50% higher than the historic rate of 4.79 mm/year [0.19 inches/year].

2.3 Storm Flooding

Two sources of data were available for estimating flood frequencies at the Alligator River bridge: a statistical analysis of water level gauge data for the Columbia, NC tide gauge and the flood study that serves as the basis for the Federal Emergency Management Agency (FEMA) floodplain maps. The flood frequencies are presented in terms of return periods (or annual exceedance probabilities) for stillwater flood levels, that include the effects of both storm surge and astronomical tide (but not wind waves).

Storm flooding is based on the model results for FEMA’s storm surge modeling study. The supporting data for the FEMA study was made available for this study by the North Carolina Association of Floodplain Managers (NCAFPM) (refer to Blanton, et al. (2010a), Blanton, et al. (2010b), and Blanton, et al. (2011)). The model results obtained for this study included flood levels for return periods of 10, 25, 50, 100, 500, and 1000 years. The data was reported for each node of the underlying FEMA storm surge model, so the resolution is variable (Figure 2-5).

The lowest return period reported in the FEMA model results is 10-years. In order to complete the analysis in this study, it was necessary to include an estimate of more frequent flooding. This was filled in from an extreme value analysis of water level data from the Columbia, NC gauge. The combined hazard curve data is summarized in Table 2-3.



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2-5: FEMA Model Output Locations

Table 2-3: Still Water Levels – Alligator River Bridge

Return Period[3] [Years]	Lambda [1/Year]	AEP [-]	Flood Level [ft NAVD88] (MSL1992)	Flood Level [ft NAVD88] (MSL2010)[4]	Source
0.22	4.61	0.990	N/A	1.48	Columbia, NC Gauge[5]
1.44	0.69	0.500	N/A	2.20	Columbia, NC Gauge
10.0	0.10	0.095	1.44	1.72[a]	FEMA
25.0	0.04	0.039	2.32	2.60	FEMA
50.0	0.02	0.020	2.85	3.13	FEMA
100.0	0.01	0.010	3.30	3.58	FEMA
500.0	0.002	0.002	4.22	4.50	FEMA
1000.0	0.001	0.001	4.57	4.85	FEMA

[a] Due to several relatively intense storms in the period of record for the gauge data, the estimate of the 0.5% AEP water level is higher than the level estimated by FEMA for the 10-year return period. In order to avoid an inflection in the water level curve, the 10-year return period water level was not used for this study.

2.4 Water Level Data

The Columbia, NC tide gauge is the nearest active tide gauge to the Alligator River bridge. The Columbia, NC water level gauge is part of the NC Flood Inundation Mapping and Alert Network (FIMAN) program. Archived water level data is available for this gauge back March 2013. However, some manual QC of the data was warranted after inspection. A portion of the dataset was extracted to use for this analysis extending from June 1, 2015, to May 31, 2020. This excludes some large gaps and unnatural segments of data and provides good dataset for this study. The water levels are reported at 5-minute intervals. This 5-minute data forms a good basis for a nuisance flooding analysis and was used for this study.

The dataset was purposefully specified to use data in whole-year increments to avoid introducing bias by including more data from one season than another (e.g., including 6 hurricane seasons in 5.5 years of data would bias the data toward higher water levels). In order to use this dataset from

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[3] Analysis assumes that storm surge events are a Poisson process, following a Poisson distribution. A Poisson distribution is described by $P(k) = e^{-\lambda}\frac{\lambda^k}{k!}$, where P is the probability of k events occurring over a given time interval, assuming that the events occur at an average rate of λ events per interval. Taking the reference interval to be 1 year, the average occurrence rate λ it taken to be the inverse of the return period (i.e., $\lambda = 1/(Return\ Period)$. The probability of at least one event in an interval (i.e., Annual Exceedance Probability [AEP], since we took the interval as one year) is one minus the probability of no occurrences on the interval, or $AEP = 1 - P(0) = 1 - e^{-\lambda}\frac{\lambda^0}{0!} = 1 - e^{-\lambda}$. Since λ is the inverse of return period, $AEP = 1 - e^{-1/RP}$, where RP is Return Period. Conversely, $RP = -1/\ln(1 - AEP)$.

[4] Flood levels have been corrected to an estimated 2010 sea level assuming a historic sea level rise rate of 4.79mm/year (NOAA 2021) since the mid-point of the last tidal epoch (18 years; from 1992 to 2010).

[5] See water level analysis below for calculation procedure to develop these water levels for Alligator River based on the Columbia, NC gauge data. See Section 3.1.1.

the gauge in Columbia, NC for the Alligator River bridge study, it was necessary to make reasonable assumptions to estimate the water levels at Alligator River bridge based on the water levels in Columbia, NC. To accomplish this, the following method was employed:

- Remove the sea level change trend from the water level records. This was accomplished by converting all the water level records to correspond to a projected 2026 mean sea level (assuming the historic rate of sea level rise).

- The mean of the data across the whole record was taken and then subtracted from the data. This "de-meaning" of the data effectively converts the data into a time-less mean sea level datum.

- The water levels were multiplied by a constant attenuation factor of 0.9 (Table 2-4), which was calculated based on the consistent lower water level amplitudes at Alligator River than at Columbia, NC based on the FEMA flood study. While the data available for this study cannot fully prove or disprove the hypothesis, it is reasonable to expect that the peak water levels are generally lower at Alligator River than at Columbia, NC based on the FEMA study. This difference is likely due to the geometry of Albemarle Sound.

- The mean water level from the year 2026 data that was subtracted out above was added back in after modulating the water level amplitudes. This results in a best estimate for a time-series of water levels at Alligator River. Based on how it was formed, this time series should be most accurate during the highwater events with lesser accuracy at low water events, which is acceptable for this analysis.

The data shown in Figure 2-6 represents the approximate time-series of water level data calculated for Alligator River based on the Columbia, NC gauge. High water levels were identified for the duration of the dataset using a peaks-over-window method such that the average rate of high-water events is one per day. The resulting dataset of high-water levels represents approximately 4.5 years of time (about 1,600 unique, high-water levels) and was used for the nuisance flooding analysis in this study (Section 3.0). Figure 2-6 illustrates the full length of tide data in the top panel and a zoomed in portion of data in the bottom panel. In both panels, the high tide levels are marked with red x's.

Table 2-4: Peak Water-level Ratios Between Alligator River and Columbia, NC

Return Period	**FEMA Model Flood Level [ft MSL]**		**Ratio [-]**
	Columbia, NC	Alligator River	
10	2.08	1.86	0.89
25	3.03	2.74	0.90
50	3.58	3.27	0.91
100	4.05	3.72	0.92

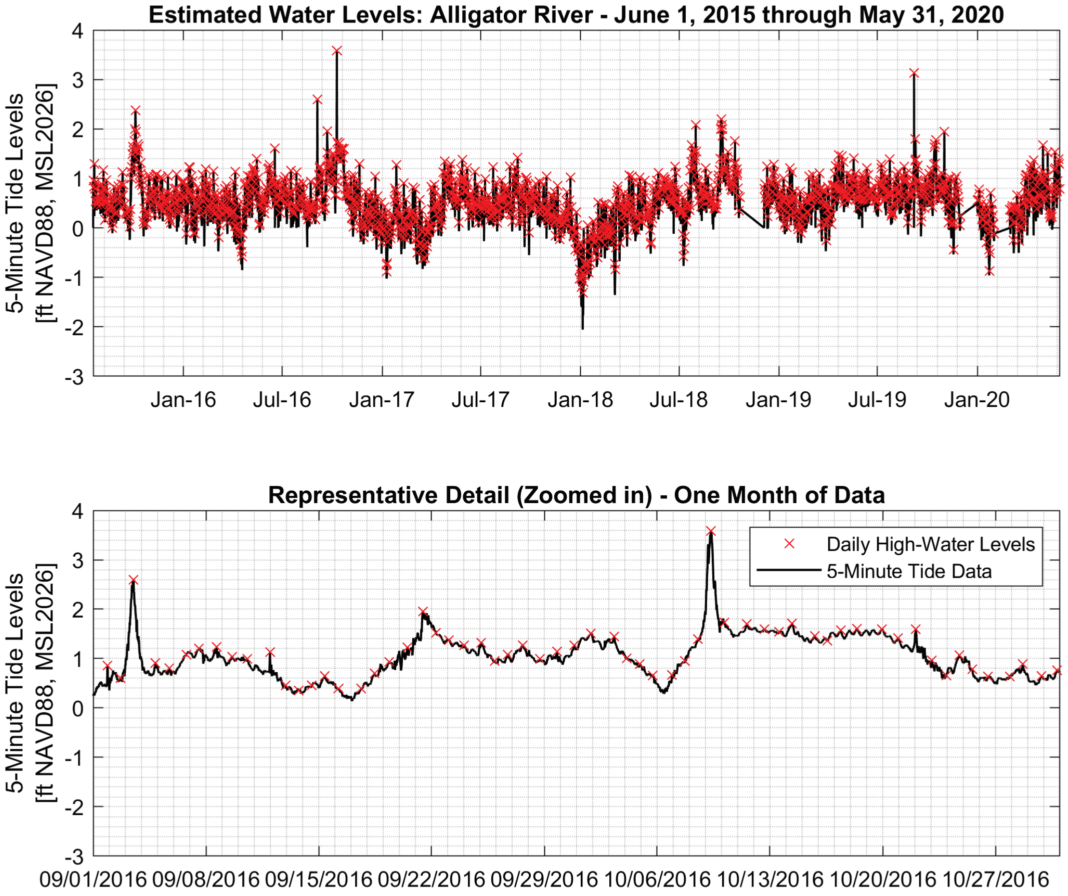

Figure 2-6: Estimated Water Levels for Alligator River

3.0 NUISANCE FLOODING

Nuisance flooding refers to low levels of inundation, not large enough to cause significant property damage or threaten public safety, but to a level that will disrupt routine activities (Moftakhari, et al. 2018). Although it is certainly true that a 100-year flood will cause a "nuisance" in some areas without causing significant property damage, the term "nuisance flooding" typically refers to flooding that is relatively frequent; return periods of 1 year or less. For example, standing water on a roadway on a sunny day would be classified as a nuisance flooding event. This section presents an analysis of potential nuisance flooding under different sea level rise scenarios for the vicinity of the Alligator River bridge.

3.1 Characterization of Historic High-Water Levels

Section 2.4 outlines the development of a water level dataset for Alligator River, which spans approximately 4.5 years (5 years, but with some gaps that reduce the effective length). This dataset was used to develop statistics for the frequency of nuisance flooding. Nuisance flooding in this case is caused almost entirely by atmospheric forcing, not astronomical. These data are shown in Figure 3-1 by plotting position.

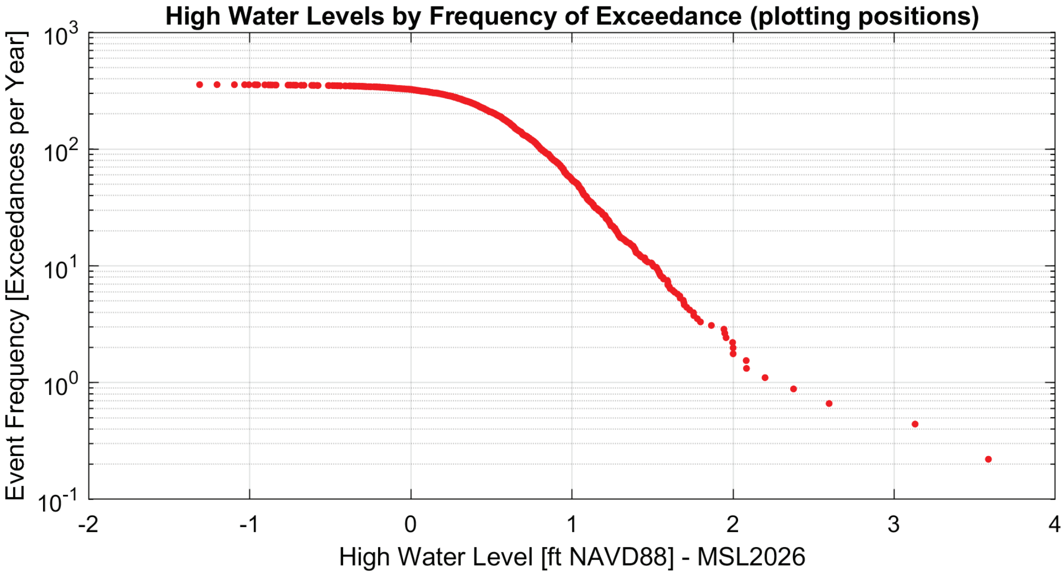

Figure 3-1: Historic High-Tide Levels by Frequency of Exceedance

While in one sense this data represents continuous "population" of high-water levels that could be fit with a probability density function for predicting future tides, there is no single probability function that accurately represents both the "typical" high-water levels and the higher "extreme" water level events. After examining the fit of several possible distribution functions, it was observed that the relatively frequent high-water events (e.g., less than 1.25 ft) are described very well by the historic data and can be represented with confidence by an empirical distribution function based on the plotting position data (Figure 3-1). The less frequent flooding can be described by a peaks-over-threshold probability function which allows for calculating confidence limits for the probability function.

The result is a continuous (though piecewise) probability density function for describing nuisance flooding water levels. This approach is very similar to the methods outlined in Kriebel et al., (2015)

For this study, a threshold high-water level of 1.25 ft (MSL2010) was used as the break between an empirical distribution and a peak-over-threshold distribution. A Generalized Pareto distribution was fit to the data exceeding elevation 1.25 ft. The distribution fit was accomplished using the method of L-moments (J. R. Hosking 1990), with confidence limits computed by Monte Carlo (i.e., “bootstrapping”) simulation (Hosking and Wallis 1997). It is understood that the highest 2-3 tide events in this record correspond with larger storms that do not fit the same distribution function as the other atmospheric-induced high tide events. However, this is not of concern for the study since flooding caused at these frequencies (e.g., 5-year return period) is addressed primarily in the storm flooding analysis (Section 4.0).

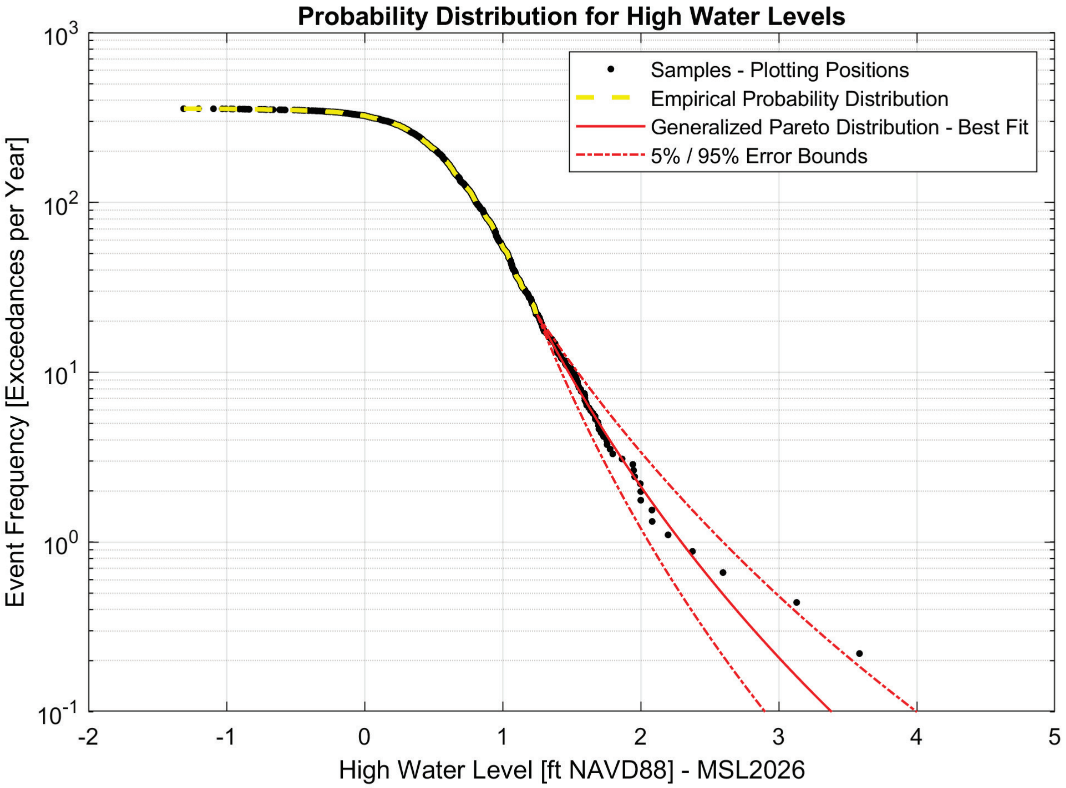

Figure 3-2: Probability Distribution Functions for High Tide Levels

3.2 Sea Level Rise

The goal of this nuisance flooding analysis is to evaluate the effects of SLR. This requires combining the piecewise probability function for high tide levels (Section 3.1) with SLR projections (Section 2.1). To accomplish this, each "fractile" curve from the SLR projections was combined with the probability distribution function for water levels. The results can be presented in figures that are similar to the format presented in Sweet et al. (2018). For specific threshold elevations, the expected number of annual flooding events can be plotted for each SLR curve.

Interpretation of nuisance flooding results depends strongly on the threshold elevations that are of interest to the project. For example, the roadway approaching the existing Alligator River bridge has elevations ranging from approximately 4.5ft to 5.5ft NAVD88[6]. For illustration here, a threshold elevation of +5.0 ft NAVD88 is used to illustrate how SLR could introduce nuisance flooding along the existing roadway and bridge.

Figure 3-3 and Figure 3-4 illustrate the projected frequencies of nuisance flooding at elevation +5.0 ft for the RCP 4.5 and RCP 8.5 climate change scenarios (additional results are included in Appendix A). Notably, for RCP 8.5, the 50th percentile (median) estimate for SLR would cause nuisance flooding (i.e., more than one flood per year on average) above elevation +5.0 ft NAVD88 around year 2100. RCP 4.5 would predict a later onset of nuisance flooding (at or around year 2126). Looking at the 83rd-percentile estimate for SLR, RCP 8.5 would predict onset of nuisance flooding around year 2085 and RCP 4.5 would lead to onset of nuisance flooding closer to 2100. Clearly there is significant uncertainty in these dates, and the goal of this study is not to figure out exactly when nuisance flooding might begin. However, this comparison illustrates the sensitivity of the results to climate scenario assumptions. The differences between RCP 4.5 and RCP 8.5 seem relatively minor for a flood threshold of elevation +5.0 ft NAVD88, with differences of approximately 10-20 years in flooding onset.

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[6] Based on the North Carolina Statewide Lidar DEM 2014 Phase 1, accessed through the NOAA Coastal Data Access Viewer: https://coast.noaa.gov/dataviewer/#/lidar/search/ (accessed September 30, 2021).

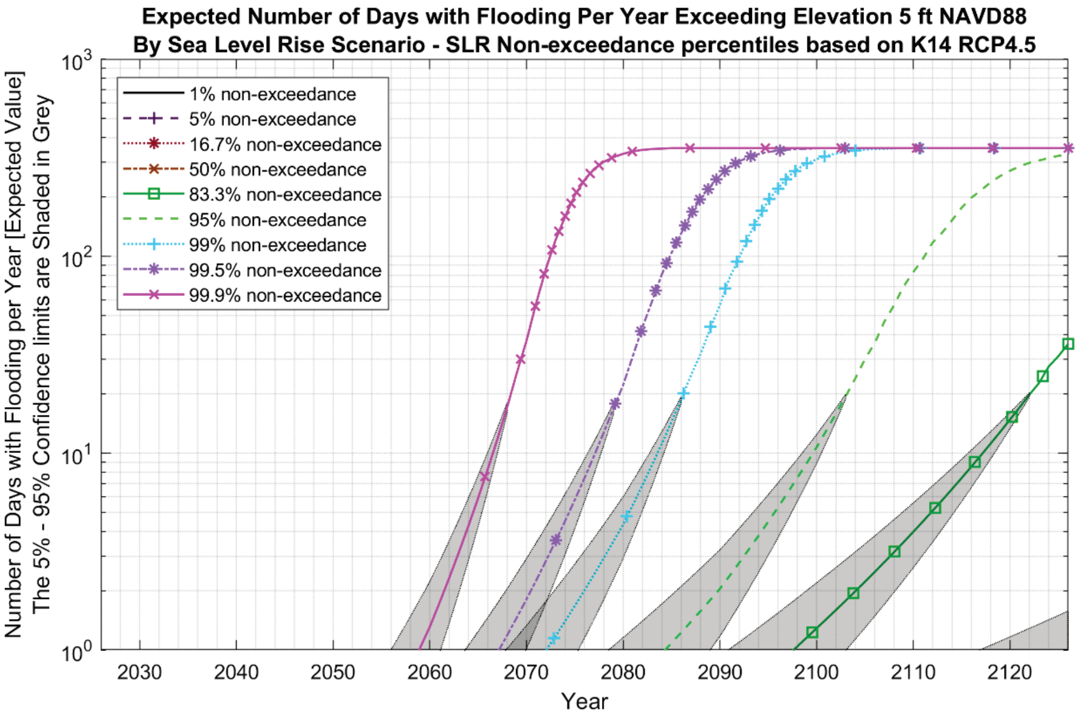

Figure 3-3: Expected Frequency of Nuisance Flooding at Elevation +5.0ft – RCP 4.5

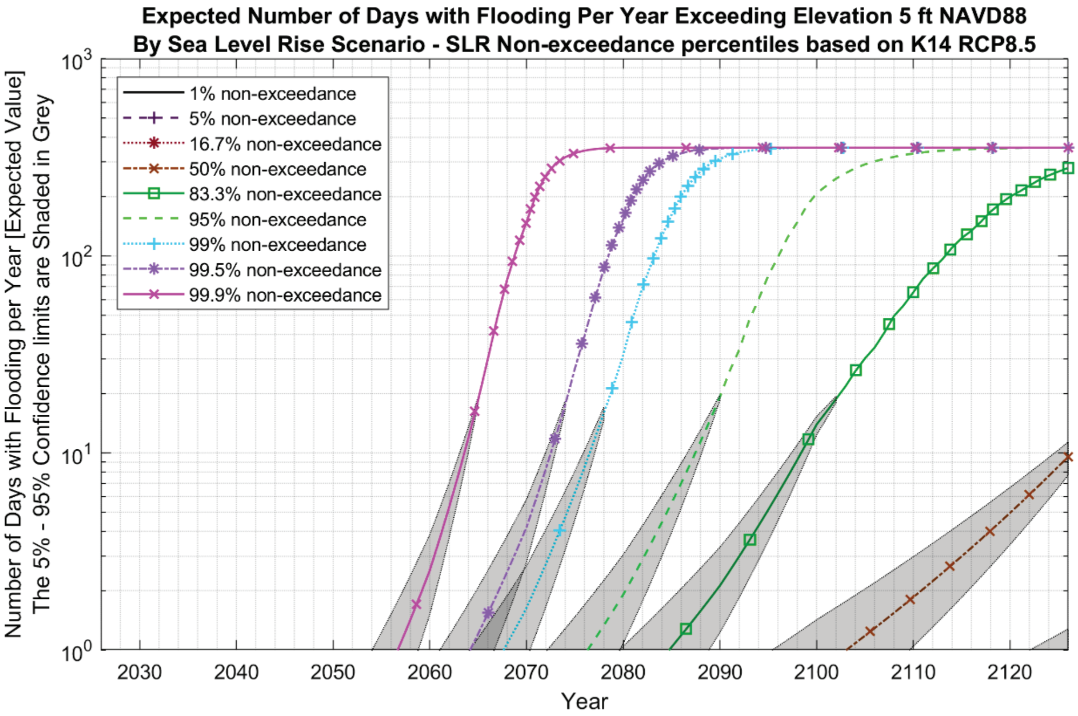

Figure 3-4: Expected Frequency of Nuisance Flooding at Elevation +5.0ft – RCP 8.5

4.0 STORM-INDUCED FLOODING

4.1 Simulation Framework

A Monte Carlo Simulation (MCS) was performed to explore many possible flooding scenarios that could occur over a 100-year period from 2026 to 2126. There were two variables under consideration for this study: 1) flood level (as storm surge plus any astronomical effects), and 2) SLR. The MCS performed for this study consisted of 1,000,000 "simulations" where each iteration of the simulation represents a potential realization of the storm surge floods between years 2026 and 2126.

The stochastic models for each flood variable are summarized in Section 2.0. With two parameters requiring sampling, Monte Carlo sampling is a straightforward approach for integrating the variables.

The inclusion of SLR in the flooding analysis introduces a non-stationary aspect to the problem. Thus, both the sampling method and presentation of results must account for the fact that the flood hazard will increase over time. The MCS approach applied for this study accounts for the time-varying nature of sea level rise using the following approach:

- Sample a pseudorandom SLR curve (e.g., from the RCP 8.5 SLR projections) to represent one potential realization of SLR between years 2026 and 2126 via inverse transform sampling from the fractile curves reported in Kopp et al. (2017). This approach is described in Section 4.2.1.

- Calculate the projected mean sea level for each project year between 2026 and 2126 based on the sampled SLR curve.

- Sample 100 pseudorandom still water flood heights (referenced to the mean sea level in the starting year for RSL projections in this project, i.e., 2010) from the flood level distribution to represent potential maximum annual flooding events for the years 2026 to 2126 (inverse transform sampling from cumulative density function). The still water flood heights are assumed to be the maximum flood height in each year. This sampling approach is described in Section 4.2.2.

- Add the modified still water flood heights to the respective sea levels for each year to determine the simulated peak flood elevation for each year of the project, i.e., the following equation (applied with units of feet, referenced to NAVD88):

  Flood Height in Year X (e.g., 2073) =

  Flood Height (MSL2010) + Relative Sea Level Change Since 2010.

- Repeat the steps above a sufficient number of times to develop a large enough dataset to provide stable statistics for the flood hazard at each year between 2026 and 2126. Visually stable results were obtainable with 1,000,000 samples for this study.

4.2 Sampling Methods

4.2.1 Sea Level Rise

Rather than choosing a single SLR curve as representative for the site, this study incorporates SLR as a stochastic variable to be sampled as part of the Monte Carlo Simulations. Because the K14 RCP 4.5 and RCP 8.5 SLR projections (e.g., Figure 2-2 for RCP 8.5) include a range of fractile curves, synthetic SLR curves can be sampled using the same inverse sampling method used for the astronomical & atmospheric water levels (Section 4.2.2). For each MCS iteration, a pseudorandom SLR curve was generated based on the projections in Figure 2-2 (i.e., 1,000,000 different SLR scenarios were considered for this study).

The sampling of SLR curves is achieved by generating uniform pseudorandom numbers between 0 and 1, and corresponding fractile curves are interpolated/extrapolated (linearly) from the SLR projections in Figure 2-2. For example, Figure 4-1 illustrates three potential SLR curves sampled from the RCP8.5 projections. The same process was followed for both the RCP4.5 and RCP8.5 projections.

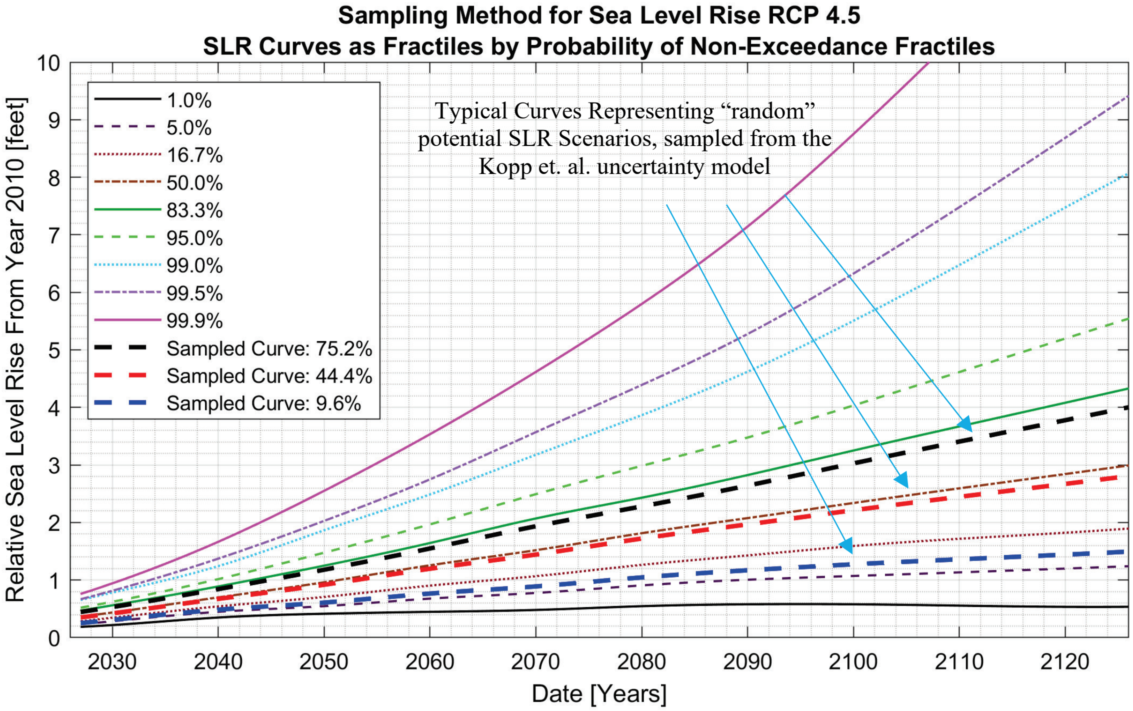

Figure 4-1: Illustration of SLR Sampling Method

4.2.2 Storm Surge

The storm surge levels and exceedance probabilities (Section 2.3) were interpolated and extrapolated (on an AEP log-scale) to provide a continuous distribution function for this study. The extrapolation is necessary to provide a complete numerical probability density function that can be used in a MCS to generate synthetic storm surge data. Synthetic data was generated using the inverse transform method, i.e., by generating uniform pseudorandom numbers between 0 and

1 and mapping each random number onto the cumulative density function for the storm surge hazard curve (Figure 4-2).

The inflection in the curve is due to the differences in trend between the FEMA flood hazard curve and the statistics from the local gauge. This is caused by several large hurricanes in recent years which increase the flood levels predicted by the gauge data. This has a minor impact on the analysis, which is primarily concerned with larger floods that are described by the portion of the curve described by the FEMA model results.

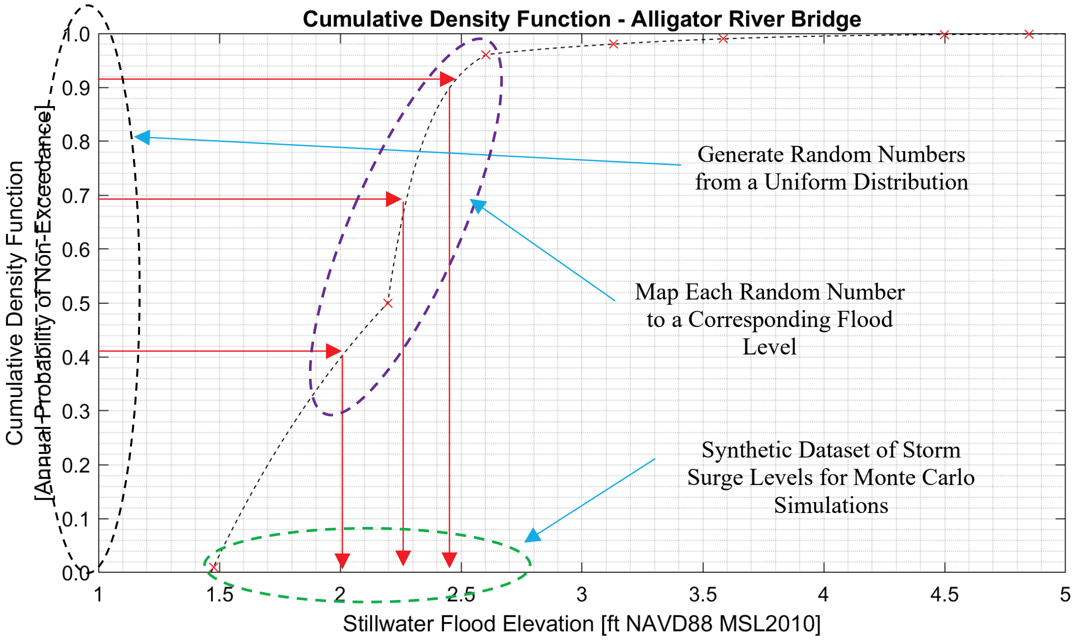

Figure 4-2: Stillwater Level Sampling Method – Inverse Transform Approach

4.2.3 Limitations

A few limitations should be noted regarding the characterization of storm surges in this study:

1. This study does not account for any increase in storm surge amplitude that could occur due to larger storms that may be induced by climate change.

2. This study is performed using an annual maximum data sampling method, which only considers the largest flooding event in a year. The results may be skewed for higher sea level rise scenarios and low site grade elevations where multiple storm surge events could cause flooding in a single year. For consideration of more frequent flooding, the results of the nuisance flooding analysis (Section 3.0) should govern.

3. The number of Monte Carlo simulations (or “samples”) used was sufficient to provide visually stable results (i.e., performing additional simulations did not result in any visible change to the figures or results).

4. Wave setup and runup are not included. The bridge design should include consideration for wind wave effects as a separate analysis.

5. This study does not provide any information on the duration of flooding, the speed at which floodwater may flow, or any of the associated forces that floodwater could exert on the bridge.

4.3 Illustration

The MSC approach generates a large dataset of synthetic storm data, representing potential flood levels that could occur between years 2026 and 2126. For illustration, Figure 4-3 shows the storm surge levels corresponding to two of the MCS iterations. For each iteration in this figure, two sets of flood levels are provided (one level per year). The first level (black dots) is the raw flood level referenced to a 2010 mean sea level. The second level (red x's) is a modified flood level to account for the "random" SLR projection for the MCS iteration (blue line).

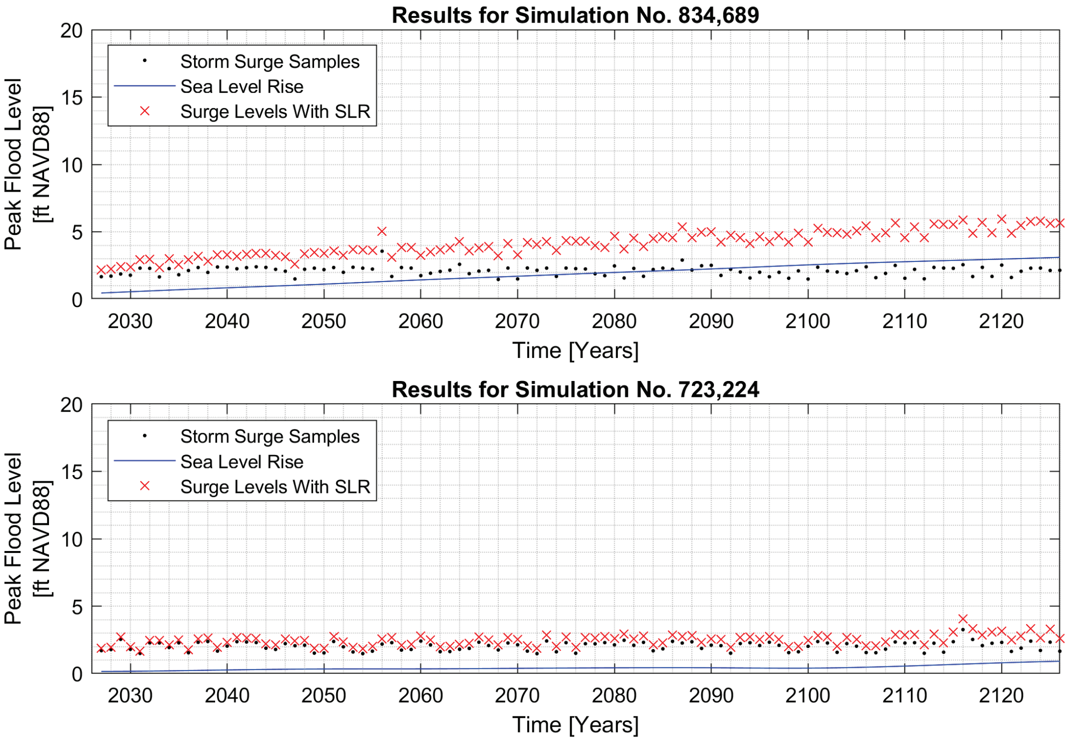

Figure 4-3: Typical MCS Simulation Data

4.4 Results

4.4.1 Annual Flood Risk

After completing the MCS simulations, the resulting dataset of synthetic surge elevations can be sorted, plotted, and tabulated in a variety of ways to illustrate the likelihood of flooding at different levels and over different periods of time. The evolution of benchmark flood levels over time (due to SLR) are presented in Figure 4-4 and Figure 4-5 for RCP 4.5 and RCP 8.5, respectively.

These curves are similar to the evolution of "return periods" (e.g., where the 1% annual chance flood would be the 100-year flood); however, the flood levels are aggregated across all SLR scenarios. Thus, using terms such as return period, may be confusing. These figures are presented in terms of the annualized likelihood of the floods occurring considering both SLR and storm surge.

Table 4-1 and Table 4-2 present the same annualized flood risk data as Figure 4-4 and Figure 4-5, but based on benchmark flood levels (every 0.5ft elevation). These annual flood risks can be compared for reference to the present-day or "no SLR" annual flood risks summarized in Table 4-3 (note that the "no SLR" case is based on an estimated 2026 SLR that assumes the historic rate of SLR between 2010 and 2026). From these tables, it is possible to see how flood risk is expected to evolve throughout the project lifetime.

Clearly there is significant uncertainty in SLR estimates out to 2070, and especially beyond 2070. However, the projections here represent the best estimates based on the current state of science for SLR.

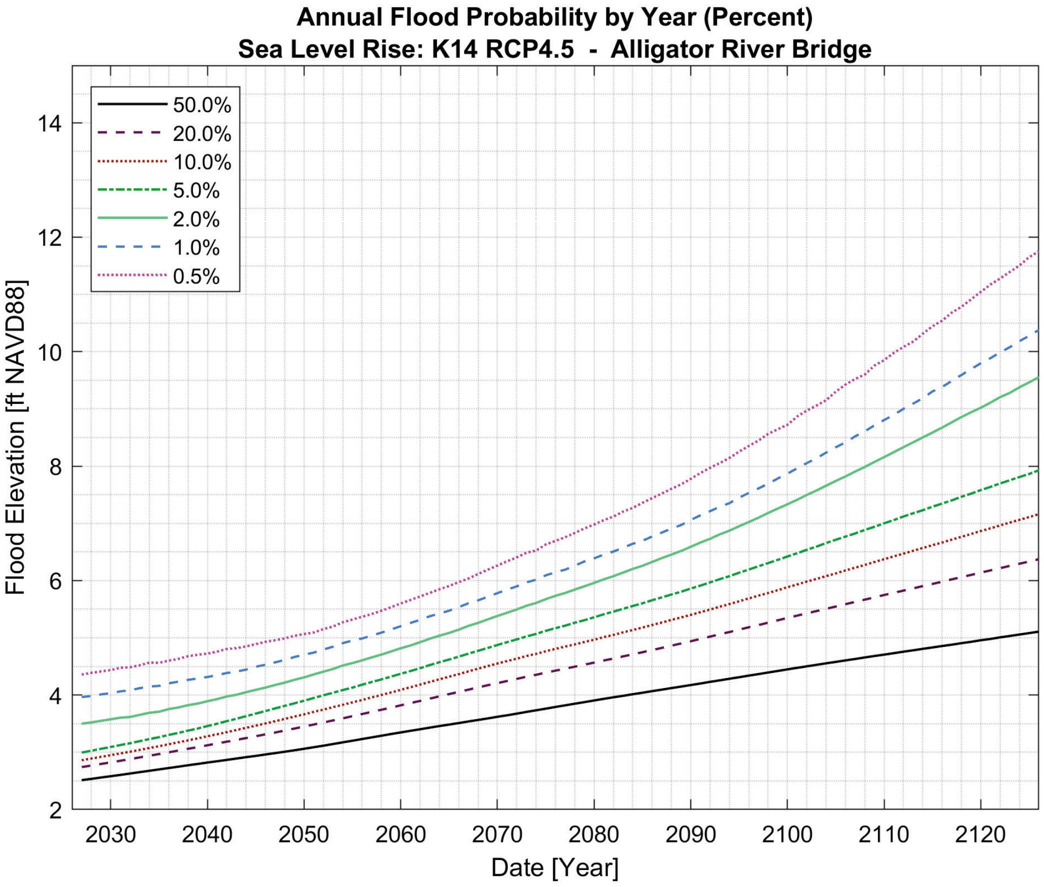

Figure 4-4: Evolution of Benchmark Flood Levels Over Time – RCP 4.5

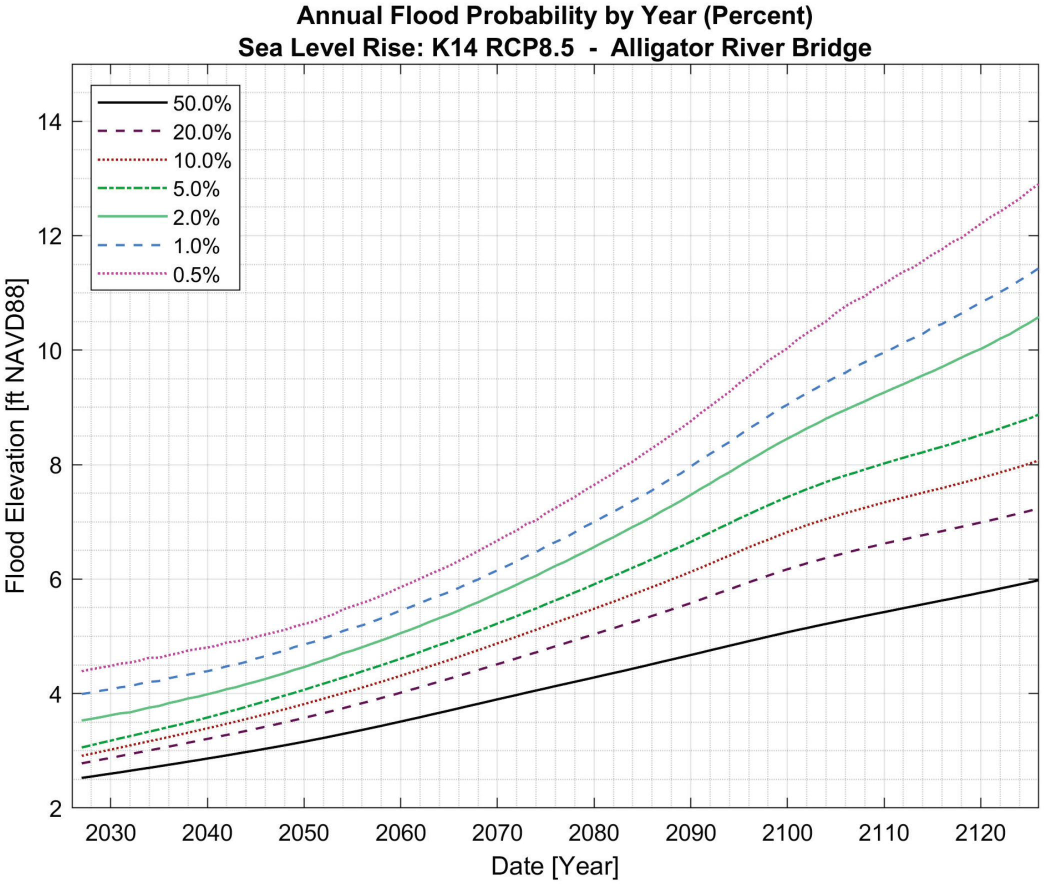

Figure 4-5: Evolution of Benchmark Flood Levels Over Time – RCP 8.5

Table 4-1: Evolution of Annual Flood Risk Over Time - K14 RCP4.5

Site Grade Level [ft NAVD88]	**Annual Likelihood of Flooding**										
	2026	2036	2046	2056	2066	2076	2086	2096	2106	2116	2126
3.0	4.9%	19.9%	46.4%	67.6%	80.8%	88.3%	92.5%	94.4%	95.2%	95.8%	96.3%
3.5	2.0%	3.0%	10.1%	30.2%	50.7%	66.8%	76.9%	83.2%	87.0%	89.2%	90.9%
4.0	0.9%	1.4%	2.5%	7.8%	22.4%	38.8%	53.4%	64.6%	72.3%	77.2%	80.7%
4.5	0.4%	0.6%	1.1%	2.5%	7.2%	17.3%	30.5%	43.3%	53.9%	61.3%	67.3%
5.0	0.2%	0.2%	0.4%	1.0%	2.7%	6.9%	14.0%	25.5%	36.4%	45.6%	53.0%
5.5	0.1%	0.1%	0.2%	0.4%	1.1%	3.0%	6.3%	12.7%	22.2%	31.3%	39.8%
6.0	0.0%	0.0%	0.1%	0.1%	0.5%	1.2%	3.2%	6.4%	12.1%	19.6%	27.6%
6.5	0.0%	0.0%	0.0%	0.1%	0.2%	0.6%	1.5%	3.7%	6.8%	11.7%	17.7%
7.0	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.8%	2.1%	4.2%	7.1%	11.5%
7.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.5%	1.0%	2.8%	4.5%	7.3%
8.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.7%	1.6%	3.4%	4.8%
8.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	0.9%	2.3%	3.8%
9.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.6%	1.5%	2.9%
9.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	0.9%	2.1%
10.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.7%	1.4%
10.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%	0.9%
11.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.7%
11.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.6%
12.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%
12.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%
13.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%
13.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%
14.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%
14.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
15.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%

Table 4-2: Evolution of Annual Flood Risk Over Time - K14 RCP8.5

Site Grade Level [ft NAVD88]	**Annual Likelihood of Flooding**										
	2026	2036	2046	2056	2066	2076	2086	2096	2106	2116	2126
3.0	6.4%	26.3%	53.1%	75.6%	88.9%	94.4%	96.7%	97.0%	98.0%	99.5%	100.0%
3.5	2.1%	3.8%	15.5%	40.0%	65.4%	80.2%	88.3%	91.4%	93.7%	97.5%	99.3%
4.0	1.0%	1.5%	3.4%	13.0%	34.9%	56.9%	71.9%	80.1%	86.0%	92.3%	96.7%
4.5	0.4%	0.7%	1.3%	3.9%	13.3%	32.5%	50.6%	64.2%	73.9%	82.7%	90.3%
5.0	0.2%	0.3%	0.5%	1.4%	4.7%	14.7%	31.1%	47.2%	58.6%	69.0%	78.9%
5.5	0.1%	0.1%	0.2%	0.6%	1.8%	6.2%	16.1%	31.4%	43.9%	53.7%	64.1%
6.0	0.0%	0.0%	0.1%	0.2%	0.8%	2.9%	8.3%	18.7%	30.3%	39.7%	49.4%
6.5	0.0%	0.0%	0.0%	0.1%	0.4%	1.2%	4.2%	10.6%	19.1%	27.1%	36.3%
7.0	0.0%	0.0%	0.0%	0.0%	0.1%	0.6%	2.3%	5.8%	11.6%	17.0%	24.5%
7.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	1.1%	3.6%	7.0%	10.9%	15.7%
8.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.6%	2.2%	4.4%	6.7%	10.7%
8.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	1.2%	3.0%	4.5%	6.8%
9.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.7%	1.9%	3.4%	4.7%
9.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	1.1%	2.4%	3.8%
10.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.8%	1.5%	2.9%
10.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.6%	1.0%	2.1%
11.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	0.7%	1.4%
11.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.6%	1.0%
12.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.5%	0.7%
12.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.6%
13.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%
13.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.4%
14.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%
14.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.3%
15.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%

Table 4-3: Annual Flood Risk – No SLR[7]

Site Grade Level [ft NAVD88]	Annual Likelihood of Flooding
3.0	3.2%
3.5	1.7%
4.0	0.7%
4.5	0.3%
5.0	0.1%
5.5	0.0%
6.0	0.0%
6.5	0.0%
7.0	0.0%
7.5	0.0%
8.0	0.0%
8.5	0.0%
9.0	0.0%
9.5	0.0%
10.0	0.0%
10.5	0.0%
11.0	0.0%
11.5	0.0%
12.0	0.0%
12.5	0.0%
13.0	0.0%
13.5	0.0%
14.0	0.0%
14.5	0.0%

4.4.2 Cumulative Flood Risk

Another way of looking at flood risk is the cumulative risk of flooding over the project lifetime. The cumulative likelihood of flooding at various elevations is shown in Figure 4-6 and Figure 4-7 (for RCP 4.5 and RCP 8.5, respectively) for potential project lifetimes. The likelihood of a flood exceeding any particular elevation is greater for a project with a longer lifetime than for a project with a shorter lifetime. This is due in part to the length of project (which provides more opportunity for flood to reach any particular elevation), but also due to SLR effects.

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[7] The “No SLR” case includes no sea level rise over the reference project time period (beginning in 2026). The historic rate of SLR is assumed between 2010 and 2026.

Table 4-4, Table 4-5, and Table 4-6 present results in tabular format. The rows represent benchmark flood elevations, the columns represent potential project durations (each starting at year 2026), and the values represent the cumulative likelihood of at least one flood exceeding the respective benchmark level during the corresponding project duration. In addition to Table 4-5 and Table 4-6 (which present the results for RCP 4.5 and RP 8.5, respectively), Table 4-4 shows the likelihood of flooding for a "No SLR" scenario.

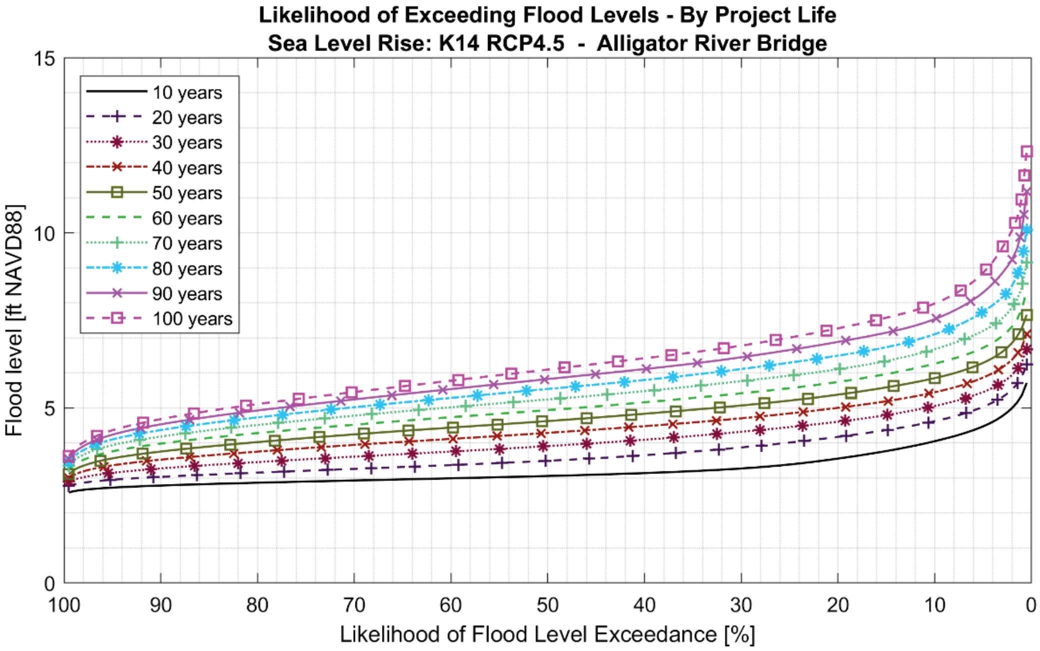

Figure 4-6: Flood Risk by Flood Level and Project Life – RCP 4.5

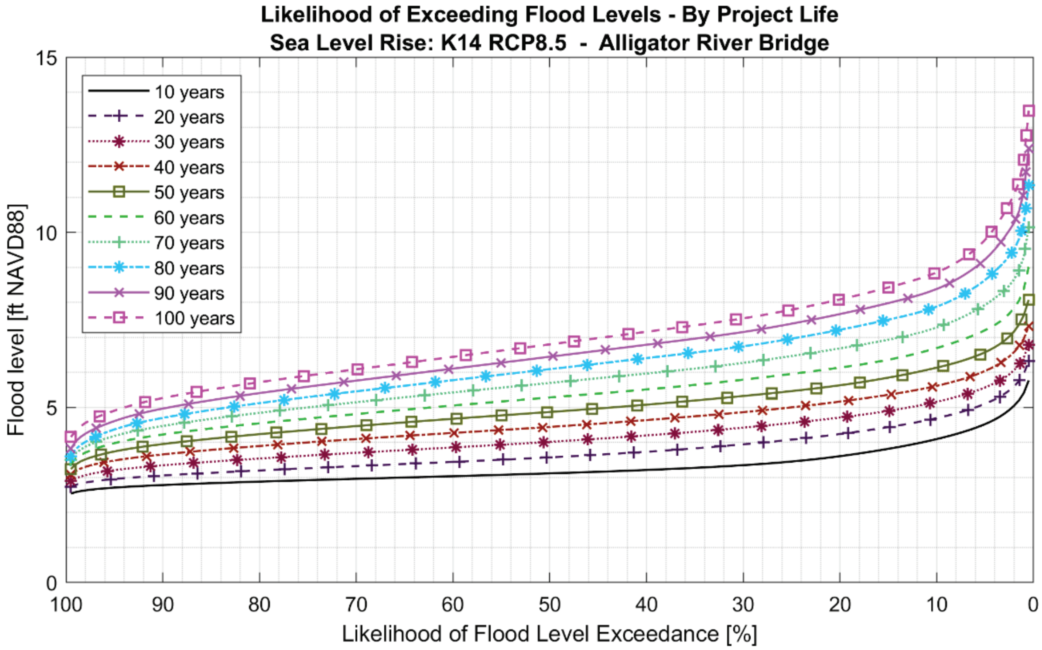

Figure 4-7: Flood Risk by Flood Level and Project Life – RCP 8.5

Table 4-4: Cumulative Flood Risk by Grade Level and Project Duration (No SLR)

Level [ft NAVD88]	Likelihood of Seeing At Least One Flood During Project Life									
	10 Years	20 Years	30 Years	40 Years	50 Years	60 Years	70 Years	80 Years	90 Years	100 Years
3.0	28.1%	48.3%	62.9%	73.3%	80.8%	86.2%	90.1%	92.9%	94.9%	96.3%
3.5	15.3%	28.3%	39.4%	48.7%	56.5%	63.2%	68.9%	73.7%	77.7%	81.1%
4.0	7.2%	13.9%	20.1%	25.9%	31.3%	36.2%	40.9%	45.1%	49.1%	52.7%
4.5	3.1%	6.0%	8.9%	11.7%	14.4%	17.0%	19.6%	22.0%	24.4%	26.7%
5.0	1.2%	2.4%	3.6%	4.7%	5.9%	7.1%	8.2%	9.3%	10.4%	11.5%
5.5	0.5%	0.9%	1.4%	1.8%	2.2%	2.7%	3.1%	3.6%	4.0%	4.5%
6.0	0.2%	0.3%	0.5%	0.7%	0.9%	1.0%	1.2%	1.4%	1.5%	1.7%
6.5	0.1%	0.1%	0.2%	0.3%	0.3%	0.4%	0.4%	0.5%	0.6%	0.6%
7.0	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.2%	0.2%	0.2%	0.2%
7.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
8.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
11.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
11.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
12.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
12.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
13.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
13.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
14.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
14.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4-5: Cumulative Flood Risk by Grade Level and Project Duration (RCP 4.5)

Level [ft NAVD88]	Likelihood of Seeing At Least One Flood During Project Life									
	10 Years	20 Years	30 Years	40 Years	50 Years	60 Years	70 Years	80 Years	90 Years	100 Years
3.0	58.4%	92.1%	98.4%	99.5%	99.8%	99.9%	100.0%	100.0%	100.0%	100.0%
3.5	21.4%	49.3%	77.1%	90.8%	96.1%	98.2%	99.0%	99.4%	99.6%	99.7%
4.0	10.8%	25.3%	44.8%	66.8%	81.0%	89.5%	94.0%	96.2%	97.4%	98.1%
4.5	4.8%	12.2%	23.4%	39.0%	56.7%	71.0%	80.4%	86.8%	90.7%	93.1%
5.0	2.0%	5.3%	10.9%	20.1%	32.8%	47.0%	60.8%	70.8%	77.8%	82.9%
5.5	0.8%	2.1%	4.6%	9.2%	17.0%	27.1%	39.2%	51.6%	61.3%	68.6%
6.0	0.3%	0.8%	1.8%	4.0%	7.9%	14.3%	22.7%	33.2%	43.8%	53.0%
6.5	0.1%	0.3%	0.7%	1.6%	3.6%	7.0%	12.4%	19.8%	28.7%	37.5%
7.0	0.0%	0.1%	0.3%	0.6%	1.6%	3.3%	6.6%	11.2%	17.7%	25.2%
7.5	0.0%	0.0%	0.1%	0.2%	0.7%	1.6%	3.3%	6.5%	10.4%	16.2%
8.0	0.0%	0.0%	0.0%	0.1%	0.3%	0.8%	1.7%	3.7%	6.5%	9.8%
8.5	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.9%	2.0%	4.2%	6.5%
9.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.6%	1.2%	2.6%	4.5%
9.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.7%	1.6%	3.2%
10.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	1.0%	2.1%
10.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.7%	1.4%
11.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.5%	1.0%
11.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.7%
12.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.6%
12.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%
13.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%
13.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.3%
14.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%
14.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
15.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%

Table 4-6: Cumulative Flood Risk by Grade Level and Project Duration (RCP 8.5)

Level [ft NAVD88]	Likelihood of Seeing At Least One Flood During Project Life									
	10 Years	20 Years	30 Years	40 Years	50 Years	60 Years	70 Years	80 Years	90 Years	100 Years
3.0	64.8%	93.1%	98.8%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3.5	23.3%	55.5%	82.3%	94.6%	98.2%	99.1%	99.5%	99.7%	99.9%	100.0%
4.0	11.6%	27.9%	51.0%	75.1%	88.6%	94.7%	97.0%	98.1%	99.1%	99.8%
4.5	5.2%	13.6%	27.1%	46.9%	68.5%	81.7%	89.3%	93.4%	96.1%	98.3%
5.0	2.2%	6.0%	12.9%	25.1%	43.6%	62.3%	75.0%	83.2%	89.4%	93.9%
5.5	0.8%	2.4%	5.7%	12.1%	23.9%	40.5%	57.4%	68.7%	77.6%	85.3%
6.0	0.3%	0.9%	2.3%	5.4%	12.2%	23.8%	38.8%	53.0%	63.1%	72.5%
6.5	0.1%	0.3%	0.9%	2.3%	5.6%	12.7%	24.2%	37.1%	48.4%	58.4%
7.0	0.0%	0.1%	0.3%	0.9%	2.6%	6.7%	13.8%	24.2%	34.0%	44.4%
7.5	0.0%	0.0%	0.1%	0.4%	1.2%	3.2%	8.0%	15.1%	22.9%	31.0%
8.0	0.0%	0.0%	0.0%	0.1%	0.6%	1.6%	4.6%	8.9%	14.7%	21.4%
8.5	0.0%	0.0%	0.0%	0.1%	0.2%	0.9%	2.4%	5.7%	9.0%	14.0%
9.0	0.0%	0.0%	0.0%	0.0%	0.1%	0.5%	1.4%	3.6%	6.0%	8.9%
9.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.8%	2.0%	4.0%	6.1%
10.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.6%	1.3%	2.6%	4.3%
10.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.8%	1.6%	3.1%
11.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.6%	1.1%	2.2%
11.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	0.8%	1.4%
12.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.6%	1.0%
12.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.5%	0.8%
13.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%	0.6%
13.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%	0.5%
14.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.4%
14.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.4%
15.0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.3%

5.0 DISCUSSION

This report illustrates the potential flooding hazards that may occur in the future due to the combined effects of storm surges and sea level rise. These projections are based on a probabilistic model for sea level rise that acknowledges the significant uncertainty in estimating the mean sea level in the future. The analysis is presented in terms of flood levels and likelihood of occurrence that can be used to inform the design of the Alligator River bridge. The study does not account for any nonlinear interaction between storm surges and sea level rise.

The storm surge floodwater level probabilities are presented in a way that highlight the data in two important ways:

1. **Cumulative probability**: The probability of experiencing a flood event can be reflected by aggregating annual probability year-over-year, creating a cumulative probability of experiencing at least one event in a specific timeframe, and used when evaluating useful design lives of infrastructure improvements.
2. **Relative probability**: The relative probability of experiencing a flood event at one elevation compared to a different elevation can be evaluated to determine incremental value changes in adjusting flood protection performance goals for infrastructure improvements.

The results presented do not result in a single definitive answer regarding an optimal elevation for new projects. However, these results can be used to inform one of several potential strategies for designing for and/or mitigating flood risk over the course of the project life. These strategies can be developed and refined as the project advances.

For developing flood risk management strategies, it is often helpful to reference the concept of "Allowances", that is, the vertical offset for a project to achieve a desired risk profile in the future. The desired risk profile could be stated in terms of an annual risk at a certain time in the future or an average/cumulative risk over the life of the project. Two kinds of flood allowances are referenced in recent SLR literature (Buchanan, et al. 2016, Rasmussen, et al. 2020):

- **Instantaneous Design Allowance**: An instantaneous design allowance is the vertical offset required to ensure that the annual flood risk does not exceed a specified threshold (e.g., present-day risk) over the life of the project. For this type of allowance, typically the flood risk is considerably below the desired threshold at the beginning of the project and meets the target threshold at the end of the project.

- **Design Life Allowance**: a design life allowance expresses the acceptable risk threshold as an average over the life of the project (or cumulative over the life of the project). This recognizes that the annual risk changes, but it is sometimes helpful to look at the risk from the perspective of the full life of the project instead of the evolving risk in each year of the project.

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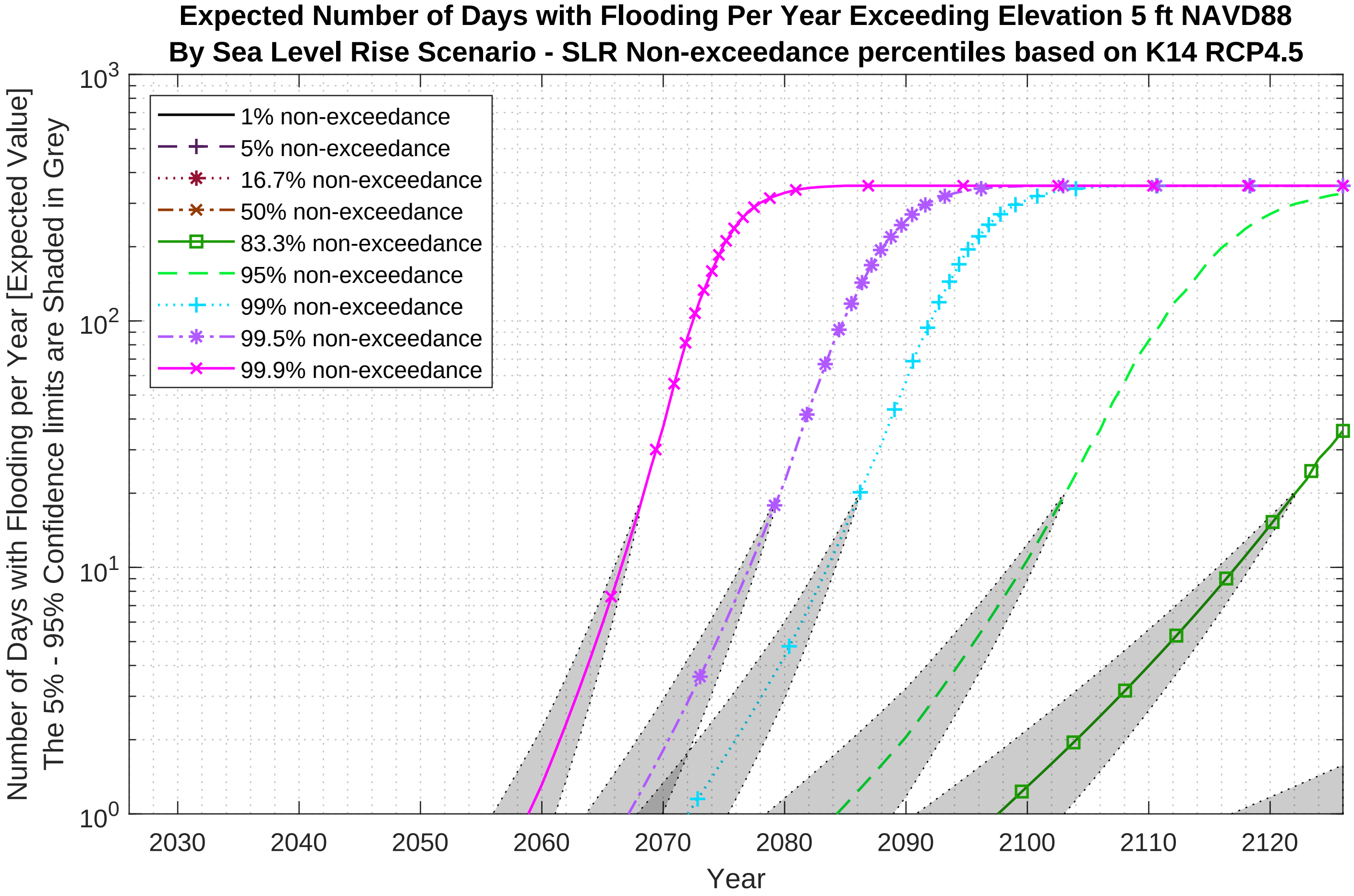
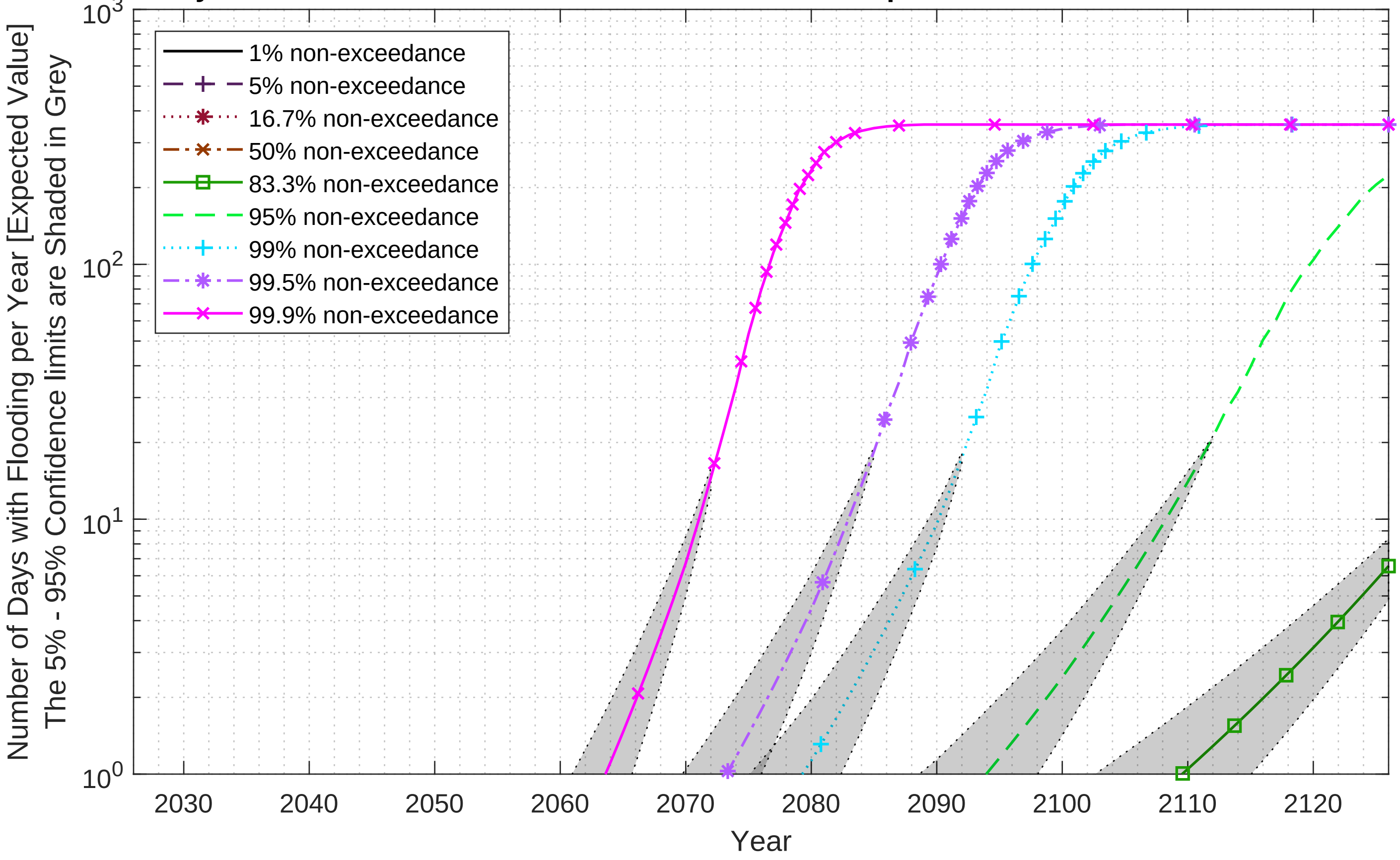
APPENDIX A

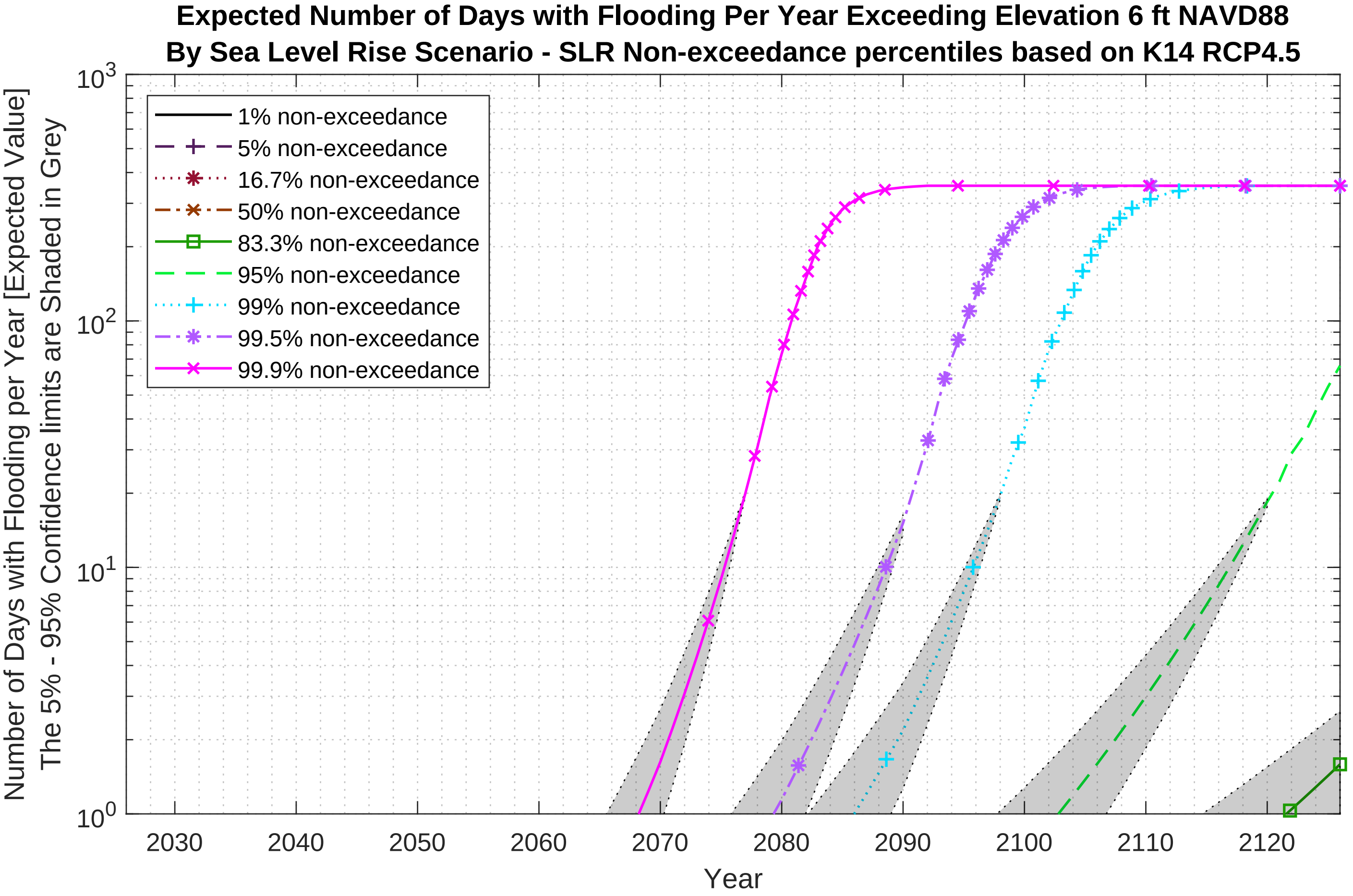
ADDITIONAL NUISANCE FLOODING RESULTS

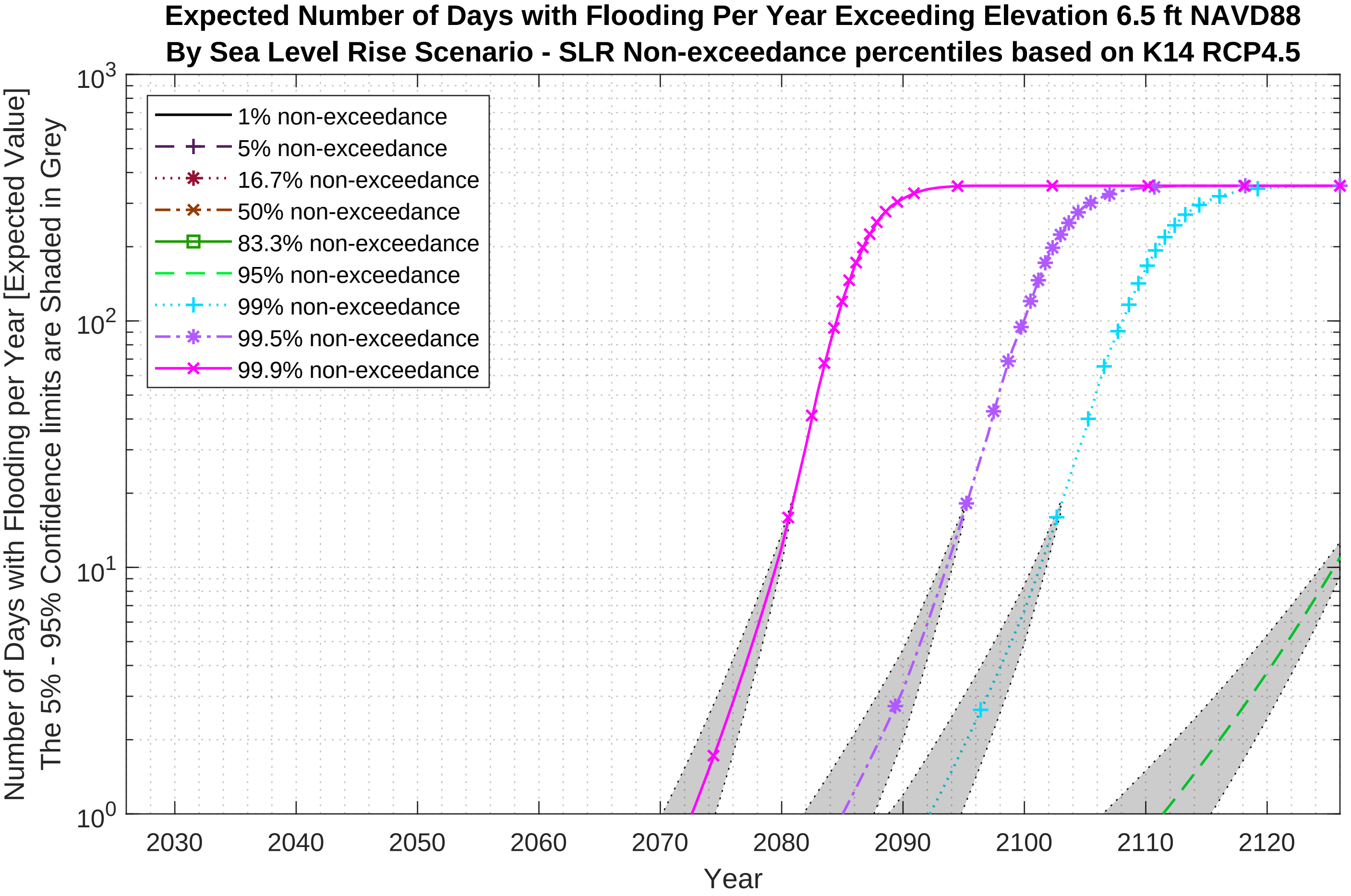


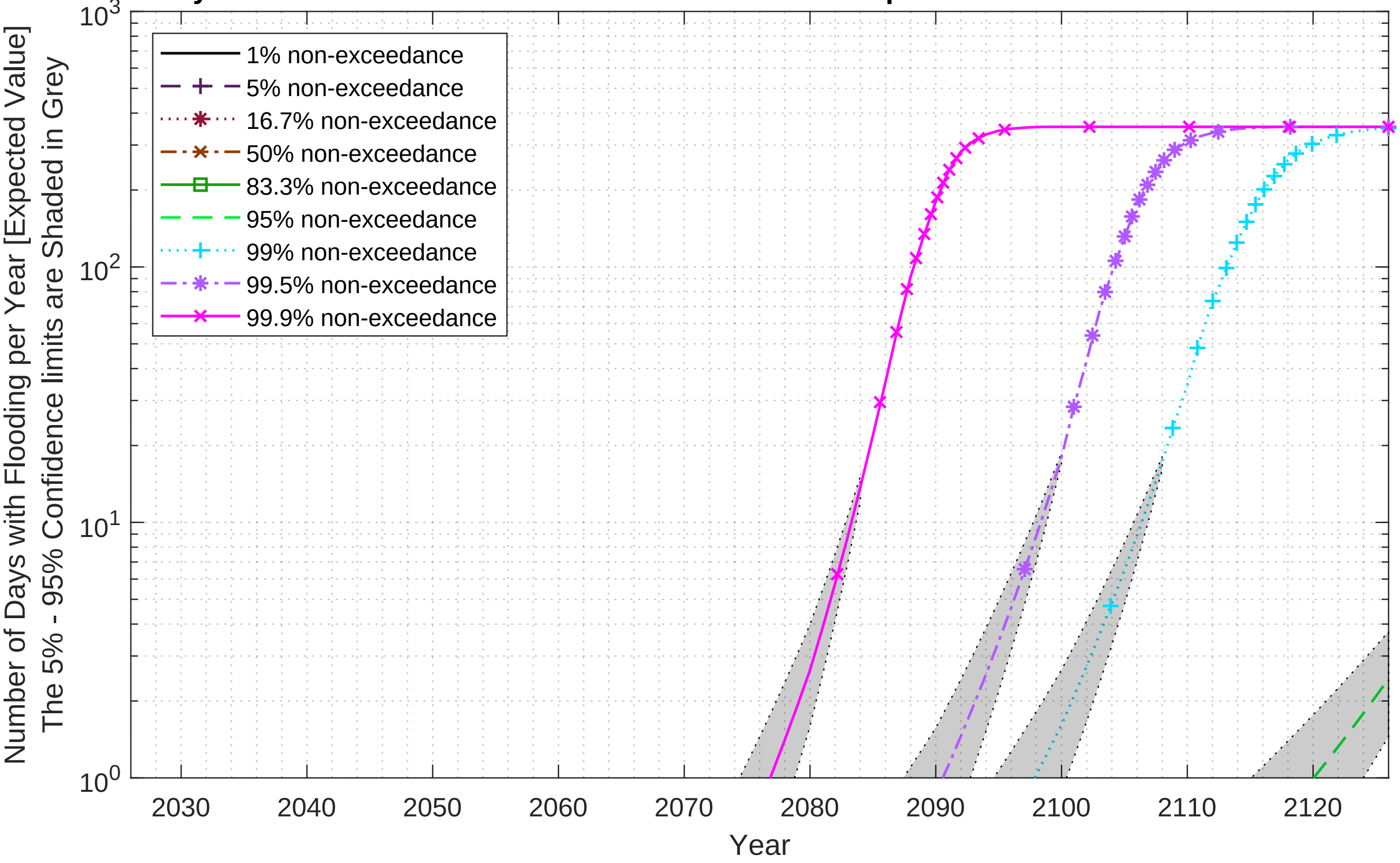
Expected Number of Days with Flooding Per Year Exceeding Elevation 5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5

Expected Number of Days with Flooding Per Year Exceeding Elevation 5.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5



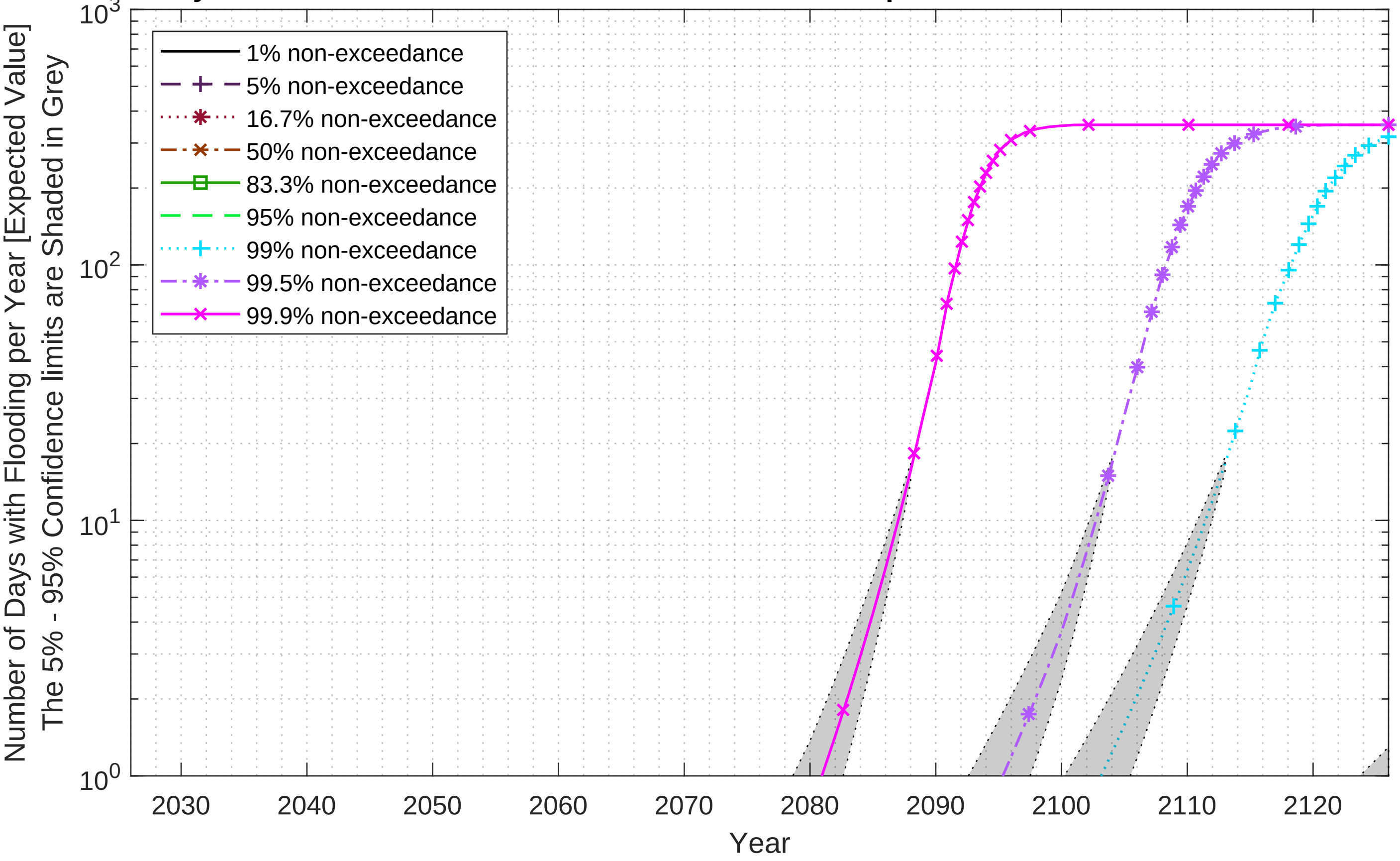

Expected Number of Days with Flooding Per Year Exceeding Elevation 6 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance

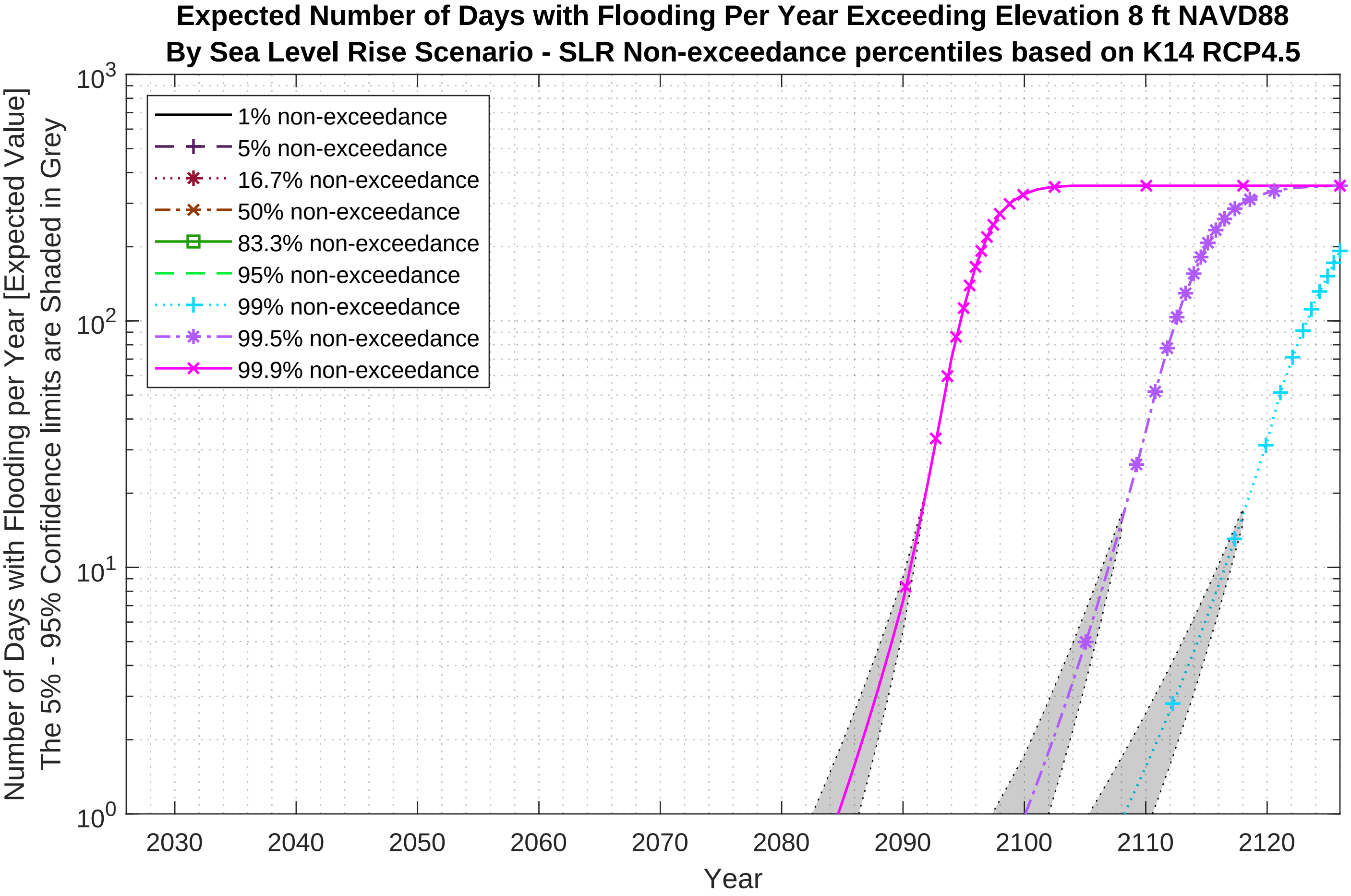

Expected Number of Days with Flooding Per Year Exceeding Elevation 6.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance



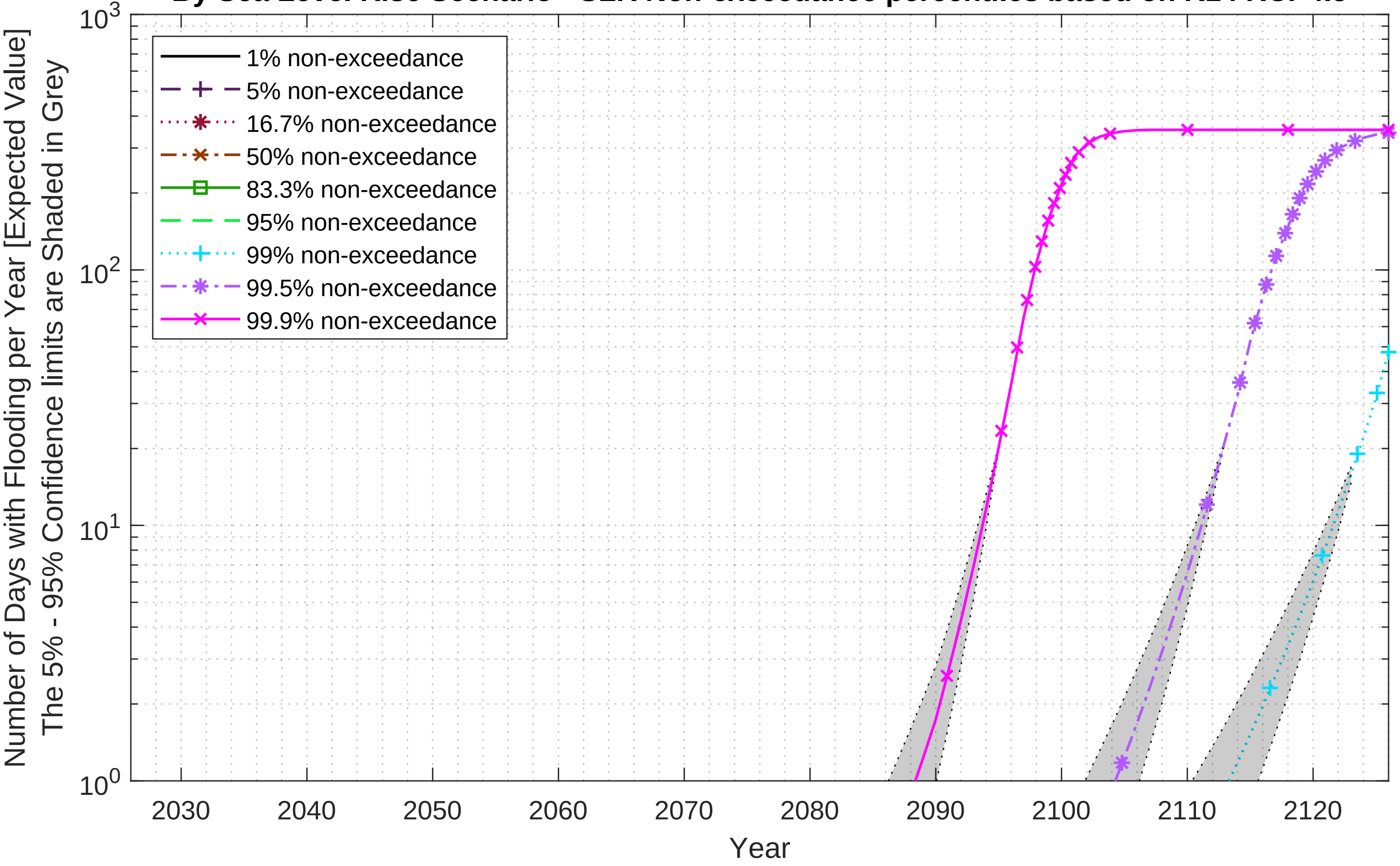
Expected Number of Days with Flooding Per Year Exceeding Elevation 7 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5

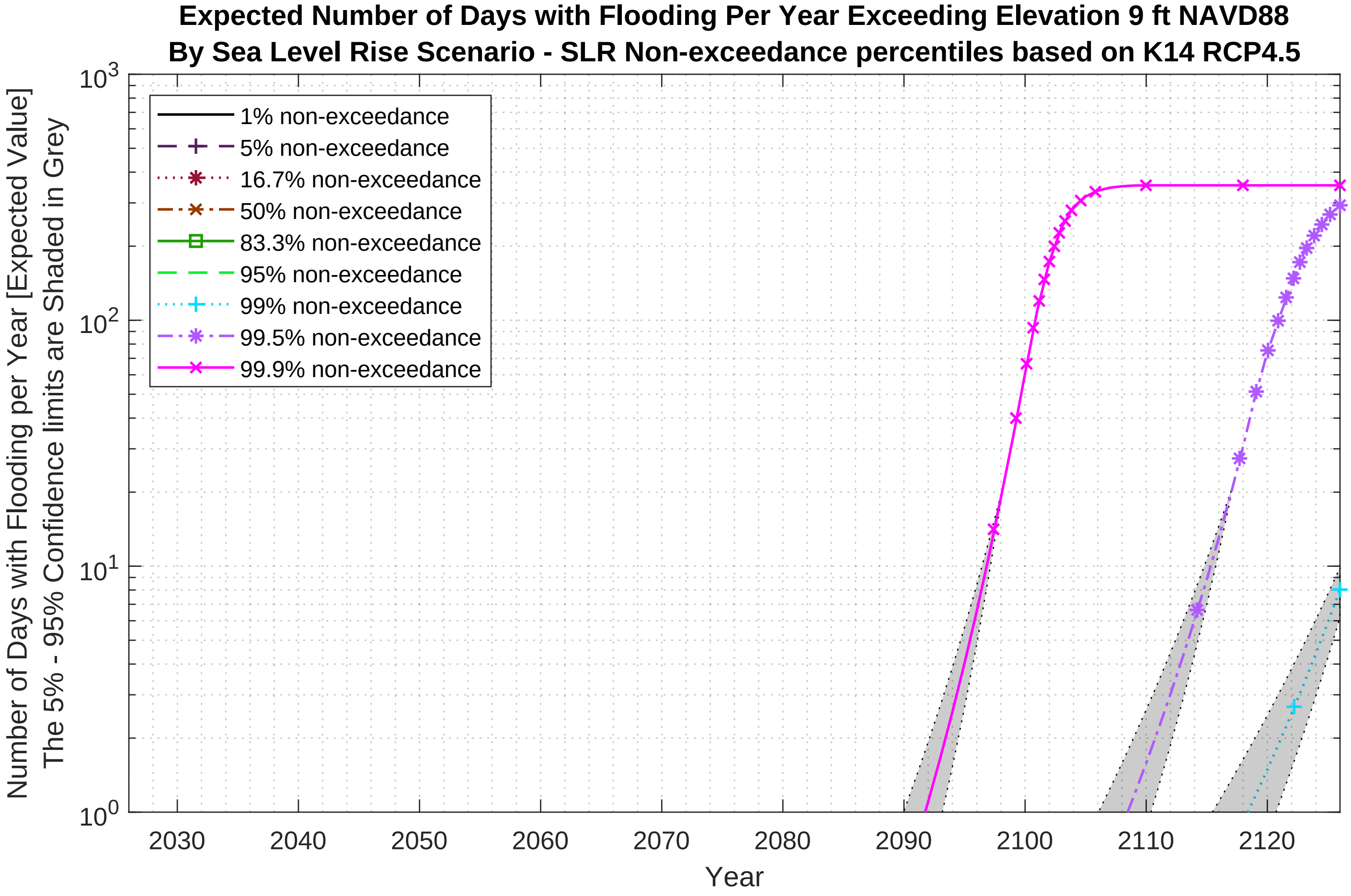
Expected Number of Days with Flooding Per Year Exceeding Elevation 7.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5




Expected Number of Days with Flooding Per Year Exceeding Elevation 8 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance

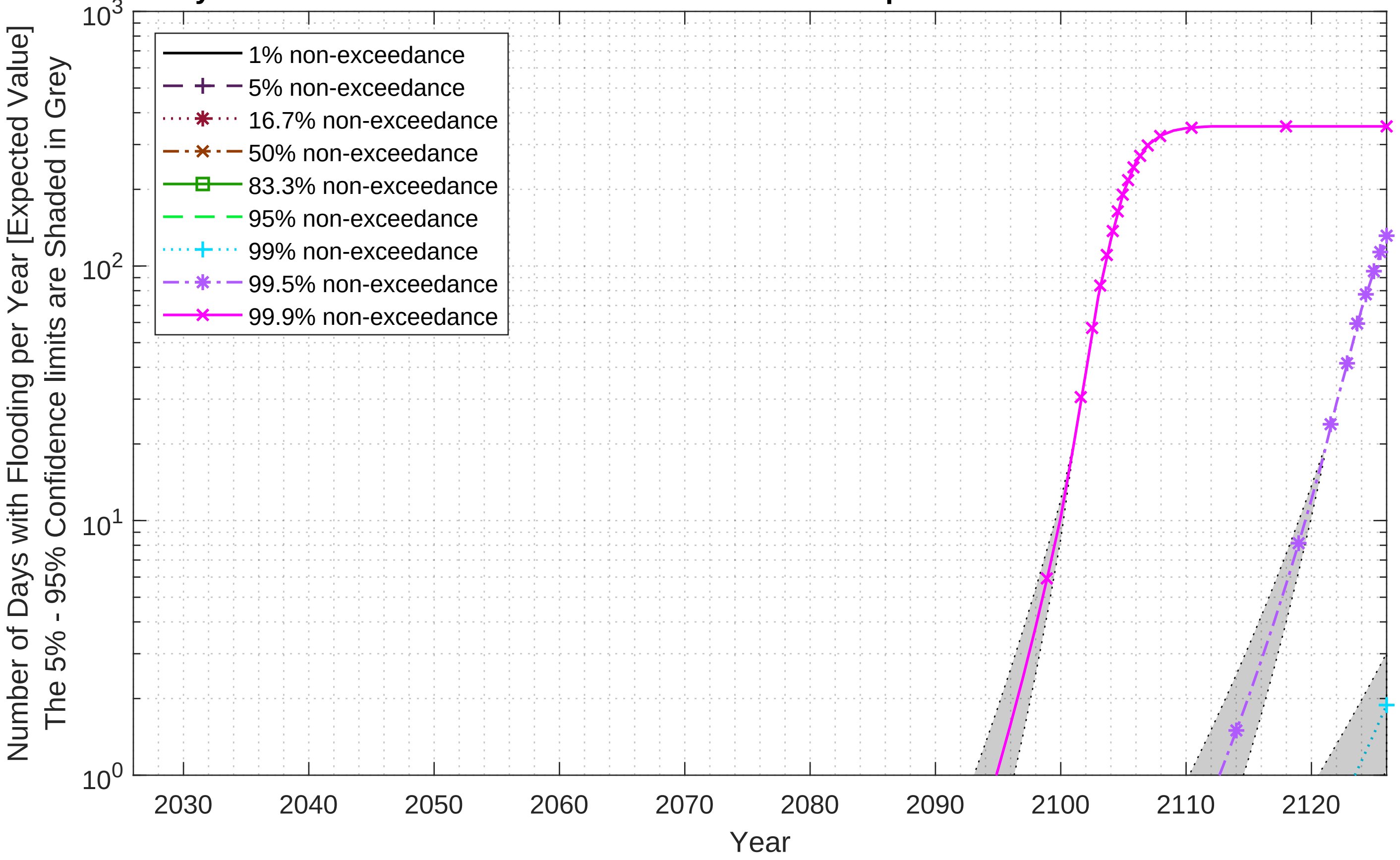
Expected Number of Days with Flooding Per Year Exceeding Elevation 8.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5

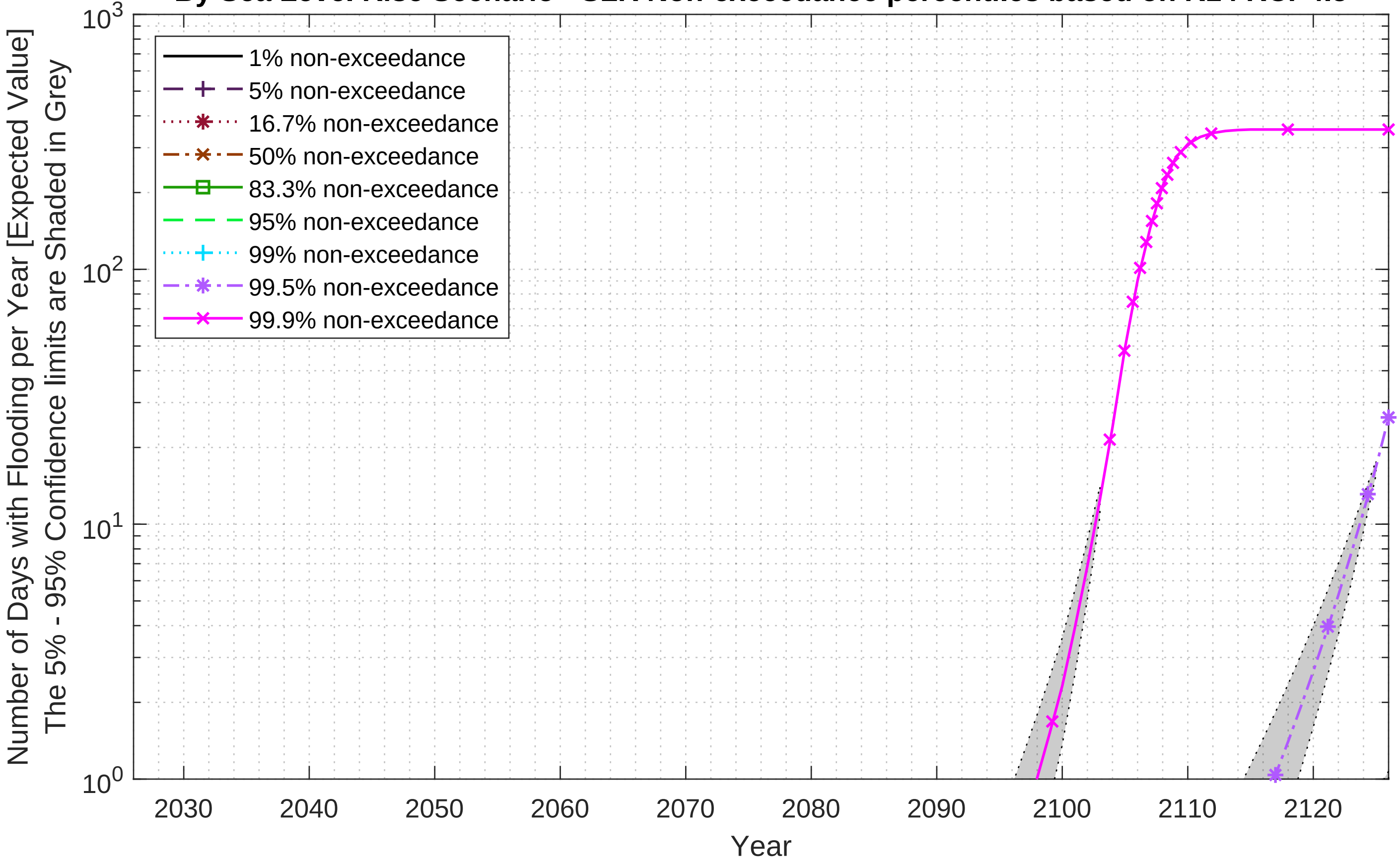




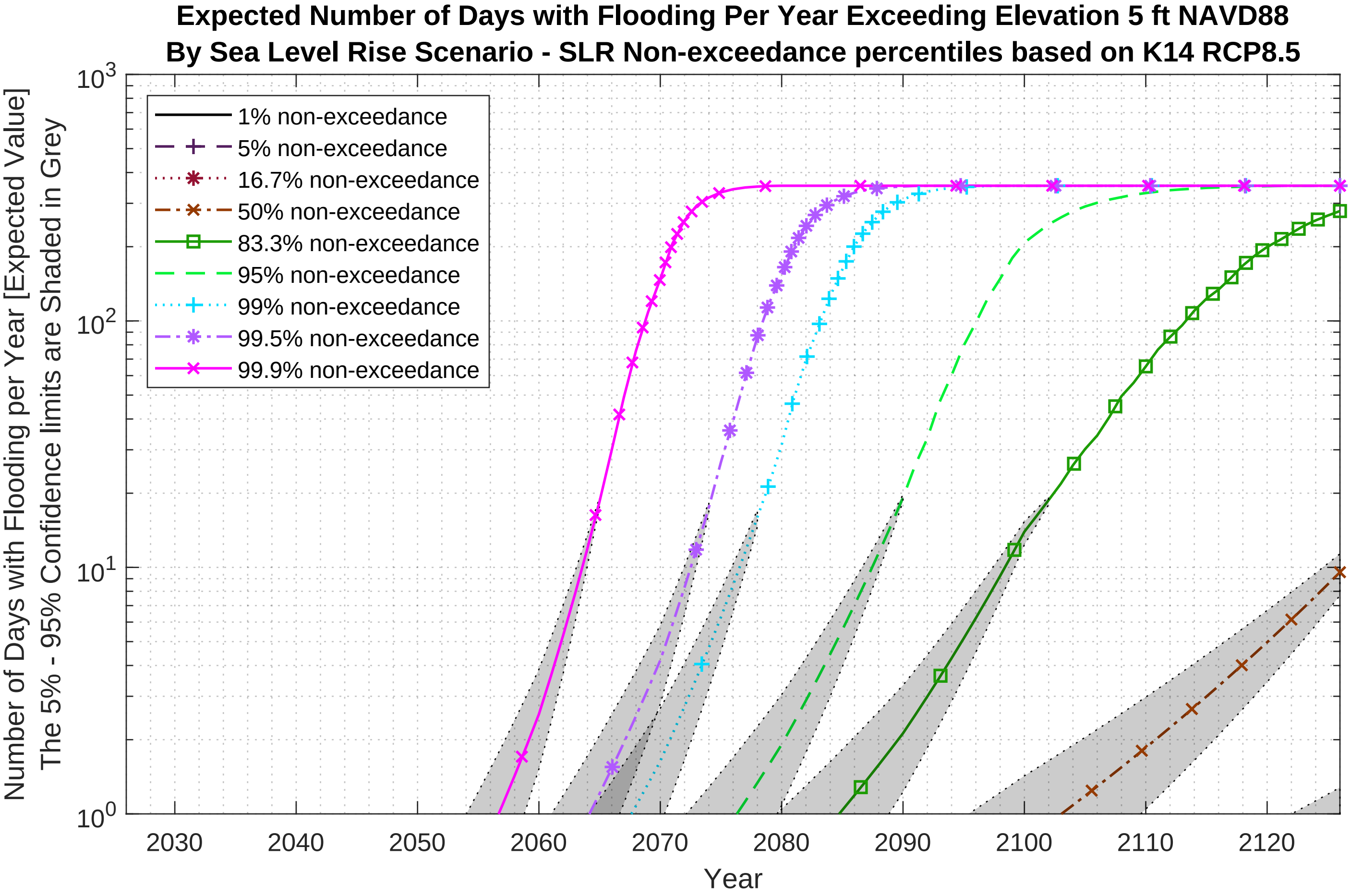
Expected Number of Days with Flooding Per Year Exceeding Elevation 9 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5

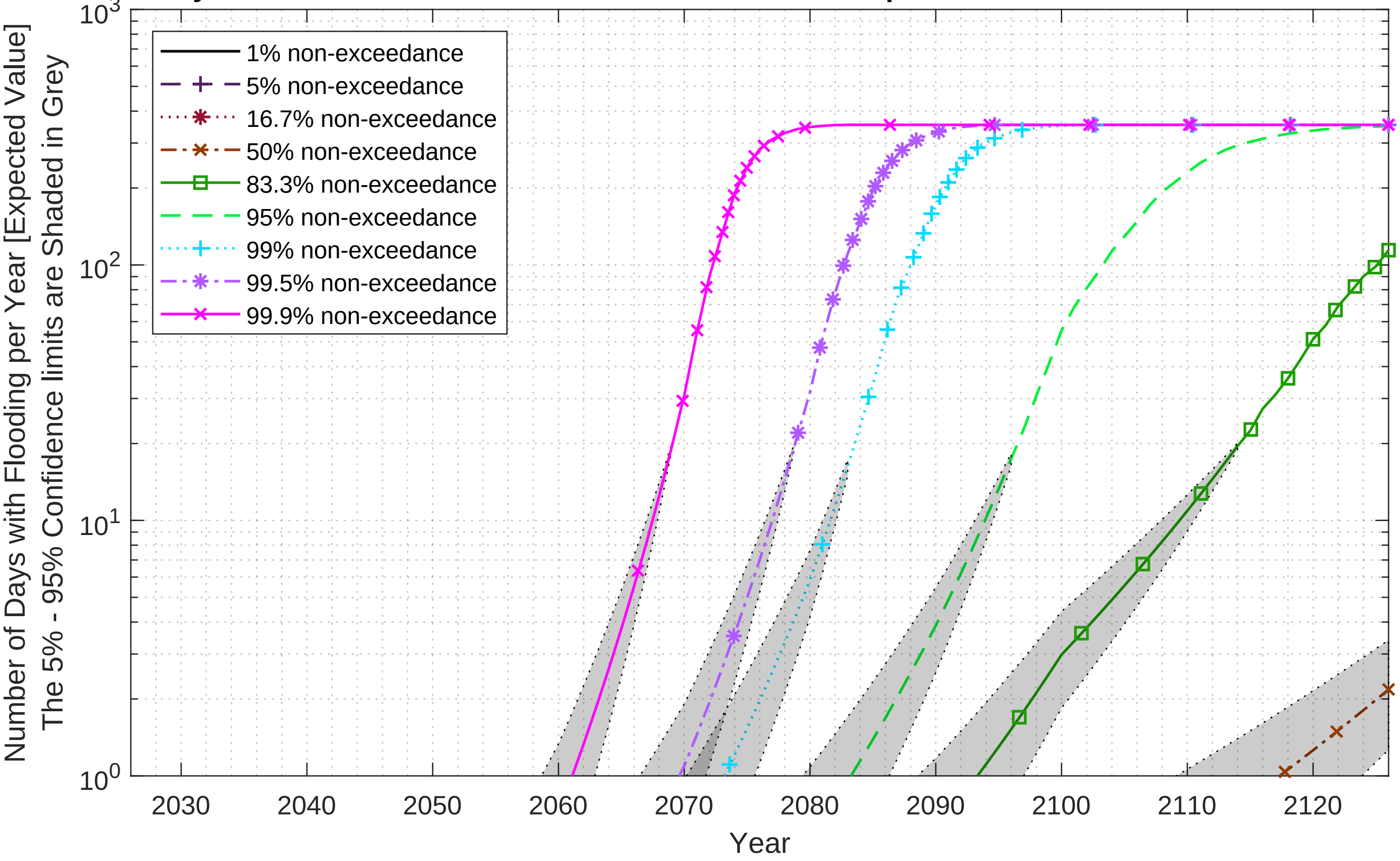
Expected Number of Days with Flooding Per Year Exceeding Elevation 9.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5



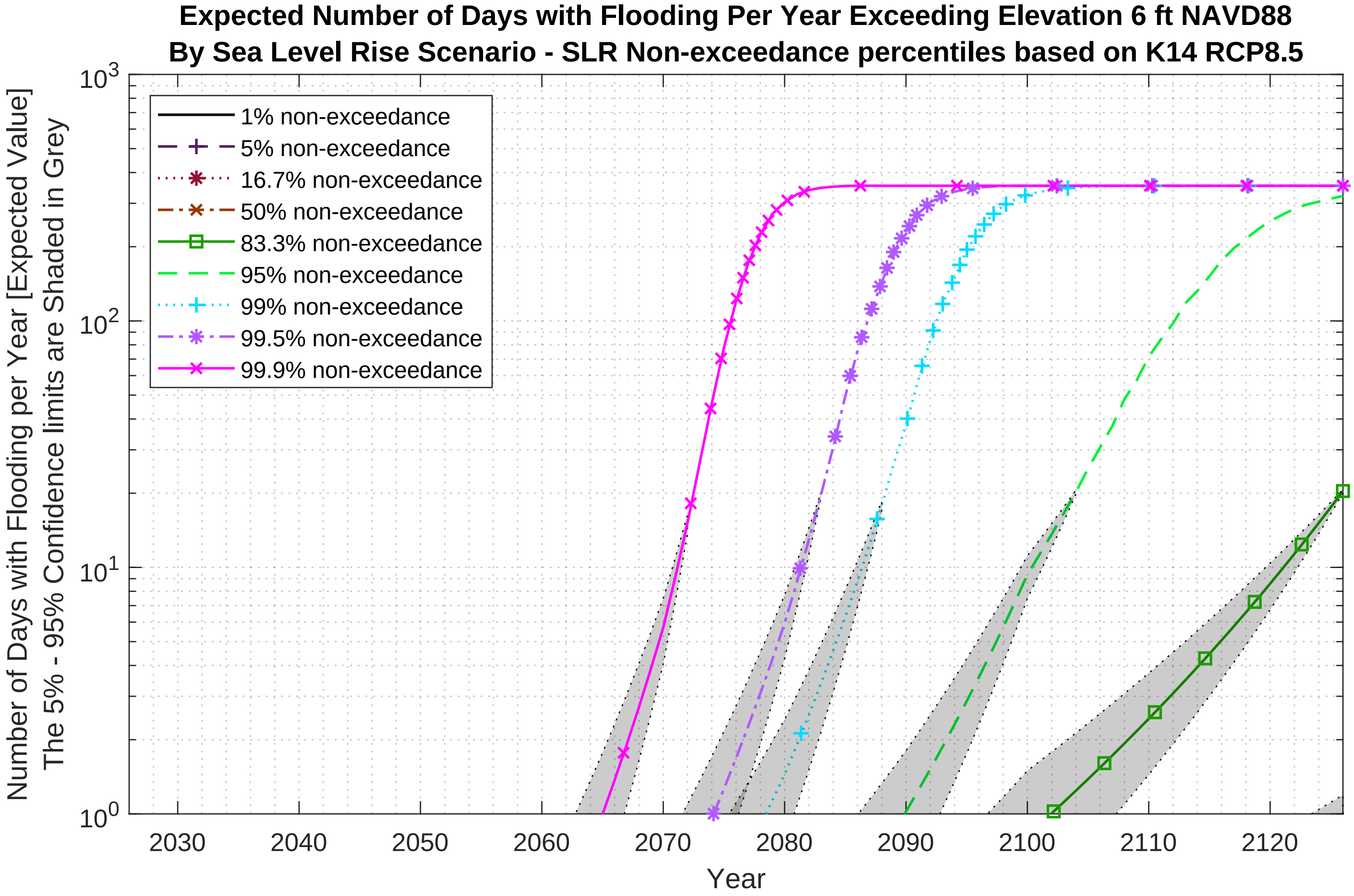


Expected Number of Days with Flooding Per Year Exceeding Elevation 10 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP4.5

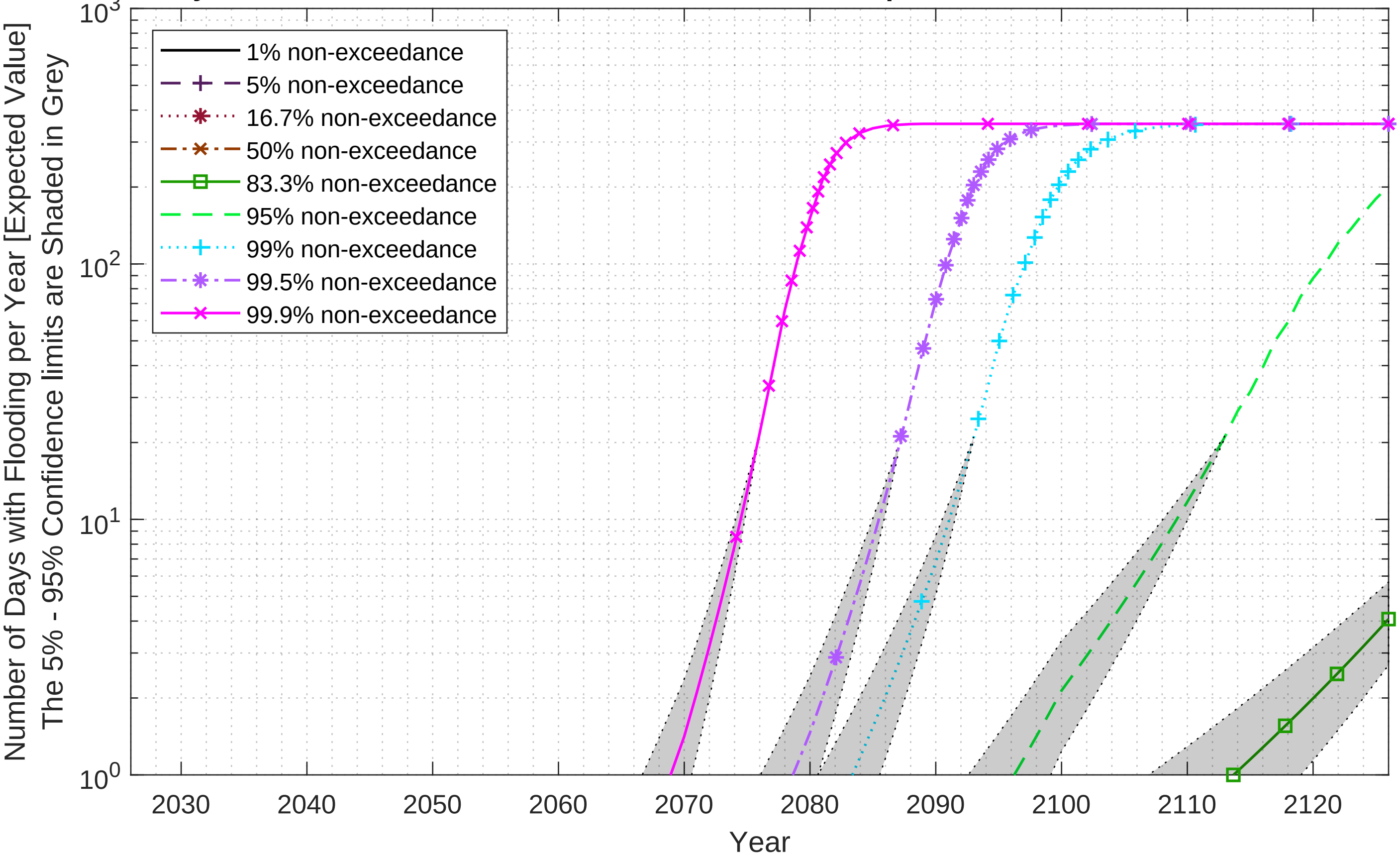

Expected Number of Days with Flooding Per Year Exceeding Elevation 5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance



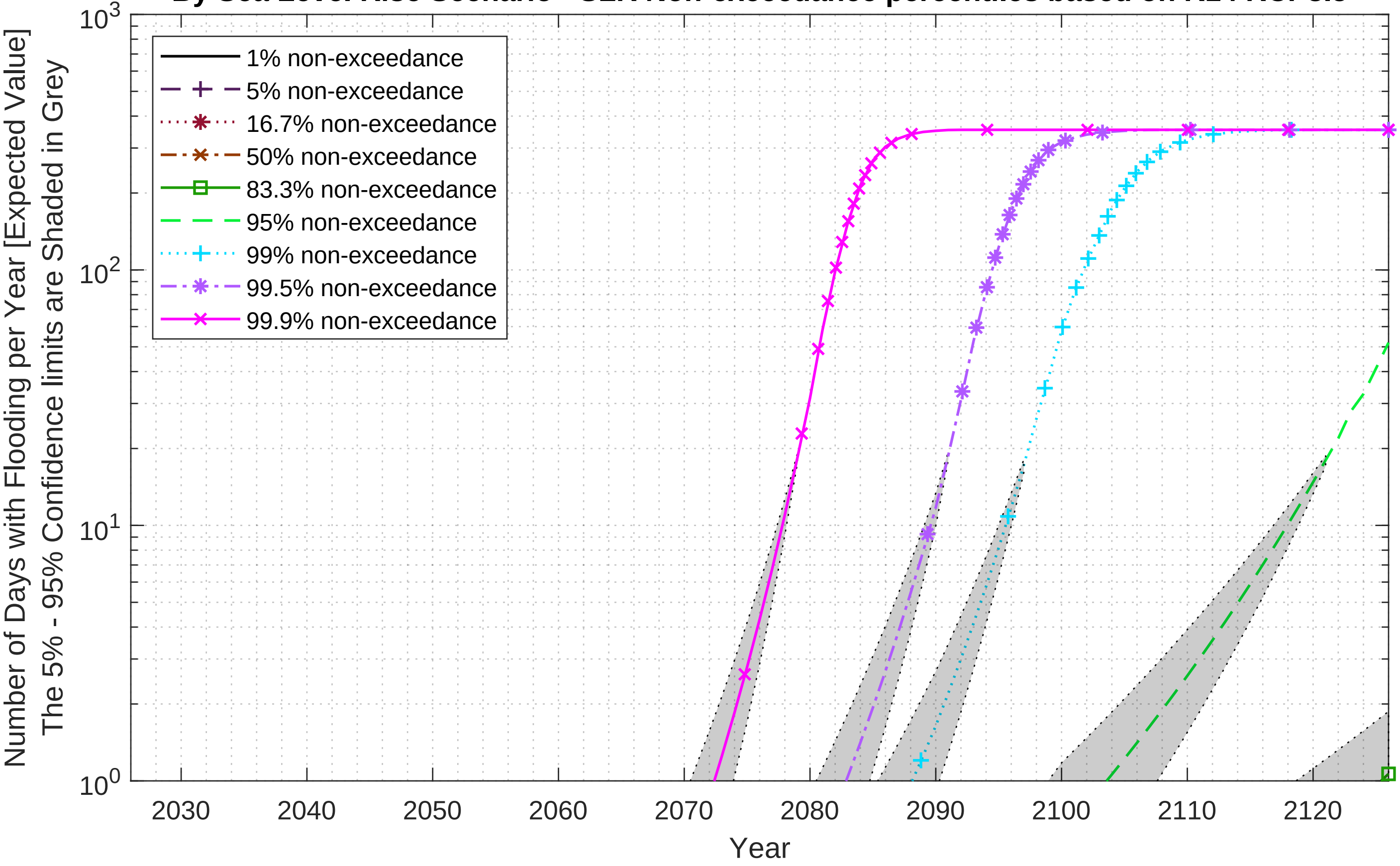
Expected Number of Days with Flooding Per Year Exceeding Elevation 5.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5


Expected Number of Days with Flooding Per Year Exceeding Elevation 6 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance

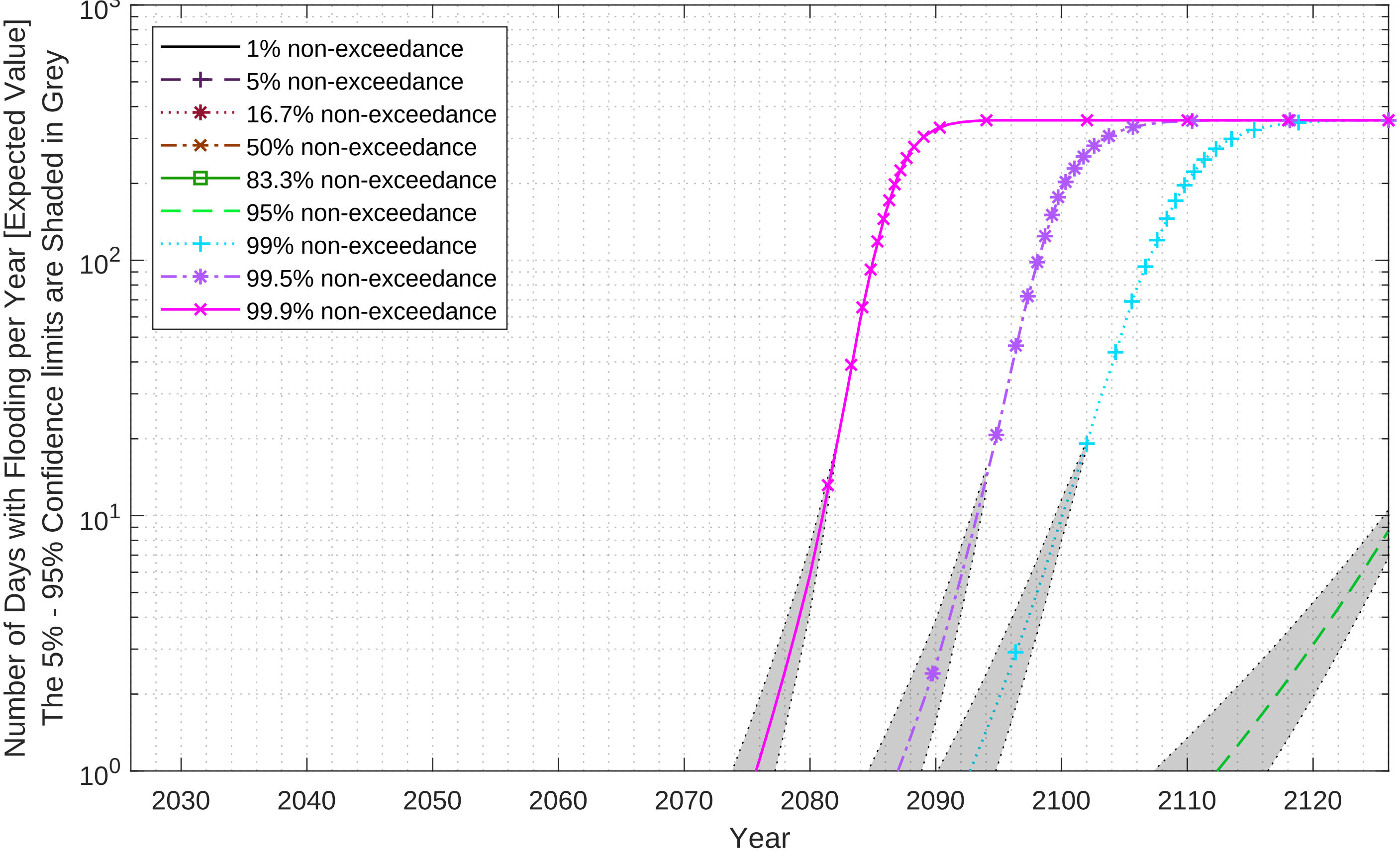
Expected Number of Days with Flooding Per Year Exceeding Elevation 6.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5

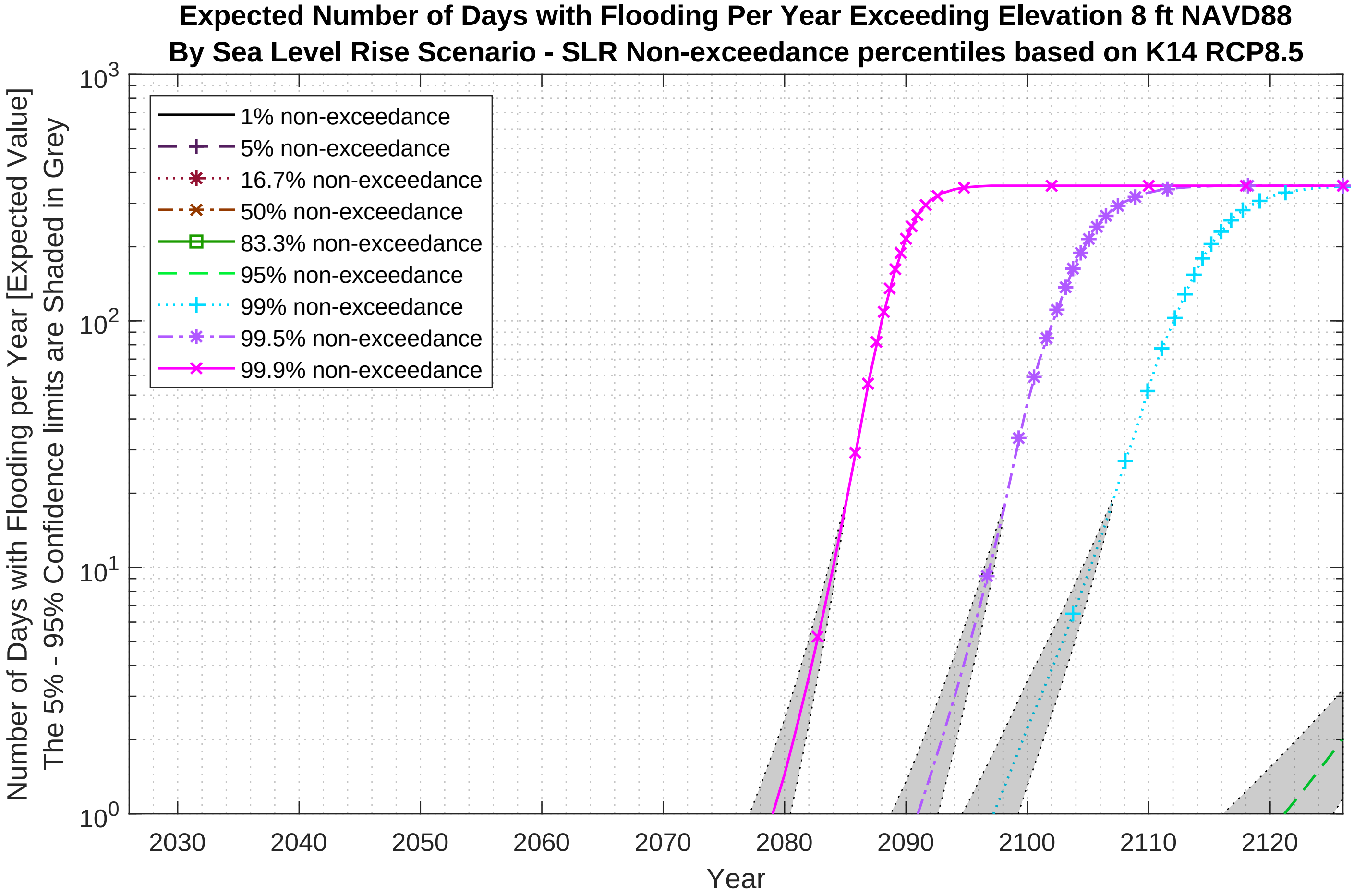


Expected Number of Days with Flooding Per Year Exceeding Elevation 7 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5

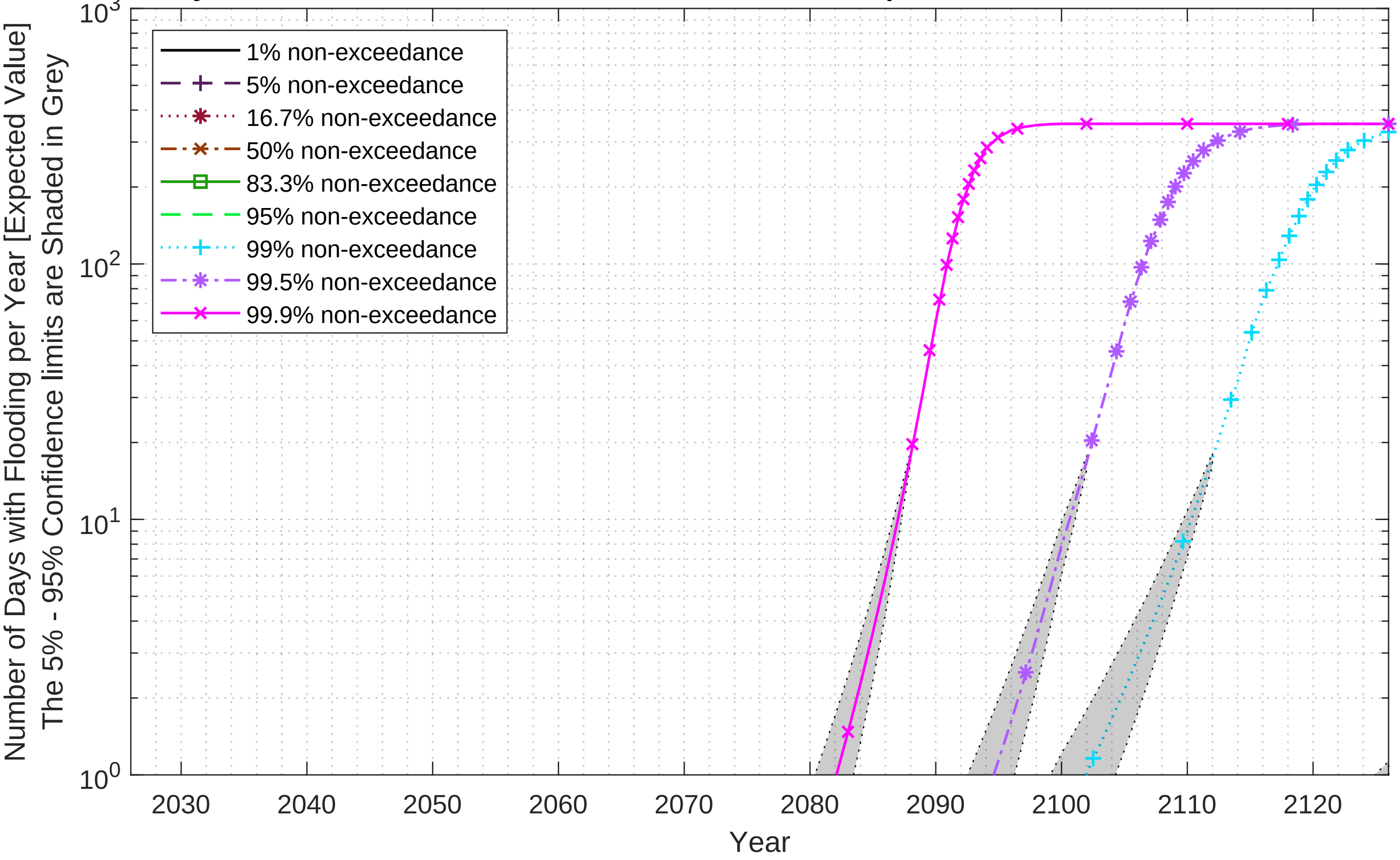


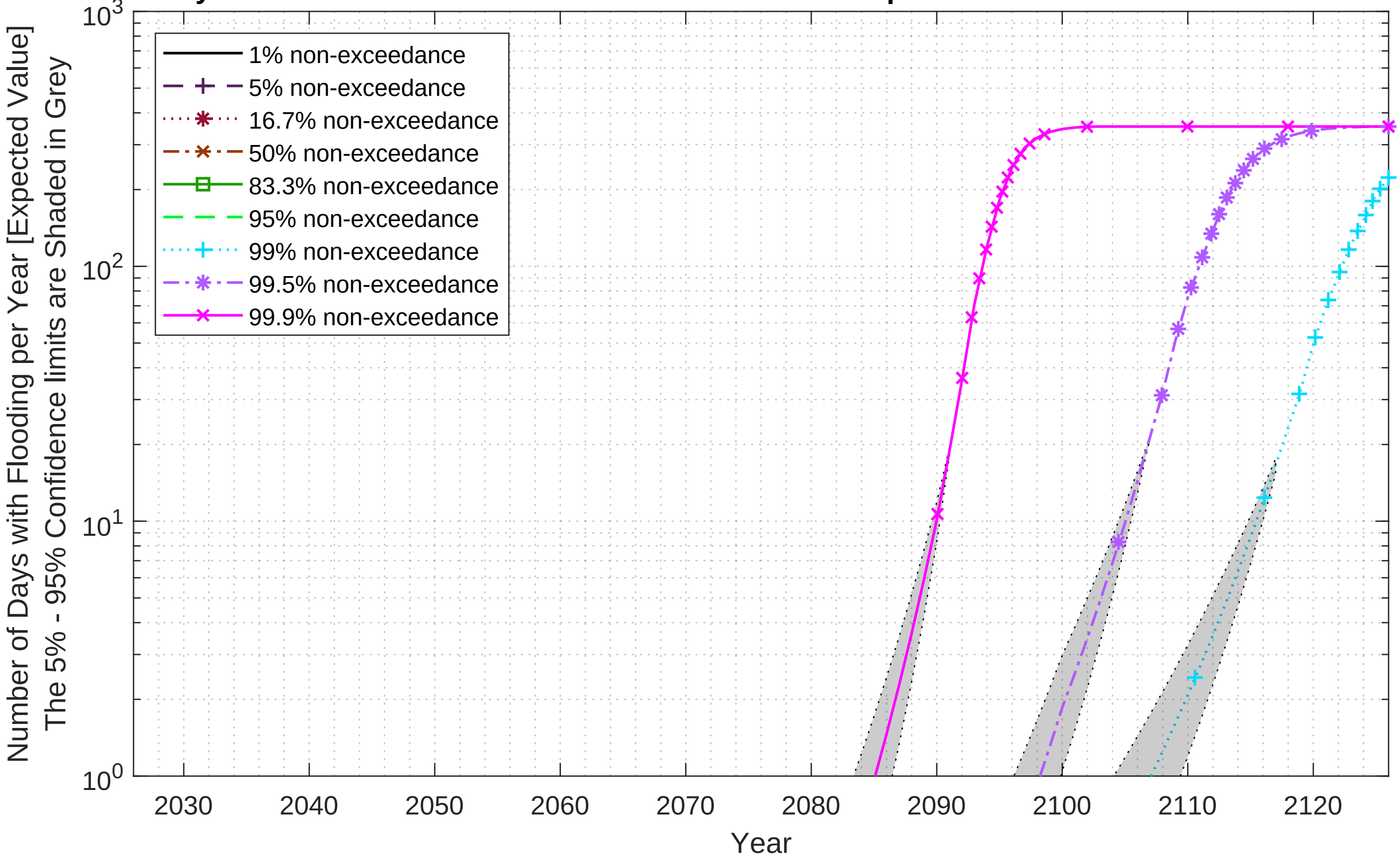
Expected Number of Days with Flooding Per Year Exceeding Elevation 7.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5



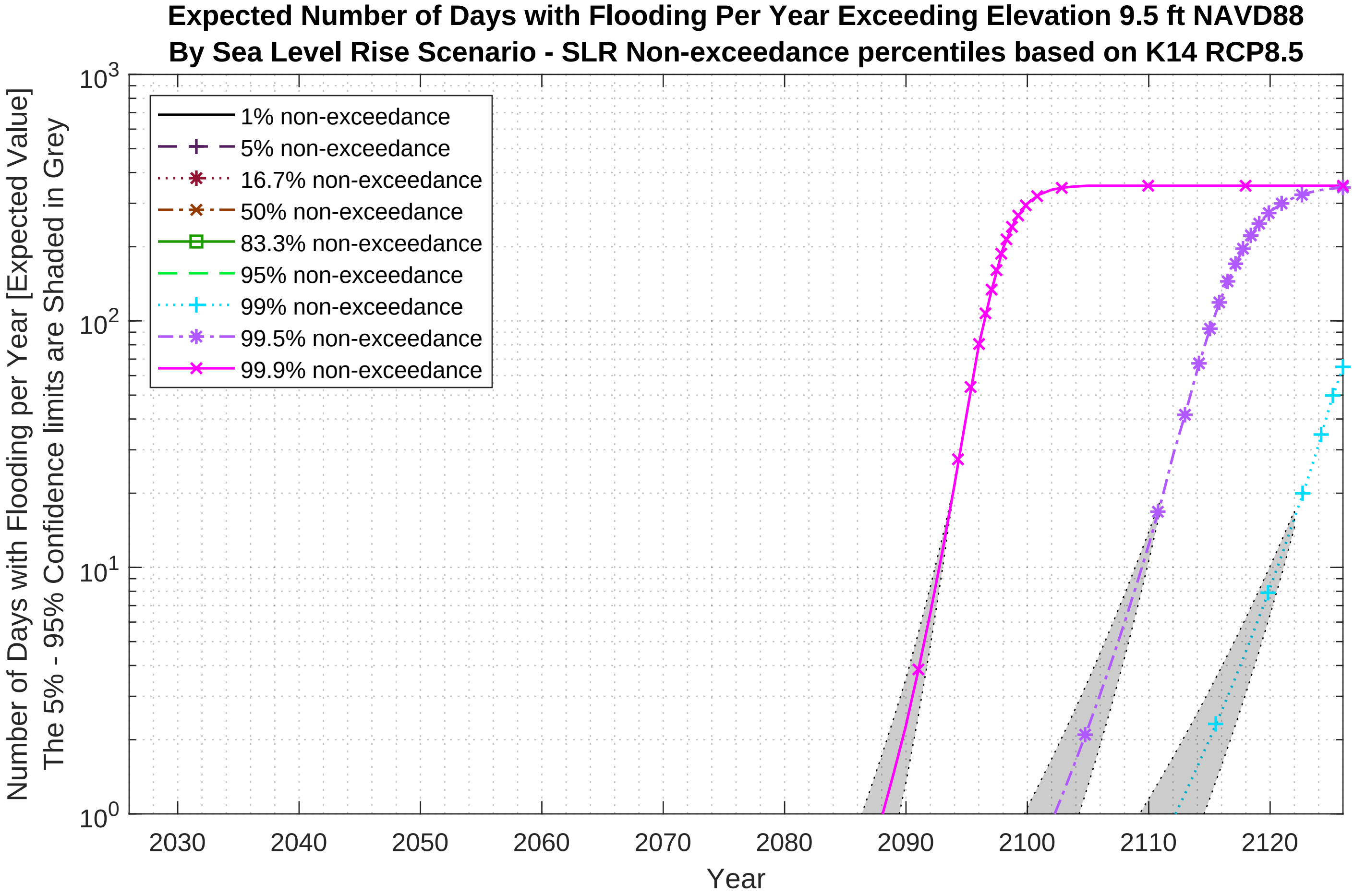

Expected Number of Days with Flooding Per Year Exceeding Elevation 8 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance

Expected Number of Days with Flooding Per Year Exceeding Elevation 8.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5





Expected Number of Days with Flooding Per Year Exceeding Elevation 9 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5


Expected Number of Days with Flooding Per Year Exceeding Elevation 9.5 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance
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2100
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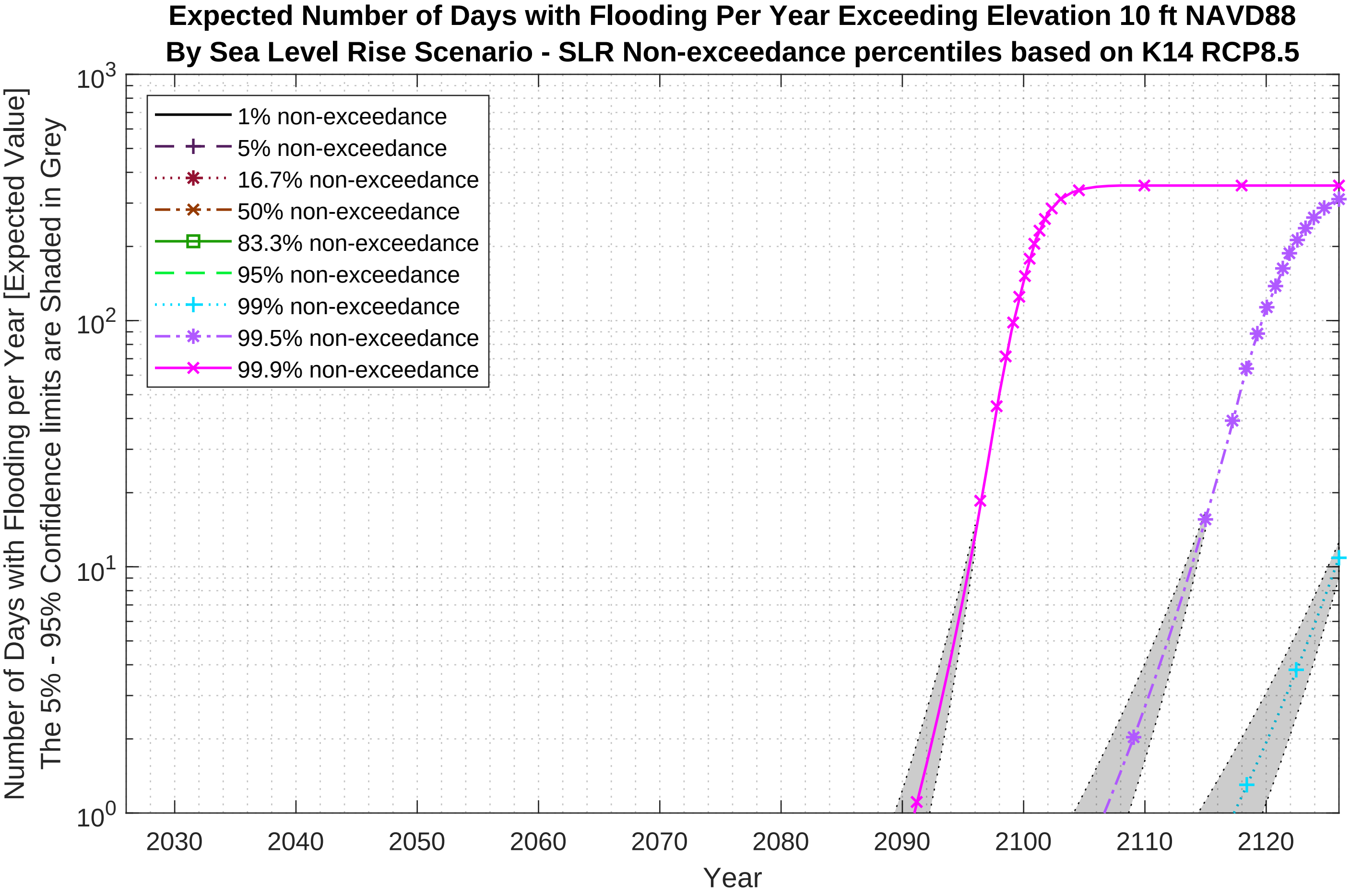
2120
Year


Expected Number of Days with Flooding Per Year Exceeding Elevation 10 ft NAVD88
By Sea Level Rise Scenario - SLR Non-exceedance percentiles based on K14 RCP8.5
Number of Days with Flooding per Year [Expected Value]
The 5% - 95% Confidence limits are Shaded in Grey
10^3
10^2
10^1
10^0
2030
2040
2050
2060
2070
2080
2090
2100
2110
2120
Year
1% non-exceedance
5% non-exceedance
16.7% non-exceedance
50% non-exceedance
83.3% non-exceedance
95% non-exceedance
99% non-exceedance
99.5% non-exceedance
99.9% non-exceedance