Evaluating North Carolina Bridge Superstructure Vulnerability to Coastal Storms and Sea Level Rise

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RESEARCH & DEVELOPMENT

Evaluating North Carolina Bridge Superstructure Vulnerability to Coastal Storms and Sea Level Rise

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16. Abstract

North Carolina's coastal bridges are exposed to storm surge, wave loading, and rising sea levels, yet previous statewide guidance did not explicitly incorporate sea level rise and relied on older wave-force methods. This study developed and applied a screening-level framework to evaluate the superstructure vulnerability of 116 selected Tier 1 and Tier 2 bridges in the state's 20 coastal counties. Structural parameters were obtained from NCDOT records, roadway LiDAR, and available bridge plans. Storm surge levels and significant wave heights were obtained from the U.S. Army Corps of Engineers South Atlantic Coastal Study. Each bridge span was evaluated under 15 scenarios consisting of 10-, 20-, 50-, 100-, and 500-year storms under present-day sea level, 2.73 ft of sea level rise, and 7.35 ft of sea level rise. FHWA HEC-25 methods were used to calculate wave forces, and spans were classified as Safe, Inundated, Uplifting, Sliding, or Rotation. A bridge was classified as Vulnerable when at least one span was not Safe. Safe and Vulnerable denote screening classifications for each evaluated scenario and do not represent determinations of current structural safety or predictions of damage or failure. Under the present-day 100-year scenario, 51 of 116 bridges were classified as Vulnerable; this count increased to 68 under 2.73 ft of sea level rise and 83 under 7.35 ft. The 10-year scenario with a 2.73-ft sea level rise resulted in approximately the same number of bridges classified as Vulnerable as the present-day 100-year scenario, while the 10-year scenario with a 7.35-ft sea level rise resulted in more bridges classified as Vulnerable than the present-day 500-year scenario. Rotation was the most common force- or moment-based dominant mode, and inundation became increasingly important as water levels rose. The study also developed the NC Coastal Bridge Vulnerability Viewer, which combines mapping, querying, summary visualizations, and access to bridge-specific results within a single interface.

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EXECUTIVE SUMMARY

Purpose and Scope

Coastal bridges provide essential transportation connections for communities, evacuation routes, emergency response, and economic activity in eastern North Carolina. Many were not originally designed for hurricane-induced wave and surge loading, and the NCDOT coastal vulnerability approach previously reflected in the hydraulic guidance did not explicitly account for sea level rise and was based on older wave-force methods. The purpose of this research was to develop an updated, practical framework for screening North Carolina coastal bridge superstructures under present and future storm conditions and to provide NCDOT with accessible data products for reviewing the results.

The initial inventory included 1,127 bridges within North Carolina's 20 designated coastal counties. Bridges were screened using four factors: presence on an evacuation route, exposure to coastal hazards, availability of a representative South Atlantic Coastal Study station, and bridge length. The final assessment included 116 Tier 1 and Tier 2 bridges considered most relevant for coastal vulnerability analysis. The study addressed superstructure vulnerability to storm surge and wave loading. It did not evaluate scour, foundation response, debris impact, riverine flooding, or other substructure hazards.

Research Approach

Structural parameters were obtained from NCDOT Structure Inspection Reports, roadway LiDAR, and available bridge plans. Hydrodynamic inputs were obtained from the U.S. Army Corps of Engineers South Atlantic Coastal Study through the Coastal Hazards System. The SACS dataset incorporated more than 1,000 simulated tropical storms and historical extratropical storms. Each bridge was evaluated for five storm return periods - 10, 20, 50, 100, and 500 years - under three sea level conditions: present-day sea level (SLR0), 2.73 ft of sea level rise (SLR1), and 7.35 ft of sea level rise (SLR2).

FHWA HEC-25 methods were used to calculate vertical and horizontal wave forces for each span. The assessment considered four vulnerability modes: inundation, uplift, sliding, and rotation. Inundation was evaluated from storm surge level relative to the top of deck. Uplift, sliding, and rotation were evaluated using dimensionless ratios that compared hydrodynamic demand with the corresponding resistance. The dominant-mode procedure accounted for reduced frictional resistance as vertical force increased and excluded sliding after assumed loss of support contact. Each span was assigned one dominant classification of Safe, Inundated, Uplifting, Sliding, or Rotation. A bridge was classified as Vulnerable when at least one evaluated span was not Safe. Vulnerable and Safe are screening classifications for the evaluated scenario; they do not constitute determinations of current structural safety or predictions of bridge damage or failure.

Principal Findings

Selected statewide bridge-level results are presented below. Values are numbers of bridges classified as Vulnerable, with percentage of the 116 assessed bridges in parentheses.

Sea level condition	Storm return period	Bridges classified as Vulnerable, n (%)
SLR0: present-day	10-year	14 (12.1%)
SLR0: present-day	100-year	51 (44.0%)
SLR0: present-day	500-year	60 (51.7%)
SLR1: 2.73 ft	10-year	52 (44.8%)
SLR1: 2.73 ft	100-year	68 (58.6%)
SLR2: 7.35 ft	10-year	74 (63.8%)
SLR2: 7.35 ft	100-year	83 (71.6%)
SLR2: 7.35 ft	500-year	86 (74.1%)

The principal finding was that sea level rise shifted vulnerability threshold exceedances from rare storms toward more frequent storms. In the 10-year scenario with SLR1 (2.73 ft of sea level rise in 2120), 52 bridges were classified as Vulnerable, approximately the same as the 51 classified under the present-day 100-year scenario. In the 10-year scenario with SLR2 (7.35 ft of sea level rise in 2120), 74 bridges were classified as Vulnerable, exceeding the 60 classified under the present-day 500-year scenario. Thus, among the assessed bridges, vulnerability levels associated with rare storms under present-day sea level were reached or exceeded under much more frequent storms when sea level rise was introduced.

At the span level, Rotation was the most common force- or moment-based dominant vulnerability mode. For the 100-year storm, the percentage of spans classified as Safe decreased from 91.39 percent under SLR0 to 85.34 percent under SLR1 and 41.14 percent under SLR2. Rotation increased from 7.33 percent to 10.14 percent and 37.38 percent across 100-year storms under the same sea level conditions, while the combined percentage of inundated spans increased from 0.60 percent to 4.06 percent and 16.29 percent. Uplifting was almost never selected as the dominant mode; however, vertical force remained important because it reduced frictional resistance, contributed to contact loss, and contributed to the driving moment used in the Rotation assessment.

Results varied substantially by region. Division 2 had the highest percentage of bridges classified as Vulnerable under the present-day 100-year scenario, while Division 1 experienced the largest increase with sea level rise and had the highest percentage under the SLR2 100-year scenario. County-level results also showed different response patterns: some counties contained assessed bridges that were classified as Vulnerable under present-day conditions, while others showed substantial increases only after sea level rise was introduced. These differences demonstrated that statewide percentages should not be applied uniformly across the coastal region.

Research Products and Recommended Next Steps

The study produced bridge screening and tier data, structural and hydrodynamic datasets, bridge- and span-level calculation files, statewide and regional results, 15 GIS maps showing the spatial distribution of Safe and Vulnerable classifications under each evaluated storm and sea level scenario, and the NC Coastal Bridge Vulnerability Viewer. The viewer allows NCDOT users to locate assessed bridges, filter results by scenario and geography, review bridge- and span-level classifications, and access supporting information. These products are intended for screening, research planning, and project scoping; they are not substitutes for bridge-specific design analysis and do not predict structural failure.

The highest-priority follow-up recommendation is to extend the same assessment framework to the 71 Tier 3 bridges and the 222 Tier 4 bridges. The existing screening database, calculation workflow, SACS station-selection procedure, and GIS structure can be reused to reduce duplicated effort and maintain consistency. NCDOT should also designate an owner for the viewer and the supporting data, provide a focused technical handoff and user training, and conduct an internal technical review before using the screening method to revise design requirements.

The results apply only to the 116 selected Tier 1 and Tier 2 bridges. A Vulnerable classification indicates that at least one span exceeded a screening criterion under the specified scenario; it does not indicate that damage or collapse will occur during a particular storm.

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Chapter 1. Introduction

1.1 Research Motivation

More than 36,000 bridges are situated within 15 nautical miles of the U.S. coastline (Douglass and Krolak, 2008). Coastal bridges are vital infrastructure, connecting transportation routes and playing a crucial role in emergency response, economic activity, and access to essential services in coastal regions. According to the North Carolina Department of Transportation, there were more than 1,100 bridges in the 20 coastal counties of North Carolina as of October 2023. These bridges constituted critical components of the state's infrastructure system, facilitating the movement of goods and people. However, many of these bridges may be exposed to coastal storms, damaging waves, and rising sea levels due to their proximity to coastal waters and relatively low deck elevations.

Traditionally, coastal bridges were not designed to withstand hurricane-induced wave and surge loads. Research has only recently shifted toward evaluating the performance of coastal bridge infrastructure during hurricane events. The NCDOT *Guidelines for Drainage Studies and Hydraulic Design* (2022) included a coastal bridge vulnerability study conducted in 2013 by Sheppard and Dompe. While that document aimed to serve as the design guideline for coastal bridges in NC, it had documented shortcomings: it employed an approach that overestimated horizontal wave loads and underestimated vertical wave loads, neglected sea level rise impacts, and was limited to 62 historical storms (Guo et al., 2015; Douglass and Webb, 2020; Moideen and Behera, 2021). This research was conducted to address those limitations using updated methods, a more comprehensive hydrodynamic dataset, and an explicit sea level rise framework.

1.2 Research Goal and Objectives

This research aimed to assess the vulnerability of North Carolina's coastal bridges to coastal storms and sea level rise over the next 100 years, providing a comprehensive resource for informed infrastructure planning and development. By incorporating sea level rise impacts through three explicitly modeled sea level change scenarios, utilizing hydrodynamic results from over 1,000 simulated storms via the USACE South Atlantic Coastal Study, and applying the 2020 third edition of FHWA HEC-25 (Douglass and Webb, 2020) to more than 100 North Carolina bridges, this study offered an updated and expanded vulnerability assessment that built upon the Sheppard and Dompe (2013) baseline. The overarching goal was to provide NCDOT and its stakeholders with critical data to enhance coastal resilience, refine coastal hydraulic design guidelines, and support informed decision-making in response to climate change.

1.3 Research Approach

To achieve the research goal, this research was divided into four main tasks, as shown in Figure 1. Task 1 identified bridges prioritized for coastal storm and sea level rise screening through geospatial analysis in ArcGIS, followed by extraction and storage of structural variables for each bridge. Task 2 quantified storm water levels, significant wave heights, and sea level rise hazards at each selected bridge using the USACE South Atlantic Coastal Study (SACS). Task 3 assessed bridge vulnerability through three force- or moment-based modes and inundation across 15 hydrodynamic scenarios — three sea level rise conditions with five storm return periods per condition. Task 4 developed a GIS-based dashboard in ArcGIS Experience Builder to display and distribute the results from the bridge vulnerability analysis.

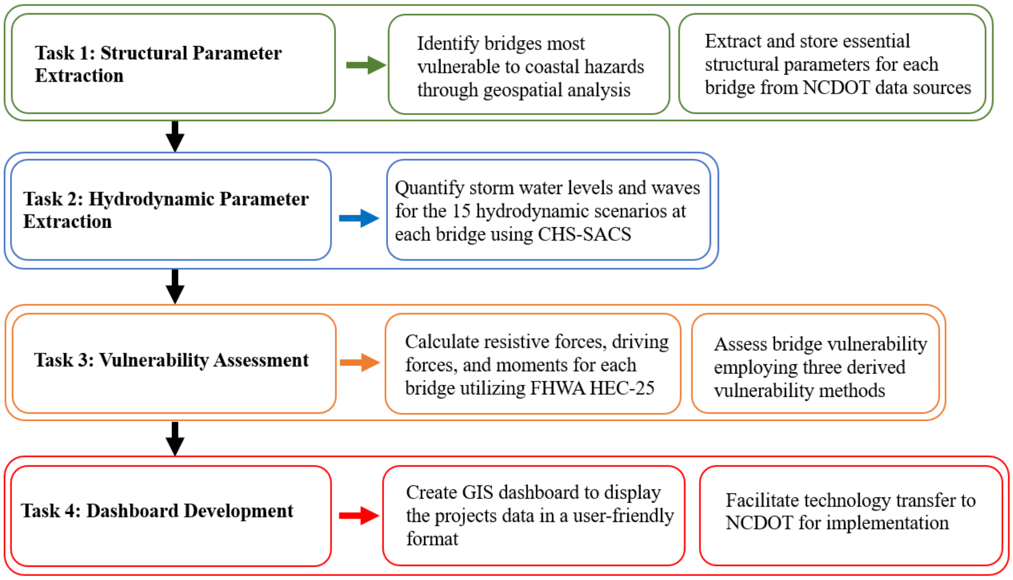

Figure 1. Proposed research workflow. The black arrows indicate the progression of the overall research project. The horizontal arrows indicate the task-specific work for individual research tasks.

1.4 Research Assumptions and Scope

This study relied on several key assumptions. Structural parameters extracted from NCDOT Structure Inspection Reports were assumed to be sufficient and accurate representations of coastal bridge characteristics. Elevations derived from the North Carolina Flood Mapping Program roadway LiDAR dataset were considered representative of bridge deck elevations, despite limitations in data resolution and the selection of a single central point per span to represent elevation across the full span.

For hydrodynamic conditions, the selected sea level rise projections from the SACS were assumed to represent future conditions. Hydrodynamic data from SACS stations were assumed sufficient to characterize storm-induced wave and surge forces, and values from a single station were applied uniformly across all spans of a given bridge due to the spatial resolution of SACS outputs. This assumption is appropriate for statewide screening but may not fully represent long crossings that extend across multiple hydrodynamic environments, such as open-water and sheltered-marsh settings. For long crossings spanning distinct hydrodynamic environments, this assumption may under- or overstate screening-level hydrodynamic demand and vulnerability for individual spans. The HEC-25 equations, primarily developed through laboratory-scale experiments, were assumed applicable to full-scale bridge structures. Bearing anchorage and connection resistance were not included in the analysis.

This study focused exclusively on superstructure vulnerability to wave forces and storm surge inundation. Fluvial processes, riverine flooding, debris impacts, and scour-related substructure failures were not considered. Within their screening-level scope, the results can support research prioritization, project scoping, and NCDOT review of potential future guidance updates.

1.5 Report Organization

Chapter 2 reviews prior research on coastal storm hazards in NC, sea level rise trends, bridge damage from coastal storms, and previous vulnerability assessment practices. Chapter 3 describes the bridge selection and structural parameter extraction process. Chapter 4 presents the South Atlantic Coastal Study and the extraction of hydrodynamic parameters across the 15 scenarios. Chapter 5 develops and applies four vulnerability modes, presenting span-level and bridge-level results at state, division, and county scales.

Chapter 6 describes the GIS-based dashboard. Chapter 7 presents conclusions and implementation recommendations. Appendix A provides the complete state, division, and county-level vulnerability statistics tables. Appendix B presents the spatial distribution of bridge vulnerability for 15 scenarios.

Chapter 2. Literature Review

2.1 Coastal Storm Hazards in North Carolina

The NC coastline features 325 miles of ocean shoreline, 23 inlets, over 5,000 miles of estuarine shoreline, and more than 3,000 square miles of brackish-water estuaries (Riggs et al., 2008). A study by the National Oceanic and Atmospheric Administration (NOAA, 2018) analyzed estimated hurricane return periods along the Gulf and East Coasts and found that portions of the NC coast have among the shortest estimated hurricane return periods along the U.S. East Coast (Figure 2). The state's protrusion into the Atlantic Ocean makes it a frequent target for tropical storms that curve northward.

Prior to 2000, a tropical storm or hurricane made direct landfall along the NC coastline on average every four years (Froehlich and Fisher, 2000). Since 2000, approximately 50 hurricanes, tropical storms, and extratropical storms have passed within 120 nautical miles of Beaufort, North Carolina, demonstrating the region's frequent exposure to coastal storms (North Carolina State Climate Office, n.d.). The warming climate is expected to further increase both the frequency and intensity of hurricanes in the future (USGCRP, 2018).

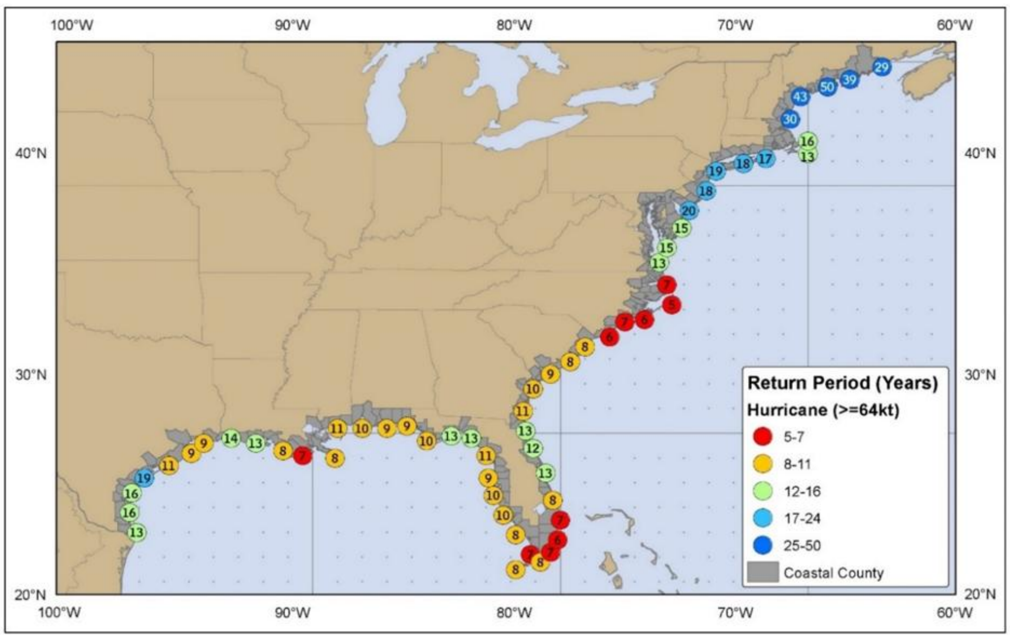

Figure 2. Map showing estimated hurricane return periods along the U.S. Gulf and Atlantic coasts, with portions of the North Carolina coast showing among the shortest return periods along the U.S. East Coast (NOAA, 2018).

2.2 Sea Level Rise in North Carolina

Sea level rise is a critical compounding factor for coastal bridge vulnerability: it raises the baseline water level against which storm surges are added, increasing the frequency and severity of any given water level at a bridge location. In the Global and Regional Sea Level Rise Scenarios for the United States, Sweet et al. (2017) projected global mean sea level rise between 1 and 8.2 ft by 2100 across six scenarios. The Mid-Atlantic coastal region has been identified as a hotspot for accelerated sea level rise (Ezer and Atkinson, 2014).

The rate of sea level rise varies along the NC coast. The USACE Engineering Regulation *ER 1100-2-8162* (USACE, 2019) and its associated Sea Level Change Curve Calculator estimated that Wilmington, NC —

which experiences the lowest sea level rise in the state — will see 0.92, 2.37, and 6.99 ft of rise by 2120 under USACE low, intermediate, and high scenarios, respectively. Duck, NC — which experiences the highest rate — is projected to see 1.59, 3.03, and 7.67 ft of rise by 2120 (SACS, 2021c). These projections are broadly consistent with NOAA Tides and Currents data, which project sea level rise between approximately 1.5 and 7 ft at Wilmington and 2 to 7 ft at Duck by 2100 (NOAA, n.d.-a; NOAA, n.d.-b). Over 2,045 square miles of land and 2,500 miles of road in NC's Coastal Plain lie less than 4 ft above the high tide line, with some areas already experiencing nearly 30 ft of landward erosion per year (Strauss et al., 2014; Covi et al., 2021).

Rising sea levels elevate the platform for storm surges, increasing the likelihood of more frequent and severe coastal flood hazards. A hindcast study by Douglass and Webb (2020) demonstrated this effect directly: vertical wave loads on the Escambia Bay Bridge (FL) during Hurricane Ivan (2004) were 70,000 pounds greater than they would have been under 1970 water levels, attributable solely to local sea level rise over those three decades. This quantified relationship between sea level rise and increased wave loading is the primary justification for incorporating three explicit sea level rise scenarios in this research.

2.3 Bridge Damage Due to Coastal Storms

Hurricanes unleash storm surges, heavy precipitation, and strong winds that harbor the potential to destroy coastal infrastructure. Hurricane Katrina (2005) damaged 44 highway bridges along the Gulf Coast, with repair and replacement costs exceeding $1 billion (Padgett et al., 2008). When all direct and indirect losses from Katrina were considered, costs were estimated to exceed $100 billion (Mosqueda et al., 2007). Hurricane Ivan (2004) caused significant damage to the Escambia Bay Bridge on Interstate 10. The hindcast study by Douglass and Webb (2020) confirmed that sea level rise contributed meaningfully to the severity of that damage.

In NC, the record of coastal bridge damage is well-documented. Hurricane Florence (2018) inflicted $13 billion in damage to NC (Cooper, 2018). In 1999, Hurricanes Floyd and Irene caused ten NC bridges to be washed out and 44 road sections to be closed (Schwab, 2000). In September 2024, a storm caused a washed-out segment of N.C. Highway 211 near Southport, NC (Allen, 2024). Moreover, the research team did not identify an existing NCDOT screening tool that combined bridge-specific structural data, SACS hydrodynamic scenarios, and span-level coastal vulnerability results. However, the development of such a tool was needed to support consistent screening, review bridge- and span-level results, identify potential vulnerability patterns, and scope additional bridge-specific evaluations.

2.4 Previous Bridge Vulnerability Design Practices

The wave load calculation approach of Sheppard and Dompe (2013), incorporated in the NCDOT *Guidelines for Drainage Studies and Hydraulic Design* (2022), was developed in conjunction with the AASHTO *Guide Specifications for Bridges Vulnerable to Coastal Storms* (Kulicki and Mertz, 2008). Subsequent research revealed that the AASHTO Guide — and therefore the Sheppard-Dompe approach — overestimated horizontal wave loads and underestimated vertical wave loads (Douglass and Webb, 2020; Guo et al., 2015; Moideen and Behera, 2021). Consequently, Sheppard and Dompe’s (2013) NC bridge vulnerability assessment, while appropriate at the time, may now be insufficient for addressing current vulnerabilities due to evolving guidance and changing coastal conditions.

FHWA's third edition of Hydraulic Engineering Circular No. 25 (HEC-25), published in 2020, revised the wave force calculation approach. The HEC-25 method estimates wave-induced forces by analyzing vertical and horizontal components separately, assumes these forces act simultaneously (consistent with Guo et al., 2015), and recommends application with an appropriate factor of safety given residual uncertainties. This study applied HEC-25 methods to NC coastal bridges at a statewide screening scale, addressing a key limitation of the 2013 Sheppard-Dompe analysis. Additionally, the values used in the 2013 study did not account for sea level rise — an omission that potentially results in underestimation of wave loads when applying those results for contemporary resilience planning.

In short, the literature review indicates that NC coastal bridges face increasing exposure from hurricane hazards and sea level rise, while the Sheppard-Dompe approach currently reflected in NCDOT guidance does not account for sea level rise and may misestimate vulnerability. For this reason, the present assessment applies FHWA HEC-25 methods and SACS hydrodynamic scenarios to evaluate bridge vulnerability under current and future coastal storm conditions.

Chapter 3. Structural Parameter Extraction

To effectively assess coastal infrastructure vulnerability, it was essential to begin with a thorough selection and screening process for the bridges under consideration. This involved identifying bridges critical to the analysis based on their role in regional connectivity and their exposure to coastal hazards, ensuring that the assessment focused on bridges where coastal exposure or transportation importance warranted priority evaluation. Once the bridges were screened into tiers, structural parameters were extracted from bridge schematics, routine Structure Inspection Reports, and LiDAR data provided by the NCDOT Hydraulics Unit.

3.1 Bridge Selection and Screening

According to the North Carolina Coastal Area Management Act, the state's 20 designated coastal counties are Beaufort, Bertie, Brunswick, Camden, Carteret, Chowan, Craven, Currituck, Dare, Gates, Hertford, Hyde, New Hanover, Onslow, Pamlico, Pasquotank, Pender, Perquimans, Tyrrell, and Washington. As of October 2023, the NCDOT Structures GIS Map included 1,127 bridges in these 20 counties (NCDOT, n.d.-b). The distribution by county is shown in Table 1.

Table 1. Number of bridges within the 20 coastal counties of North Carolina (NCDOT Structures GIS Map, October 2023).

Coastal County	Number of Bridges
Beaufort	118
Bertie	75
Brunswick	125
Camden	19
Carteret	44
Chowan	32
Craven	108
Currituck	14
Dare	26
Gates	25
Hertford	43
Hyde	43
New Hanover	103
Onslow	109
Pamlico	35
Pasquotank	40
Pender	69
Perquimans	31
Tyrrell	22
Washington	46

All 1,127 bridges were initially considered in the selection process. The goal was to identify bridges most critical to a coastal vulnerability assessment based on four screening factors, chosen in coordination with NCDOT to ensure relevance to a coastal vulnerability context:

1. **Presence along designated NC evacuation routes**: bridges on evacuation routes were prioritized due to their importance to public safety and emergency response, with consideration of local setting to avoid over-weighting short bridges on shallow inland crossings.
2. **Proximity to a SACS modeling station**: a bridge could only be included if a nearby SACS station was located in a comparable hydrodynamic environment, evaluated on hydrodynamic context rather than geographic distance alone.

3. **Potential exposure to coastal hazard threats**: assessed through satellite imagery by evaluating each bridge's hydrologic connection to large open water bodies such as sounds, estuaries, intracoastal waterways, wide rivers, or ocean inlets capable of generating fetch-driven wave conditions.
4. **Bridge length**: larger structures with higher replacement costs were captured even if not on evacuation routes, reflecting their importance to the coastal infrastructure system.

An extensive visual ranking process was completed in ArcGIS Pro. Each of the 1,127 bridges was reviewed and ranked for all four criteria. Based on these rankings, bridges were categorized into one of five tiers, as shown in Table 2. Tier 1 and Tier 2 bridges — 116 total — were considered the most relevant to this study, as they include those with high exposure to coastal hazards and stronger data support for hydrodynamic analysis. These tiers served as the focus for the coastal bridge vulnerability assessment.

Table 2. Bridge selection ranking and tier classification based on four screening factors. Tier 1 represents the highest priority for coastal vulnerability analysis.

Selection Factor	Ranking	Tier 1 (92)	Tier 2 (24)	Tier 3 (71)	Tier 4 (222)	Tier 5 (717)
Evacuation route	Presence	✓		✓		NA
Coastal hazard threat	High	✓	✓			
	Medium			✓	✓	
	Low					✓
Proximity to SACS station	Very close	✓	✓			
	Varies			✓	✓	✓
Bridge length	Large	✓	✓			✓
	Small	✓		✓	✓	✓

One initially ranked Tier 1 bridge in Pender County (Bridge ID 700021) was subsequently excluded because representative SACS wave data were unavailable. Accordingly, Table 2 and Figure 3 include 1,126 bridges.

The spatial distribution of all five tiers across the 20 coastal counties is shown in Figure 3. The most influential factors driving county-by-county variation in the number of study bridges were the presence of NC evacuation routes adjacent to large water bodies and the coastal hazard exposure specific to each county.

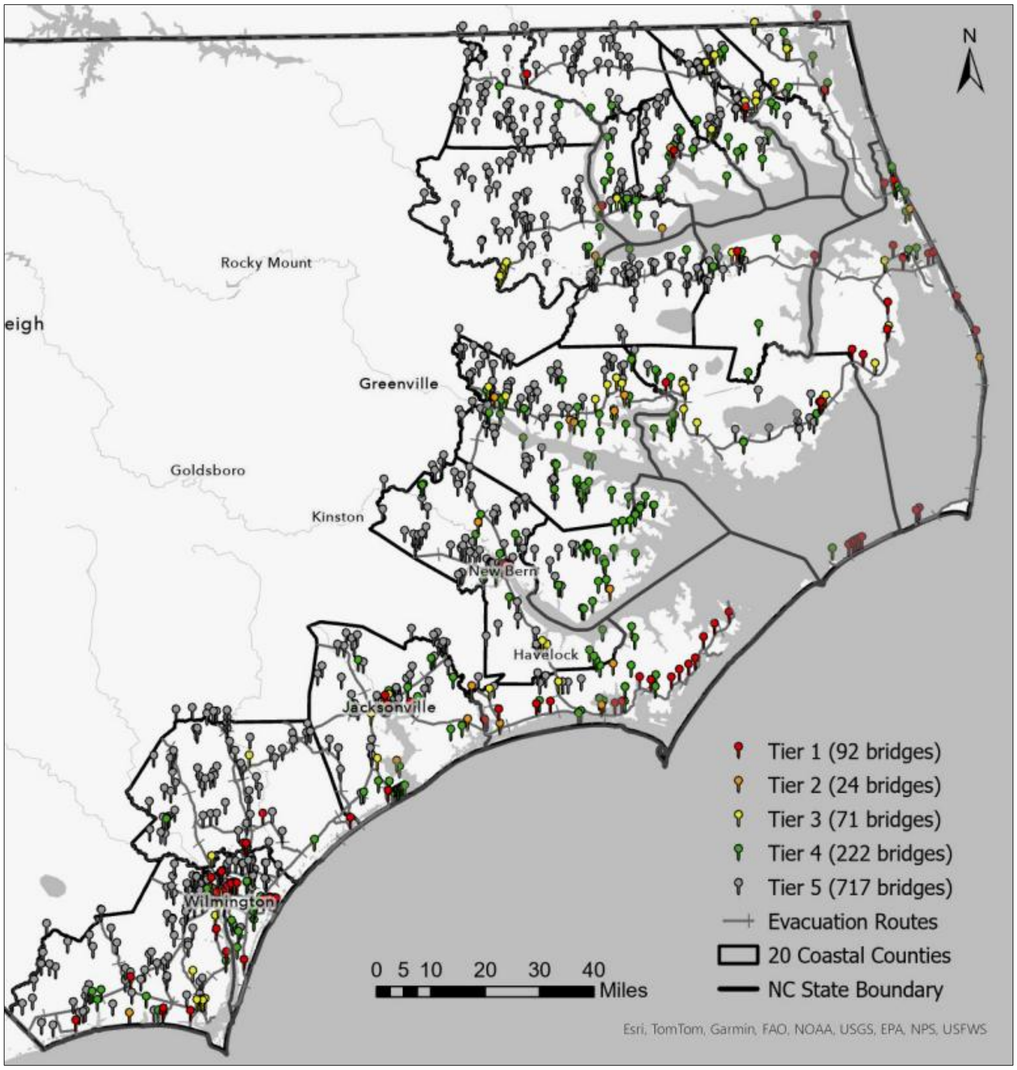

Figure 3. Spatial distribution of bridge tiers across the 20 coastal counties. Tier 1 bridges represent the highest priority for coastal vulnerability assessment, with decreasing priority through Tier 5.

3.2 Structural Parameter Extraction

Structural parameters were extracted for each of the 116 Tier 1 and Tier 2 bridges on a county-by-county basis. Structural data were primarily obtained from NCDOT Structure Inspection Reports; elevation values were derived from North Carolina Flood Mapping Program roadway LiDAR data, supplemented by design or as-built schematics where available.

Structure Inspection Reports provided nearly all necessary parameters for evaluating bridge spans: deck information (material, length, width, and height), rail information (height and design), girder details (material, number per span, spacing, height, width, and type), and pier cap material. The majority of the necessary parameters can be visualized in Figure 4. The North Carolina Flood Mapping Program roadway LiDAR data provided the elevation of the top of the bridge deck, taken at a point near the center of each span (see Figure 5 for an example). Using these parameters, the low-chord elevation, bridge centroid elevation, and bottom deck elevation were calculated for each span.

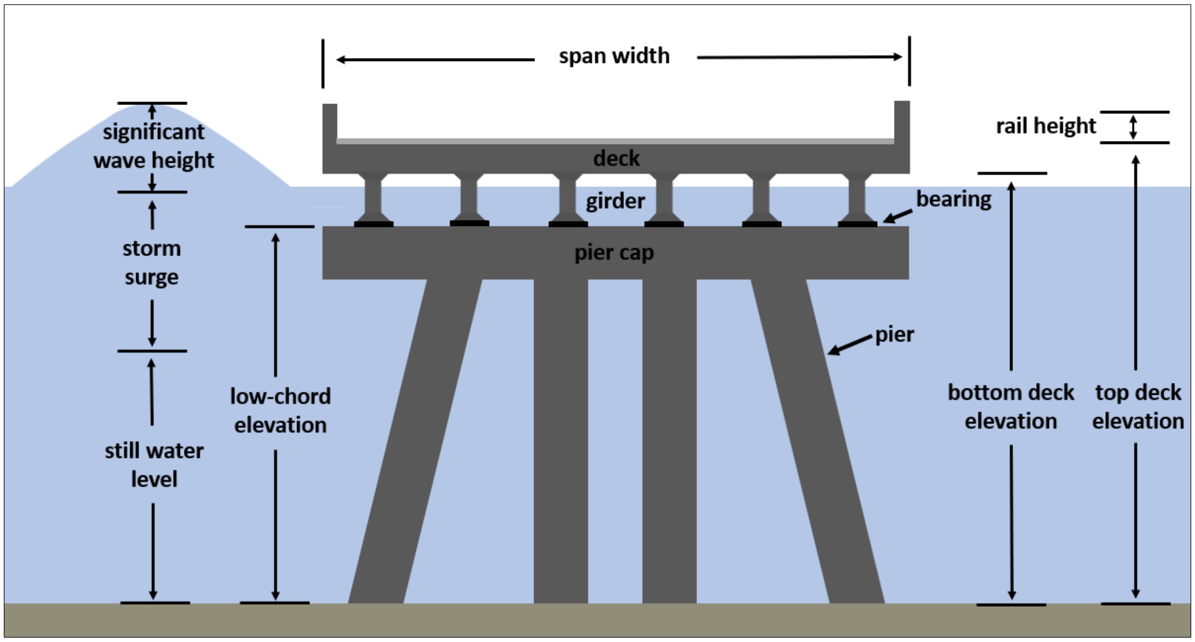

Figure 4. Illustration of structural and hydrodynamic parameters used in this research. Note that the span length is the distance into the screen.

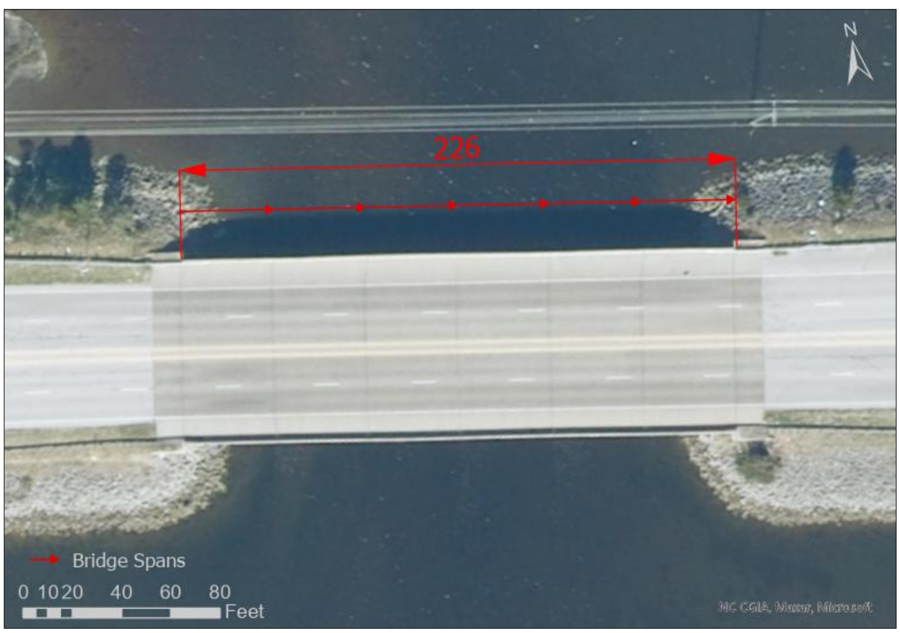

Figure 5. Example of LiDAR data extraction in ArcGIS. Span lengths from Structure Inspection Reports were measured in ArcGIS, and a point near the center of each span was selected for elevation measurement.

Chapter 4. Hydrodynamic Parameter Extraction

Accurate hydrodynamic parameters were crucial for evaluating coastal bridge vulnerability. The hydrodynamic values used in this research were obtained from the USACE South Atlantic Coastal Study (SACS) via the USACE Coastal Hazards System (CHS). By analyzing detailed numerical modeling results including storm surge water levels and significant wave heights across five storm return periods and three sea level rise scenarios, this research quantified the hydrodynamic conditions to which each of the 116 study bridges was exposed.

4.1 South Atlantic Coastal Study

The SACS assessed risks and vulnerabilities related to increased hurricane and storm damage due to sea level rise along 65,000 miles of shoreline across North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Puerto Rico, and the U.S. Virgin Islands. The CHS stored detailed numerical modeling results for storm responses, including storm surge water levels, significant wave heights, and related coastal hazard parameters.

The high-fidelity numerical model employed the CSTORM (Coastal Storm Modeling System) suite, integrating atmospheric input from the Planetary Boundary Layer Cyclone Model, regional waves from WAVEWATCH III, nearshore waves from STWAVE, and storm surge from ADCIRC. These models were configured with the elevation data used in the SACS project and validated against historical hurricane events (SACS, 2021a and 2021b). The SACS study area was separated into three basins: the South Atlantic from North Carolina through the Florida Keys, the Gulf of Mexico from the Florida Keys through Mississippi, and the Puerto Rico and U.S. Virgin Islands basin. In the South Atlantic basin — which encompasses the entire North Carolina coastline — storm surge water levels and wave hazards were computed using over 1,000 synthetic tropical storms and historical extratropical storms at more than 34,000 locations from South Florida to North Carolina.

4.2 Sea Level Rise and Storm Return Periods

Three sea level rise scenarios were modeled in the SACS, as shown in Table 3. SLR0 represents the SACS baseline sea level condition, referred to as present-day sea level in this report. SLR1 represents the basin-wide average corresponding to the USACE Intermediate projection for 2120, with 2.73 ft of sea level rise, and is broadly consistent with NOAA intermediate-high projections for the North Carolina coast. SLR2 represents the basin-wide average corresponding to the USACE High projection for 2120, with 7.35 ft of sea level rise, and provides a high-end planning condition. These sea level rise increments were applied uniformly across the South Atlantic study domain.

Table 3. Sea level rise scenarios simulated in the South Atlantic basin by the SACS (SACS, 2021a and 2021b).

	SLR0	SLR1	SLR2
Sea level rise (ft)	0	2.73	7.35

The SACS sea level conditions were consistent with the range of North Carolina projections summarized in Section 2.2. Under the SACS high sea level condition (SLR2), significant wave heights were projected to increase by more than 3 ft across much of the South Atlantic basin, further supporting the inclusion of all three sea level conditions in the vulnerability assessment.

The 100-year event is commonly considered in hydraulic design and vulnerability assessment; this research incorporated four additional return periods — 10, 20, 50, and 500 years — providing a broader understanding of the likelihood and impact of different storm scenarios on bridge vulnerability. A 10-year return period corresponds to a 10% annual probability, a 100-year return period to 1%, and a 500-year return period to 0.2%. In short, each bridge span is assessed by considering 15 hydrodynamic scenarios: three sea level rise scenarios, each combined with five storm return periods.

4.3 Hydrodynamic Parameter Extraction

The CHS graphical user interface was used to download storm surge and wave results for each bridge, as shown in Figure 6. One representative SACS station was selected for each bridge, and its surge and wave values were applied to all evaluated spans of that bridge. The latitude and longitude of each bridge were entered into the GUI. A nearby SACS station was then selected based on its position relative to the bridge, particularly its location near the center of the structure and within the water channel, to improve the representativeness of the hydrodynamic conditions. Stations were selected on the downstream side of the bridge to account for storm surge moving inland during coastal storms. In many cases, the nearest station was not the most representative; proximity was therefore evaluated based on hydrodynamic context rather than geographic distance alone.

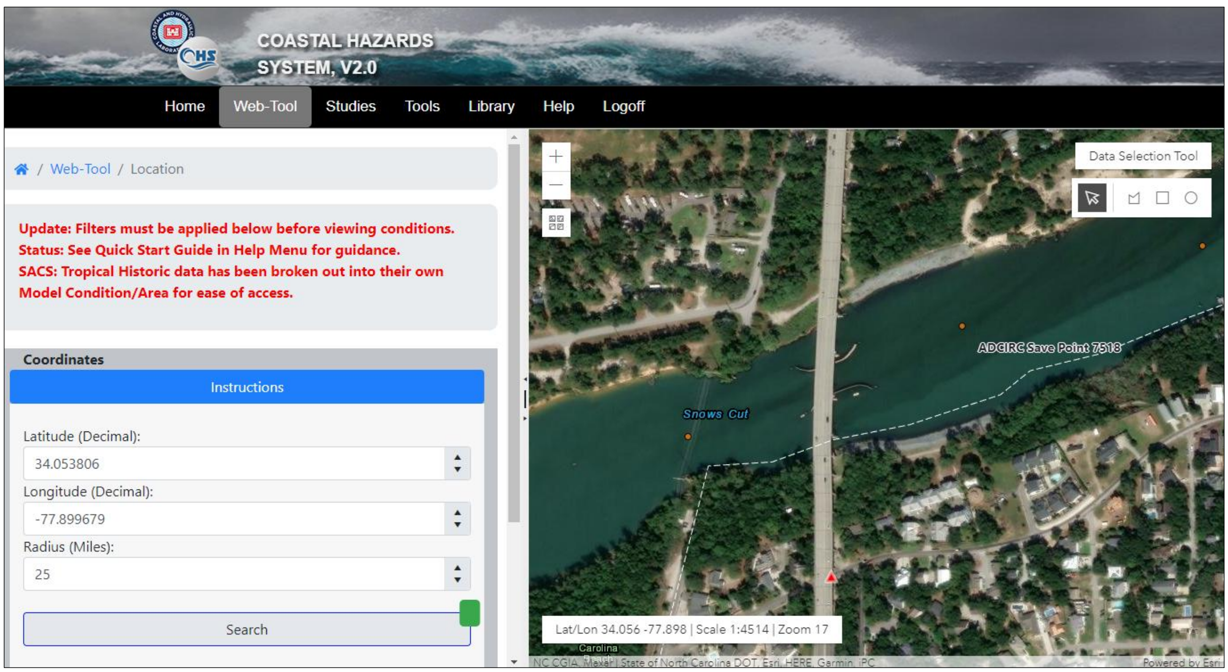

Figure 6. Visualization of the CHS GUI interface facilitating the selection of a SACS station for each bridge. The red triangle denotes the designated bridge, while the orange circles represent the accessible SACS stations.

For each selected SACS station, Excel files containing significant wave height (H_s) and storm surge water level (η) for the SLR0, SLR1, and SLR2 conditions were downloaded. Values for the 10-, 20-, 50-, 100-, and 500-year return periods were extracted and stored for the vulnerability calculations. Table 4 provides an example of extracted values for a representative bridge (ADCIRC station 7518, New Hanover County). The maximum wave crest elevation (η_{max}) shown in the table is defined as $\eta + (0.75)(1.7)H_s = \eta + 1.275H_s$, which was simplified in the calculations to $\eta + 1.3H_s$.

Table 4. Example of extracted hydrodynamic values for a single bridge (ADCIRC station 7518, New Hanover County).

Condition	Variable	10-yr	20-yr	50-yr	100-yr	500-yr	Units
SLR0	H_s	2.36	2.66	2.99	3.24	3.76	ft
	η	6.10	7.25	8.67	9.54	11.22	ft NAVD88
	η_{max}	9.17	10.71	12.56	13.75	16.11	ft NAVD88
SLR1	H_s	2.59	2.98	3.54	3.93	4.74	ft
	η	8.83	9.96	11.34	12.16	13.75	ft NAVD88
	η_{max}	12.20	13.83	15.94	17.26	19.92	ft NAVD88
SLR2	H_s	3.62	4.14	4.75	5.15	5.96	ft
	η	13.57	14.60	15.88	16.65	18.23	ft NAVD88
	η_{max}	18.28	19.98	22.06	23.35	25.98	ft NAVD88

Chapter 5. Bridge Superstructure Vulnerability Assessment

With the structural parameters extracted in Chapter 3 and the hydrodynamic parameters extracted in Chapter 4, this chapter evaluates the vulnerability of bridge superstructures subjected to storm surge and wave loading. The assessment was completed for each span of the selected bridges under the 15 hydrodynamic scenarios described in Section 4.3. The method represents a static rigid-body screening assessment and was developed to identify potential superstructure vulnerability under the specified loading conditions.

The assessment considered four vulnerability modes: inundation, uplift, sliding, and rotation. Inundation was evaluated directly from the storm surge water level relative to the top-of-deck elevation. The remaining three modes were evaluated using force or moment ratios that compared hydrodynamic demand with the corresponding resistance. The calculations described below were used to determine the vulnerability mode reported for each span and to summarize bridge-level vulnerability under each hydrodynamic scenario.

5.1 Forces

5.1.1 Hydrodynamic Forces

The method used to calculate wave forces on bridge spans followed the recommendations in HEC-25 (Douglass and Webb, 2020). This method was a revision of the approach originally proposed by Douglass et al. (2006) and was consistent with the wave-load framework discussed in Section 2.4. The method estimates the wave-induced force acting on a bridge span by calculating the vertical and horizontal components separately. The variables used in these calculations are illustrated conceptually in Figure 7.

$$F_v = C_v \ \gamma_w \ (\Delta z_v) \ A_v \tag{1}$$

and

$$F_h = [1 + c_r \ (N - 1)] \ C_h \ \gamma_w \ (\Delta z_h) \ A_h \tag{2}$$

where:

- F_v[lbf] = maximum of the vertical wave-induced force
- F_h[lbf] = maximum of the horizontal wave-induced force
- C_v = empirical coefficient for the vertical force (recommended value is C_v = 2)
- C_h = empirical coefficient for the horizontal force (recommended value is C_h = 2)
- c_r = reduction coefficient for reduced horizontal force on the internal (i.e., not the waveward-most) girders (recommended value was c_r = 0.4, or c_r = 0 if the bridge lacks girders)
- N = the number of girders supporting the bridge span deck
- A_v [ft^2] = the area of the bridge contributing to vertical uplift, i.e., the projection of the bridge deck onto the horizontal plane (width of the deck times the length of the deck)
- A_h [ft^2] = the area of the seaward side of the bridge contributing to horizontal forces, i.e., the projection of the bridge deck onto the vertical plane (girder, deck, and rail height combined times the length of the deck)
- Δz_v [ft] = difference between the elevation of the crest of the maximum wave (η_{max}) and the elevation of the underside of the bridge deck
- Δz_h [ft] = difference between the elevation of the crest of the maximum wave (η_{max}) and the elevation of the centroid of $\mathrm{A_h}$
- η_{max} [ft] = crest of maximum wave (design storm surge water level $+(0.75)(1.7)H_s$)
- H_s [ft] = significant wave height (average of the highest one-third of waves over a defined period)
- γ_w [lbf/ft^3] = specific weight of water (64 for salt water)

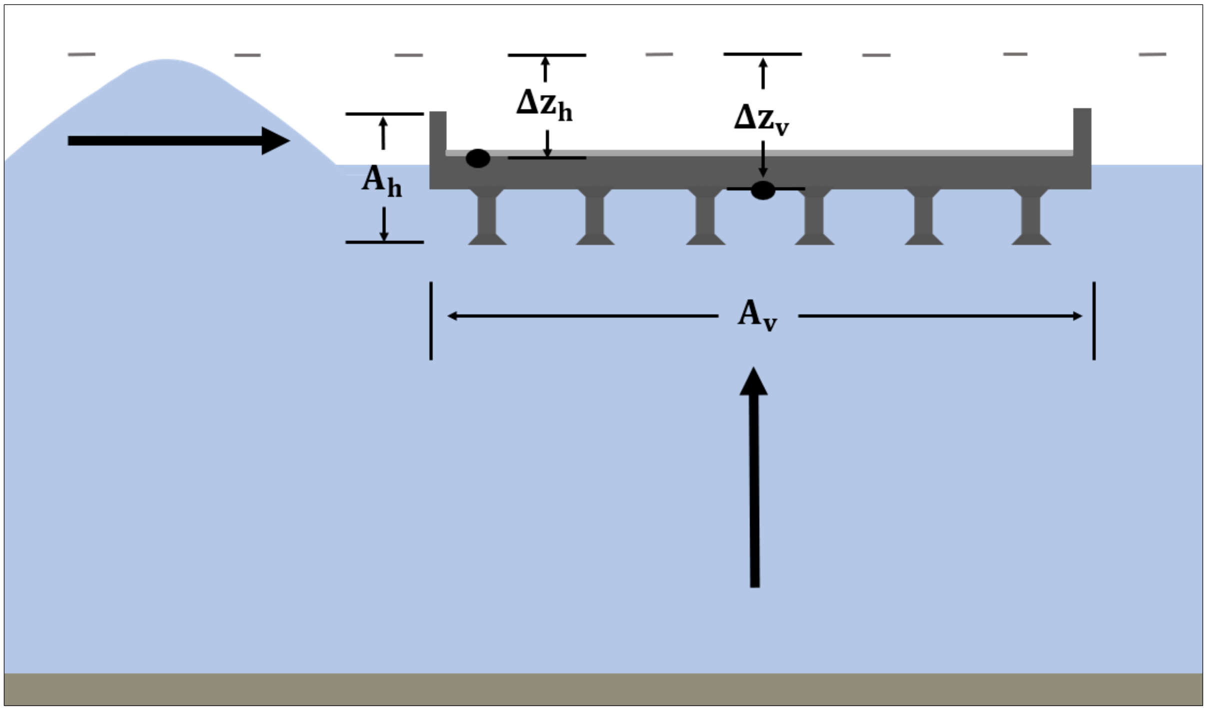

Figure 7. Illustration of variables used in the calculation of vertical and horizontal hydrodynamic forces acting on the bridge span.

The HEC-25 method estimates the total vertical and horizontal forces acting on the span rather than resolving the distribution of pressure over the bridge surface. The forces were therefore applied at representative locations defined by the bridge geometry and the corresponding moment arms. The method was most applicable when the maximum wave crest was near the bridge deck. When the maximum wave-crest elevation did not reach the underside of the bridge deck, the vertical and horizontal hydrodynamic forces were taken as zero. The same calculated wave-induced forces were subsequently used in the uplift, sliding, and rotation assessments.

5.1.2 Dead Weight

The dead weight of the span's superstructure (Equation 3) was determined by combining the weight of the deck and girders, based on the respective material properties:

$$W = (\gamma_{deck}\, V_{deck}) + (\gamma_{girder}\, V_{girder}\, N) \tag{3}$$

where:

W[lbf] = span dead weight
γ_{deck} [$\mathrm{lbf/ft^3}$] = unit weight of deck material (concrete = 140)
V_{deck} [$\mathrm{ft^3}$] = volume of deck
γ_{girder} [$\mathrm{lbf/ft^3}$] = unit weight of girder material
V_{girder} [$\mathrm{ft^3}$] = volume of girder
N = the number of girders supporting the bridge span deck

While reinforced concrete typically has a unit weight ranging from 145 to 150 $\mathrm{lbf/ft^3}$, a conservative value of 140 $\mathrm{lbf/ft^3}$ was used in this analysis to account for the variability in materials used across different bridge designs (FHWA, 2006). Unit weights of 140, 490, and 40 $\mathrm{lbf/ft^3}$ were used for concrete, steel, and timber girders, respectively. The dead weight was used as the primary vertical resistance in the uplift and rotation assessments and contributed to the normal force available for frictional resistance.

5.1.3 Effective Normal Force and Friction Resistance

The horizontal resistance available from friction depends on the contact force between the bridge superstructure and its supports. Because the upward vertical hydrodynamic force reduces this contact force, the full dead weight cannot be used directly to calculate frictional resistance when F_v is greater than zero. The effective normal force was therefore calculated as:

$$N_{eff} = \max(W - F_v, 0) \tag{4}$$

where:

N_{eff} [lbf] = effective normal force acting at the superstructure-support interface
W [lbf] = dead weight of the span superstructure
F_v [lbf] = maximum vertical wave-induced force

The maximum function prevented the effective normal force from becoming negative. When the vertical hydrodynamic force equaled or exceeded the dead weight, N_{eff} was set to zero, indicating loss of contact within the assumptions of the rigid-body screening method.

The friction resistance was calculated by multiplying the effective normal force by the friction coefficient between the girder and pier-cap materials:

$$F_f = \mu N_{eff} \tag{5}$$

where:

F_f [lbf] = friction resistance at the superstructure-support interface
μ = friction coefficient between the girder and pier-cap materials (see Table 5)
N_{eff} [lbf] = effective normal force

Table 5. Friction coefficients between bridge component materials.

	Concrete	Steel	Timber
Concrete	0.8	-	-
Steel	0.45	0.65	-
Timber	0.62	0.4	0.375

As F_v increased, N_{eff} and the available friction resistance decreased. If N_{eff} was zero, friction-based sliding resistance was no longer available, and the sliding ratio was not evaluated. This treatment distinguishes loss of contact from sliding while contact remains and avoids reporting a zero or infinite sliding ratio after the assumed support contact has been lost.

5.1.4 Treatment of Bearing Anchorage and Structural Details

Bridge bearing type, anchorage, connection details, retrofit history, and deterioration conditions can substantially influence actual bridge response during coastal storms. Bridge-specific bearing anchorage and connection details were not consistently available for all 116 bridges. Therefore, additional resistance provided by bearing anchorage or connection restraint (see Figure 8) was not explicitly included in the vulnerability assessment. Such restraint may increase resistance to uplift, sliding, and rotation for individual bridges.

5.2 Moments

5.2.1 Driving Moments

Rotation was evaluated about the assumed landward support edge of the bridge superstructure. The vertical and horizontal hydrodynamic forces both contributed to the driving moment. The driving moments caused by vertical force and horizontal force are illustrated in Figure 8 and were calculated as:

$$DM_v = F_v \ r_{F_v} \tag{6}$$

and

$$DM_h = F_h \ r_{F_h} \tag{7}$$

where:

DM_v[lbf ft] = maximum driving vertical moment
DM_h [lbf ft] = maximum driving horizontal moment
r_{F_v} [ft] = vertical force moment arm
r_{F_h} [ft] = horizontal force moment arm

5.2.2 Resisting Moment

The resisting moment was provided by the dead weight of the bridge superstructure acting about the same assumed rotation point:

$$RM = W \, r_w \tag{8}$$

where:

RM [lbf ft] = resisting moment
r_w [ft] = dead weight moment arm

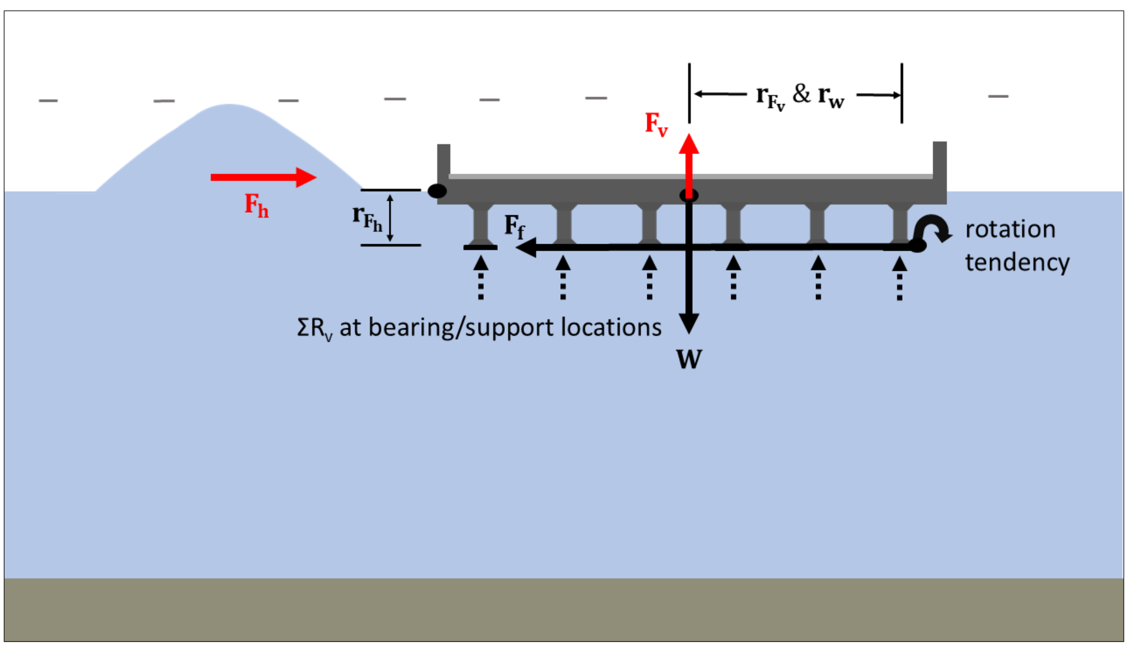

Figure 8. Conceptual schematic of hydrodynamic demand, resisting quantities, support reactions, and moment arms used to define vulnerability indices for a bridge superstructure subjected to storm surge and wave loading. Dashed arrows indicate girder support, bearing, and potential anchorage forces. Anchorage and connection resistance were excluded in this study.

5.3 Superstructure Vulnerability Modes

Four vulnerability modes were evaluated for each span. Inundation was evaluated from water level and deck elevation and was not based on a force or moment ratio. Uplift, sliding, and rotation were evaluated using dimensionless ratios that compared hydrodynamic demand with the corresponding resistance. A ratio equal to or greater than 1.0 indicated that the demand reached or exceeded the resistance for that mode before application of the dominant-mode logic described in Section 5.4.

5.3.1 Inundation

Inundation was evaluated independently from the force- and moment-based vulnerability modes. The inundation depth was calculated as the difference between the storm surge water level and the top-of-deck elevation near the center of the span:

$$d_{in} = \eta - z_{deck} \tag{9}$$

where:

d_{in} [ft] = inundation depth
η [ft] = storm surge water level
z_{deck} [ft] = top-of-deck elevation at the evaluated span

A span was classified as inundated when the inundation depth was greater than 1 ft. The 1-ft inundation threshold was adopted as a project-specific screening assumption to account for deck slope and uncertainty associated with using one representative deck elevation per span. Inundation was checked before the force- and moment-based modes because the HEC-25 force equations may overestimate hydrodynamic forces when the bridge deck is substantially submerged. Accordingly, when d_{in} was greater than 1 ft, inundation was reported as the dominant vulnerability mode.

5.3.2 Uplift

The uplift vulnerability ratio compared the maximum vertical hydrodynamic force with the span dead weight:

$$R_v = F_v/W \tag{10}$$

where:
R_v = uplift vulnerability ratio
F_v [lbf] = maximum vertical wave-induced force
W [lbf] = dead weight of the span superstructure

The uplift ratio represents the vertical demand relative to gravity resistance. A value of 1.0 indicates that the vertical force equals the dead weight. Under the load-factor-adjusted assessment described in Section 5.4.1, an adjusted uplift ratio equal to or greater than 1.0 was treated as contact loss for purposes of selecting the dominant vulnerability mode.

5.3.3 Sliding

The sliding vulnerability ratio compared the maximum horizontal hydrodynamic force with the available friction resistance:

$$R_s = \frac{F_h}{F_f} = \frac{F_h}{\mu N_{eff}} \tag{11}$$

where:

R_s = sliding vulnerability ratio
F_h [lbf] = maximum horizontal wave-induced force
F_f [lbf] = friction resistance based on the effective normal force
μ = friction coefficient
N_{eff} [lbf] = effective normal force

The sliding ratio was evaluated only when N_{eff} was greater than zero. When the vertical force reduced the effective normal force to zero, the assumed friction resistance was unavailable, and the sliding mode was not evaluated. This condition was recorded as contact loss rather than as a numerical sliding ratio.

5.3.4 Rotation

The rotation mode evaluated the tendency of the superstructure to rotate about an assumed support edge rather than complete overturning of the span. The rotation vulnerability ratio compared the combined driving moments caused by the vertical and horizontal hydrodynamic forces with the resisting moment provided by the span dead weight:

$$R_r = \left(F_v r_{F_v} + F_h r_{F_h}\right)/(\mathrm{W}\, r_W) \tag{12}$$

where:

R_r = rotation vulnerability ratio
F_v [lbf] = maximum vertical wave-induced force
F_h [lbf] = maximum horizontal wave-induced force
r_{F_v} [ft] = moment arm of the vertical hydrodynamic force
r_{F_h} [ft] = moment arm of the horizontal hydrodynamic force
W [lbf] = dead weight of the span superstructure
r_W [ft] = moment arm of the dead weight

Consistent with the HEC-25 loading assumption, the vertical and horizontal hydrodynamic forces were treated as acting simultaneously. A rotation ratio equal to or greater than 1.0 indicated that the combined driving moment reached or exceeded the resisting moment.

5.4 Dominant Vulnerability Determination

5.4.1 Load-factor Adjustment

Consistent with Section 2.4, the HEC-25 hydrodynamic force equations may be applied conservatively using an appropriate safety factor (Douglass and Webb, 2020). HEC-25 notes that the AASHTO *Guide Specifications for Bridges Vulnerable to Coastal Storms* requires a load factor of $L_f = 1.75$ for coastal hydrodynamic loads. The earlier NCDOT coastal bridge vulnerability study applied this factor to bridges classified as critical or essential and applied a factor of $L_f = 1.0$ to bridges classified as typical (Sheppard and Dompe, 2013). Following that precedent, this study treated Tier 1 bridges as critical or essential for load-factor assignment and applied a factor of $L_f = 1.75$. Tier 2 bridges were treated as typical and assigned a factor of $L_f = 1.0$.

The force- and moment-based vulnerability ratios were then adjusted as follows:

$$R_{v,a} = L_f R_v \tag{13}$$

$$R_{s,a} = L_f R_s \tag{14}$$

$$R_{r,a} = L_f R_r \quad (15)$$

The load factor was applied to the vulnerability ratios rather than to the inundation depth. Inundation continued to be evaluated directly using the 1-ft depth threshold.

5.4.2 Contact Loss and Dominant Mode Logic

A bridge span may experience several vulnerability modes at the same time. In this study, a single dominant vulnerability mode was assigned to each span for each hydrodynamic scenario. Figure 9 shows the workflow used to determine the dominant vulnerability mode. The dominant-mode logic was applied in the following order. First, the inundation depth was evaluated. If d_{in} was greater than 1 ft, the span was classified as Inundated, and no other mode was reported as dominant.

If the inundation threshold was not exceeded, the adjusted uplift, sliding, and rotation ratios were evaluated. When all valid adjusted ratios were less than 1.0, the span was classified as Safe. When the adjusted uplift ratio was equal to or greater than 1.0, contact loss was assumed, and sliding was excluded from the dominant-mode comparison. The adjusted uplift and rotation ratios were then compared. Rotation was selected when $R_{r,a} \geq R_{v,a}$; otherwise, uplifting was selected.

When the adjusted uplift ratio was less than 1.0, contact remained available and all valid adjusted ratios were compared. The largest ratio equal to or greater than 1.0 was selected as the dominant vulnerability mode. Sliding was included in this comparison only when N_{eff} was greater than zero. This logic ensured that friction-based sliding was not reported after contact loss and that rotation remained evaluated using the complete vertical and horizontal moment contributions.

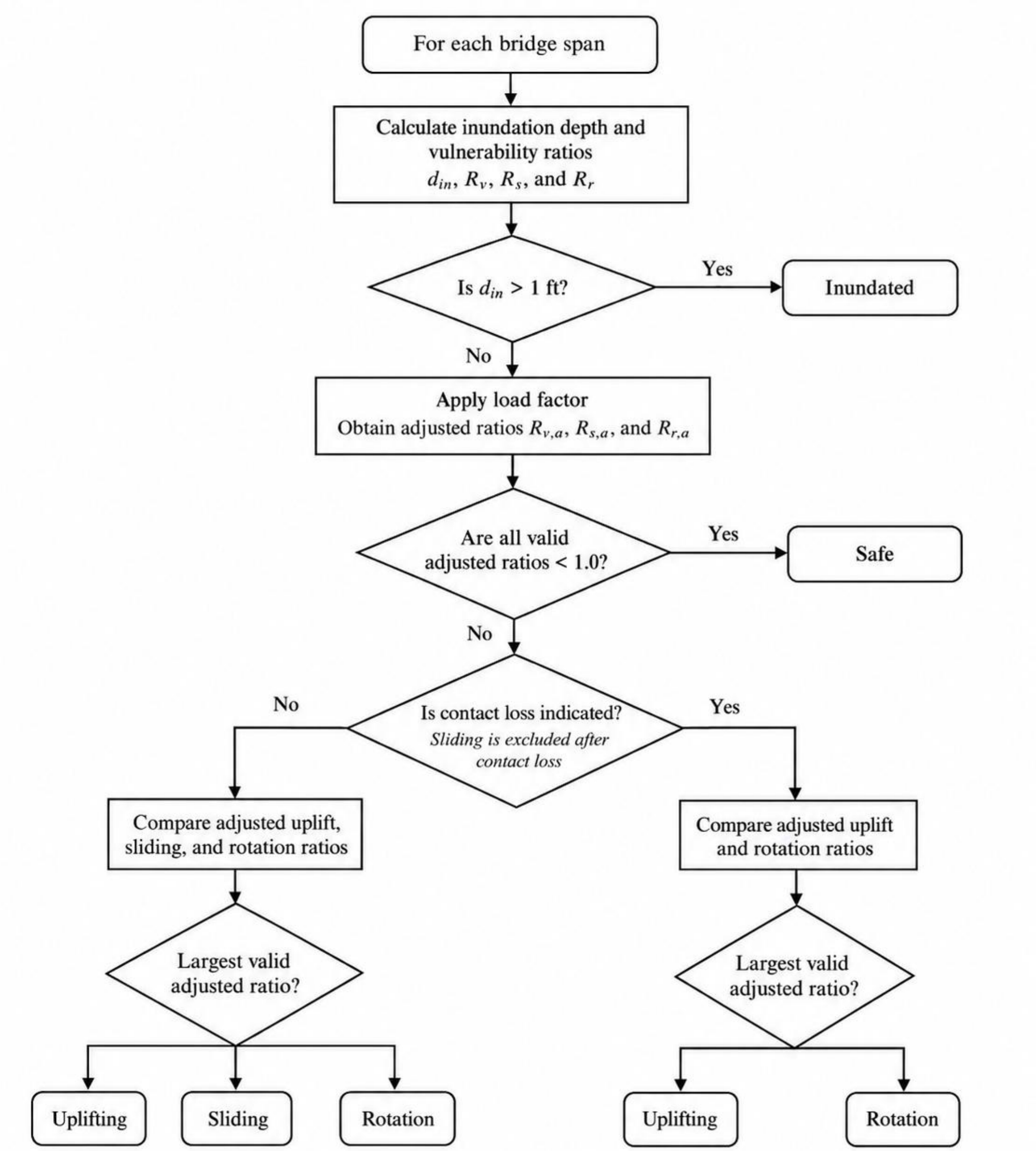

Figure 9. Flowchart for determining the dominant vulnerability mode for individual spans. In this workflow, contact loss denotes the load-factor-adjusted uplift condition under which sliding is excluded from the dominant-mode comparison.

5.4.3 Span- and Bridge-Level Classification

The result for each span consisted of a vulnerability mode and a corresponding value. For inundated spans, the reported value was the inundation depth in feet. For uplifting, sliding, and rotation, the reported value was the adjusted vulnerability ratio. Spans without a threshold exceedance were classified as Safe. A bridge was classified as Vulnerable when at least one evaluated span was not Safe; otherwise, the bridge was classified as Safe. For purposes of this screening assessment, Safe indicates that no evaluated span exceeded a screening criterion under the specified scenario; it should not be interpreted as a determination of structural adequacy. Likewise, Vulnerable indicates a screening-level threshold exceedance rather than predicted damage or failure.

For GIS dashboard reporting in Chapter 6, the lowest span was defined as the span with the minimum top-of-deck elevation. Because the same storm surge elevation and significant wave height were applied to all spans of a bridge under a given scenario, the lowest span was treated as the span most likely to control the bridge response. Its dominant vulnerability mode was reported separately as supplemental span-level information. The bridge-level classification remained based on the results of all evaluated spans.

5.5 Results

The structural parameters from Task 1 and the hydrodynamic parameters from Task 2 were used to complete the force, moment, and vulnerability calculations in Microsoft Excel. The results were summarized for the 116 selected Tier 1 and Tier 2 bridges and their individual spans under the 15 hydrodynamic scenarios described in Section 4.3. The vulnerability mode of each span was determined first. As described in Section 5.4.3, a bridge was classified as Vulnerable under a scenario when at least one span was assigned a dominant vulnerability mode other than Safe.

This section presents selected results that address the effects of storm intensity and sea level rise on bridge vulnerability and the variation of those effects across the coastal region. The complete statewide, NCDOT division, and county-level statistics for all 15 scenarios are provided in Appendix A. The complete series of bridge vulnerability maps is provided in Appendix B. The classifications represent screening-level threshold exceedances under the evaluated scenarios and should not be interpreted as deterministic predictions of bridge damage or collapse. In addition, the results represent the 116 bridges selected for this study rather than the complete bridge inventory within the coastal counties.

5.5.1 Effects of Storm Intensity and Sea Level Rise

The statewide bridge-level results showed that the percentage of bridges classified as Vulnerable increased with both storm return period and sea level rise. Table 6 summarizes the number and percentage of bridges classified as Vulnerable under all 15 hydrodynamic scenarios. Safe and Vulnerable bridge counts for the same scenarios are provided in Appendix A.

Table 6. Statewide number and percentage of bridges classified as Vulnerable under the 15 hydrodynamic scenarios (116 assessed bridges).

Storm return period	SLR0 (0 ft)	SLR1 (2.73 ft)	SLR2 (7.35 ft)
10-year	14 (12.1%)	52 (44.8%)	74 (63.8%)
20-year	25 (21.6%)	60 (51.7%)	78 (67.2%)
50-year	41 (35.3%)	64 (55.2%)	82 (70.7%)
100-year	51 (44.0%)	68 (58.6%)	83 (71.6%)
500-year	60 (51.7%)	74 (63.8%)	86 (74.1%)

Note: Values are number of bridges classified as Vulnerable, with percentage of the 116 assessed bridges in parentheses.

Under the present-day sea level condition (SLR0), the number of bridges classified as Vulnerable increased from 14 bridges, or 12.1 percent of the assessed bridges, under the 10-year storm to 60 bridges, or 51.7 percent, under the 500-year storm. Under the 2.73-ft sea level rise condition (SLR1), the number increased from 52 bridges, or 44.8 percent, under the 10-year storm to 74 bridges, or 63.8 percent, under the 500-year storm. Under the 7.35-ft sea level rise condition (SLR2), 74 bridges, or 63.8 percent, were classified as Vulnerable under the 10-year storm, and 86 bridges, or 74.1 percent, were classified as Vulnerable under the 500-year storm. For the 100-year storm, the number of bridges classified as Vulnerable increased from 51 under SLR0 to 68 under SLR1 and 83 under SLR2.

Comparison across sea level conditions demonstrated the principal statewide finding of the assessment: sea level rise shifted vulnerability threshold exceedances from relatively rare storms toward more frequent storms. The SLR1 10-year scenario resulted in 52 bridges classified as Vulnerable, which was nearly the same as the count of 51 bridges classified as Vulnerable under the SLR0 100-year scenario. The SLR2 10-year scenario resulted in 74 bridges classified as Vulnerable, exceeding the count of 60 bridges classified as Vulnerable under the SLR0 500-year scenario and equaling the number identified under the SLR1 500-year scenario. Therefore, among the assessed bridges, the number of threshold exceedances associated with a rare storm under present-day sea level could be reached or exceeded by a substantially more frequent storm when the baseline sea level was increased.

The increase in the number of bridges classified as Vulnerable from the 10-year to the 500-year storm was 46 bridges under SLR0, 22 bridges under SLR1, and 12 bridges under SLR2. This pattern did not indicate that storm intensity became unimportant at higher sea levels. Instead, the elevated baseline water level caused many bridges to exceed a vulnerability criterion under the lower return period storms, leaving fewer additional bridges to be newly classified as Vulnerable as storm intensity increased.

5.5.2 Changes in Dominant Span Vulnerability Modes

The span-level results were used to identify the mechanisms associated with the statewide bridge-level patterns. Each span was assigned one dominant classification of Safe, Inundated, Uplifting, Sliding, or Rotation under each hydrodynamic scenario. Table 7 presents the statewide distribution of dominant span vulnerability modes for the representative 100-year storm under the three sea level conditions. The corresponding results for all 15 scenarios, including separate inundation-depth categories, are provided in Appendix A.

Table 7. Statewide percentages of dominant span vulnerability modes for the 100-year storm under the three sea level conditions.

Sea level condition	Rotation	Sliding	Uplifting	Inundated	Safe
SLR0 (0 ft)	7.33%	0.67%	0.00%	0.60%	91.39%
SLR1 (2.73 ft)	10.14%	0.46%	0.00%	4.06%	85.34%
SLR2 (7.35 ft)	37.38%	5.20%	0.00%	16.29%	41.14%

Note: Inundated combines the 1-3 ft, 3-5 ft, and greater-than-5-ft inundation-depth categories reported separately in Appendix A. Minor differences from 100 percent result from rounding.

For the 100-year storm, the percentage of spans classified as Safe decreased from 91.39 percent under SLR0 to 85.34 percent under SLR1 and 41.14 percent under SLR2. Rotation was the most frequent non-safe span classification under these scenarios, increasing from 7.33 percent under SLR0 to 10.14 percent under SLR1 and 37.38 percent under SLR2. The percentage classified as Sliding was 0.67 percent under SLR0, 0.46 percent under SLR1, and 5.20 percent under SLR2. The combined percentage of inundated spans increased from 0.60 percent under SLR0 to 4.06 percent under SLR1 and 16.29 percent under SLR2. In addition to becoming more common, Inundation shifted toward the deeper categories as sea level and storm intensity increased.

Across the complete set of scenarios shown in Appendix A, Rotation remained the most common force- or moment-based dominant vulnerability mode. Its statewide percentage increased from 0.84 percent under the SLR0 10-year scenario to 42.13 percent under the SLR2 500-year scenario. Uplifting was not selected as the dominant mode in the first 14 scenarios and accounted for 0.02 percent of spans under the SLR2 500-year scenario. This result should not be interpreted as an absence of vertical hydrodynamic effects. The vertical force contributed to contact loss, reduced the effective normal force available for sliding resistance, and contributed to the driving moment used in the Rotation assessment. In addition, Inundation was assigned before the force- and moment-based classifications when the inundation-depth threshold was exceeded.

Sliding did not increase monotonically with storm return period under SLR2. The statewide Sliding percentage increased to 11.28 percent under the SLR2 50-year scenario and then decreased to 5.20 percent under the 100-year scenario and 0.84 percent under the 500-year scenario. This pattern was consistent with the dominant-mode logic described in Section 5.4.2. As the hydrodynamic conditions increased, a span previously classified as Sliding could instead be classified as Rotation or Inundated, and Sliding was excluded after the assumed loss of support contact. Consequently, the percentage assigned to an individual dominant mode did not necessarily increase monotonically even though the overall number of bridges classified as Vulnerable increased.

5.5.3 Regional Variation by NCDOT Division

The statewide results were not distributed uniformly across the three NCDOT divisions included in the study. Table 8 compares bridge vulnerability by division for the 100-year storm under SLR0, SLR1, and SLR2. The complete division-level results for all storm return periods are provided in Appendix A.

Table 8. Number and percentage of bridges classified as Vulnerable by NCDOT division for the 100-year storm under the three sea level conditions.

NCDOT division	Assessed bridges	SLR0 (0 ft)	SLR1 (2.73 ft)	SLR2 (7.35 ft)
Division 1	38	14 (36.8%)	26 (68.4%)	34 (89.5%)
Division 2	36	25 (69.4%)	27 (75.0%)	31 (86.1%)
Division 3	42	12 (28.6%)	15 (35.7%)	18 (42.9%)

Note: Values in the three scenario columns are number of bridges classified as Vulnerable, with division percentage in parentheses.

Division 2 therefore had the highest percentage of assessed bridges classified as Vulnerable under the present-day 100-year scenario: 25 of 36 bridges, or 69.4 percent. Division 1 had 14 of 38 bridges classified as Vulnerable, or 36.8 percent, and Division 3 had 12 of 42 bridges classified as Vulnerable, or 28.6 percent. Under SLR1, the corresponding 100-year results increased to 26 bridges classified as Vulnerable in Division 1 (68.4 percent), 27 in Division 2 (75.0 percent), and 15 in Division 3 (35.7 percent).

Under the SLR2 100-year scenario, Division 1 had 34 of 38 bridges classified as Vulnerable (89.5 percent), Division 2 had 31 of 36 bridges classified as Vulnerable (86.1 percent), and Division 3 had 18 of 42 bridges classified as Vulnerable (42.9 percent). Division 2 therefore had the highest percentage of assessed bridges classified as Vulnerable under the present-day 100-year scenario, whereas Division 1 experienced the largest change with sea level rise and had the highest percentage under SLR2. From SLR0 to SLR2 for the 100-year storm, the percentage classified as Vulnerable increased by approximately 52.7 percentage points in Division 1, 16.7 percentage points in Division 2, and 14.3 percentage points in Division 3.

These results indicated that sea level rise could change both the magnitude and the regional ranking of bridge vulnerability. The assessment did not separately quantify the causes of the division-level differences. The observed variation reflected the combined influence of local hydrodynamic conditions, bridge elevations and geometry, and the distribution of the selected Tier 1 and Tier 2 bridges within each division.

5.5.4 County-Level and Spatial Patterns

County-level results provided additional details on the regional variation. Table 9 presents the 100-year storm results for Carteret, Dare, Craven, and New Hanover Counties. These counties were selected for the main-text comparison because each contained more than 10 assessed bridges and because their results illustrated different vulnerability patterns. Complete results for all counties and all 15 scenarios are provided in Appendix A.

Table 9. Number and percentage of bridges classified as Vulnerable in selected counties for the 100-year storm.

County	Assessed bridges	SLR0 (0 ft)	SLR1 (2.73 ft)	SLR2 (7.35 ft)
Carteret	18	15 (83.3%)	16 (88.9%)	16 (88.9%)
Dare	14	6 (42.9%)	10 (71.4%)	14 (100.0%)
Craven	11	5 (45.5%)	5 (45.5%)	8 (72.7%)
New Hanover	24	4 (16.7%)	5 (20.8%)	5 (20.8%)

Note: Values in the three scenario columns are number of bridges classified as Vulnerable, with county percentage in parentheses.

Carteret County had a high percentage of assessed bridges classified as Vulnerable under the present-day 100-year scenario, with 15 of 18 assessed bridges classified as Vulnerable (83.3 percent). The count increased to 16 bridges (88.9 percent) under SLR1 and remained at 16 under SLR2. Dare County showed a stronger response to sea level rise. The number increased from 6 of 14 bridges (42.9 percent) under SLR0 to 10 (71.4 percent) under SLR1 and all 14 assessed bridges under SLR2. In Craven County, 5 of 11 bridges (45.5 percent) were classified as Vulnerable under both SLR0 and SLR1, increasing to 8 (72.7 percent) under SLR2. New Hanover County had the lowest percentages among the four selected counties, increasing from 4 of 24 bridges (16.7 percent) under SLR0 to 5 (20.8 percent) under SLR1 and remaining at 5 under SLR2.

The county comparisons showed that a single statewide percentage did not represent all coastal areas. Some counties contained assessed bridges that were classified as Vulnerable under the present-day 100-year condition, while other counties showed a larger increase only after sea level rise was introduced. County percentages should be interpreted relative to the number and characteristics of the selected bridges in each county and should not be applied to the complete county bridge inventory.

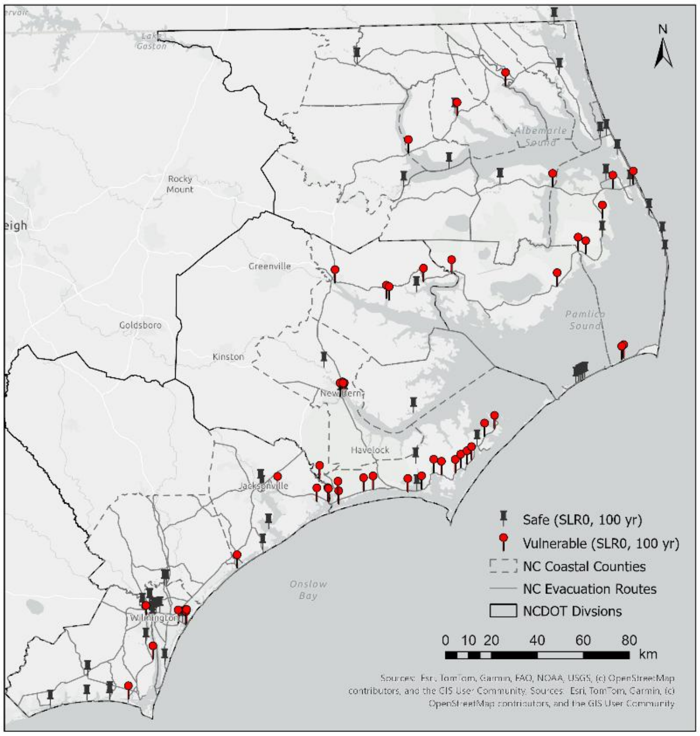

Figure 10. Spatial distribution of bridge vulnerability under present-day sea level and 100-year storm.

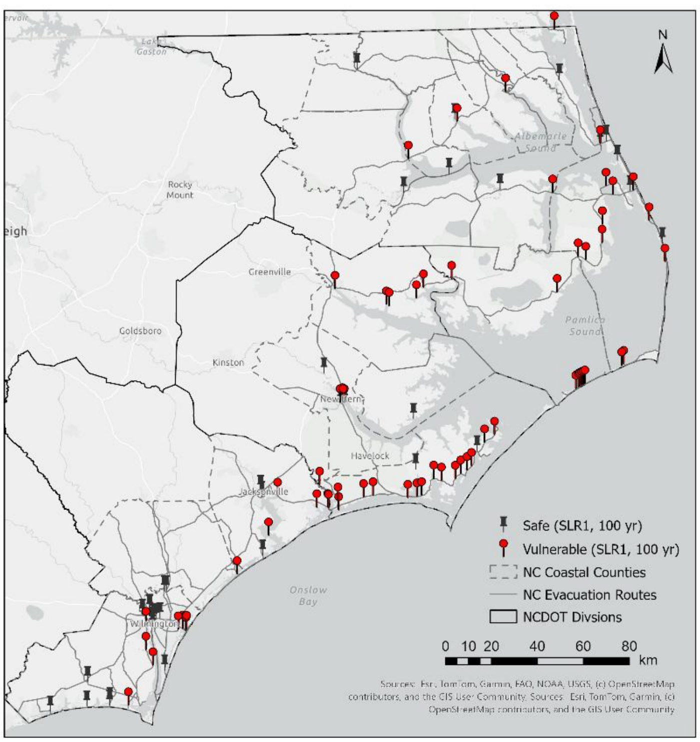

Figure 11. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 100-year storm.

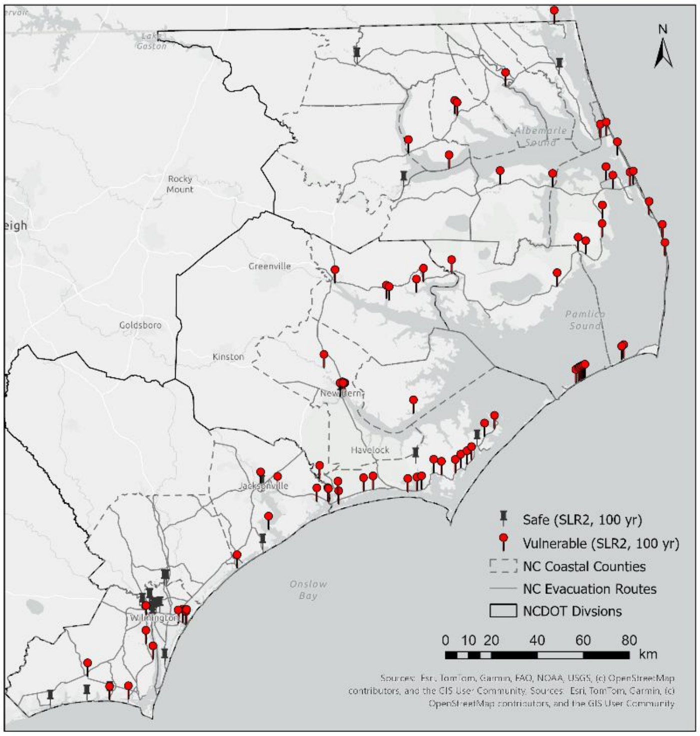

Figure 12. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 100-year storm.

The spatial distributions for the representative 100-year scenarios are shown in Figures 10 to 12. The present-day map showed bridges classified as Vulnerable distributed across the coastal study area, with notable concentrations along the central coast and several sound and barrier-island crossings. The SLR1 and SLR2 maps showed an expansion of the Vulnerable classification across the study area. The increase was particularly evident in Division 1 under SLR2, consistent with the division-level statistics, while groups of assessed bridges remained Safe in portions of Division 3 and other locations. The complete set of maps for the 10-, 20-, 50-, 100-, and 500-year storms under all three sea level conditions is provided in Appendix B.

In summary, the results showed that sea level rise substantially changed the frequency context of coastal bridge vulnerability. Among the assessed bridges, vulnerability levels associated with rare storms under present-day sea level were reached or exceeded under more frequent storms after sea level rise was introduced. Rotation was the principal non-safe span classification, and Inundation became increasingly important as water levels increased. The magnitude of these changes varied by division and county, supporting the use of bridge-specific results and regional patterns to prioritize additional evaluation. Because the method was developed as a screening assessment, a Vulnerable classification identified a threshold exceedance requiring further consideration rather than a prediction of structural failure.

Chapter 6. Dashboard Development

The final task of this research was the development of a GIS-based dashboard to display bridge vulnerability assessment results in a format that could be reviewed and used by NCDOT engineers. The vulnerability assessment produced a large amount of bridge-level and span-level information for 116 selected bridges under 15 hydrodynamic scenarios. Although the results could be stored in spreadsheets, static tables alone were not sufficient for reviewing the spatial distribution of bridges classified as Vulnerable, comparing results across counties and divisions, or examining detailed span behavior for an individual bridge. Therefore, a web-based viewer was developed to combine mapping, querying, summary visualizations, and access to bridge-specific results within a single interface.

The dashboard was designed as an implementation component of the research rather than as a separate analysis method. The structural parameters, hydrodynamic parameters, and vulnerability assessment results described in the previous chapters were processed and organized for display in the viewer. The resulting application, referred to as the NC Coastal Bridge Vulnerability Viewer, allows users to locate assessed bridges, filter bridges by selected criteria, review vulnerability classifications under different storm and sea level rise scenarios, and access related span-level data. The dashboard was developed using ArcGIS Pro, ArcGIS Online hosted feature layers, a web map, and ArcGIS Experience Builder.

6.1 Analysis of Existing Tools

Before the dashboard was created, existing NCDOT mapping tools and data resources were reviewed to understand how bridge information and transportation layers were commonly displayed. The NCDOT Structures Map provided bridge inventory information and helped support the initial bridge screening process described in Chapter 3. Other existing data sources, such as evacuation routes, county boundaries, state boundary layers, and SACS station locations, were also reviewed because they provided important context for interpreting the vulnerability results. These tools were useful for viewing individual data layers, but they were not developed specifically to summarize the results of the coastal bridge vulnerability assessment.

The primary need identified during this review was an interactive tool that could link the engineering results to bridge locations and allow users to compare results across scenarios. The dashboard, therefore, needed to support both broad screening and detailed review. At the broad scale, users needed to identify patterns such as which counties had bridges classified as Vulnerable or which bridges were classified as Vulnerable under a specific sea level rise and storm return period. At the detailed scale, users needed to select an individual bridge and review the bridge attributes, hydrodynamic conditions, vulnerability results, and span-level vulnerability results. This requirement guided the organization of the GIS database and the Experience Builder interface.

6.2 Dashboard Creation

The dashboard was created through a multi-step process that converted engineering analysis results into web-accessible GIS layers and tables. The general workflow is shown in Figure 13. The engineering calculations were completed outside the GIS environment. The bridge-level results and span-level results were then imported into a file geodatabase in ArcGIS Pro. The geodatabase was used to organize the primary bridge feature class, supporting reference layers, span data tables, and relationship classes. The completed GIS database was then published as a hosted feature layer and used in a web map. Finally, the web map and associated data sources were connected to an Experience Builder application to create the final viewer.

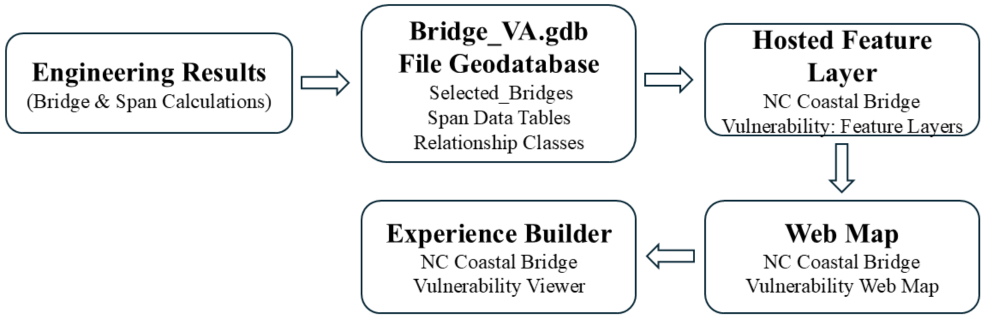

Figure 13. General workflow used to develop the NC Coastal Bridge Vulnerability Viewer.

6.2.1 ArcGIS Pro

ArcGIS Pro was used to prepare the GIS database that supported the dashboard. Figure 14 shows the GIS database structure used to organize bridge-level and span-level vulnerability results. Several datasets are packed into a file geodatabase called *Bridge_VA.gdb*. The central dataset was a point feature class named *Selected_Bridges*. This feature class contained the location of each assessed bridge and the primary bridge-level attributes used in the dashboard. These attributes included general bridge information, such as bridge number, county, division, year built, number of spans, material information, and selected elevation values. The feature class also contained hydrodynamic summary values and scenario-based vulnerability results. Because the dashboard needed to support querying and filtering, the bridge-level feature class was designed to include the fields most likely to be used directly in user selections.

In addition to the *Selected_Bridges* feature class, several supporting GIS layers were included to provide spatial context. These included *Excluded_Bridges*, *Evacuation_Routes*, *NC_Coastal_Counties*, *NC_State_Boundary*, and *SACS_Locations*. The excluded bridge layer was retained to document bridges that were screened but not included in the primary analysis. The evacuation route and county layers provided transportation and administrative context. The SACS locations layer showed the hydrodynamic stations used to support the extraction of surge and wave parameters.

The span-level results were stored separately from the bridge-level feature class. One span table was created for each assessed bridge, resulting in 116 span data tables. Each span table contained the individual span information for the corresponding bridge, including span number, elevation values, structural attributes, and vulnerability results for the 15 hydrodynamic scenarios. Relationship classes were created in the geodatabase to connect each bridge record in *Selected_Bridges* with its corresponding span table. This structure allowed the dashboard to summarize bridge-level results while still preserving detailed span-level information for review.

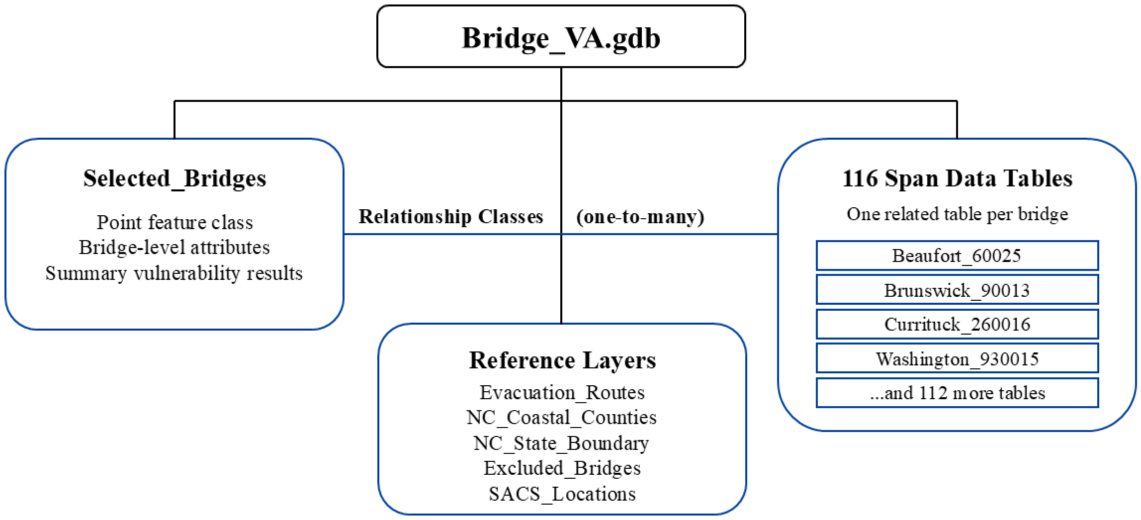

Figure 14. GIS database structure used to organize bridge-level and span-level vulnerability results.

This database structure was selected because bridge-level and span-level results served different purposes. Bridge-level fields were used to support filtering, mapping, and summary displays. Span-level tables were used to provide detailed supporting information for each bridge. Keeping the span data in related tables reduced the size and complexity of the primary feature class while allowing the detailed engineering results to remain accessible from the viewer.

6.2.2 Experience Builder

ArcGIS Experience Builder was used to develop the web-based interface for the dashboard. Experience Builder allowed the hosted feature layer and web map to be combined with query, list, table, chart, and information widgets (Esri, n.d.). The application was organized to allow users to move from a general overview of the study to more detailed bridge-specific information. The final dashboard included three thematic pages, query and filtering tools, map displays, result lists, bridge information panels, span-level tables, summary visualizations, and a footer link to the user guide.

A key component of the dashboard was the Query widget. The Query widget was configured to filter the *Selected_Bridges* layer by priority tier, NCDOT division, county, selected storm and sea level rise scenario, and vulnerability result. Internally, scenario-based vulnerability fields and vulnerability codes support compact filtering of bridge results, while the user-facing query window presents the options in a simplified form. This allowed users to select one or more hydrodynamic scenarios and identify bridges that met the selected vulnerability conditions.

The dashboard was also configured to display information in multiple forms at the same time. When a query was applied, the map, result list, table, and charts were updated to reflect the selected records. This helped users review both the spatial pattern of bridges classified as Vulnerable and the associated attribute information. For individual bridges, the user could review bridge-level parameters and access the related span table to examine span-by-span vulnerability results. This organization provided a connection between the summary results shown in the main dashboard and the detailed engineering calculations produced during the assessment.

6.3 Dashboard Interface

The dashboard interface was organized to support both broad screening and bridge-specific review of the superstructure vulnerability results. The viewer combines four primary interface components: an interactive map, bridge result panels, summary charts, and query tools. The map provides the spatial context for the 116 selected bridges and supporting reference layers. The left panel lists bridge-level vulnerability classifications for the active selection, while the right panel displays detailed information for the selected bridges. The bottom panel provides charts and summary visualizations that update according to the selected dashboard page and active query.

The interface was designed so that users can begin with a general view of the selected coastal bridges, filter the bridge set using the query tool, and then review results in three thematic pages: Bridge & Superstructure, Wave & Surge Conditions, and Superstructure Vulnerability. These three pages use the same general layout but display different types of information. This organization allows users to move from bridge characteristics to hydrodynamic conditions to vulnerability outcomes without leaving the same dashboard environment.

The dashboard also preserves the connection between bridge-level summaries and detailed engineering results. The bridge-level panels and charts provide a quick way to compare multiple bridges, counties, divisions, or scenarios. When more detailed information is needed, the viewer provides access to related span-level tables through the data table functions. This structure allows the dashboard to support both screening-level review and more detailed investigation of individual bridge behavior.

6.3.1 Query and Filtering Tool

The Query tool allows users to narrow the displayed bridge records before reviewing the map, information panels, and charts. The query window is opened from the bottom-right portion of the dashboard and provides several filter categories, including Priority Tier, DOT Division, County, and Storm/SLR Scenario. These filters allow users to identify bridges that match a selected administrative area, screening priority, or vulnerability scenario.

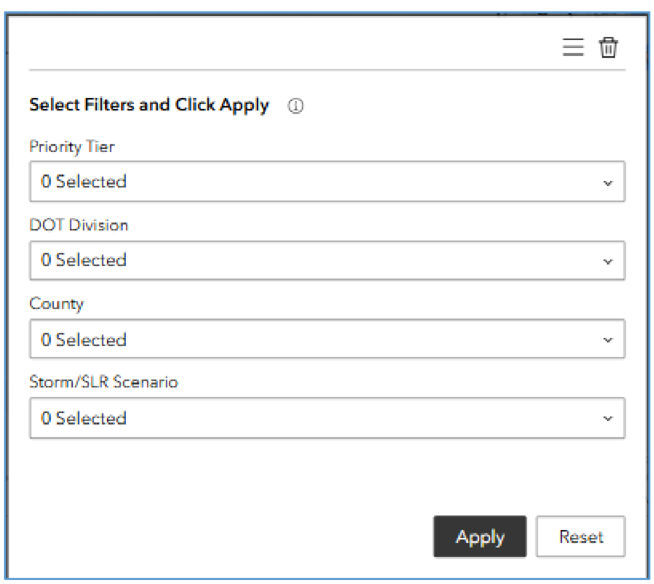

Figure 15. Query interface showing filters for priority tier, NCDOT division, county, and storm/sea level rise scenario.

Figure 15 shows the query interface used to filter bridge records in the viewer. A user can select one or more filter criteria and then click the Apply button to update the dashboard. After the query is applied, the map, bridge lists, right-side information panel, and bottom charts update to reflect the returned bridges. For example, a user can filter bridges within a specific county or DOT division, or identify bridges classified as Vulnerable under a selected combination of sea level rise and storm return period. The Reset button clears the selected query values and allows the user to return to a broader bridge set.

The query tool is important because it allows the dashboard to support both statewide review and targeted analysis. Without filtering, the viewer displays the selected bridge inventory as a whole. With filtering, the same interface can be used to focus on a particular county, a priority group, or a scenario of concern. This makes the viewer useful for identifying spatial patterns, comparing groups of bridges, and selecting individual bridges for more detailed review.

6.3.2 Bridge & Superstructure Page

The Bridge & Superstructure page presents bridge-level characteristics and selected superstructure information used in the vulnerability assessment. This page is intended to help users understand the physical characteristics of the bridges shown in the current query or selection. The right panel displays attribute information for selected bridges, while the bottom panel provides charts that compare bridge characteristics across the active result set.

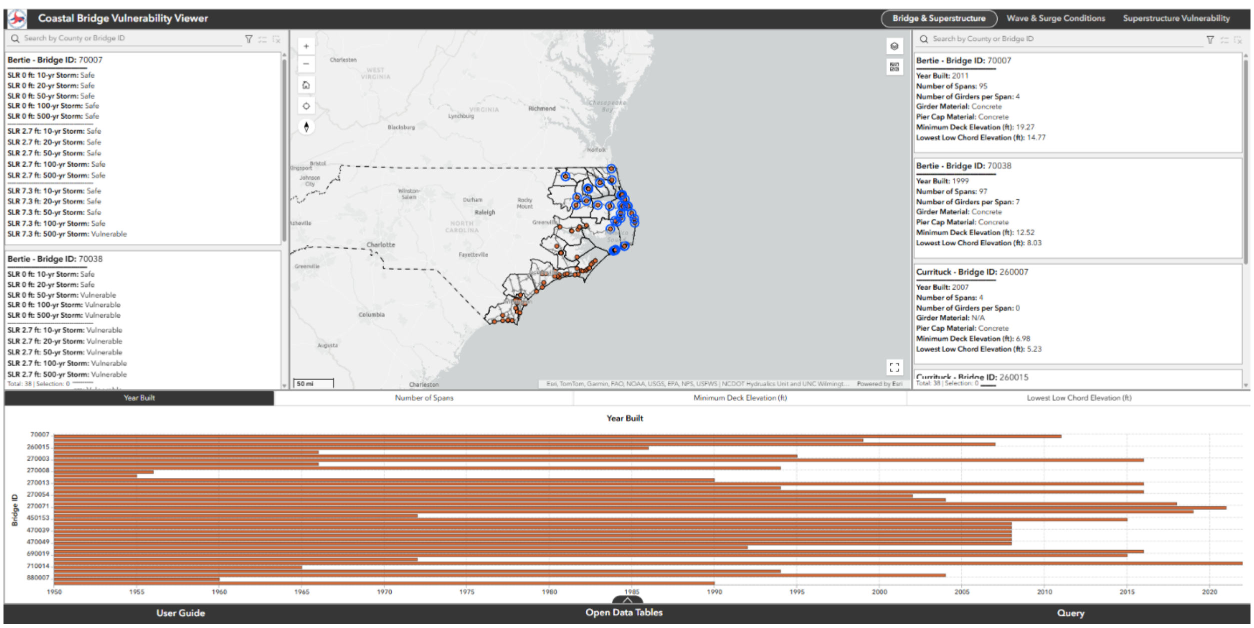

Figure 16. Bridge & Superstructure page showing bridge attributes, mapped bridge locations, and characteristic summary charts.

Figure 16 shows the Bridge & Superstructure page. The center map displays the bridge locations returned by the active query, with queried bridges highlighted and supporting spatial context provided by the reference layers. The left panel retains the bridge-level vulnerability classifications so that users can continue to see scenario-based results while reviewing bridge characteristics. The right panel lists bridge attributes for selected bridges, including items such as year built, number of spans, number of girders per span, girder material, pier cap material, minimum deck elevation, and lowest low-chord elevation. The bottom panel summarizes selected bridge characteristics using chart tabs. These tabs allow users to compare attributes such as year built, number of spans, minimum deck elevation, and lowest low-chord elevation for the active bridge set.

When a query is applied, these charts update to summarize only the bridges returned by the query. This allows users to evaluate whether the filtered bridges share common structural or elevation characteristics. For example, the page can help identify whether bridges classified as Vulnerable tend to have lower deck elevations or lower low-chord elevations, or whether a selected county contains bridges with longer span configurations.

This page is useful at the beginning of a review because it provides context for interpreting later hydrodynamic and vulnerability results. The bridge and superstructure attributes shown here are not vulnerability classifications by themselves, but they help explain why some bridges may be more exposed or more susceptible under the evaluated storm and sea level rise scenarios.

6.3.3 Wave & Surge Conditions Page

The Wave & Surge Conditions page presents the hydrodynamic inputs associated with the selected bridges. These values are the environmental conditions used in the superstructure vulnerability assessment. The page focuses on significant wave heights and storm surge elevations for the modeled sea level rise and storm return period combinations.

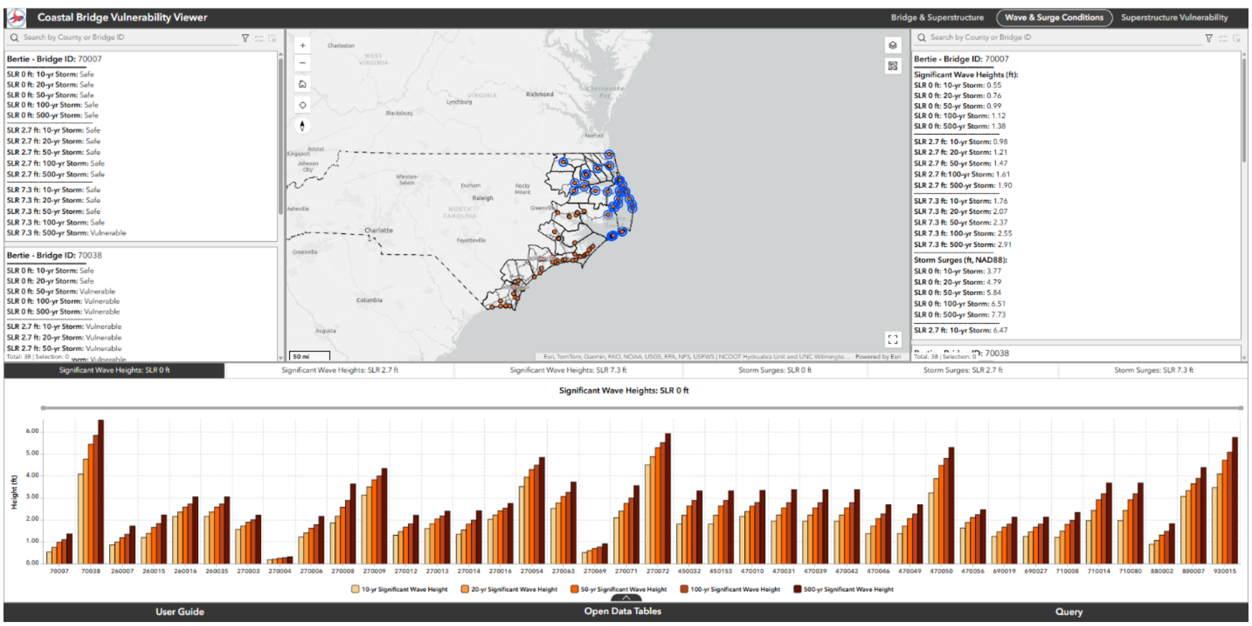

Figure 17. Wave & Surge Conditions page showing significant wave height and storm surge information for the active bridge selection.

Figure 17 shows the Wave & Surge Conditions page. The right panel lists significant wave height and storm surge values for selected bridges. The bottom panel provides chart tabs that summarize significant wave heights and storm surges under the three sea level rise conditions. Within each sea level rise condition, values are shown for the 10-, 20-, 50-, 100-, and 500-year storm return periods.

This page allows users to compare hydrodynamic forcing conditions before reviewing vulnerability classifications. A bridge may be exposed to different combinations of wave height and surge depending on its location and the selected scenario. By presenting the hydrodynamic values separately from the vulnerability results, the dashboard allows users to distinguish the environmental forcing from the structural response. This is useful when comparing bridges across counties or when examining why a bridge is classified as Vulnerable under higher storm return periods or sea level rise conditions.

The hydrodynamic information is also useful for checking the progression of scenario severity. In general, larger storm return periods and higher sea level rise conditions are expected to produce greater hydraulic demand on the bridge superstructure. The charts on this page help users evaluate these trends across the active bridge set rather than reviewing each bridge only in tabular form.

6.3.4 Superstructure Vulnerability Page

The current viewer presents superstructure wave-load vulnerability only; pier, foundation, and scour vulnerability results are not included. The Superstructure Vulnerability page presents the bridge-level Safe or Vulnerable classification and the dominant vulnerability mode of the lowest span, defined as the span with the minimum top-of-deck elevation. The bridge-level classification is based on whether any evaluated span is not Safe. The lowest-span mode is displayed separately to provide span-level information. In the current viewer, a Safe lowest-span result is labeled “No Failure”; this label does not indicate observed performance or guarantee that failure cannot occur. The information shown on this page represents the superstructure wave-load vulnerability assessment and should not be interpreted as a complete evaluation of all bridge hazards or substructure failure mechanisms.

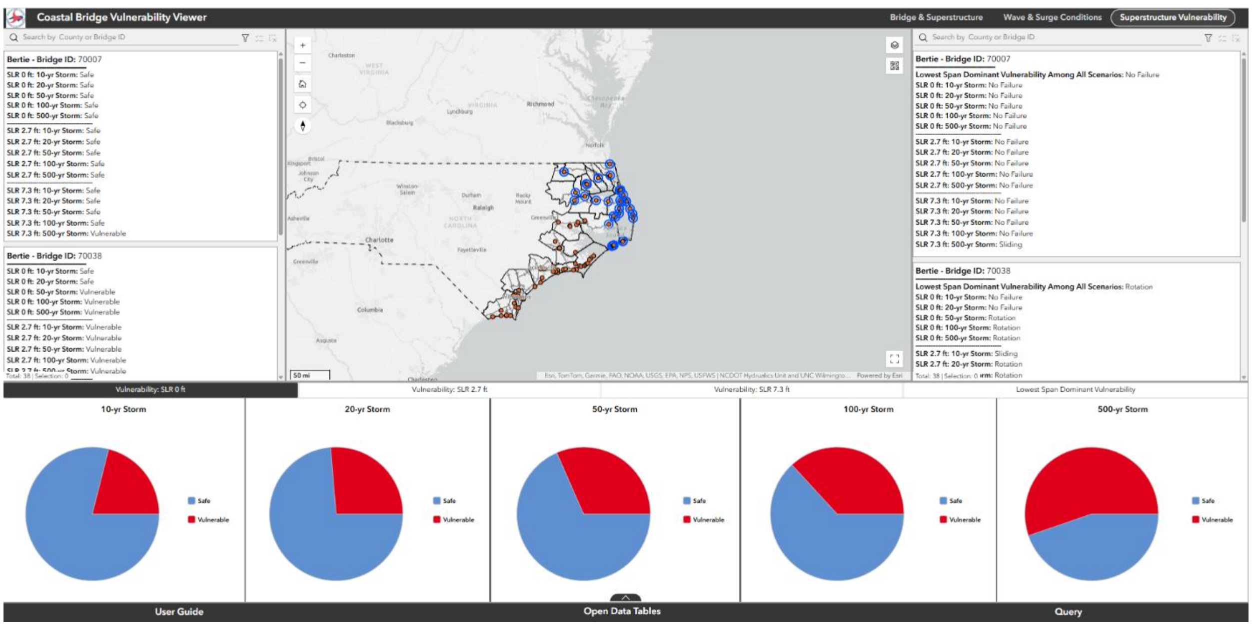

Figure 18. Superstructure Vulnerability page showing bridge-level classifications and the dominant vulnerability mode of the lowest span.

Figure 18 shows the Superstructure Vulnerability page. The left panel lists the bridge-level classification for each of the 15 hydrodynamic scenarios. These scenarios are formed from three sea level rise conditions and five storm return periods. The classification indicates whether the bridge was evaluated as Safe or Vulnerable for the selected scenario. A bridge is classified as Vulnerable when at least one evaluated span meets a vulnerability condition under that scenario.

The right panel displays the dominant vulnerability mode of the lowest span under each scenario. The displayed categories include No Failure, which is equivalent to Safe in the report terminology, Inundated, Uplifting, Sliding, and Rotation. This lowest-span result is supplemental span-level information; the bridge-level Safe or Vulnerable classification remains based on the results of all evaluated spans.

The bottom panel provides summary visualizations for the active bridge set. The vulnerability tabs summarize bridge-level Safe and Vulnerable classifications by storm return period for each sea level rise condition. The lowest-span dominant vulnerability tab summarizes the dominant vulnerability modes among the selected bridges. These charts are particularly useful when the user applies a county, division, priority tier, or scenario filter because they show how vulnerability patterns change for the filtered subset of bridges.

Together, the three dashboard pages provide a sequence for interpreting the assessment results. The Bridge & Superstructure page describes the physical bridge characteristics, the Wave & Surge Conditions page describes the hydrodynamic forcing conditions, and the Superstructure Vulnerability page presents the resulting vulnerability classifications and dominant vulnerability modes. This organization allows users to move from input characteristics to environmental conditions and then to final vulnerability outcomes within a single interactive viewer.

6.3.5 Open Data Tables Function

In addition to the three thematic pages, the dashboard provides an Open Data Tables function in the footer of the viewer. This tool allows users to access the underlying tabular data associated with the selected bridges.

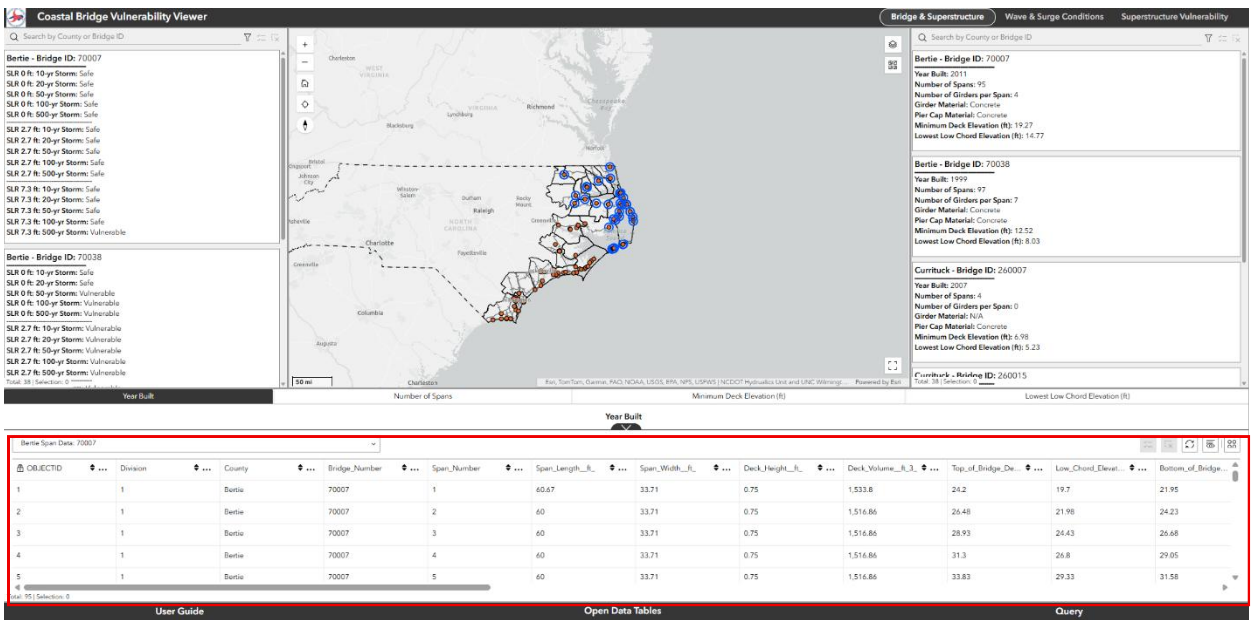

Figure 19. Open Data Tables function used to access bridge-specific span data tables through a dropdown menu.

Figure 19 shows the table panel opened from the dashboard footer. Through the dropdown menu, users can select bridge-specific span data tables and review detailed span-level information, including span identifiers, geometric attributes, elevation values, and scenario-based result fields. Because each bridge-specific table can contain many fields, users may need to scroll horizontally to review the full set of span attributes and scenario-based results. This function is important because the dashboard panels and charts present summarized bridge-level information, while the data tables provide access to the more detailed records used to support those summaries. For example, a user can first identify a bridge as Safe or Vulnerable in the Superstructure Vulnerability page and then open the corresponding span data table to examine the span-level values associated with that bridge. The viewer also includes a User Guide button in the footer, which provides users with documentation for navigating the dashboard, applying queries, interpreting results, and accessing the data tables.

6.4 Dashboard Access and Future Maintenance

The NC Coastal Bridge Vulnerability Viewer was developed as a web-accessible tool so that results could be reviewed without requiring users to open the original engineering spreadsheets or ArcGIS Pro project files. The viewer was hosted through the NCDOT GIS platform using a hosted feature layer, web map, and Experience Builder application. This hosting approach allowed the dashboard to be shared with project stakeholders while maintaining a structured GIS data source behind the application.

Future updates to the dashboard require the engineering results and GIS data sources to remain synchronized. The bridge-level results are stored in the *Selected_Bridges* feature class, while the span-level results are stored in the related span tables. When updated vulnerability calculations are completed, both the bridge-level summary results and the span-level tables must be updated before the existing hosted feature layer is overwritten. Overwriting the existing layer helps preserve the web map and Experience Builder connections while updating the underlying records. The general maintenance workflow is shown in Figure 20.

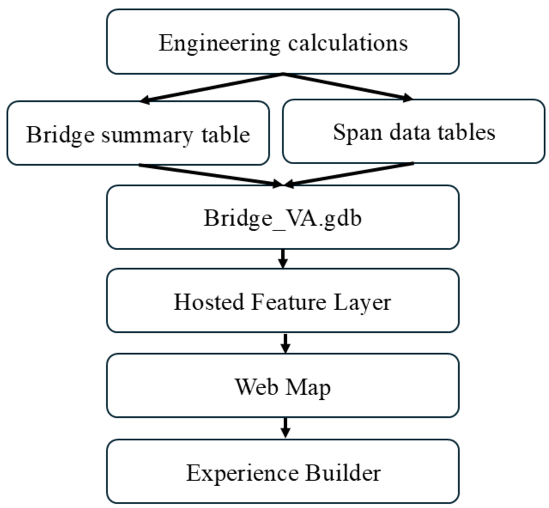

Figure 20. General data maintenance workflow for updating the dashboard with new vulnerability results.

The dashboard was developed to support future use by NCDOT and related stakeholders. Potential future improvements include adding newly screened bridges, incorporating additional hydrodynamic scenarios, linking the viewer to the updated bridge inventory, improving automated data update procedures, and expanding the reporting functions. The current database structure provides a foundation for these updates because it separates bridge-level summary information from detailed span-level results while preserving the relationship between the two datasets.

Chapter 7. Findings, Conclusions, Recommendations, and Implementation

7.1 Findings and Conclusions

This research developed and applied a screening-level framework for evaluating the superstructure vulnerability of selected North Carolina coastal bridges to storm surge, wave loading, and sea level rise. The assessment included 116 Tier 1 and Tier 2 bridges and their individual spans under 15 hydrodynamic scenarios consisting of five storm return periods and three sea level conditions. Structural parameters were obtained from NCDOT records and roadway LiDAR data, hydrodynamic conditions were obtained from the USACE South Atlantic Coastal Study, and wave forces were calculated using the FHWA HEC-25 method. The study also produced the NC Coastal Bridge Vulnerability Viewer to provide access to bridge-level and span-level results.

The principal finding was that sea level rise shifted vulnerability threshold exceedances from rare storms toward more frequent storms. Under the present-day sea level condition, 51 of the 116 assessed bridges were classified as Vulnerable under the 100-year storm, and 60 were classified as Vulnerable under the 500-year storm. For the 100-year storm, the number increased to 68 bridges under 2.73 ft of sea level rise and 83 bridges under 7.35 ft of sea level rise. The 2.73-ft sea level rise 10-year scenario resulted in 52 bridges classified as Vulnerable, approximately equal to the count of 51 bridges classified as Vulnerable under the present-day 100-year scenario. The 7.35-ft sea level rise 10-year scenario resulted in 74 bridges classified as Vulnerable, exceeding the count of 60 classified as Vulnerable under the present-day 500-year scenario. These results demonstrated that increased baseline sea level could cause vulnerability levels associated with rare present-day storms to occur under substantially more frequent future storms.

At the span level, Rotation was the most common force- or moment-based dominant vulnerability mode. The percentage of spans classified as Safe decreased as storm intensity and sea level increased, while Rotation and Inundation became more common. Uplifting was almost never selected as the dominant mode; however, this did not indicate that vertical hydrodynamic forces were unimportant. Vertical force reduced the effective normal force available for frictional resistance, contributed to contact loss, and contributed to the driving moment used in the Rotation assessment.

The bridge-level results also varied substantially across NCDOT divisions and counties. Division 2 had the highest percentage of bridges classified as Vulnerable under the present-day 100-year scenario, whereas Division 1 experienced the largest increase as sea level rose and had the highest percentage under the 7.35-ft sea level rise 100-year scenario. County results similarly showed that some groups of assessed bridges included relatively high percentages classified as Vulnerable under present-day modeled conditions, while others crossed vulnerability thresholds primarily after sea level rise was introduced. The classifications apply only to the selected bridges and represent screening-level threshold exceedances rather than deterministic predictions of bridge damage or collapse. Within that intended use, the study established a repeatable framework and a set of data products that can support future assessment, planning, and research by NCDOT.

7.2 Recommendations

7.2.1 Extend the Assessment to Additional Bridge Tiers

The highest-priority follow-up recommendation is to extend the superstructure vulnerability assessment to bridges not analyzed in the present study. A follow-up study should evaluate the 71 Tier 3 bridges on evacuation routes and the 222 Tier 4 bridges. The existing screening database, tier classifications, structural parameter workflow, SACS station-selection procedure, vulnerability calculation framework, and GIS database structure should be reused to maintain consistency with the Tier 1 and Tier 2 assessment. Before calculations are completed, the follow-up study should confirm that representative hydrodynamic stations and sufficient structural information are available for each bridge. The phased approach would expand geographic and inventory coverage while allowing NCDOT to control the cost and quality of the additional analysis.

7.2.2 Use the Viewer as a Screening and Scoping Resource

The NC Coastal Bridge Vulnerability Viewer should be maintained as a screening and information resource for NCDOT. The viewer can be used to compare the assessed bridges across sea level and storm scenarios, review regional patterns, and access bridge-level and span-level results when planning future research or project-specific studies. The viewer should not be used by itself to determine structural adequacy, establish a design requirement, or predict bridge failure. NCDOT should designate an organizational owner for the hosted feature layers, web map, Experience Builder application, and the supporting calculation files so that access and data continuity are maintained after the project is completed.

Within its screening-level limitations, potential NCDOT applications include supporting bridge replacement evaluations, informing long-range and programmed transportation planning, such as the Comprehensive Transportation Plan (CTP) and State Transportation Improvement Program (STIP), helping prioritize post-storm bridge inspections when the screening classifications are considered together with event-specific information on storm-impacted areas, and identifying bridges for more detailed hydrodynamic and sea level rise analyses.

7.2.3 Conduct an NCDOT Technical Review of the Assessment Method

NCDOT should conduct a technical review to determine how the methods and results from this study may inform future coastal hydraulic guidance or refine the current *Guidelines for Drainage Studies and Hydraulic Design* (2022). As part of this review, NCDOT should evaluate the sensitivity of the results to the use of one representative SACS station per bridge, particularly for the state's longest coastal crossings. A targeted multi-station sensitivity comparison should be completed for selected long coastal crossings before the framework is used to inform bridge-specific design guidance. The review should also consider the use of the current HEC-25 wave-force method, the treatment of effective normal force and contact loss, the Rotation terminology and calculation, the inundation threshold, bridge-tier load factors, and the use of explicit sea level rise scenarios. As a whole, this study was a screening assessment. Because anchorage and connection resistance were not included, the assessment may be conservative with respect to those resistance mechanisms. However, the overall degree of conservatism was not quantified. Any change to NCDOT design requirements informed by this study should follow additional technical review, pilot application, or validation.

7.2.4 Translate the Assessment Method into an Operational Tool

Another follow-up project is recommended to translate the Excel-based vulnerability calculations into an operational coastal bridge screening tool. Two implementation options should be evaluated: a standalone application that accepts forecast surge and wave inputs, or integration of the bridge database and calculation method into NCDOT’s existing FIMAN-T platform (NCDOT, n.d.-a). FIMAN-T already supports real-time and forecast flood information for roads, bridges, and other NCDOT assets. Under either option, the tool would automatically evaluate all spans, identify threshold exceedances and dominant vulnerability modes, and produce a standardized bridge summary as forecasts change. Such a tool could also support storm-response and recovery activities by identifying bridges within an affected area whose screening results indicate greater susceptibility to wave impacts. NCDOT could use this information to help prioritize post-event bridge inspections, while recognizing that the screening classification does not indicate that damage actually occurred during the event. A feasibility study should compare system integration, maintenance, data ownership, user access, and long-term support before selecting the preferred approach.

7.3 Implementation and Technology Transfer Plan

Implementation of this research should focus on preserving the completed project products, maintaining access to the vulnerability results, extending the assessment to additional bridge tiers, and supporting development of an operational coastal bridge screening tool.

7.3.1 Research Products and Implementation Actions

The primary research products, intended users, and proposed implementation actions are summarized in Table 10.

Table 10. Research products, intended NCDOT users, and proposed implementation actions.

Research products	Intended NCDOT users	Proposed uses	Next implementation actions
Bridge screening and tier database for the 20 coastal counties	Hydraulics Unit, Structures Management Unit, and Research and Development Unit	Support selection and scoping of bridges for future coastal vulnerability studies	Archive the final database, tier definitions, screening criteria, and data dictionary in an NCDOT-controlled location
Bridge- and span-level structural data and vulnerability calculation method	Hydraulics Unit, Structures Management Unit, and future research teams	Reproduce the assessment, evaluate additional bridge tiers, and support development of an operational screening tool	Transfer the calculation files, assumptions, quality-control procedures, and workflow documentation
NC Coastal Bridge Vulnerability Viewer and supporting GIS database	Hydraulics Unit, Structures Management Unit, Transportation Planning staff, GIS staff, and NCDOT Divisions 1, 2, and 3	Support screening for bridge replacement evaluations and project scoping; provide screening-level vulnerability information to inform CTP and STIP processes; prioritize bridges for post-event inspection in storm-impacted areas; and identify bridges that warrant more detailed hydrodynamic and sea level rise evaluation.	Assign an organizational owner, maintain hosted layers and user permissions, document the data-update process, and develop user guidance for applying the results to screening, planning, and post-event inspection prioritization.
State, division, and county wide result tables and bridge vulnerability maps	NCDOT technical, planning, research, and resilience staff	Review and communicate statewide and regional vulnerability patterns	Retain accessible final versions with the project archive and link them to the viewer or other NCDOT data resources

7.3.2 Training and Technology Transfer

Implementation should include a technical handoff to the NCDOT units responsible for maintaining and using the project products. The handoff should address the bridge and span database, calculation files, scenario definitions, GIS data structure, viewer administration, update procedures, and limitations of the screening classifications. A brief user demonstration and written guidance should also be provided for the NC Coastal Bridge Vulnerability Viewer.

Technology-transfer activities may include briefings for the Steering and Implementation Committee and NCDOT Divisions 1, 2, and 3; presentations for the Hydraulics, Structures, GIS, Research, and Resilience staff; conference presentations; and technical publications. These activities should clearly describe the results as screening-level classifications for the selected bridges rather than predictions of bridge damage or collapse.

Implementation costs would primarily consist of staff or consultant time for product transfer, documentation, training, data maintenance, follow-up assessment of additional bridge tiers, and development or integration of an operational tool. The principal benefit is the reuse of the bridge database, calculation framework, and GIS structure developed through this project. Reuse of these products would reduce repeated data collection and method-development effort, promote consistent evaluation of additional bridges, provide a foundation for more rapid bridge-specific screening during future coastal storm events, and could support improvements in coastal transportation resilience.

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Appendix A. State, NCDOT Division, and County-Level Bridge Vulnerability Statistics

Appendix A presents the complete bridge-level and span-level vulnerability statistics for the 116 Tier 1 and Tier 2 bridges evaluated in this study. Results are provided for all 15 hydrodynamic scenarios, consisting of the 10-, 20-, 50-, 100-, and 500-year storms under three sea level conditions. SLR0 represents present-day sea level, SLR1 incorporates 2.73 ft of sea level rise, and SLR2 incorporates 7.35 ft of sea level rise.

The results are organized at three geographic levels: statewide, NCDOT division, and individual county. The bridge-level tables report the numbers of bridges classified as Safe and Vulnerable. A bridge was classified as Vulnerable when at least one evaluated span was assigned a dominant vulnerability mode other than Safe. A bridge was classified as Safe only when all evaluated spans were classified as Safe.

The span-level tables report the percentage of evaluated spans assigned to each dominant vulnerability mode. Each span was assigned one classification of Safe, Rotation, Sliding, Uplifting, or Inundated under each hydrodynamic scenario using the procedure described in Section 5.4. Inundated spans were further separated into inundation depths of 1 to 3 ft, 3 to 5 ft, and greater than 5 ft. Percentages may not sum to exactly 100 percent because of rounding.

These results apply only to the 116 bridges selected for this study and should not be interpreted as statistics for the complete bridge inventory within a division or county. A Vulnerable classification represents a screening-level threshold exceedance under the evaluated scenario and does not constitute a prediction of bridge damage or collapse.

A.1. Statewide Results

The statewide results include all 116 assessed bridges and their evaluated spans. Table A-1 presents the number of bridges classified as Safe and Vulnerable under each of the 15 hydrodynamic scenarios. Table A-2 presents the corresponding percentages of dominant span vulnerability modes. These tables provide complete statewide results supporting the selected comparisons presented in Section 5.5.

Table A-1. Statewide number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	102	14
SLR0 20 yr	91	25
SLR0 50 yr	75	41
SLR0 100 yr	65	51
SLR0 500 yr	56	60
SLR1 10 yr	64	52
SLR1 20 yr	56	60
SLR1 50 yr	52	64
SLR1 100 yr	48	68
SLR1 500 yr	42	74
SLR2 10 yr	42	74
SLR2 20 yr	38	78
SLR2 50 yr	34	82
SLR2 100 yr	33	83
SLR2 500 yr	30	86

Table A-2. Statewide percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.84	0.28	0.00	0.00	0.00	0.00	98.89
SLR0 20 yr	2.69	0.35	0.00	0.00	0.00	0.00	96.96
SLR0 50 yr	5.71	0.39	0.00	0.30	0.00	0.00	93.60
SLR0 100 yr	7.33	0.67	0.00	0.53	0.07	0.00	91.39
SLR0 500 yr	9.81	0.65	0.00	1.39	0.49	0.09	87.56
SLR1 10 yr	6.03	0.53	0.00	0.37	0.00	0.07	92.99
SLR1 20 yr	9.12	0.56	0.00	0.70	0.19	0.07	89.37
SLR1 50 yr	9.98	0.44	0.00	2.04	0.51	0.14	86.89
SLR1 100 yr	10.14	0.46	0.00	2.90	0.79	0.37	85.34
SLR1 500 yr	12.30	0.56	0.00	3.29	2.51	1.07	80.28
SLR2 10 yr	17.03	0.93	0.00	7.63	2.74	1.11	70.56
SLR2 20 yr	25.36	1.16	0.00	7.91	3.55	2.11	59.91
SLR2 50 yr	26.47	11.28	0.00	6.59	4.22	4.45	46.98
SLR2 100 yr	37.38	5.20	0.00	5.82	4.34	6.13	41.14
SLR2 500 yr	42.13	0.84	0.02	5.45	3.53	8.96	39.07

A.2. NCDOT Division-Level Results

The division-level tables present results separately for the three NCDOT divisions containing the assessed bridges. The study included 38 bridges in Division 1, 36 bridges in Division 2, and 42 bridges in Division 3. For each division, the first table reports bridge-level Safe and Vulnerable counts, and the second table reports the distribution of dominant vulnerability modes among the evaluated spans.

Differences between divisions should be interpreted in relation to the number and characteristics of the selected bridges within each division. The results do not represent an assessment of every bridge maintained within the divisions.

Table A-3. Division 1 number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	30	8
SLR0 20 yr	28	10
SLR0 50 yr	26	12
SLR0 100 yr	24	14
SLR0 500 yr	17	21
SLR1 10 yr	16	22
SLR1 20 yr	15	23
SLR1 50 yr	12	26
SLR1 100 yr	12	26
SLR1 500 yr	10	28
SLR2 10 yr	6	32
SLR2 20 yr	5	33
SLR2 50 yr	4	34
SLR2 100 yr	4	34
SLR2 500 yr	3	35

Table A-4. Division 1 percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.65	0.34	0.00	0.00	0.00	0.00	99.01
SLR0 20 yr	1.44	0.08	0.00	0.00	0.00	0.00	98.48
SLR0 50 yr	1.82	0.19	0.00	0.00	0.00	0.00	97.99
SLR0 100 yr	2.39	0.30	0.00	0.00	0.00	0.00	97.30
SLR0 500 yr	4.26	0.19	0.00	0.15	0.00	0.00	95.40
SLR1 10 yr	3.95	0.23	0.00	0.15	0.00	0.11	95.55
SLR1 20 yr	4.90	0.11	0.00	0.15	0.00	0.11	94.72
SLR1 50 yr	5.51	0.15	0.00	0.46	0.00	0.11	93.77
SLR1 100 yr	5.66	0.23	0.00	0.49	0.11	0.11	93.39
SLR1 500 yr	10.87	0.27	0.00	0.80	0.11	0.11	87.84
SLR2 10 yr	19.84	0.87	0.00	7.26	1.75	0.99	69.29
SLR2 20 yr	34.70	0.99	0.00	7.34	1.52	1.37	54.09
SLR2 50 yr	36.41	17.60	0.00	7.03	1.79	1.86	35.31
SLR2 100 yr	54.50	8.02	0.00	6.54	2.17	2.13	26.64
SLR2 500 yr	63.06	0.61	0.04	6.46	2.32	2.58	24.93

Table A-5. Division 2 number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	33	3
SLR0 20 yr	27	9
SLR0 50 yr	17	19
SLR0 100 yr	11	25
SLR0 500 yr	10	26
SLR1 10 yr	17	19
SLR1 20 yr	11	25
SLR1 50 yr	11	25
SLR1 100 yr	9	27
SLR1 500 yr	7	29
SLR2 10 yr	8	28
SLR2 20 yr	8	28
SLR2 50 yr	6	30
SLR2 100 yr	5	31
SLR2 500 yr	5	31

Table A-6. Division 2 percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	1.05	0.23	0.00	0.00	0.00	0.00	98.71
SLR0 20 yr	4.32	0.93	0.00	0.00	0.00	0.00	94.74
SLR0 50 yr	12.50	1.17	0.00	0.47	0.00	0.00	85.86
SLR0 100 yr	17.52	1.99	0.00	1.05	0.00	0.00	79.44
SLR0 500 yr	25.23	2.34	0.00	2.22	0.70	0.00	69.51
SLR1 10 yr	10.16	1.75	0.00	0.35	0.00	0.00	87.73
SLR1 20 yr	16.94	2.34	0.00	1.87	0.23	0.00	78.62
SLR1 50 yr	21.61	1.52	0.00	5.26	1.05	0.00	70.56
SLR1 100 yr	24.07	1.40	0.00	6.66	2.10	0.47	65.30
SLR1 500 yr	22.31	1.64	0.00	8.18	6.78	2.22	58.88
SLR2 10 yr	18.34	1.75	0.00	7.71	5.96	1.29	64.95
SLR2 20 yr	16.94	2.22	0.00	9.93	7.24	4.21	59.46
SLR2 50 yr	17.17	2.34	0.00	8.29	9.23	9.70	53.27
SLR2 100 yr	17.06	0.93	0.00	7.24	9.58	14.02	51.17
SLR2 500 yr	14.49	1.29	0.00	6.43	7.48	22.90	47.43

Table A-7. Division 3 number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	39	3
SLR0 20 yr	36	6
SLR0 50 yr	32	10
SLR0 100 yr	30	12
SLR0 500 yr	29	13
SLR1 10 yr	31	11
SLR1 20 yr	30	12
SLR1 50 yr	29	13
SLR1 100 yr	27	15
SLR1 500 yr	25	17
SLR2 10 yr	28	14
SLR2 20 yr	25	17
SLR2 50 yr	24	18
SLR2 100 yr	24	18
SLR2 500 yr	22	20

Table A-8. Division 3 percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	1.22	0.12	0.00	0.00	0.00	0.00	98.66
SLR0 20 yr	4.98	0.61	0.00	0.00	0.00	0.00	94.41
SLR0 50 yr	11.06	0.24	0.00	1.09	0.00	0.00	87.61
SLR0 100 yr	12.52	0.49	0.00	1.70	0.36	0.00	84.93
SLR0 500 yr	11.54	0.36	0.00	4.50	1.82	0.49	81.29
SLR1 10 yr	8.38	0.24	0.00	1.09	0.00	0.00	90.28
SLR1 20 yr	14.46	0.12	0.00	1.22	0.73	0.00	83.48
SLR1 50 yr	12.15	0.24	0.00	3.77	1.58	0.36	81.90
SLR1 100 yr	9.96	0.24	0.00	6.68	1.58	1.09	80.44
SLR1 500 yr	6.44	0.36	0.00	6.20	5.71	2.92	78.37
SLR2 10 yr	6.68	0.24	0.00	8.75	2.55	1.34	80.44
SLR2 20 yr	4.25	0.61	0.00	7.65	6.20	2.31	78.98
SLR2 50 yr	4.37	0.36	0.00	3.40	6.80	7.29	77.76
SLR2 100 yr	3.77	0.61	0.00	2.07	5.83	10.69	77.04
SLR2 500 yr	4.01	1.09	0.00	1.22	3.28	14.82	75.58

A.3. County-Level Results

County-level results are presented for each coastal county containing at least one of the 116 bridges selected for the vulnerability assessment. For each county, the first table reports bridge-level Safe and Vulnerable counts under the 15 hydrodynamic scenarios, and the second table reports the percentages of dominant span vulnerability modes.

The number of assessed bridges varied substantially among counties. Consequently, county results based on one or only a few assessed bridges should be interpreted cautiously. A change in the classification of one bridge may represent a large percentage of the county sample. The county-level results apply only to the selected Tier 1 and Tier 2 bridges and should not be interpreted as countywide bridge-inventory vulnerability rates.

Camden, Chowan, and Gates Counties are not presented because no bridges within those counties were included in the final Tier 1 and Tier 2 assessment dataset.

County – Beaufort

Table A-9. Beaufort County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	5	1
SLR0 20 yr	4	2
SLR0 50 yr	1	5
SLR0 100 yr	1	5
SLR0 500 yr	1	5
SLR1 10 yr	1	5
SLR1 20 yr	1	5
SLR1 50 yr	1	5
SLR1 100 yr	0	6
SLR1 500 yr	0	6
SLR2 10 yr	0	6
SLR2 20 yr	0	6
SLR2 50 yr	0	6
SLR2 100 yr	0	6
SLR2 500 yr	0	6

Table A-10. Beaufort County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	4.17	0.60	0.00	0.00	0.00	0.00	95.24
SLR0 20 yr	11.90	1.19	0.00	0.00	0.00	0.00	86.90
SLR0 50 yr	28.57	2.38	0.00	1.19	0.00	0.00	67.86
SLR0 100 yr	39.29	2.98	0.00	4.17	0.00	0.00	53.57
SLR0 500 yr	55.36	4.76	0.00	6.55	2.38	0.00	30.95
SLR1 10 yr	23.81	2.38	0.00	0.60	0.00	0.00	73.21
SLR1 20 yr	40.48	4.76	0.00	5.95	0.00	0.00	48.81
SLR1 50 yr	52.98	2.38	0.00	9.52	4.17	0.00	30.95
SLR1 100 yr	58.33	2.38	0.00	13.69	5.36	1.19	19.05
SLR1 500 yr	50.00	1.19	0.00	21.43	10.12	6.55	10.71
SLR2 10 yr	42.86	1.79	0.00	19.64	13.10	5.36	17.26
SLR2 20 yr	30.95	1.79	0.00	23.81	18.45	13.69	11.31
SLR2 50 yr	25.60	1.79	0.00	19.64	22.02	27.98	2.98
SLR2 100 yr	20.83	1.79	0.00	15.48	24.40	36.90	0.60
SLR2 500 yr	17.26	0.00	0.00	6.55	16.67	59.52	0.00

County – Bertie

Table A-11. Bertie County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	2	0
SLR0 20 yr	2	0
SLR0 50 yr	1	1
SLR0 100 yr	1	1
SLR0 500 yr	1	1
SLR1 10 yr	1	1
SLR1 20 yr	1	1
SLR1 50 yr	1	1
SLR1 100 yr	1	1
SLR1 500 yr	1	1
SLR2 10 yr	1	1
SLR2 20 yr	1	1
SLR2 50 yr	1	1
SLR2 100 yr	1	1
SLR2 500 yr	0	2

Table A-12. Bertie County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	0.52	0.52	0.00	0.00	0.00	0.00	98.96
SLR0 100 yr	1.04	0.52	0.00	0.00	0.00	0.00	98.44
SLR0 500 yr	2.60	0.00	0.00	0.00	0.00	0.00	97.40
SLR1 10 yr	0.00	0.52	0.00	0.00	0.00	0.00	99.48
SLR1 20 yr	1.04	0.00	0.00	0.00	0.00	0.00	98.96
SLR1 50 yr	2.60	0.00	0.00	0.00	0.00	0.00	97.40
SLR1 100 yr	2.60	0.52	0.00	0.00	0.00	0.00	96.88
SLR1 500 yr	4.17	0.00	0.00	0.00	0.00	0.00	95.83
SLR2 10 yr	3.65	0.00	0.00	0.00	0.00	0.00	96.35
SLR2 20 yr	4.17	0.00	0.00	0.00	0.00	0.00	95.83
SLR2 50 yr	5.73	1.04	0.00	0.52	0.00	0.00	92.71
SLR2 100 yr	7.81	0.52	0.00	0.52	0.00	0.00	91.15
SLR2 500 yr	13.54	4.17	0.52	1.04	0.00	0.00	80.73

County – Brunswick

Table A-13. Brunswick County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	8	1
SLR0 20 yr	8	1
SLR0 50 yr	7	2
SLR0 100 yr	6	3
SLR0 500 yr	6	3
SLR1 10 yr	7	2
SLR1 20 yr	6	3
SLR1 50 yr	6	3
SLR1 100 yr	5	4
SLR1 500 yr	3	6
SLR2 10 yr	5	4
SLR2 20 yr	3	6
SLR2 50 yr	3	6
SLR2 100 yr	3	6
SLR2 500 yr	3	6

Table A-14. Brunswick County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	3.65	0.00	0.00	0.00	0.00	0.00	96.35
SLR0 20 yr	3.65	0.00	0.00	0.00	0.00	0.00	96.35
SLR0 50 yr	8.76	0.00	0.00	3.65	0.00	0.00	87.59
SLR0 100 yr	17.52	2.19	0.00	3.65	0.00	0.00	76.64
SLR0 500 yr	25.55	0.00	0.00	0.00	3.65	0.00	70.80
SLR1 10 yr	7.30	0.00	0.00	3.65	0.00	0.00	89.05
SLR1 20 yr	21.90	0.00	0.00	0.00	3.65	0.00	74.45
SLR1 50 yr	24.82	0.73	0.00	0.00	1.46	2.19	70.80
SLR1 100 yr	29.20	0.73	0.00	0.00	0.00	3.65	66.42
SLR1 500 yr	22.63	0.00	0.00	13.14	0.00	3.65	60.58
SLR2 10 yr	15.33	0.73	0.00	13.87	0.00	3.65	66.42
SLR2 20 yr	9.49	1.46	0.00	21.90	1.46	3.65	62.04
SLR2 50 yr	8.76	0.00	0.00	14.60	13.14	3.65	59.85
SLR2 100 yr	5.11	0.73	0.00	8.03	21.90	5.11	59.12
SLR2 500 yr	5.11	0.73	0.00	2.92	16.06	16.79	58.39

County – Carteret

Table A-15. Carteret County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	17	1
SLR0 20 yr	12	6
SLR0 50 yr	7	11
SLR0 100 yr	3	15
SLR0 500 yr	2	16
SLR1 10 yr	7	11
SLR1 20 yr	3	15
SLR1 50 yr	3	15
SLR1 100 yr	2	16
SLR1 500 yr	2	16
SLR2 10 yr	2	16
SLR2 20 yr	2	16
SLR2 50 yr	2	16
SLR2 100 yr	2	16
SLR2 500 yr	2	16

Table A-16. Carteret County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.54	0.00	0.00	0.00	0.00	0.00	99.46
SLR0 20 yr	3.81	1.63	0.00	0.00	0.00	0.00	94.55
SLR0 50 yr	14.71	1.36	0.00	0.54	0.00	0.00	83.38
SLR0 100 yr	20.71	1.91	0.00	0.54	0.00	0.00	76.84
SLR0 500 yr	28.07	2.45	0.00	1.36	0.54	0.00	67.57
SLR1 10 yr	11.99	2.18	0.00	0.54	0.00	0.00	85.29
SLR1 20 yr	19.62	1.91	0.00	1.36	0.54	0.00	76.57
SLR1 50 yr	21.80	1.63	0.00	7.08	0.54	0.00	68.94
SLR1 100 yr	23.16	1.36	0.00	8.72	2.18	0.54	64.03
SLR1 500 yr	20.16	0.82	0.00	8.72	10.63	1.91	57.77
SLR2 10 yr	17.71	2.18	0.00	8.72	7.08	0.54	63.76
SLR2 20 yr	16.89	3.00	0.00	11.17	7.90	3.00	58.04
SLR2 50 yr	15.80	0.82	0.00	7.36	10.63	8.99	56.40
SLR2 100 yr	14.44	0.00	0.00	6.54	9.26	14.71	55.04
SLR2 500 yr	9.54	0.82	0.00	7.63	6.54	23.43	52.04

County – Craven

Table A-17. Craven County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	10	1
SLR0 20 yr	10	1
SLR0 50 yr	8	3
SLR0 100 yr	6	5
SLR0 500 yr	6	5
SLR1 10 yr	8	3
SLR1 20 yr	6	5
SLR1 50 yr	6	5
SLR1 100 yr	6	5
SLR1 500 yr	4	7
SLR2 10 yr	5	6
SLR2 20 yr	5	6
SLR2 50 yr	4	7
SLR2 100 yr	3	8
SLR2 500 yr	3	8

Table A-18. Craven County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.34	0.00	0.00	0.00	0.00	99.66
SLR0 20 yr	1.01	0.00	0.00	0.00	0.00	0.00	98.99
SLR0 50 yr	1.68	0.34	0.00	0.00	0.00	0.00	97.98
SLR0 100 yr	2.69	1.68	0.00	0.00	0.00	0.00	95.62
SLR0 500 yr	6.73	1.01	0.00	1.01	0.00	0.00	91.25
SLR1 10 yr	1.01	1.01	0.00	0.00	0.00	0.00	97.98
SLR1 20 yr	1.68	1.68	0.00	0.34	0.00	0.00	96.30
SLR1 50 yr	5.39	1.01	0.00	1.01	0.00	0.00	92.59
SLR1 100 yr	7.74	1.01	0.00	0.67	0.34	0.00	90.24
SLR1 500 yr	11.11	3.03	0.00	0.67	0.67	0.34	84.18
SLR2 10 yr	6.73	1.35	0.00	0.34	1.01	0.00	90.57
SLR2 20 yr	10.44	1.68	0.00	1.35	0.67	0.67	85.19
SLR2 50 yr	15.49	4.38	0.00	3.70	1.01	1.01	74.41
SLR2 100 yr	19.19	1.68	0.00	4.04	2.36	1.35	71.38
SLR2 500 yr	19.19	2.69	0.00	5.39	4.04	3.37	65.32

County – Currituck

Table A-19. Currituck County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	4	0
SLR0 20 yr	4	0
SLR0 50 yr	4	0
SLR0 100 yr	4	0
SLR0 500 yr	4	0
SLR1 10 yr	3	1
SLR1 20 yr	3	1
SLR1 50 yr	2	2
SLR1 100 yr	2	2
SLR1 500 yr	1	3
SLR2 10 yr	1	3
SLR2 20 yr	1	3
SLR2 50 yr	1	3
SLR2 100 yr	1	3
SLR2 500 yr	1	3

Table A-20. Currituck County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 100 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 500 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 10 yr	0.19	0.00	0.00	0.00	0.00	0.00	99.81
SLR1 20 yr	0.76	0.00	0.00	0.00	0.00	0.00	99.24
SLR1 50 yr	0.76	0.19	0.00	0.00	0.00	0.00	99.05
SLR1 100 yr	0.95	0.00	0.00	0.00	0.00	0.00	99.05
SLR1 500 yr	1.14	0.95	0.00	0.00	0.00	0.00	97.92
SLR2 10 yr	4.73	0.76	0.00	0.00	0.76	0.00	93.75
SLR2 20 yr	5.87	0.38	0.00	0.00	0.57	0.19	92.99
SLR2 50 yr	7.01	71.40	0.00	0.19	0.00	0.76	20.64
SLR2 100 yr	78.79	0.38	0.00	0.19	0.00	0.76	19.89
SLR2 500 yr	79.36	0.76	0.00	0.76	0.00	0.76	18.37

County – Dare

Table A-21. Dare County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	9	5
SLR0 20 yr	9	5
SLR0 50 yr	9	5
SLR0 100 yr	8	6
SLR0 500 yr	7	7
SLR1 10 yr	6	8
SLR1 20 yr	6	8
SLR1 50 yr	4	10
SLR1 100 yr	4	10
SLR1 500 yr	4	10
SLR2 10 yr	1	13
SLR2 20 yr	1	13
SLR2 50 yr	0	14
SLR2 100 yr	0	14
SLR2 500 yr	0	14

Table A-22. Dare County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.54	0.86	0.00	0.00	0.00	0.00	98.59
SLR0 20 yr	1.73	0.00	0.00	0.00	0.00	0.00	98.27
SLR0 50 yr	1.73	0.22	0.00	0.00	0.00	0.00	98.05
SLR0 100 yr	1.95	0.22	0.00	0.00	0.00	0.00	97.84
SLR0 500 yr	3.35	0.32	0.00	0.11	0.00	0.00	96.22
SLR1 10 yr	3.46	0.32	0.00	0.11	0.00	0.32	95.78
SLR1 20 yr	3.78	0.00	0.00	0.11	0.00	0.32	95.78
SLR1 50 yr	4.86	0.11	0.00	0.22	0.00	0.32	94.49
SLR1 100 yr	4.97	0.00	0.00	0.43	0.00	0.32	94.27
SLR1 500 yr	18.16	0.00	0.00	0.76	0.00	0.32	80.76
SLR2 10 yr	46.38	1.51	0.00	15.57	1.73	1.41	33.41
SLR2 20 yr	47.57	2.16	0.00	15.78	1.62	1.62	31.24
SLR2 50 yr	49.84	0.97	0.00	15.24	1.62	2.16	30.16
SLR2 100 yr	50.81	0.43	0.00	14.81	1.73	2.49	29.73
SLR2 500 yr	51.57	0.22	0.00	14.92	1.51	2.70	29.08

County – Hertford

Table A-23. Hertford County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	2	0
SLR0 20 yr	2	0
SLR0 50 yr	2	0
SLR0 100 yr	2	0
SLR0 500 yr	2	0
SLR1 10 yr	2	0
SLR1 20 yr	2	0
SLR1 50 yr	2	0
SLR1 100 yr	2	0
SLR1 500 yr	2	0
SLR2 10 yr	2	0
SLR2 20 yr	2	0
SLR2 50 yr	2	0
SLR2 100 yr	2	0
SLR2 500 yr	2	0

Table A-24. Hertford County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0	0	0	0	0	0	100
SLR0 20 yr	0	0	0	0	0	0	100
SLR0 50 yr	0	0	0	0	0	0	100
SLR0 100 yr	0	0	0	0	0	0	100
SLR0 500 yr	0	0	0	0	0	0	100
SLR1 10 yr	0	0	0	0	0	0	100
SLR1 20 yr	0	0	0	0	0	0	100
SLR1 50 yr	0	0	0	0	0	0	100
SLR1 100 yr	0	0	0	0	0	0	100
SLR1 500 yr	0	0	0	0	0	0	100
SLR2 10 yr	0	0	0	0	0	0	100
SLR2 20 yr	0	0	0	0	0	0	100
SLR2 50 yr	0	0	0	0	0	0	100
SLR2 100 yr	0	0	0	0	0	0	100
SLR2 500 yr	0	0	0	0	0	0	100

County – Hyde

Table A-25. Hyde County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	6	2
SLR0 20 yr	6	2
SLR0 50 yr	6	2
SLR0 100 yr	6	2
SLR0 500 yr	0	8
SLR1 10 yr	0	8
SLR1 20 yr	0	8
SLR1 50 yr	0	8
SLR1 100 yr	0	8
SLR1 500 yr	0	8
SLR2 10 yr	0	8
SLR2 20 yr	0	8
SLR2 50 yr	0	8
SLR2 100 yr	0	8
SLR2 500 yr	0	8

Table A-26. Hyde County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	20.00	0.00	0.00	0.00	0.00	0.00	80.00
SLR0 20 yr	20.00	0.00	0.00	0.00	0.00	0.00	80.00
SLR0 50 yr	20.00	0.00	0.00	0.00	0.00	0.00	80.00
SLR0 100 yr	20.00	0.00	0.00	0.00	0.00	0.00	80.00
SLR0 500 yr	80.00	0.00	0.00	12.00	0.00	0.00	8.00
SLR1 10 yr	88.00	0.00	0.00	12.00	0.00	0.00	0.00
SLR1 20 yr	88.00	0.00	0.00	12.00	0.00	0.00	0.00
SLR1 50 yr	88.00	0.00	0.00	12.00	0.00	0.00	0.00
SLR1 100 yr	88.00	0.00	0.00	0.00	12.00	0.00	0.00
SLR1 500 yr	80.00	0.00	0.00	8.00	12.00	0.00	0.00
SLR2 10 yr	0.00	0.00	0.00	80.00	8.00	12.00	0.00
SLR2 20 yr	0.00	0.00	0.00	80.00	0.00	20.00	0.00
SLR2 50 yr	0.00	0.00	0.00	68.00	12.00	20.00	0.00
SLR2 100 yr	0.00	0.00	0.00	32.00	48.00	20.00	0.00
SLR2 500 yr	0.00	0.00	0.00	0.00	80.00	20.00	0.00

County – New Hanover

Table A-27. New Hanover County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	22	2
SLR0 20 yr	20	4
SLR0 50 yr	20	4
SLR0 100 yr	20	4
SLR0 500 yr	19	5
SLR1 10 yr	20	4
SLR1 20 yr	20	4
SLR1 50 yr	19	5
SLR1 100 yr	19	5
SLR1 500 yr	19	5
SLR2 10 yr	19	5
SLR2 20 yr	19	5
SLR2 50 yr	19	5
SLR2 100 yr	19	5
SLR2 500 yr	17	7

Table A-28. New Hanover County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.96	0.19	0.00	0.00	0.00	0.00	98.84
SLR0 20 yr	6.55	0.19	0.00	0.00	0.00	0.00	93.26
SLR0 50 yr	8.29	0.39	0.00	0.77	0.00	0.00	90.56
SLR0 100 yr	7.71	0.00	0.00	1.73	0.58	0.00	89.98
SLR0 500 yr	1.93	0.00	0.00	5.78	1.93	0.77	89.60
SLR1 10 yr	7.90	0.00	0.00	0.77	0.00	0.00	91.33
SLR1 20 yr	7.90	0.00	0.00	1.93	0.19	0.00	89.98
SLR1 50 yr	2.50	0.00	0.00	5.59	2.12	0.00	89.79
SLR1 100 yr	1.73	0.00	0.00	5.39	2.50	0.77	89.60
SLR1 500 yr	1.16	0.00	0.00	1.35	5.01	3.66	88.82
SLR2 10 yr	1.54	0.00	0.00	4.82	2.89	1.16	89.60
SLR2 20 yr	1.35	0.00	0.00	1.35	5.39	2.70	89.21
SLR2 50 yr	1.54	0.00	0.00	0.96	1.35	7.71	88.44
SLR2 100 yr	1.93	0.19	0.00	0.19	1.35	8.67	87.67
SLR2 500 yr	2.50	0.77	0.00	0.19	0.19	10.02	86.32

County – Onslow

Table A-29. Onslow County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	8	0
SLR0 20 yr	7	1
SLR0 50 yr	5	3
SLR0 100 yr	4	4
SLR0 500 yr	4	4
SLR1 10 yr	4	4
SLR1 20 yr	4	4
SLR1 50 yr	4	4
SLR1 100 yr	3	5
SLR1 500 yr	3	5
SLR2 10 yr	4	4
SLR2 20 yr	3	5
SLR2 50 yr	2	6
SLR2 100 yr	2	6
SLR2 500 yr	2	6

Table A-30. Onslow County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	1.45	2.90	0.00	0.00	0.00	0.00	95.65
SLR0 50 yr	25.36	0.00	0.00	0.00	0.00	0.00	74.64
SLR0 100 yr	27.54	0.00	0.00	0.00	0.00	0.00	72.46
SLR0 500 yr	34.06	2.17	0.00	4.35	0.00	0.00	59.42
SLR1 10 yr	12.32	1.45	0.00	0.00	0.00	0.00	86.23
SLR1 20 yr	33.33	0.72	0.00	0.00	0.00	0.00	65.94
SLR1 50 yr	35.51	0.72	0.00	1.45	0.00	0.00	62.32
SLR1 100 yr	21.74	0.72	0.00	18.84	0.00	0.00	58.70
SLR1 500 yr	9.42	0.72	0.00	18.12	14.49	0.00	57.25
SLR2 10 yr	16.67	0.00	0.00	19.57	4.35	0.00	59.42
SLR2 20 yr	8.70	0.72	0.00	18.12	14.49	0.00	57.97
SLR2 50 yr	8.70	0.72	0.00	1.45	21.74	10.87	56.52
SLR2 100 yr	7.97	1.45	0.00	2.17	7.25	25.36	55.80
SLR2 500 yr	6.52	1.45	0.00	3.62	1.45	32.61	54.35

County – Pamlico

Table A-31. Pamlico County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	1	0
SLR0 20 yr	1	0
SLR0 50 yr	1	0
SLR0 100 yr	1	0
SLR0 500 yr	1	0
SLR1 10 yr	1	0
SLR1 20 yr	1	0
SLR1 50 yr	1	0
SLR1 100 yr	1	0
SLR1 500 yr	1	0
SLR2 10 yr	1	0
SLR2 20 yr	1	0
SLR2 50 yr	0	1
SLR2 100 yr	0	1
SLR2 500 yr	0	1

Table A-32. Pamlico County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 100 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 500 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 50 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 100 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 500 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR2 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR2 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR2 50 yr	0.00	4.17	0.00	0.00	0.00	0.00	95.83
SLR2 100 yr	4.17	0.00	0.00	0.00	0.00	0.00	95.83
SLR2 500 yr	12.50	0.00	0.00	0.00	0.00	0.00	87.50

County – Pasquotank

Table A-33. Pasquotank County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	2	0
SLR0 20 yr	0	2
SLR0 50 yr	0	2
SLR0 100 yr	0	2
SLR0 500 yr	0	2
SLR1 10 yr	0	2
SLR1 20 yr	0	2
SLR1 50 yr	0	2
SLR1 100 yr	0	2
SLR1 500 yr	0	2
SLR2 10 yr	0	2
SLR2 20 yr	0	2
SLR2 50 yr	0	2
SLR2 100 yr	0	2
SLR2 500 yr	0	2

Table A-34. Pasquotank County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	18.92	5.41	0.00	0.00	0.00	0.00	75.68
SLR0 50 yr	32.43	0.00	0.00	0.00	0.00	0.00	67.57
SLR0 100 yr	37.84	2.70	0.00	0.00	0.00	0.00	59.46
SLR0 500 yr	54.05	0.00	0.00	0.00	0.00	0.00	45.95
SLR1 10 yr	54.05	0.00	0.00	0.00	0.00	0.00	45.95
SLR1 20 yr	59.46	2.70	0.00	0.00	0.00	0.00	37.84
SLR1 50 yr	45.95	0.00	0.00	18.92	0.00	0.00	35.14
SLR1 100 yr	40.54	5.41	0.00	24.32	0.00	0.00	29.73
SLR1 500 yr	40.54	0.00	0.00	32.43	0.00	0.00	27.03
SLR2 10 yr	18.92	0.00	0.00	10.81	32.43	21.62	16.22
SLR2 20 yr	27.03	2.70	0.00	10.81	24.32	29.73	5.41
SLR2 50 yr	21.62	0.00	0.00	13.51	21.62	37.84	5.41
SLR2 100 yr	27.03	0.00	0.00	10.81	21.62	40.54	0.00
SLR2 500 yr	16.22	0.00	0.00	18.92	10.81	54.05	0.00

County – Pender

Table A-35. Pender County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	1	0
SLR0 20 yr	1	0
SLR0 50 yr	0	1
SLR0 100 yr	0	1
SLR0 500 yr	0	1
SLR1 10 yr	0	1
SLR1 20 yr	0	1
SLR1 50 yr	0	1
SLR1 100 yr	0	1
SLR1 500 yr	0	1
SLR2 10 yr	0	1
SLR2 20 yr	0	1
SLR2 50 yr	0	1
SLR2 100 yr	0	1
SLR2 500 yr	0	1

Table A-36. Pender County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	3.45	0.00	0.00	0.00	0.00	0.00	96.55
SLR0 100 yr	3.45	3.45	0.00	0.00	0.00	0.00	93.10
SLR0 500 yr	10.34	0.00	0.00	3.45	0.00	0.00	86.21
SLR1 10 yr	3.45	0.00	0.00	0.00	0.00	0.00	96.55
SLR1 20 yr	6.90	0.00	0.00	0.00	0.00	0.00	93.10
SLR1 50 yr	13.79	0.00	0.00	0.00	0.00	0.00	86.21
SLR1 100 yr	10.34	0.00	0.00	3.45	0.00	0.00	86.21
SLR1 500 yr	10.34	6.90	0.00	3.45	3.45	0.00	75.86
SLR2 10 yr	10.34	3.45	0.00	3.45	0.00	0.00	82.76
SLR2 20 yr	10.34	6.90	0.00	3.45	3.45	0.00	75.86
SLR2 50 yr	13.79	6.90	0.00	3.45	3.45	0.00	72.41
SLR2 100 yr	10.34	3.45	0.00	6.90	3.45	3.45	72.41
SLR2 500 yr	13.79	6.90	0.00	0.00	6.90	6.90	65.52

County – Perquimans

Table A-37. Perquimans County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	3	0
SLR0 20 yr	3	0
SLR0 50 yr	2	1
SLR0 100 yr	1	2
SLR0 500 yr	1	2
SLR1 10 yr	2	1
SLR1 20 yr	1	2
SLR1 50 yr	1	2
SLR1 100 yr	1	2
SLR1 500 yr	0	3
SLR2 10 yr	0	3
SLR2 20 yr	0	3
SLR2 50 yr	0	3
SLR2 100 yr	0	3
SLR2 500 yr	0	3

Table A-38. Perquimans County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	0.00	1.63	0.00	0.00	0.00	0.00	98.37
SLR0 100 yr	6.50	2.44	0.00	0.00	0.00	0.00	91.06
SLR0 500 yr	11.38	0.81	0.00	0.00	0.00	0.00	87.80
SLR1 10 yr	0.00	1.63	0.00	0.00	0.00	0.00	98.37
SLR1 20 yr	8.94	1.63	0.00	0.00	0.00	0.00	89.43
SLR1 50 yr	12.20	1.63	0.00	0.00	0.00	0.00	86.18
SLR1 100 yr	13.82	1.63	0.00	0.00	0.00	0.00	84.55
SLR1 500 yr	17.89	1.63	0.00	0.00	0.00	0.00	80.49
SLR2 10 yr	9.76	2.44	0.00	8.13	0.00	0.00	79.67
SLR2 20 yr	13.01	2.44	0.00	9.76	0.00	0.00	74.80
SLR2 50 yr	15.45	1.63	0.00	5.69	6.50	0.00	70.73
SLR2 100 yr	16.26	17.89	0.00	6.50	8.13	0.00	51.22
SLR2 500 yr	36.59	0.00	0.00	4.88	9.76	0.81	47.97

County – Tyrrell

Table A-39. Tyrrell County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	1	1
SLR0 20 yr	1	1
SLR0 50 yr	1	1
SLR0 100 yr	1	1
SLR0 500 yr	1	1
SLR1 10 yr	1	1
SLR1 20 yr	1	1
SLR1 50 yr	1	1
SLR1 100 yr	1	1
SLR1 500 yr	1	1
SLR2 10 yr	0	2
SLR2 20 yr	0	2
SLR2 50 yr	0	2
SLR2 100 yr	0	2
SLR2 500 yr	0	2

Table A-40. Tyrrell County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	1.95	0.28	0.00	0.00	0.00	0.00	97.77
SLR0 20 yr	2.79	0.00	0.00	0.00	0.00	0.00	97.21
SLR0 50 yr	3.90	0.00	0.00	0.00	0.00	0.00	96.10
SLR0 100 yr	4.46	0.28	0.00	0.00	0.00	0.00	95.26
SLR0 500 yr	6.13	0.28	0.00	0.00	0.00	0.00	93.59
SLR1 10 yr	8.08	0.00	0.00	0.00	0.00	0.00	91.92
SLR1 20 yr	9.19	0.00	0.00	0.00	0.00	0.00	90.81
SLR1 50 yr	10.31	0.00	0.00	0.00	0.00	0.00	89.69
SLR1 100 yr	10.86	0.28	0.00	0.00	0.00	0.00	88.86
SLR1 500 yr	13.09	0.00	0.00	0.00	0.00	0.00	86.91
SLR2 10 yr	11.70	0.56	0.00	3.62	3.34	0.56	80.22
SLR2 20 yr	13.37	0.00	0.00	3.06	3.62	1.11	78.83
SLR2 50 yr	14.48	20.33	0.00	3.62	3.62	1.67	56.27
SLR2 100 yr	35.93	50.70	0.00	3.62	3.06	2.51	4.18
SLR2 500 yr	85.52	0.56	0.00	3.62	3.06	3.62	3.62

County – Washington

Table A-41. Washington County number of bridges classified as Safe and Vulnerable under each of the 15 scenarios.

Condition	Safe	Vulnerable
SLR0 10 yr	1	0
SLR0 20 yr	1	0
SLR0 50 yr	1	0
SLR0 100 yr	1	0
SLR0 500 yr	1	0
SLR1 10 yr	1	0
SLR1 20 yr	1	0
SLR1 50 yr	1	0
SLR1 100 yr	1	0
SLR1 500 yr	1	0
SLR2 10 yr	1	0
SLR2 20 yr	0	1
SLR2 50 yr	0	1
SLR2 100 yr	0	1
SLR2 500 yr	0	1

Table A-42. Washington County percentages of dominant vulnerability modes for bridge spans under the 15 scenarios.

Condition	Rotation %	Sliding %	Uplifting %	Inundated (1-3 ft) %	Inundated (3-5 ft) %	Inundated (5+ ft) %	Safe %
SLR0 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 50 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 100 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR0 500 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 20 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 50 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 100 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR1 500 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR2 10 yr	0.00	0.00	0.00	0.00	0.00	0.00	100.00
SLR2 20 yr	86.33	0.00	0.00	0.00	0.00	0.00	13.67
SLR2 50 yr	88.73	0.00	0.00	0.00	0.00	0.00	11.27
SLR2 100 yr	89.69	0.00	0.00	0.00	0.00	0.00	10.31
SLR2 500 yr	90.89	0.00	0.00	0.00	0.00	0.00	9.11

Appendix B. Spatial Distribution of Bridge Vulnerability Classifications

Appendix B presents the spatial distribution of bridge-level vulnerability classifications for all 15 hydrodynamic scenarios evaluated in this study. The maps include the 116 Tier 1 and Tier 2 bridges selected through the screening process described in Section 3.1. For each scenario, a bridge was classified as Vulnerable when at least one evaluated span was assigned a dominant vulnerability mode other than Safe. A bridge was classified as Safe only when all evaluated spans were classified as Safe.

The maps are organized by sea level condition. Sections B.1, B.2, and B.3 present results for present-day sea level, 2.73 ft of sea level rise, and 7.35 ft of sea level rise, respectively. Within each section, maps are provided for the 10-, 20-, 50-, 100-, and 500-year storms. County boundaries, NCDOT division boundaries, and evacuation routes are included to provide geographic and transportation context.

The mapped classifications represent screening-level threshold exceedances under the evaluated hydrodynamic scenarios. A Vulnerable classification does not indicate that bridge damage or collapse will occur during a specific storm. Rather, it identifies a bridge for which at least one span exceeded an inundation, uplift, sliding, or rotation criterion and may warrant additional bridge-specific evaluation. The maps apply only to the selected bridges and should not be interpreted as a complete assessment of all bridges within the coastal counties.

B.1. Present-day sea level

Figures B-1 through B-5 show the spatial distribution of bridge vulnerability under the present-day sea level condition. As the storm return period increased, both the number and spatial extent of bridges classified as Vulnerable increased. The number of bridges classified as Vulnerable increased from 14 of the 116 assessed bridges under the 10-year storm to 25 under the 20-year storm, 41 under the 50-year storm, 51 under the 100-year storm, and 60 under the 500-year storm. These maps provide the present-day baseline against which the two sea level rise conditions were compared.

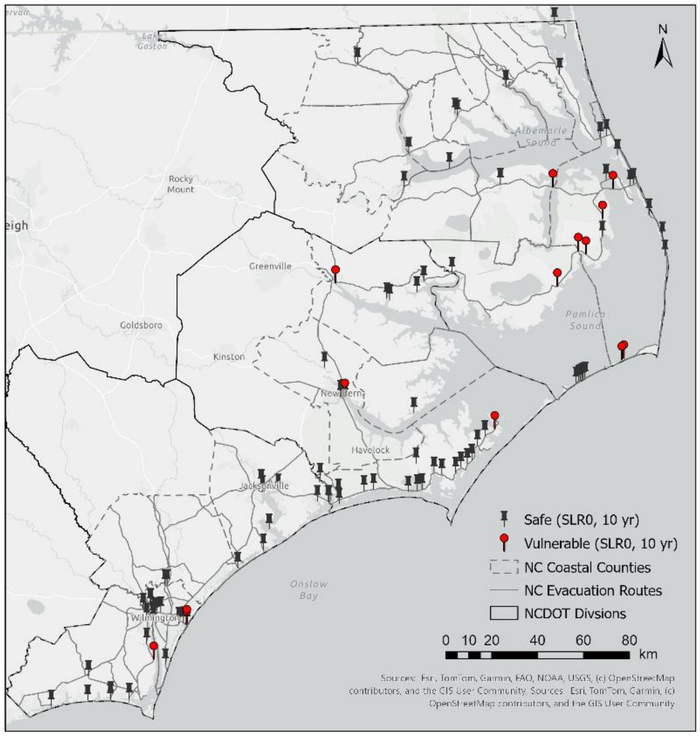

Figure B-1. Spatial distribution of bridge vulnerability under present-day sea level and 10-year storm.

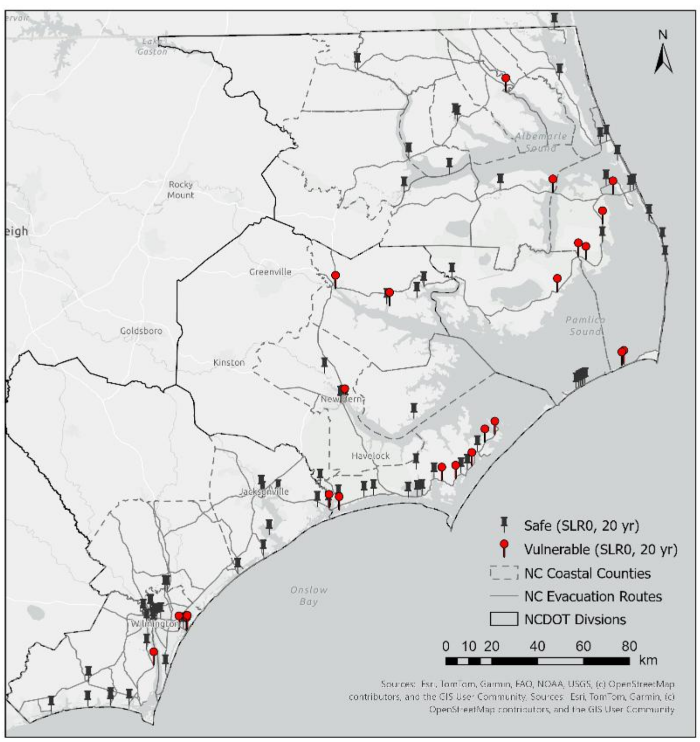

Figure B-2. Spatial distribution of bridge vulnerability under present-day sea level and 20-year storm.

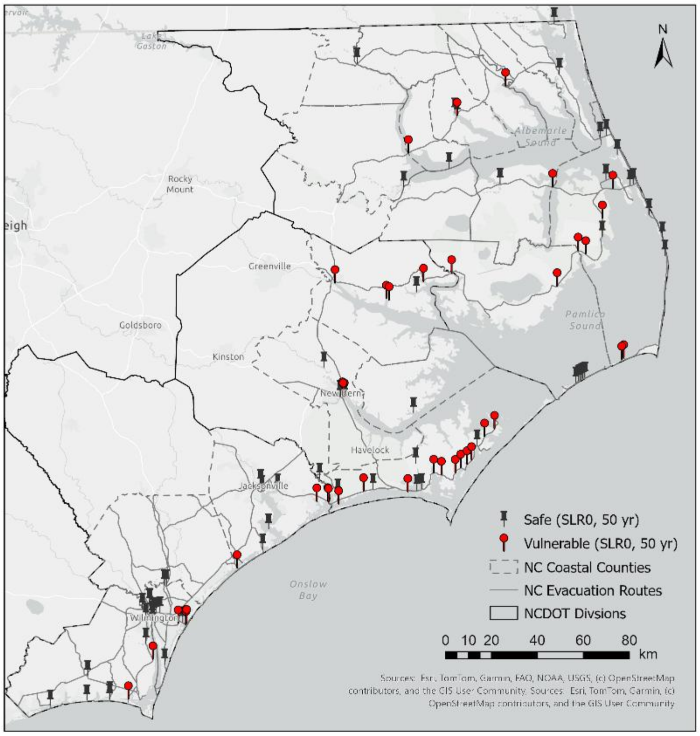

Figure B-3. Spatial distribution of bridge vulnerability under present-day sea level and 50-year storm.

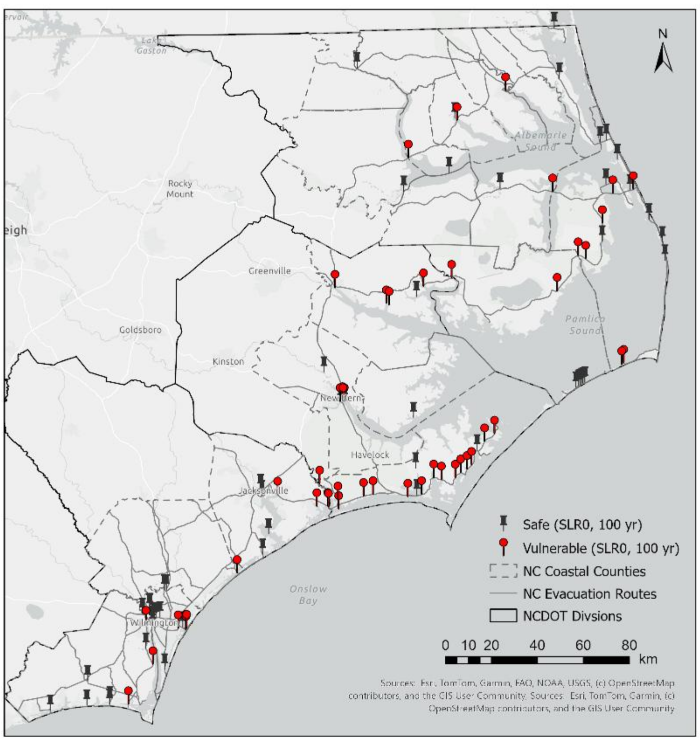

Figure B-4. Spatial distribution of bridge vulnerability under present-day sea level and 100-year storm.

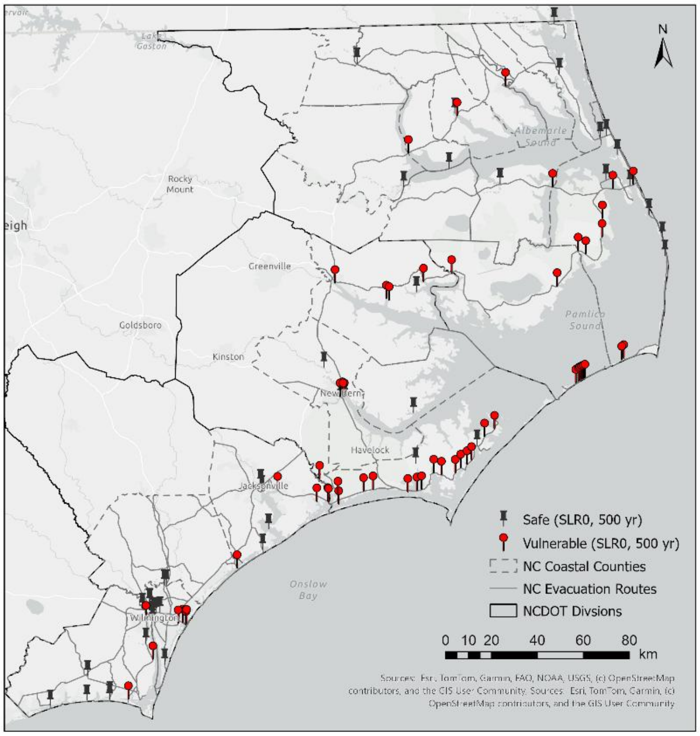

Figure B-5. Spatial distribution of bridge vulnerability under present-day sea level and 500-year storm.

Under present-day sea level, the largest changes occurred between the more frequent storm scenarios and the 100-year storm. Even under the 500-year storm, however, 56 of the assessed bridges remained classified as Safe. The spatial variation demonstrated that storm return period alone did not determine the classification; the results also depended on the hydrodynamic conditions and structural characteristics associated with each bridge.

B.2. Sea level rise of 2.73 ft

Figures B-6 through B-10 show bridge vulnerability under the SLR1 condition, which incorporated 2.73 ft of sea level rise. The elevated baseline water level increased the number of bridges classified as Vulnerable under every storm return period when compared with the corresponding present-day scenario. The number of bridges classified as Vulnerable increased from 52 under the 10-year storm to 60 under the 20-year storm, 64 under the 50-year storm, 68 under the 100-year storm, and 74 under the 500-year storm.

The SLR1 10-year scenario resulted in 52 bridges classified as Vulnerable, which was approximately equal to the count of 51 bridges classified as Vulnerable under the present-day 100-year scenario. This comparison illustrates that sea level rise shifted vulnerability threshold exceedances toward more frequent storms. The maps also showed that the increase was not spatially uniform; some bridges remained Safe across all SLR1 scenarios, while others were newly classified as Vulnerable under the lower return period storms.

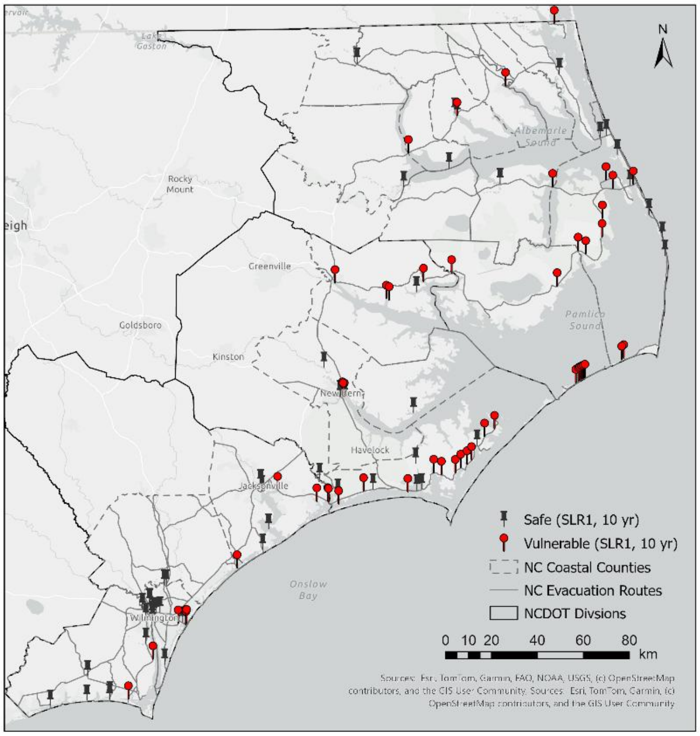

Figure B-6. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 10-year storm.

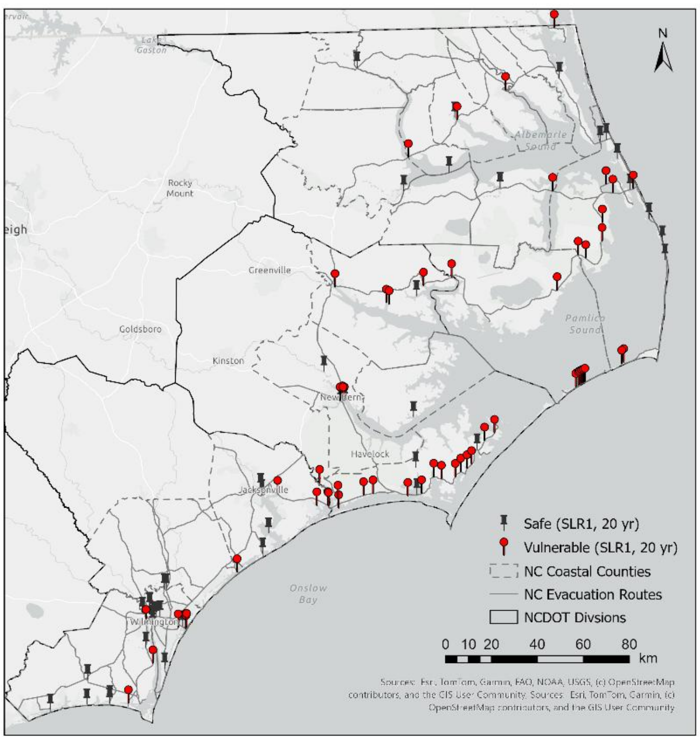

Figure B-7. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 20-year storm.

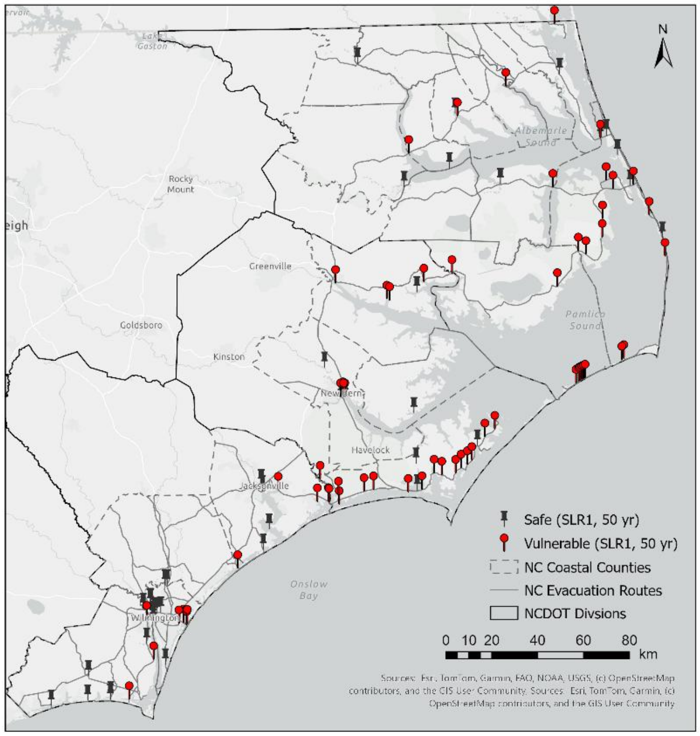

Figure B-8. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 50-year storm.

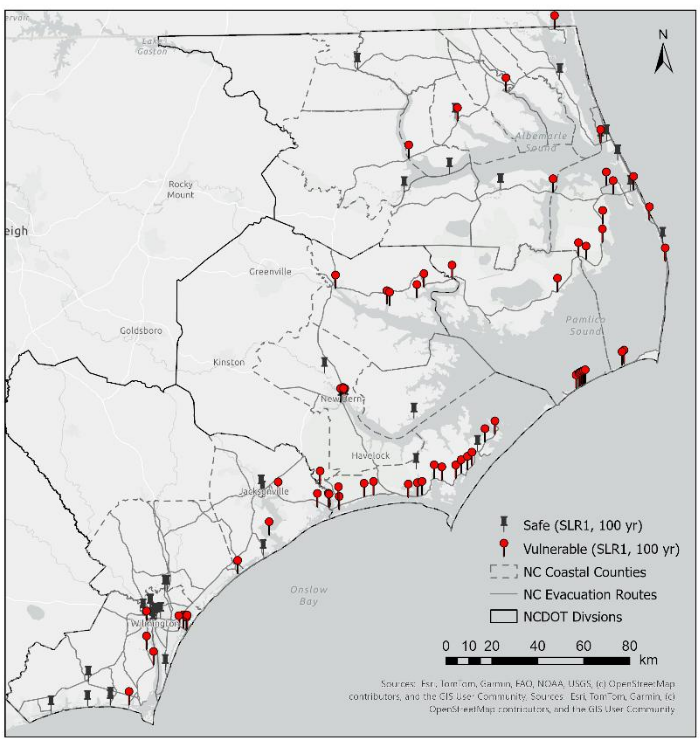

Figure B-9. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 100-year storm.

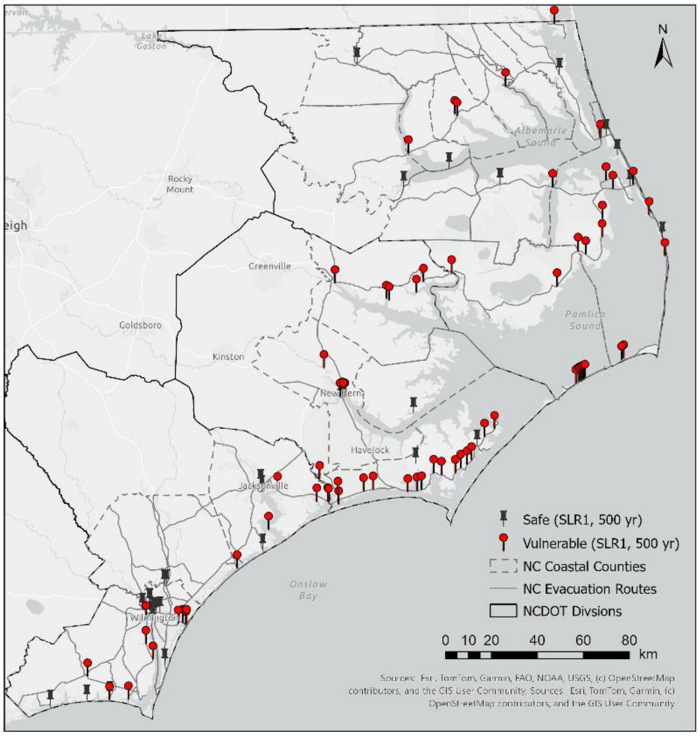

Figure B-10. Spatial distribution of bridge vulnerability under sea level rise of 2.73 ft and 500-year storm.

The difference between the SLR1 10-year and 500-year scenarios was 22 bridges. This increase was smaller than the corresponding 46-bridge increase under present-day sea level because many bridges had already exceeded a vulnerability criterion under the SLR1 10-year storm.

B.3. Sea level rise of 7.35 ft

Figures B-11 through B-15 show the spatial distribution of bridge vulnerability classifications under the SLR2 condition, which incorporated 7.35 ft of sea level rise. Under this condition, a majority of the assessed bridges were classified as Vulnerable under every evaluated storm return period. The number of bridges classified as Vulnerable increased from 74 under the 10-year storm to 78 under the 20-year storm, 82 under the 50-year storm, 83 under the 100-year storm, and 86 under the 500-year storm.

The SLR2 10-year scenario resulted in more bridges classified as Vulnerable than the present-day 500-year scenario, which identified 60 bridges classified as Vulnerable. This comparison further demonstrated that increased sea level changed the frequency context of vulnerability. Under the high sea level rise condition, many bridges exceeded a vulnerability criterion during the more frequent storms, and increases in storm return period produced comparatively smaller changes in the statewide bridge count.

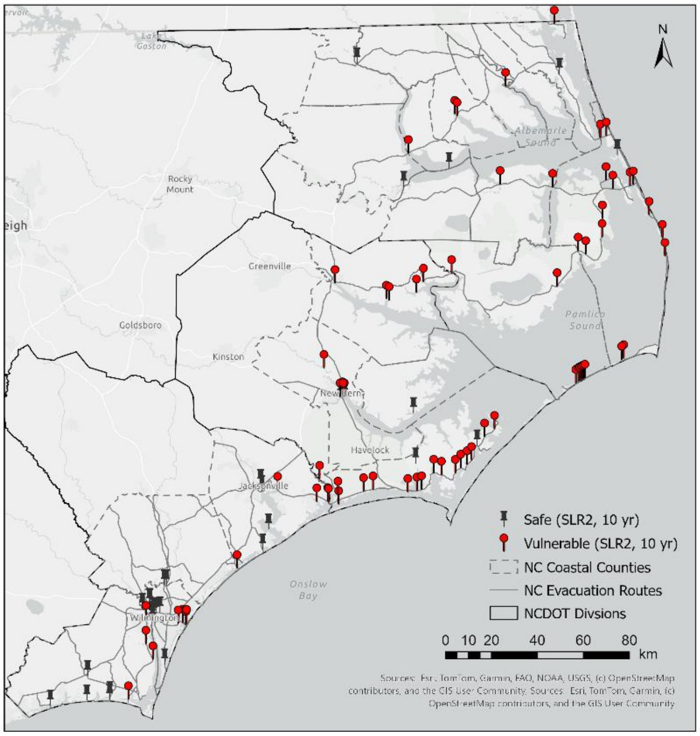

Figure B-11. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 10-year storm.

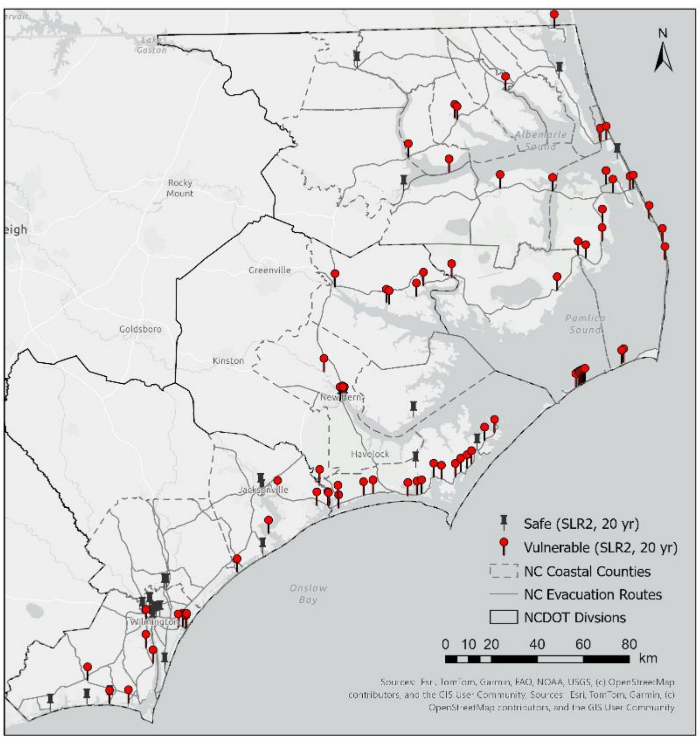

Figure B-12. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 20-year storm.

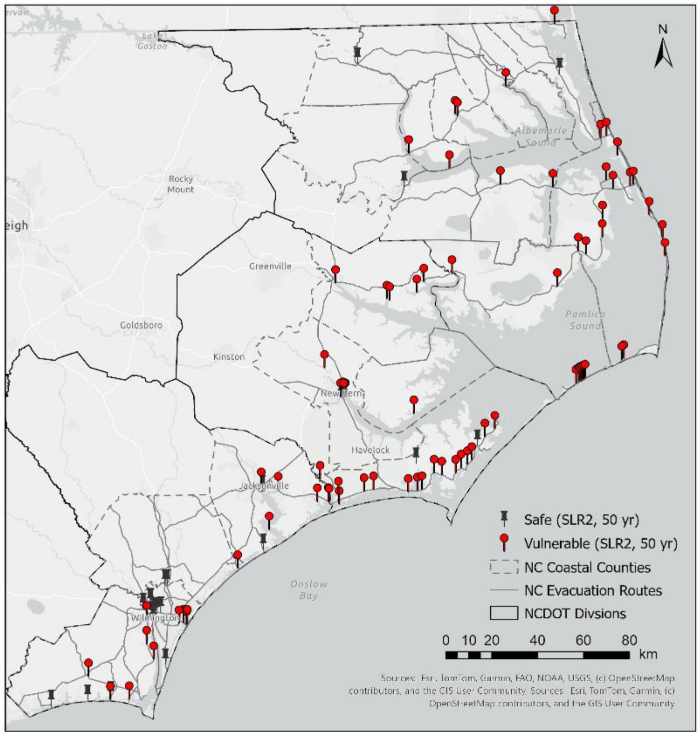

Figure B-13. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 50-year storm.

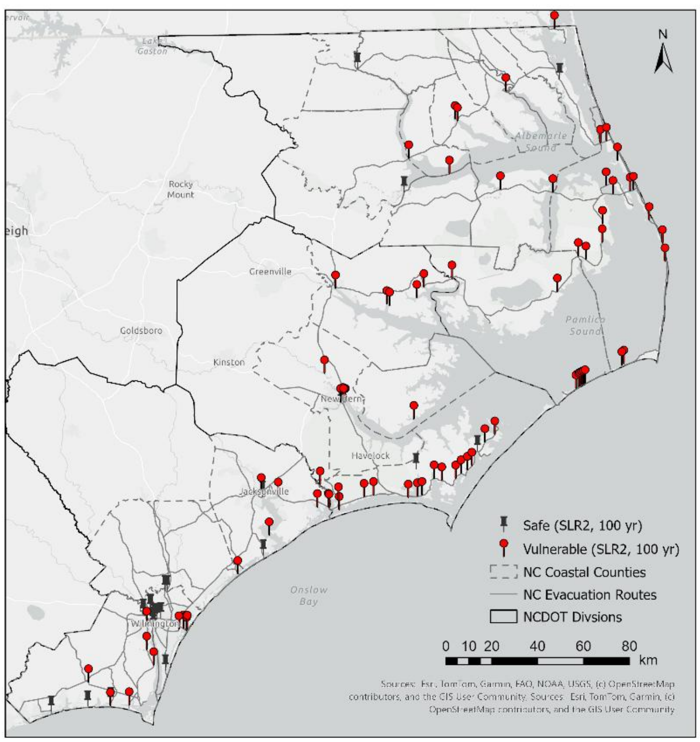

Figure B-14. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 100-year storm.

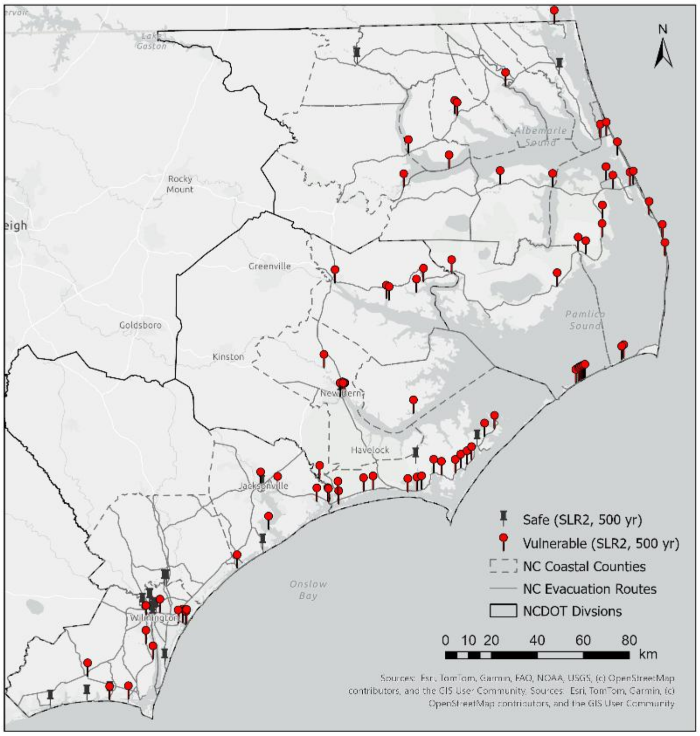

Figure B-15. Spatial distribution of bridge vulnerability under sea level rise of 7.35 ft and 500-year storm.

Although the Vulnerable classification became widespread under SLR2, 30 of the assessed bridges remained classified as Safe under the 500-year storm. The persistence of Safe classifications under the most severe evaluated scenario indicated that the results were bridge-specific and reflected the combined effects of bridge elevation, superstructure geometry, storm surge, and wave conditions.