THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

TECHNICAL REPORT 0-7055-1
TxDOT PROJECT NUMBER 0-7055

Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events – Final Report

Kyle Bathgate
Jingran Sun
Shidong Pan
Srijith Balakrishnan
Zhanmin Zhang
Michael Murphy
Zhe Han
Lisa Loftus-Otway

December 2021; Published May 2022

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-22/0-7055-1		

4. Title and Subtitle	5. Report Date
Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events – Final Report	Submitted: December 2021 Published: May 2022
	6. Performing Organization Code
7. Author(s) Kyle Bathgate, Jingran Sun, Shidong Pan, Srijith Balakrishnan, Zhanmin Zhang, Michael Murphy, Zhe Han, Lisa Loftus-Otway	8. Performing Organization Report No. 0-7055-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3925 W. Braker Lane, 4th Floor Austin, TX 78759	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-7055
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Division 125 E. 11th Street Austin, TX 78701	13. Type of Report and Period Covered Technical Report (January 2020 – December 2021) 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

Extreme weather events may disrupt port and coastal freight operations, resulting in direct and indirect economic losses to ports, supporting infrastructure, and reliant industry systems. Therefore, understanding the existing resilience capacity of the Texas port system to extreme weather events is necessary. To accomplish this, the weather hazards present along the Texas Gulf Coast are quantified. Stakeholder workshops, surveys, and interviews inform our understanding of the current status of resilience practice in Texas ports. Frameworks for assessing the criticality, vulnerability, exposure, risk, and resilience of the Texas port system are developed. The economic impacts of port disruptions from hurricanes are quantified using input-output tables. A tool, PortRESECO, is developed to be used by port stakeholders to assess the resilience of a port facility and view the results of the economic analysis. Finally, recommendations are made for implementation to increase the resilience of coastal freight operations in Texas.

17. Key Words	18. Distribution Statement
Resilience, ports, infrastructure, landside operations (ports), extreme weather events, natural hazards, hurricanes, risk assessment, economic impacts	No restrictions. This document is available to the public through the National Technical Information Service, Alexandria, Virginia 22312; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	230	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events – Final Report

Kyle Bathgate
Jingran Sun
Shidong Pan
Srijith Balakrishnan
Zhanmin Zhang
Michael Murphy
Zhe Han
Lisa Loftus-Otway

CTR Technical Report:	0-7055-1
Report Date:	Submitted: December 2021
Project:	0-7055
Project Title:	Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th floor
Austin, TX 78759

http://ctr.utexas.edu/

Disclaimers

Author's Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Research Supervisor: Zhanmin Zhang

Acknowledgments

The research team is grateful to Joanne Steele (TxDOT RTI), Emily Hampton (TxDOT Maritime Division), Tricia Hasan (TxDOT Maritime Division), Sherry Pifer (TxDOT Freight Planning Division), and Mathew Heinze (TxDOT Maintenance Division) for their project guidance. The research team would also like to thank the port representatives and coastal freight stakeholders for their participation in the project. Finally, the researchers would like to thank Dr. Taehoon Lim, for his earlier work on the input-output table methodology and calculations that have contributed to the indirect macro-economic impact assessment of this chapter.

Products

The first product developed by this project is the integrated GIS dataset of port and supporting infrastructure and port trade layers (0-7055-P1). The second product developed by this project is the Excel-based tool for port resilience assessment (PortRESECO) (0-7055-P2). Both products are available for download by invited individuals at:
https://utexas.box.com/s/lnlpweb23wbrgbcydo6no6ucal8b8lk1

To request access to the products as an invited individual, please contact Zhanmin Zhang at z.zhang@mail.utexas.edu

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1 Background

The Texas port system, situated along the coast of the Gulf of Mexico, plays a crucial role in the state and national economy. In 2020, three out of the top eight U.S. ports in terms of total tonnage were in Texas and ports in Texas led all U.S. states in terms of total freight tonnage transported (Institute for Water Resources, 2020)(Institute for Water Resources, 2020). Texas ports facilitate a wide range of economic activities, such as energy exploration and production, manufacturing, agriculture, and warehousing and distribution. According to Texas Port Association, Texas ports generate $449.6 billion annually in economic activity, $7.8 billion in state and local tax, and approximately 1.8 million direct and indirect jobs (Martin Associates, 2019)(Martin Associates, 2019). In addition to maritime trade, Texas ports are also of strategic importance, facilitating surface deployment and distribution of military cargo to other parts of the world.

While continued operations of Texas ports are thus equally important for both the economy and national security, the Texas Gulf Coast is frequently exposed to extreme weather events, such as hurricanes, tropical storms, tornadoes, and flooding. Such events pose a severe threat to the uninterrupted functioning of ports. Disruptions to port infrastructure systems incur significant economic costs to ports in terms of direct damages and import/export revenue. However, the indirect losses to dependent industries are even larger, given the strong reliance of those sectors on ports for their business continuity. Disruptions to port systems in Texas can also have significant macroeconomic impacts, especially job losses and long-term fall in commodity consumption. It is therefore of utmost importance to enhance the resilience of the Texas port system against such events.

From a systems perspective, resilience is defined as the "ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)" (Bruneau et al., 2003)(Bruneau et al., 2003). In the context of infrastructure systems, the White House (2013)(2013) defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions." Most of the frameworks for assessing resilience in infrastructure systems are based on the well-known relationship connecting hazard, exposure, vulnerability, and risk.

Risk may be considered as a function of hazard intensity, exposure of system components to the hazard, and intrinsic vulnerabilities associated with system components. The vulnerabilities are determined by the resilience capabilities of the system. The resilience of a system improves with the adoption of strategies that reflect the hazard risks to an infrastructure system. Thus, resilience enhancement is a continuous process. Resilience assessments help infrastructure agencies to evaluate the progress of the adopted measures and fine-tune them to achieve desired resilience in the system.

The identification of those infrastructure components critical for port operations and supporting infrastructure systems, which could cause cascading impacts on ports, are essential for exhaustive port risk assessments. The components in a port-related infrastructure can be broadly divided into two categories: (a) port system comprising ports, inland and marine waterways leading to the ports, freight highways, railroads, and pipelines; (b) supporting infrastructure including all utility services that are essential for the functioning of ports, such as energy grids, and communications.

Ports are essentially a multimodal hub facilitating the transfer of commodities from land freight modes to marine freight modes and vice versa. For the same reason, failure of ports would hinder the transfer of commodities, while failure access facilities like roads, railroads, and channels could lead to delay in logistics of import and exports. In addition, failure of supporting infrastructure such as energy grids could lead to a partial shutdown of port operations.

Port vulnerabilities are the intrinsic system inadequacies that could inflict potential physical and economic losses (risks) in the system when impacted by an extreme weather event. As far as port operations are concerned, business continuity is ensured only if all physical, organizational, human, and economic components of ports are maintained at acceptable levels of functioning during and immediately after an event. However, the most important among these components is the physical infrastructure, which has the highest susceptibility due to their direct exposure to extreme weather events.

1.2 Research Objectives

Extreme weather events, such as hurricanes and tropical storms, pose considerable challenges to the Texas port system. Given the economic and strategic significance of the Texas port system, ensuring its resilience against such hazards is essential. Although resilience is a vague concept defined differently by different entities, the specific aspects of port system resilience need to be identified and incorporated in resilience enhancement programs. Moreover, achieving optimal resilience of port systems requires a thorough understanding of the port network functions, identification of port infrastructure vulnerabilities, and quantification of resultant risks.

Therefore, the UT/CTR research team investigates the extreme weather resilience of Texas ports by undertaking a holistic analysis of the current resilience capabilities of the Texas port system and suggesting measures to improve them. UT/CTR develops an integrated GIS dataset and an Excel-based tool for resilience scoring. UT/CTR also quantifies the physical and economic risks of port disruptions and develops metrics linking the characteristics of extreme events to the associated criticality, vulnerability, exposure, and risks of both port and supporting infrastructure systems. Finally, UT/CTR provides resilience enhancement recommendations for immediate implementation based on the study findings. The specific project research objectives are:

- Identify and characterize potential extreme weather events

- Identify the network and port-level vulnerabilities of Texas ports and supporting infrastructure
- Quantify the physical and economic risks posed by extreme events to Texas ports
- Develop metrics and evaluate the resilience of Texas ports
- Provide recommendations for improving Texas port system resilience

1.3 Work Plan

Figure 1.1 illustrates the work plan of the project. The work plan comprises a systematic investigation of the resilience of the Texas port system using state-of-the-art methodologies to understand and characterize various extreme weather-related threats to Texas port system, identify the network-level and project-level vulnerabilities in the system, quantify the physical and economic risks posed by such events on the system and assess the resilience of the port system. The work plan employs techniques capable for assessing both quantitative and qualitative aspects of risk and resilience so that the findings from the project could be implemented to improve real-world practices. In the following chapters, the methods and results of the tasks detailed in the work plan are discussed in detail.

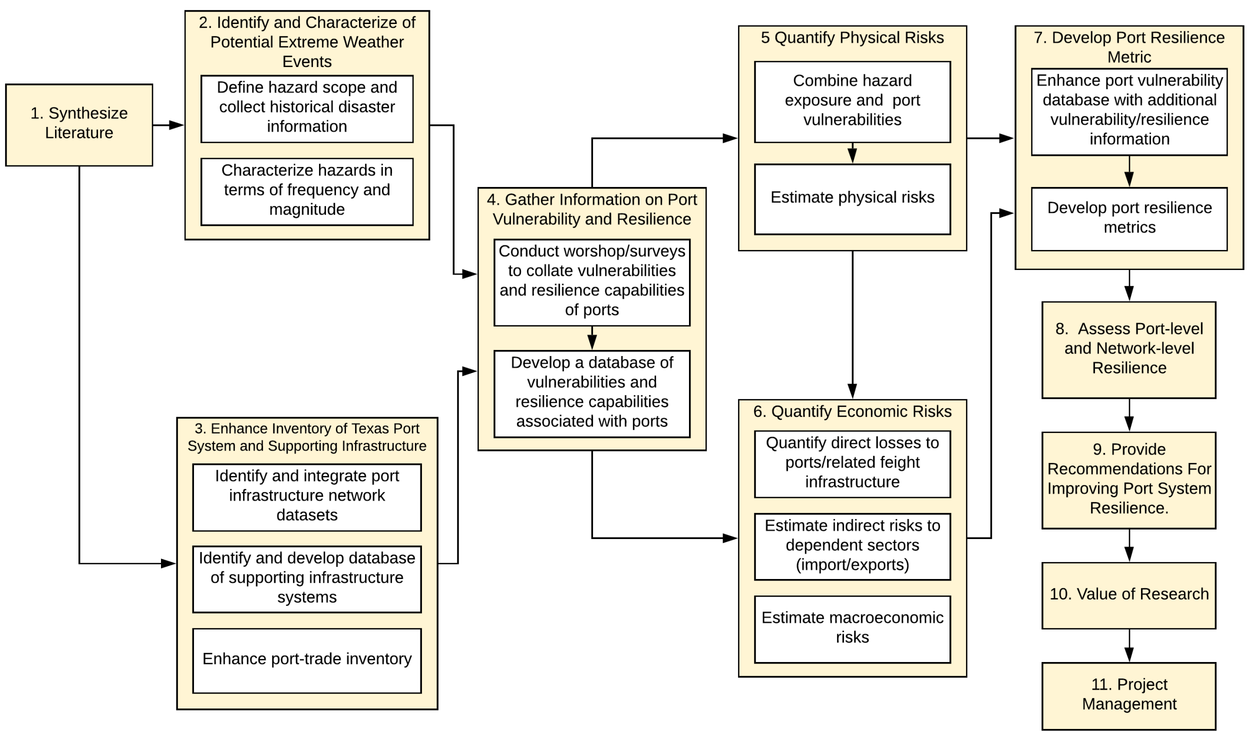


Figure 1.1 Structure of the project work plan and tasks

Chapter 2. Literature Review

2.1. Introduction

To achieve the project goals, a thorough understanding of existing port resilience methods and studies is necessary. Therefore, this chapter provides the results of a review of existing literature to collect information on different methodologies, models, tools, and data sources related to risk and resilience assessment of ports. In addition, the review also focuses on the various measures and interventions implemented by port authorities and government agencies to improve the resilience capabilities of ports both in the U.S and abroad. This chapter is divided into two sections: (a) review of existing literature, and (b) available data sources. The literature review section focuses on four specific aspects of the study as follows:

1. State-of-the-art methodologies used for modeling and characterization of extreme weather events which pose significant threats to port systems;
2. Best practices for identification of port system vulnerabilities, and quantification of physical and economic risks of port failures;
3. Available resilience metrics used for ports and other major transportation infrastructure networks; and
4. Resilience enhancement measures implemented by various agencies, including states and local governments, and their effectiveness in reducing physical and economic loss in subsequent disasters.

The data sources section presents details of some of the potential data sets which could be used for risk and resilience analyses of ports.

The scope of the physical infrastructure is limited to port systems and supporting infrastructure systems, including energy grids, freight highways, railroads, and communications. Only those weather events with high exposure in the coastal regions are considered for the review.

2.1 Modeling and Characterization of Natural Disasters

Many studies have focused on characterizing the exposure of coastal infrastructure and port systems to extreme weather events. These studies indicate that water inundation from flooding is one of the most important concerns for port facilities. Storm surges associated with hurricanes lead to damages from both high waters and winds. Seismic activity, tornadoes, fog, and wildfires also may potentially damage physical assets or disrupt port operations. By understanding the geographical exposure of natural disasters that cause damage to coastal infrastructure, the resilience of individual port assets and the holistic port system may be more thoroughly understood.

Port systems and supporting infrastructure, being located along coasts, are frequently affected by extreme-weather events resulting from ocean processes and circulation changes. The ports along the East and Gulf Coasts of the U.S. are more exposed to hurricanes than those on the West, as most hurricanes and tropical cyclones are formed in the Atlantic Ocean (Landsea, 1999)(Landsea, 1999). In addition, ports are also susceptible to several other events, such as sea-level rise, tornadoes, and earthquakes. Table 2.1 presents a list of selected historical extreme weather events that have severely impacted ports in the U.S.

Table 2.1 Major extreme weather events which disrupted seaport operations in the U.S.

Event Type	Event	Year	Seaports affected
Hurricane	Katrina	2005	Gulfport, MS; Miami, FL, Mobile, AL; Morgan City, LA; New Orleans, LA, Pascagoula, MS
Hurricane	Rita	2005	Freeport, TX; Houston, TX; Miami, FL; Morgan City, LA; New Orleans, LA; Port Arthur, TX
Hurricane	Ike	2008	Port Arthur/Beaumont, TX; Freeport, TX; Galveston, TX; Houston, TX; Texas City, TX
Hurricane	Irene	2011	East Coast ports including Wilmington and Morehead City, NC; Norfolk, VA; Baltimore, MD, Philadelphia, PA; Newark, NJ; and New York, NY
Hurricane	Harvey	2017	Port Arthur, TX; Houston, TX; Galveston, TX; Freeport, TX; Corpus Christi, TX
Hurricane	Florence	2018	Wilmington NC; Morehead City, NC; Charleston, SC
Super storm	Sandy	2012	Northeast coast ports, including Norfolk, VA; Baltimore, MD; Newark, NJ; and New York City, NY
Earthquake	Nisqually	2001	Tacoma, WA
Earthquake	Loma Prieta	1989	Richmond and Oakland, CA

Extreme weather events inflict severe costs on civil infrastructure. For instance, the overall damage costs caused by hurricanes Harvey, Irma, and Maria in 2017 were estimated to be $265 billion (State of the Climate: Tropical Cyclones for Annual 2017, 2018)(State of the Climate: Tropical Cyclones for Annual 2017, 2018). Another example is Hurricane Katrina, that resulted in overall damage costs of more than $160 billion, including $15 billion in cleanup and reconstruction costs of bridges and roads damaged (Kafalenos et al., 2012)(Kafalenos et al., 2012). Port operations are highly sensitive to the impact of extreme weather events, especially hurricanes. For example, due to Hurricane Harvey, the Port of Houston was closed for over five consecutive days, disrupting cargo operations, and impacting different industries like petrochemical and refinery industries. Similar disruptions were experienced in the ports of New York/New Jersey and Mobile during extreme weather events. For this reason, at the national-, state-, and local levels, there have been several efforts to understand the effects of weather-related hazards and their exposure in coastal regions. Most studies focus on hurricanes and related storm surge as those hazards have proven to be more frequent and costly in the past. Some major studies that focused on characterizing coastal hazards are presented in Table 2.2.

Table 2.2 Studies on hazard exposure of U.S. coastal infrastructure systems

Study	Hazard Focus	Infrastructure Systems	Geographical scope	Key objectives
(Bradbury et al., 2015)(Bradbury et al., 2015)	Flooding due to hurricanes and sea level rise	Energy facilities	Gulf Coast	Characterize exposure of oil refineries, SPR storage facilities, power plants, substations, etc. based on future sea-level projections
(McLeod et al., 2019)(McLeod et al., 2019)	Storm surge and sea level rise	Marine port facilities	Virginia	Exposure of port terminal structure to flooding was evaluated using inundation models
(Maloney & Preston, 2014)(Maloney & Preston, 2014)	Hurricane storm surge and sea level rise	Coastal infrastructure	Gulf Coast and East Coast	Case studies on exposure of energy infrastructure, housing units, and other coastal infrastructure to storm surges
(Needham, 2014)(Needham, 2014)	Hurricane storm surge	Energy facilities	Gulf Coast	Characterize storm surge vulnerability for oil refineries and power plants on US Gulf Coast
(Keim et al., 2007)(Keim et al., 2007)	Hurricane strikes/wind	Coastal infrastructure	Gulf Coast to New England	Analyze geographic and temporal distribution of storm strikes along US Gulf and Atlantic coastlines for vulnerability prediction
(Shepard et al., 2012)(Shepard et al., 2012)	Hurricane storm surge and sea level rise	Coastal infrastructure	Long Island, New York	Case study on storm surge risk changes in Long Island, NY due to sea level rise
(Sebastian et al., 2014)	Hurricane storm surge	Coastal infrastructure	Galveston Bay, Texas	Characterize vulnerability of upper Texas Gulf region to hurricane storm surge and flooding
(Padgett et al., 2012)	Hurricane storm surge	Bridges	Gulf Coast	Assess bridge damage from Hurricane Katrina using statistical methods and create empirical fragility curves
(Weisberg & Zheng, 2006)	Hurricane storm surge	Coastal infrastructure	Tampa Bay, Florida	Determine storm surge impacts on localities in Tampa Bay, FL under different hurricane approaches
(Sweet et al., 2018)	High tide flooding	Coastal infrastructure	U.S. Coast	Characterize high tide flooding and prepare future projections

Hurricanes, along with less intense tropical storms and depressions, belong to the broader "tropical cyclone" weather classification. Hurricanes are known for their intense wind, large volumes of rainfall, and storm surges at landfall which lead to widespread flooding and damage in coastal areas. All of the above destructive characteristics of hurricanes may threaten seaports, from both the aspect of physical infrastructure damages and operational disruptions. Of the studies listed in Table 2.2, the majority focus on tropical cyclone events. Methodologies range from empirical or statistical analyses of a broad geographic region to in-depth simulations for specific harbor areas. It is common for researchers to incorporate Geographic Information Systems (GIS) into their studies to analyze hazards spatially. Bradbury et al. (2015), McLeod et al. (2019), Maloney & Preston (2014), and Shepard et al. (2012) all applied the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model developed by the National Hurricane Center. SLOSH seeks to predict maximum storm surge heights in an area for a simulated hurricane track and intensity. This is one GIS-based model that is commonly used to determine potential storm surge height and identify vulnerable communities and assets. Another technique was employed by Weisberg & Zheng (2006), which used a three-dimensional, finite volume coastal ocean model with a bathymetric- topographic data set to assess hurricane storm surge exposure for localities in Tampa Bay, Florida. Another model used in hurricane surge applications is ADvanced CIRCulation (ADCIRC), which models advanced ocean circulation. ADCIRC has been used extensively by the U.S. Army Corp of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) to model storm surges and flood risk. A study by Sebastian et al. (2014) incorporated the Simulating Waves Nearshore (SWAN) model with ADCIRC to model the storm surge impacts of Hurricane Ike in Galveston Bay in Texas. Utilizing both models in tandem allows for wave and circulation interactions to be simulated simultaneously, giving more accurate results.

SLOSH results are applied to determine how future hurricane storm surges are likely to change when accounting for sea level rise (SLR). Bradbury et al. (2015), McLeod et al. (2019), Maloney & Preston (2014), and Shepard et al. (2012) examined how maximum storm surge exposure would change as a result of SLR. With higher mean sea levels, the destructive surges from hurricanes will travel further inland and water inundation will become a possibility for facilities that were previously out of harm's way. This places new vulnerabilities on coastal port infrastructure and related industries, such as the energy and petrochemical sectors. SLR also will exacerbate coastal nuisance flooding and extreme tides. Water inundation from these events may additionally threaten seaport infrastructures.

Other hurricane modeling studies use empirical data to analyze event return periods. Keim et al. (2007) categorized tropical cyclone intensity into return periods for storms from 1901 to 2005. The return periods were calculated using a point-based approach. Figure 2.1 shows the results of this return period analysis. Texas is most exposed to tropical cyclones along the northern portion of the Gulf Coast: Galveston Bay is prone to tropical storm or greater events every three years.

In addition to damaging or destroying physical port assets, hurricanes can disrupt port operations. Sedimentation is one of the most prominent reasons for functional disruption of ports. The vast quantities of precipitation and violent storm surges of hurricanes bring eroded silt and other sediment into port bays and channels, impacting port operations by reducing the maximum allowable draft for ships in navigable waterways. To restore operations, shipping channels must be dredged to remove the sediment deposits. The Port of Houston experienced disruptions in 2017 as around 18 years of the average annual sediment load for Galveston Bay was deposited by Hurricane Harvey (Du et al., 2019). The Army Corp of Engineers had to increase dredging efforts to restore full operational capacity for the ports in the surrounding areas. This impact was previously experienced in Galveston Bay in 2008 with Hurricane Ike (Goff et al., 2010), in Port Canaveral, Florida in 2004 with Hurricane Charley (Bigger et al., 2009), and others.

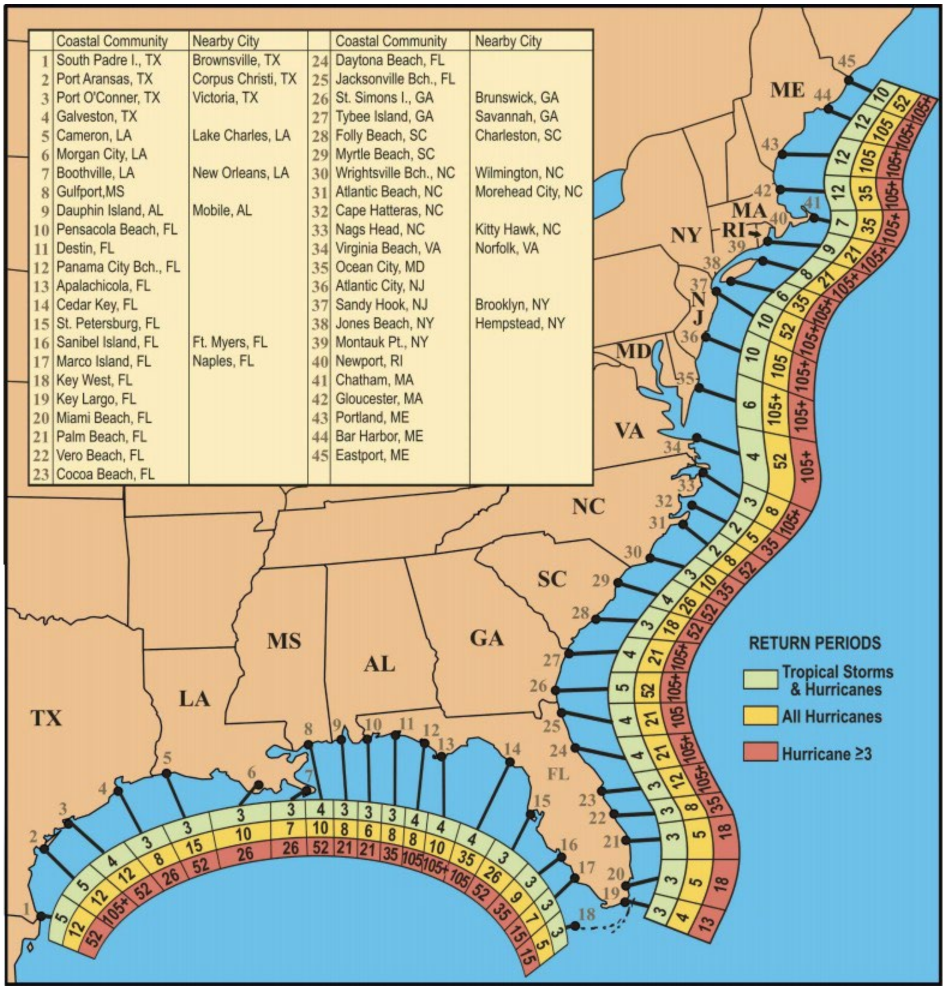


Figure 2.1 Hurricane return periods, (Keim et al., 2007)

Another hazard that may impact seaport facilities are tornadoes. Tornadoes are high velocity rotational wind columns that form in storm cells. While tornadoes are accompanied by high volumes of precipitation and lightning strikes, they are most destructive due to their extreme wind speeds. Tornadoes are much smaller than tropical cyclones, but a direct hit on a port could be disastrous. Little research has focused on the impacts of tornadoes explicitly on seaports in the United States. However, significant work has been performed analyzing the geographic locations that tornadoes commonly impact. "Tornado Alley" refers to locations in the Great Plains where tornadoes are most common. A study examining tornado events from 1921 to 1995 identified a region spanning from Texas to North Dakota, and as far east as Pennsylvania, to be most susceptible to tornadoes (Concannon et al., 2000). While Texas is included in most "Tornado Alley" regions, it is generally the northern and eastern areas of the state that experience the most frequent and severe tornado events (H. E. Brooks et al., 2003). Coastal counties from Brazoria north to the Louisiana border–containing ports at Houston, Texas City, Galveston, Beaumont, Port Arthur, Port Neches, and more–are most likely to experience tornado events, although tornadoes are possible (with less likelihood) in other Texas coastal regions. Figure 2.2 shows typical tornado exposure throughout the United States.

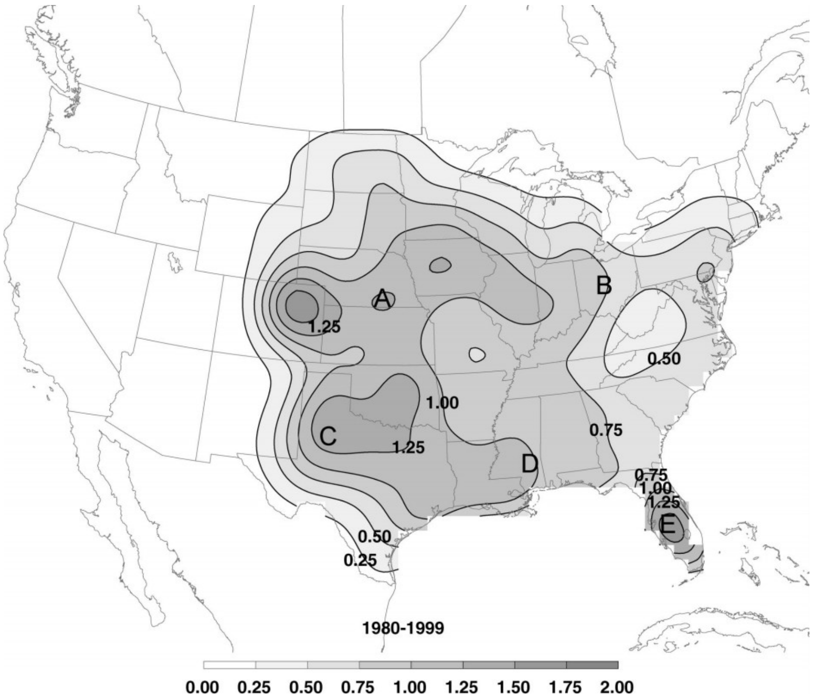


Figure 2.2 Tornado days per year from 1980-1999 record (H. E. Brooks et al., 2003)

Given that many ports in Texas support chemical, petrochemical, and plastic polymer production supply chains, fires are a risk. In 2019, an explosion at a chemical plant in Port Neches, Texas forced the evacuation of surrounding communities, although it is currently unknown whether the fire was natural or man-made (Toal et al., 2019). In 1947, one of the largest non-nuclear explosions to ever occur on U.S. soil happened in Texas City, Texas when a vessel carrying ammonium nitrate fertilizer caught fire and detonated, resulting in over 500 deaths (*Hundreds Killed, Thousands Injured in Texas City Disaster of 1947*, 2020). While it is likely that the Texas City explosion was a man-made disaster, there are natural fire-causing mechanisms as well. Lightning strikes are the most common natural cause of forest fires, followed by fires in coal seams and other incidents (Narendran, 2001). Wildfires may indirectly impact port operations by disrupting the land-based intermodal infrastructure assets that link to the seaport. In 2016, the Blue Cut Fire in California led to the closure of several railroad routes and Interstate 15 through Cajon Pass, one of the main trucking routes into Los Angeles (Phillips & Calfas, 2016). Consequently, this led to freight bottlenecks for Southern California seaports and freight distribution centers. Texas is exposed to wildfires, especially in drought years. High temperatures and dry brush create an environment suitable to fires. Past wildfires have occurred throughout the state of Texas, although no major port disruptions have been widely reported due to these events.

Earthquakes and other seismic activity may disrupt ports as well. The 1989 Loma Prieta earthquake in California not only destroyed many roadway and railway structures but also directly impacted the four ports in San Francisco Bay. The Seaport of San Francisco faced an estimated $8-10 million in damages due to fill soil liquefaction resulting in differential settlement of piers (Schiff & Holzer, 1997). Several port owned buildings experienced structural damage and were condemned. The Seaport of Oakland experienced significant pier settlement from fill liquefaction, asphalt pavement uplift, damage to 23 container cranes, rail track displacements, and more. In all, the Seaport of Oakland incurred an estimated $75 million (Schiff & Holzer, 1997) in damages. While earthquakes have the potential to severely impact port functions, events similar to the 6.9 magnitude Loma Prieta earthquake are unlikely to occur in Texas. Earthquakes with magnitudes greater than 5.0 have only occurred in the Western and Panhandle regions of the state. A relatively small number of earthquakes have been recorded in the Gulf Coast region with magnitudes all under 5.0 (Frohlich, 2013). These quakes are primarily caused by petroleum production. Therefore, the Gulf Coast seaports of Texas are unlikely to be significantly disrupted by seismic activities.

Heavy fogs can impact port operations by limiting visibility. This is a common occurrence on the Texas Gulf Coast from October to March as interactions between warmer sea air and cooler land air are conducive to fog formation. In 2018, the Port of Houston reported 537 closure hours due to fog ("Fog Delays Houston-Area Ports for Seventh Day," 2019). Fog disruptions may be costly, yet current models for fog formation are relatively inaccurate for visibility prediction as fog micro-physics are not fully understood (Gultepe et al., 2009).

2.2 Vulnerability and Risk Analysis of Port Systems

The operational continuity of ports is critical because of the growing reliance of domestic and international trade on ports and their significance in the growth of national and international economies. This increasing dependence of the economy on port operations has also become a concern in recent decades. Maritime transportation systems are identified as one of the vital infrastructure systems by the Presidential Policy Directive 21 (Office of the Press Secretary, 2013) that are critical for security, national economic security, and national public health or safety. Extreme weather events pose severe threats to ports and associated infrastructure due to their proximity to the oceans and rivers. The physical and operational impacts of extreme weather events are not only dependent on the geographical exposure of the events but also the intrinsic shortcomings of the port in mitigating such impacts which are otherwise known as port vulnerabilities.

2.2.1 Assessment of Physical Vulnerability and Risks

For port operations, business continuity is ensured only if all physical, organizational, human, and economic components of ports are maintained at acceptable levels of functioning during and immediately after an event. However, the most important among these components is the physical infrastructure, which has the highest susceptibility due to its direct exposure to extreme weather events. Several studies have been performed to identify the physical vulnerabilities of port systems. Prominently among them is Arnold et al. (2006), which identified the following major vulnerabilities to be addressed in port resilience programs:

- Loss of shipboard and intermodal cargo handling equipment;
- Loss of terminal/port access/egress routes;
- Loss of terminal storage space;
- Loss of navigable channel clearances (channel depths);
- Loss of navigation support vessels;
- Damage to port servicing truck, rail, inland barge, or pipeline assets;
- Loss of on-dock storage space;
- Loss/damage to within and outside port communications;
- Loss/damage to cargo/container/vessel tracking/security systems;
- Utility (power and/or water) system failures;
- Loss/lack of waste and debris removal assets;
- Lack of availability of transportation fuels;
- Lack of availability of financial resources;
- Lack of availability of labor; and
- Uncertainty/lack of coordination among responding agencies.

The above vulnerabilities may lead to disruptions to port operations and tremendous direct and indirect economic risks. Along with vulnerability analyses, estimating physical and economic risks of extreme events on the port system also need adequate focus. Physical risks are expressed in terms of functionality losses and physical damages. The HAZUS-MH software developed by FEMA (Schneider & Schauer, 2006) can undertake such analyses. In this model, physical losses are expressed in terms of the loss of functionality using fragility curves. Fragility curves link the hazard exposure (wind speed, permanent ground deformation, etc.) to the probability of physical damage based on the structural material and construction characteristics of infrastructures.

Regarding infrastructure physical risk assessment, the U.S. Department of Transportation (USDOT) conducted an extensive two-phase study of the impacts of climate change to the Gulf Coast Region transportation assets (Federal Highway Administration, 2019). In the first phase, the study focused on a regional area stretching from the Ports of Houston and Galveston in Texas to Mobile, Alabama. One of the aims of the study was to analyze the viability of using climate data and projections to assess the impact on transportation assets due to climate change. One of the key findings of the study was that extreme weather events could increase in intensity and that ports are highly sensitive to more intense storm surge and precipitation. The second phase comprised a case study application of the city of Mobile, Alabama. The study analyzed the potential increase in storm surge, winds, and precipitation, among other factors, and their impact on transportation modes, including ports. The researchers analyzed 11 storm scenarios using Hurricanes Katrina and

Georges as base storms. The study assessed the criticality and vulnerability of transportation assets. The study concluded that the port and marine system is highly vulnerable to storm surge.

The physical risks of extreme weather events can be estimated using software packages, such as HAZUS-MH. To assess risks, this software requires study region, hazards information (lists of hazards of interest, hazard profile, and hazard map), and infrastructure inventory data (tables and maps of the inventory data). Since detailed port inventory is not available in HAZUS-MH, additional port-related data may need to be incorporated for analysis.

Several other studies have investigated the physical vulnerability of port infrastructure using various quantitative and qualitative methods. A few of them are presented in Table 2.3.

2.2.2 Assessment of Economic Vulnerability and Risks

The physical disruptions to port infrastructure or supporting infrastructure can incur direct costs to the port agencies and indirect costs to port dependent industries and nearby communities. Quantifying economic risks in a common unit (mostly in US$) could help not only in planning risk-based resilience strategies but also in comparing various resilience alternatives and project prioritization. Economic vulnerability and associated risks highly influence a port's competitiveness, which is a measure of the port's ability to provide operational functions (Yuen et al., 2012). Studies on economic risks of ports can be broadly classified into two categories: (a) those which analyze port disruptions from the perspective of a single or group of supply chain(s) with a focus on a specific economic sector (Lam & Su, 2015); and (b) those which analyze port disruptions from the perspective of a port agency or a government, with an emphasis on the overall economic impacts to a region or a country, and with or without identifying sector-wise losses (Y. Zhang & Lam, 2015). The mitigation strategies that are developed in these two sets of studies are divergent: while the industry/supply chain-specific studies aim at minimizing the cumulative delays/losses incurred by that industry due to a port shutdown, the system-level analyses evaluate mitigation strategies that aim at reducing the total duration of shutdowns by improving resilience of ports and related infrastructure. Table 2.4 enlists some examples of studies that belong to the above two categories along with the specific evaluation methodologies used.

The most widely used frameworks for quantifying system-level economic impacts of port shutdowns are input-output models, gravity models, and computable equilibrium models (Lam & Su, 2015). Regarding the methods that focus on individual supply chain disruptions, multi-agent simulations and network models like Petri nets (Kano et al., 2014; Lam & Yip, 2012; Tan et al., 2015; Y. Zhang & Lam, 2016) and Bayesian networks (Garvey et al., 2015; Soberanis & Elizabeth, 2010) are commonly adopted.

Recently, (Wei et al., 2016) presented a detailed framework for evaluating the economic losses of port disruptions. Though the study mainly focused on the petroleum industry, the methodology can be extended to other industries that are dependent on ports. The framework broadly classified the economic risks under two heads, namely, microeconomic, and macroeconomic risks. Microeconomic impacts mainly deal with the cost incurred by port agencies and dependent industries due to revenue losses, cargo damages, import/export delays, etc. Macroeconomic costs are much more extensive and are related to the fall in commodity production, raw material, intermediate commodity shortage, etc.

Table 2.3 Physical vulnerability analysis studies specific to port infrastructure

Study	Objectives	Methods	Type of Hazard
(Kong et al., 2013)	Identify key port infrastructure elements vulnerable to climate change Determine the deterioration rates	Research site visits and workshops to determine critical infrastructure. Deterioration models combined with simulated models.	Long term changes in temperature and sea level
(Hsieh, 2014)	Investigate the risks of port failures by examining vulnerable features. Develop risk maps based on loss potential.	Vulnerability assessment using the concept of transportation diversity. Risk maps created using GIS to demonstrate analytic results.	Hurricane and tsunami
(Shafieezadeh & Ivey Burden, 2014)	Propose a probabilistic framework for resilience assessment of infrastructure systems. Uses framework to examine seaport resilience regarding seismic activity.	Scenario-based framework for seismic resilience of a hypothetical seaport.	Earthquakes
(John et al., 2016)	Develop a quantitative risk assessment model for ports using Bayesian Networks (BNs) Identify the major causes of seaport disruptions.	Implemented Bayesian framework for resiliency. Conducted interviews with 3 experts with extensive maritime knowledge to determine seriousness of a specific failure. Sensitivity analysis to determine influence of specific nodes.	Generic
(Chhetri et al., 2015)	Examine the impact of extreme weather events and rising sea levels on port operations and infrastructure.	Key operational assets identified and referenced on a DTM. Perceptions of threat of extreme weather on port operations were evaluated. Visual outputs were developed to give ability to respond to risks.	Sea level rise, flooding

Table 2.4 Examples of port-centric and supply chain-centric studies focusing on economic impacts of port disruptions

Type	Study	Shutdown reason	Method for analysis	Economic impacts analyzed
Port-centric studies	(Y. Zhang & Lam, 2015)	Extreme wind events	• Regression model for predicting cyclic and trend components of terminal throughput. • Historical climate data to identify port shut-down days.	Direct loss to reputation, shippers, carrier, and port.
	(Pant et al., 2014)	Generic	• Direct delays using discrete-event queuing model. • Interdependent effects using multi-regional input-output model.	Port-level and industry-specific economic loss
	(Rose & Wei, 2013)	Generic	• Input-output model. • Various resilience strategies evaluated assuming 90-days shutdown.	Port-level (direct) and economic (in-direct) losses
	(Jung et al., 2009)	Labor dispute	• International-Trade Inoperability Input-Output Model.	Impact on U.S. gross trade economy and domestic output
	(Rosoff & von Winterfeldt, 2007)	Simulated terrorist attacks	• Scenario generation and pruning, project risk analysis, direct consequence modeling and indirect economic impact assessment.	Human health and direct economic costs.
Supply chain-centric studies	(Y. Zhang & Lam, 2016)	Generic	• Petri net models to model supply chains. • Evaluated effect of mitigation strategies (optimal inventory control) using simulations.	Sector-wise economic loss of industry clusters.
	(Loh & Thai, 2015)	Supply chain disruptions like port strikes and congestion	• Simulations using additive models	Supply chain management costs including production costs, warehousing cost, and transportation costs.
	(Lewis et al., 2006)	Generic	• Markov Decision Process	Increase in costs for supply chain management.

14

2.2.3 Port and Supporting Infrastructure Resilience Metrics

For characterization and quantification, Bruneau et al. (2003) suggested that infrastructure resilience can be represented using the following four dimensions (properties):

- Robustness, which refers to the ability of a system or a component to endure a given level of stress, shock or demand without consequences on its level of functioning.
- Redundancy, which is the ability of the system to satisfy its functional requirements and achieve stated goals by substituting its elements of the system itself in the event of disruption, degradation of loss of functionality.
- Resourcefulness, which is defined as the ability of the system to recognize failures in the system, prioritize restoration activities, and mobilize resources during conditions that threaten to disrupt the functions of the system.
- Rapidity, which is the capacity of the system to recognize problems and mobilize resources to contain and avoid further losses due to an external stress in a timely manner.

The above 4 R's framework can be adopted to measure the resilience of port systems. The resilience of port systems is the combined technical, organizational, social, and economic capabilities that could reduce the total physical damages, minimize downtime and recover to pre-disaster operational efficiency quickly. The NCFRP Report 30 (Southworth et al., 2014) identifies all such actions for mitigating the effects of extreme weather events on maritime transportation into three categories:

1. Prior actions adopted for avoiding or limiting the impacts of the disruption (preparedness)
2. Actions taken to deal with the immediate impacts of the disruption (response)
3. Actions taken for minimizing the downtime of ports and resumption of normal operations (recovery)

The above three categories of actions can be improved through planning, redundancy, and flexibility. Planning helps to prepare for disruptions and enhance response efficiency. Redundancies are duplication in the port system to facilitate continued operations and throughput during or immediately after port disruptions. Flexibility, on the other hand, is the ability of the port system to redistribute system operations for handling normal commodity flow during an event. The methods and tools used for evaluation must encompass the above capabilities of ports reflective of their overall resilience to extreme weather events.

In 2017, the FHWA sponsored a multi-year project to assess the resiliency of transportation systems in the New York/New Jersey after Hurricane Sandy (Sietfhoff et al., 2017). Compared to the previous Gulf Coast resilience study that conducted analyses based on hypothetical scenarios, this study analyzed the resilience based on the recorded impact of historic extreme weather events, such as Nor'easter Alfred (2011), Tropical Storm Lee (2011), Hurricane Irene (2011), and Hurricane Sandy (2012). Furthermore, this study used historical data on disruptions to simulate future scenarios. Extensive data regarding transportation disruptions during the selected extreme weather events was collected. The study was conducted at three levels. The first level was at a regional level, where the assessment of exposure of transportation systems to extreme weather events was analyzed. The second level was more localized, analyzing vulnerability and risk assessment of specific corridors and a coastal network. The third level consisted of a selection of facilities for engineering assessments of resiliency. One of the facilities selected was the Port Jersey Marine Terminal, in which the greatest hazards were the sea-level rise and storm surges. The most affected critical components at Port Jersey were electrical installations. The study highlighted the importance of conducting the resilience study at different levels, and how disruptions from recent events can better assess the current resiliency of the system.

When port systems consist of multiple major ports which are distributed over large geographical regions, such as the Gulf Coast, comparing the resilience of individual ports may be of interest. Such an exercise could reveal the weak components in the system, whose resilience could enhance the system resilience significantly. From a stakeholder's point of view, the metrics must reflect the practical realities of port resilience and should be valuable in indicating the vulnerabilities. This needs adequate consideration of different aspects of port resilience. One such resilience metric that was recently developed is the Port Resilience Index (PRI) developed by the Gulf of Mexico Alliance (Morris, 2017). The Port Resilience Index (PRI) is a self-assessment tool developed for aiding port and marine industry stakeholders for evaluating the resilience of ports along the Gulf of Mexico coast. The tool considers a wide range of resilience aspects concerning the ports and scores them accordingly to evaluate the overall resilience of ports. Table 2.5 enlists the major resilience indicator categories considered in the development of PRI and their respective objectives in the resilience assessment.

The key advantage of PRI is that it indirectly considers all four dimensions of resilience–namely robustness, redundancy, rapidity, and resourcefulness–from technical, organizational, social, and economic perspectives. Hence, from the stakeholders' point of view, the PRI is more effective than other available port resilience metrics which focus only on a subset of resilience characteristics. However, the PRI is intended to be used by port authority stakeholders for a "rough" assessment of the current port resilience status using yes/no questions and the final score is given as number ranging from 0 to 100. This results in a simple assessment that uses no numeric inputs and a final score that may not directly indicate the resilience areas that most need to be targeted for improvements. Therefore, there exists a need for a new port resilience assessment metric capable of providing a more in-depth score that relies on a multitude of input question formats and types.

Several additional metrics have been developed for quantifying resilience of port infrastructure components as well as other infrastructure systems that support port operations. A summary of such metrics is presented in Table 2.6.

Table 2.5 Resilience indicator categories considered for developing PRI by Gulf of Mexico Alliance

Resilience Indicator Category	Objective
Planning documents for hazards and threats	Evaluate the ability to streamline procedures for responding to an extreme event
Hazard assessment: Infrastructure and assets	Assess all hazards and risks to facilities an infrastructure
Insurance and risk management	Assess if ports have the right property insurance strategy based on hazard and risk assessment
Continuity of operations planning for infrastructure facilities	Improve response and recovery by considering appropriate pre-storm measures
Internal port authority communications	Ensure robust and sustainable communications are in place for port employees for times of crisis and normal operations
Emergency operations location	Evaluate the ability and preparedness of run and maintain emergency operations by itself
Critical records and finance	Determine the strategies to address vital records, payroll, emergency spending, and banking during emergencies

2.2.4 Best Practices for Port Resilience Enhancement

Resilience is an emerging field, with academic research first arising in the mid-2000s. Implementation in public-sector, long-term infrastructure planning is still not widespread, although the trend is beginning to catch on in some localities. As such, gaps in understanding exist regarding specific physical or operational improvements that may best improve resilience.

Academic studies assessing resilience perceptions via surveys among port stakeholders have found that resilience measures are implemented differently. Becker & Caldwell (2015) found that port authorities and state government agencies are the stakeholders most able to affect changes in resilience. Port authorities may improve resilience through construction of more robust facilities and implementation of thorough emergency management plans. State agencies may enact resiliency practices through governance measures such as construction standards or land use codes. Becker & Caldwell (2015) state, "The maritime transportation infrastructure system should be considered as a whole to prevent a “weak link” effect of losing one component (e.g., the rail link) while other parts of the system are built to an increased resiliency standard." Owing to the complexity of maritime transportation systems, resilient port components, individual ports, and port systems are needed to create overall port resilience (Rice & Trepte, 2012). Through a survey, Rice and Trepte report that improving "communication/information systems and flexible labor agreements" were selected by port stakeholders as the two most important measures to increase resilience. It is worth noting that these actions describe operational processes, which are relatively flexible to implement in comparison to the construction of physical redundancies.

Table 2.6 Selected metrics used for quantifying resilience of maritime infrastructure systems

System	Study	Resilience Metric	Factors Considered	Methodology
Port	(Pant et al., 2014)	(a) Time to total system restoration, (b) time to full system service resilience, (c) time to α×100% resilience	Incoming and outgoing commodity flows, unit handling capabilities.	Discrete event simulation/queuing model
Port	(Touzinsky et al., 2018)	(a) Net vessel count, (b) cumulative dwell time	Incoming and outgoing vessel counts, vessel dwell times	Data-driven, data from Hurricane Matthew
Port	(Hossain et al., 2019)	Port performance measure	Port facility, port availability, port economics, port service, port connectivity, and port environment	Bayesian network
Comms.	(Ibrahim, 2018)	Level of resilience	Percentage of traffic dropped, reduction in quality of service, recovery time.	*Opnet Modeler*
Transportation	(Chen & Miller-Hooks, 2011)	Network resilience indicator	Pre-disaster and post-disaster link capacity	Simulations
Transportation	(Ganin et al., 2017)	Average annual delay per peak-period auto commuter	Commuter load on road segments, traffic speeds, extent of impact	Trip distribution model
Energy	(Bagchi et al., 2009)	Load loss damage index	Total load lost, total duration of the event	Simulations
Energy	(Brancucci Martínez-Anido et al., 2012)	(a) Energy not supplied, (b) total loss of power, (c) restoration time	Extent of power disruption, shortage in generation, ability of network to restore	Data-driven

Operational processes provide efficiency to the system, while physical redundancies, typically in the form of capacity increases, are not beneficial until they are used. Therefore, Rice & Trepte (2012) state, "While the systems are deemed to be critical, the recommended actions are for improving the processes and not adding capacity to systems." In intermodal seaports, redundancy may entail investing in additional equipment such as cranes or maintaining a minimum number of open berths. Flexibility may entail training employees to be proficient at a multitude of tasks or adjusting gate operations to improve the flow of truck traffic into and out of the facility. The most cost-effective measures for port resilience improvements involve changes to increase port operation flexibility and robustness. Government agencies may instill resilience practices by including such measures in construction codes and long-term planning documents.

Practical implementations of resilience planning are becoming more commonplace. Historically, port authorities would not implement resilience measures until after a disaster had occurred. In recent years, some port authorities are taking a more proactive planning approach. Table 2.7 provides examples of strategies currently regarded as best practices for resilience. The Port of Long Beach, in California, created a Climate Adaptation and Coastal Resiliency Plan (CRP) (Port of Long Beach & AECOM, 2017). Primary objectives of the Port of Long Beach CRP were to identify port assets most vulnerable to climate change and possible strategies to protect said assets. Sea level and storm surge hazards were assessed to determine the vulnerabilities of the piers, transportation network, critical facilities, utilities, and breakwater of the port. After conducting a workshop with port staff, five resilience strategies spanning from governance to infrastructure improvements were determined. Governance strategies such as incorporating resilience measures into port planning policy and design guideline documents ensures that considerations of resilience are included from the conception of a project. Infrastructure strategies selected in the CRP are specific to the Port of Long Beach: shoreline protection and additional protection of an electrical substation. After analyzing several alternatives, the port authority decided to retrofit an existing seawall to protect against 36" of SLR and a 100-year storm surge. To protect the substation, it was decided to invest in a three-foot high, temporary floating barrier.

The Florida Ports Council (FPC) established resilience strategies such as identifying telecommunications and electric equipment as most vulnerable to SLR and implemented projects to waterproof and elevate these assets. The FPC also established the strategy of incorporating up to date SLR data with capital maintenance scheduled for the end of pier and dock design life. This ensures that scheduled capital maintenance projects will raise the elevations of vulnerable structures. The FPC states that this strategy is more cost-effective than major capital expenditures to immediately increase critical asset elevations (prior to the end of their design life) (Littlejohn Mann & Associates, 2019). Choate et al. (2014) performed analyses on vulnerable coastal infrastructure assets in Mobile, Alabama. From this, an 11-step framework to determine specific infrastructure improvements to reduce vulnerabilities was established. It was found that most port pier structures in Port of Mobile were designed to withstand lateral loading that is significantly higher than the those caused by storm surges. Hence, structural improvements are not typically necessary. However, equipment and assets on the port piers are vulnerable to damages from water inundation. This indicates that port improvements may not need to target pier structural capacity, but elevation raises or protective seawalls may be better options to increase port resilience.

2.3 Available Data Sources for Analysis

To conduct the vulnerability and risk analyses of ports for evaluating the expected losses from port damages and disruptions, the Performing Agency undertook extensive efforts to identify pertinent data sets. The data sets belong to four aspects of the analysis, namely port and supporting infrastructure, port trade, extreme weather-related hazards, and topography of the port region. Table 2.8 presents the list of the data sets identified under each category, and details related to their accessibility and procurement status.

Table 2.7 Port resilience best practices from selected studies

Source	Year	Location	Agency	Strategy	Measures
(The Port Authority of NY & NJ, 2018)	2015	New York, NewYork	Port Authority of NY & NJ	Governance	Implemented Climate Resilience Design Guidelines (CRG) incorporating port-specific measures into building codes and adopted ASCE Standard 24 (Flood Resistant Design and Construction)
(Port of Long Beach & AECOM, 2017)	2016	Long Beach, California	Port of Long Beach	Governance, Research, Physical	Comprehensive Climate Adaptation and Coastal Resiliency Plan (CRP) determined strategies from inclusion of climate change impacts in port policy and design guidelines to protective seawall retrofit and funding additional research into flood vulnerability
(Averett et al., 2014)	2014	Georgia	Coastal Regional Commission of Georgia	Governance	Assessed vulnerability in coastal regions of Georgia to integrate hazard assessment into the Regional Plan of Georgia for future long-term plans and design guidelines
(Littlejohn Mann & Associates, 2019)	2019	Florida	Florida Ports Council	Governance, Physical	Published Florida Seaports Resiliency Report to assess how Florida ports may increase resilience. Waterproofing/raising elevation of telecommunication and electric infrastructure identified as critical issues and scheduled capital dock rehab projects are designed with elevation increases to account for SLR and storm surge
(Kim & Ross, 2019)	1997	Rotterdam, Netherlands	Dutch Ministry of Waterways and Public Works	Physical	Constructed Maeslantkering, a vast floodgate protecting the Port of Rotterdam and surrounding infrastructure and communities from storm surges
(Choate et al., 2014)	2014	Mobile, Alabama	USDOT Center for Climate Change and Environmental Forecasting	Physical	Created 11-step framework for selecting specific infrastructure improvement projects to address coastal/port vulnerabilities such as bridge abutment retrofits, road re-alignments, and lateral loading improvements to shipping piers

Table 2.8 Selected data sources identified for vulnerability and risk analysis of port infrastructure

Data	Source	Proprietary	Content	Description	Link	Procured
Infrastructure	HIFLD	No	Major US Port Facilities	Point layer of general seaport locations in the US	Link	Yes
Infrastructure	HIFLD	No	Texas port facilities	Point layer of maritime infrastructure components in the US. Locations are based off aerial imagery	Link	Yes
Infrastructure	TxDOT	No	Texas Freight Highways	Texas Highway Freight Network as identified during development of the Texas Freight Mobility Plan 2017, SHP and ID data	Link	Yes
Infrastructure	TxDOT	No	Texas Railroads	Rail lines digitized from aerial photography, also contains data on owner and track type	Link	Yes
Infrastructure	TxDOT	No	Texas Pipelines	Snapshot of the Railroad Commission data on pipelines. SHPs and attributes of complete state pipeline data	Link	Yes
Infrastructure	HIFLD	No	US Electric Grid	US electric transmission lines, digitized as GIS layers from aerial photography	Link	Yes
Infrastructure	Port Authorities	Yes	Port Shapefiles	GIS layers of port-specific infrastructure components and boundaries	-	No
Trade	US Trade Online	No	Import/Export Data	Import/export data by commodity type for select Texas ports in annual amounts	Link	Yes
Hazard	NHC (NOAA)	No	Atlantic hurricane database	Six-hourly information on location, max winds, pressure, and size of all known tropical cyclones from 1851 to 2019	Link	Yes
Hazard	NOAA	No	Sea Level Rise Inundation	GIS data from online NOAA SLR viewer, shows SLR inundation from 0 to 10 m depths, also flood frequency	Link	Yes
Hazard	University of Texas Institute for Geophysics	No	Texas earthquakes >M3	Complete list of Texas earthquakes >M3 (1847-present)	Link	Yes
Hazard	NCEI (NOAA)	No	International Best Track Archive for Climate Stewardship (IBTrACS)	Most complete record of worldwide tropical cyclone best track data, dating to 1842. CSV and SHP files, contains location, time, intensity, etc.	Link	Yes
Hazard	Storm Prediction Center (NWS/NOAA)	No	Past tornado tracks and data (SVRGIS)	Tornado events from SPC severe weather database. Gives start/stop points of past tornadoes, intensity, etc.	Link	Yes

2.4 Summary

This chapter identifies key findings from a comprehensive review of relevant literature and potential data sources for use in later stages of the project. Major hazards with high exposure in coastal regions were assessed. Tropical cyclones are the most destructive storm events present in the Gulf Coast where Texas ports are located. Storm surges and water inundation damages port assets and disrupt normal operations. Sea level rise will exacerbate these issues and lead to more frequent nuisance flooding and king tide events. Other hazards that the Texas port system is exposed to includes tornadoes, wildfires, earthquakes, and fog events. GIS-based models and statistical methods are commonly employed to quantify natural hazard exposure.

Vulnerability of port systems is due to several factors, ranging from fragile physical infrastructure components, such as the cargo handling equipment, to operational reasons, such as a lack of available fuel or labor. Port stakeholders generally identify electric and telecommunications infrastructure as the systems most critical to operations. Vulnerability analyses also focus on estimating the economic risk of hazards. HAZUS-MH software is often used to model disaster risks and physical losses are expressed as losses of functionality from fragility curves which link hazard exposure to probabilities of physical damage. Probabilistic methods, empirical methods, and analytical methods are often used for vulnerability and risk analyses. Economic losses resulting from physical and operational disruptions, both direct and indirect, are further studied with a variety of models and methods.

Port resilience metrics seek to quantify the resilience of port systems with respect to disaster preparedness, response, and recovery. Resilience of port systems is the combined technical, organizational, social, and economic capabilities that could reduce the total physical and economic damages, minimize downtime, and recover to pre-disaster operational efficiency quickly. Studies indicate that previous port disruptions are useful to assess system shortcomings and resilience. Existing frameworks, such as the Gulf of Mexico Alliance's PRI, provide standard templates for qualitatively evaluating port resilience.

Current best practices for improving port resilience include governance measures, operational adjustments, and investments in physical improvements. Public agencies may influence resilience measures by creating new design standards and land use codes for coastal regions. Previous surveys with port stakeholders indicate that operational improvements may be preferred to physical improvements, when possible, as operational improvements are often more cost-effective and easier to implement. Physical improvements such as protective seawalls and elevation raises are also viable alternatives.

Chapter 3. Identify and Characterize Extreme Weather Events

3.1 Introduction

This chapter discusses the typical natural disasters that may impact the Texas Gulf Coast. Understanding the hazard exposure of coastal regions is vital for assessing the resilience of the Texas port system. As intermodal seaports are necessarily located at the intersection of sea and land, they are vulnerable to a myriad of both land-borne and sea-borne natural disasters. The specific disasters analyzed in this chapter are:

1. Tropical cyclones – encompassing tropical depressions, tropical storms, and hurricanes
2. Flooding – detailing storm surges and sea level rise
3. Tornadoes – relating to high-speed, rotational winds
4. Wildfires – detailing natural-origin wildfires
5. Earthquakes – relating to seismic movements

For each hazard, three subsections are provided. The first subsection is dedicated to describing the basic formation mechanisms and characteristics of the natural hazard. The second subsection describes the data sources used for hazard and exposure analysis. The third subsection details the results of the hazard analysis, including the spatial intensity and frequency of various natural hazards under consideration.

The scope of the hazard characterization is limited to the above hazards, as these events were identified as having the highest exposure on the Texas Gulf Coast in Chapter 2. A primary focus is given to tropical cyclones and flooding as these events are most devastating in a coastal environment.

3.2 Hazard Characterization

3.2.1 Tropical Cyclones and Hurricanes

Background

Tropical cyclones are rotational storm systems characterized by a low-pressure center, high wind speeds, and heavy rains. Tropical cyclones are referred to as hurricanes in the Atlantic Ocean. Other terminology used to describe tropical cyclones includes tropical depression, tropical storm, and sometimes simply cyclone. The main differentiation between a tropical storm and a hurricane lies in its wind speed: cyclones with wind speeds below 33 m/s (75 mph) are known as tropical storms and those with speeds over 33 m/s are referred to as hurricanes (Tannehill, 1956). Hurricanes and other cyclonic storms are immensely destructive as a result of their high wind speeds, torrential rainfall volumes which produce widespread flooding, and severe coastal water inundation resulting from amplified waves and storm surges (Peduzzi et al., 2012).

The National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center (NHC) is responsible for emergency assessment regarding tropical storms and hurricanes. The NHC provides forecasts for tropical cyclones and releases warning and watch notices. A "Hurricane Watch" is issued approximately 48 hours prior to the possible arrival of hurricane-level (>75 mph) winds while a "Hurricane Warning" is issued approximately 36 hours prior to the expected arrival of hurricane-level wind (National Oceanic and Atmospheric Administration, 2021). NHC releases Tropical Cyclone Forecast/Advisories periodically, which contains all current information on storm watches and warnings, cyclone location, intensity, and system motion. The Advisories also include forecasts for cyclone locations, intensities, and wind movements for the next 12, 24, 36, 48, and 72 hours. These Advisories are released every 6 hours, but intermittent updates may be released if a drastic change to the cyclone's behavior is detected (Lindell et al., 2007).

Tropical Storm Data Sources

For characterizing the tropical storm exposure to Texas coastal regions, the hurricane best track data for the North Atlantic Basin (Atlantic HURDAT2) provided by the National Hurricane Center was used. The HURDAT2 dataset contains six-hour information on the location, maximum winds, central pressure, and size of all recorded tropical cyclones between 1851 and 2019. Due to data reliability considerations, only the tracks dating from 1901 to the present day were used for this study. Figure 3.1 shows the track data contained in HURDAT2.

Tropical Storm Exposure Characterization

Tropical cyclones typically form between 5 and 30 degrees of latitude in the northern hemisphere and move from east to west. This places Texas in a susceptible location where tropical cyclone events are prone to occur. The Texas coast of the Gulf of Mexico has experienced many past cyclone storm events. The Galveston Hurricane of 1900 is considered to be the deadliest natural disaster in United States history, with an estimated 12,000 total deaths and 2,636 destroyed homes (U.S. National Park Service, 2019). In all, there were 66 hurricane events (Category 1 or higher) that made landfall in Texas between 1851 and 2006 (Islam et al., 2009). This number does not include the additional tropical storms and depressions that also impacted the Texas Gulf during this era. A study analyzing 105 years of storm data from 1901 to 2005 found that the return period for the Texas Gulf is approximately 3 to 5 years for events with tropical storm intensity or greater (Keim et al., 2007). Another analysis of historical hurricane data determined that, in any fifty-mile-long segment along the Texas Gulf coast, the frequency of hurricane occurrence is around once every six years (Roth, 2010). The relative frequency of tropical cyclones and the accompanying wind and flood characteristics place Texas intermodal port facilities at great risk.

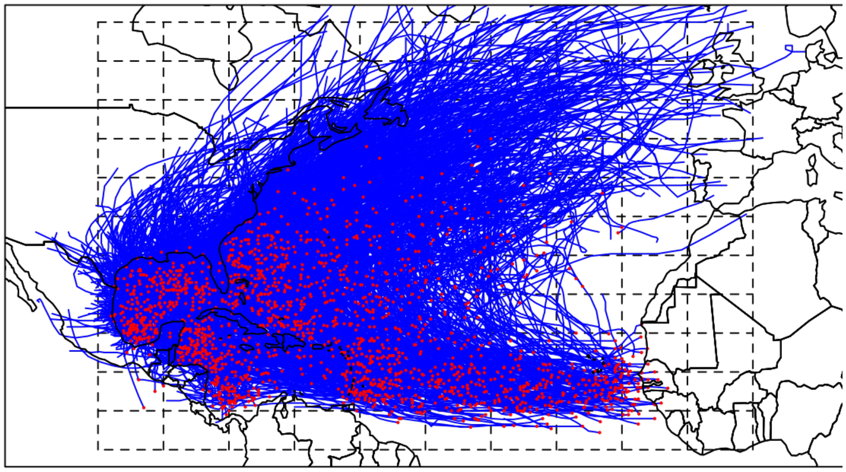


Figure 3.1 Tracks of tropical storms in the North Atlantic Basin as recorded in HURDAT2 dataset

For characterizing the exposure of tropical storms to coastal regions, two factors were considered: intensity and frequency of hurricanes. For intensity, hurricanes are classified into five categories using the Saffir-Simpson Hurricane Wind Scale (SSHWS). The scale is characterized by sustained wind speed, which was selected to provide a rough estimate for property damage likely to be incurred by a storm. The scale ranges from Category 1 (74 to 95 mph sustained wind speed) to a maximum of Category 5 (greater than 156 mph sustained wind speed) (National Hurricane Center, n.d.-a). At wind speeds greater than 156 mph, catastrophic destruction will occur to most built structures. The hurricane categories and corresponding wind speeds are presented in Table 3.1. The hurricanes in the HURDAT2 dataset (between 1901 and 2020) were classified into these five standard categories based on sustained wind speeds.

The next step was to characterize the return periods of hurricanes of various intensities. Keim et al. (2007) presents a framework for the calculation of tropical cyclone return periods for point locations. As per Keim et al. (2007), the cyclone return periods for storms of each SSHWS category may be determined for a point location by extruding the width of the storm and determining if the storm width intersects with the point. The National Hurricane Center (n.d.-b) states that a hurricane passing within 50 nautical miles (58 statute miles) of a point may be considered a strike.

This strike definition and methodology was adopted for the analysis of tropical storm return periods in the study. First, a 25 km (15.5 mile) grid of analysis points was generated in ArcGIS. This grid was clipped to cover the coastal region of Texas and the 25 km resolution was selected to ensure that the density of the analysis points would be adequate for capturing the intensity of each cyclone.

Table 3.1 Hurricane Categories based on Saffir-Simpson Wind Scale (Source: National Hurricane Center)

Category	Sustained Winds	Potential Damages
Category 1	74-95 mph	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap, and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
Category 2	96-110 mph	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
Category 3	111-129 mph	Devastating damage will occur: Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
Category 4	130-156 mph	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
Category 5	157 mph or higher	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Tracks from 1901 to present, within 50 nautical miles of an analysis point, were recorded as strikes. Attributes recorded for each storm were the storm name, year, unique storm ID, SSHWS category, and wind speed in knots. The strike data was then analyzed to determine the total number of strikes of each storm category at each analysis point. Finally, the return periods were calculated by dividing the length of the analysis period (119.6 years, from January 1901 through July 2020) by the count of each category of storms. Since return periods are exceedance rates, the return periods were calculated for the specified storm intensity and greater. For example, the Category 3 storm return periods represent the number of years expected for a Category 3 *or higher* hurricane event.

Return periods for cyclones of different intensities at specific locations are shown in Figure 3.2. The analysis points are spaced at approximately 100-mile intervals along the Texas Gulf Coast. While there is some variation in the return periods, each location is prone to experience a tropical cyclone of any intensity (tropical depression, tropical storm, or hurricane) around every 4 years. Hurricanes (Category 1 and greater) have a slightly larger return period, ranging from 7 to 10 years for the points shown. Major hurricanes (Category 3 and greater) are the rarest and have the largest return periods, with these events likely to occur every 20 to 40 years.

Figure 3.3 shows the results of the return period analysis. The minimum return period for a tropical cyclone of any magnitude is 2.5 years in Galveston. The occurrence of high intensity hurricanes (Category 4 and 5) are very rare and more frequent in the southwest Texas Coast.

3.2.2 Flooding

Background

Flooding is the submergence or inundation of land-side regions which are typically not submerged. In coastal areas, flooding is primarily caused by storm surges, mean sea level rise, extreme tides, or waves.

Storm surges form as a consequence of hurricanes. While low pressure contributes to the surge, the main driving force is wind speed, which creates an uplift of water that exceeds the typical, expected tide. The severity of a surge is dependent on many factors. Higher category (intensity) storms generally produce larger storm surges as they have higher sustained wind speeds. Storms with higher forward speeds (not wind speed, but rather how fast the storm travels along its track) also produce larger surges. Additional factors that affect the size of storm surges include the shape of the coastline, storm angle of approach, slope of seabed at landfall location, and tides. Storm surges that occur at high tide are much more devastating than those that hit at low tide as piers, docks, and cranes may become damaged. Landside port access infrastructure, such as roads, railways, and pipelines may be harmed from storm surge water inundation or erosion (*Storm Surge*, 2020).

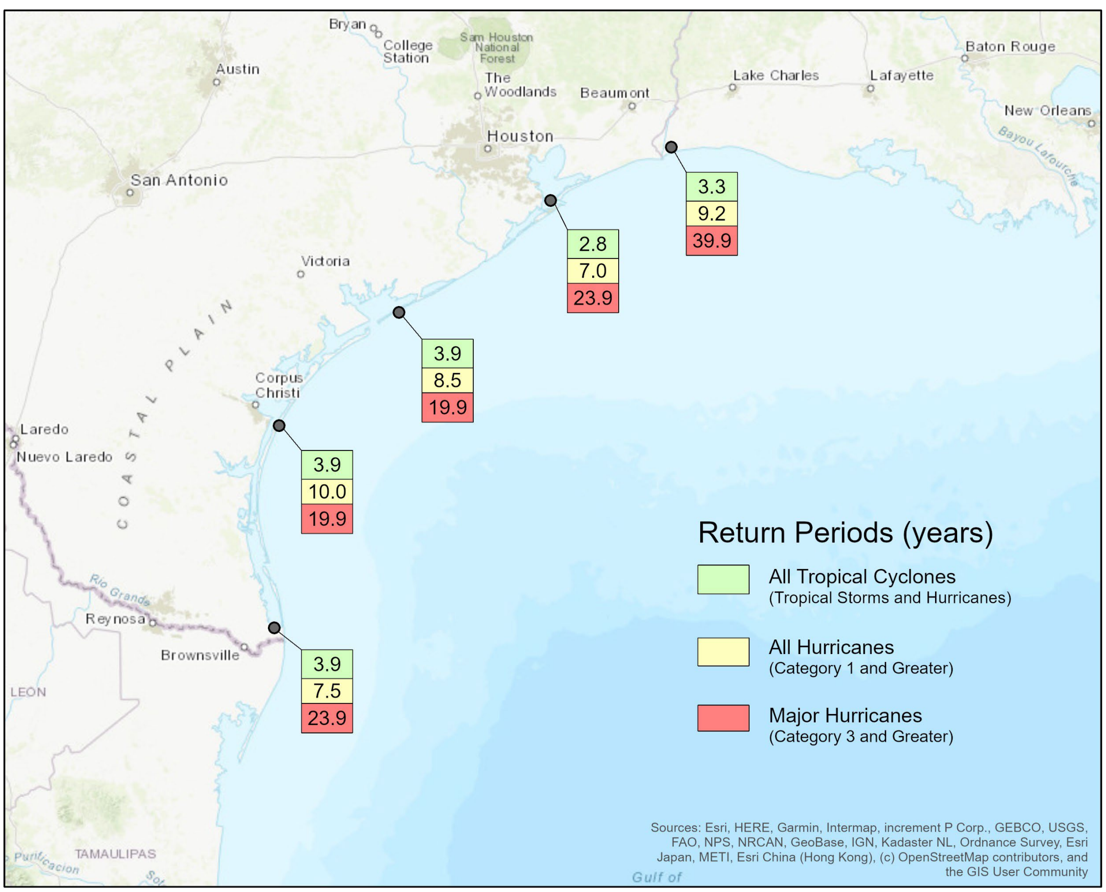


Figure 3.2 Return periods by cyclone intensity, January 1901 through July 2020

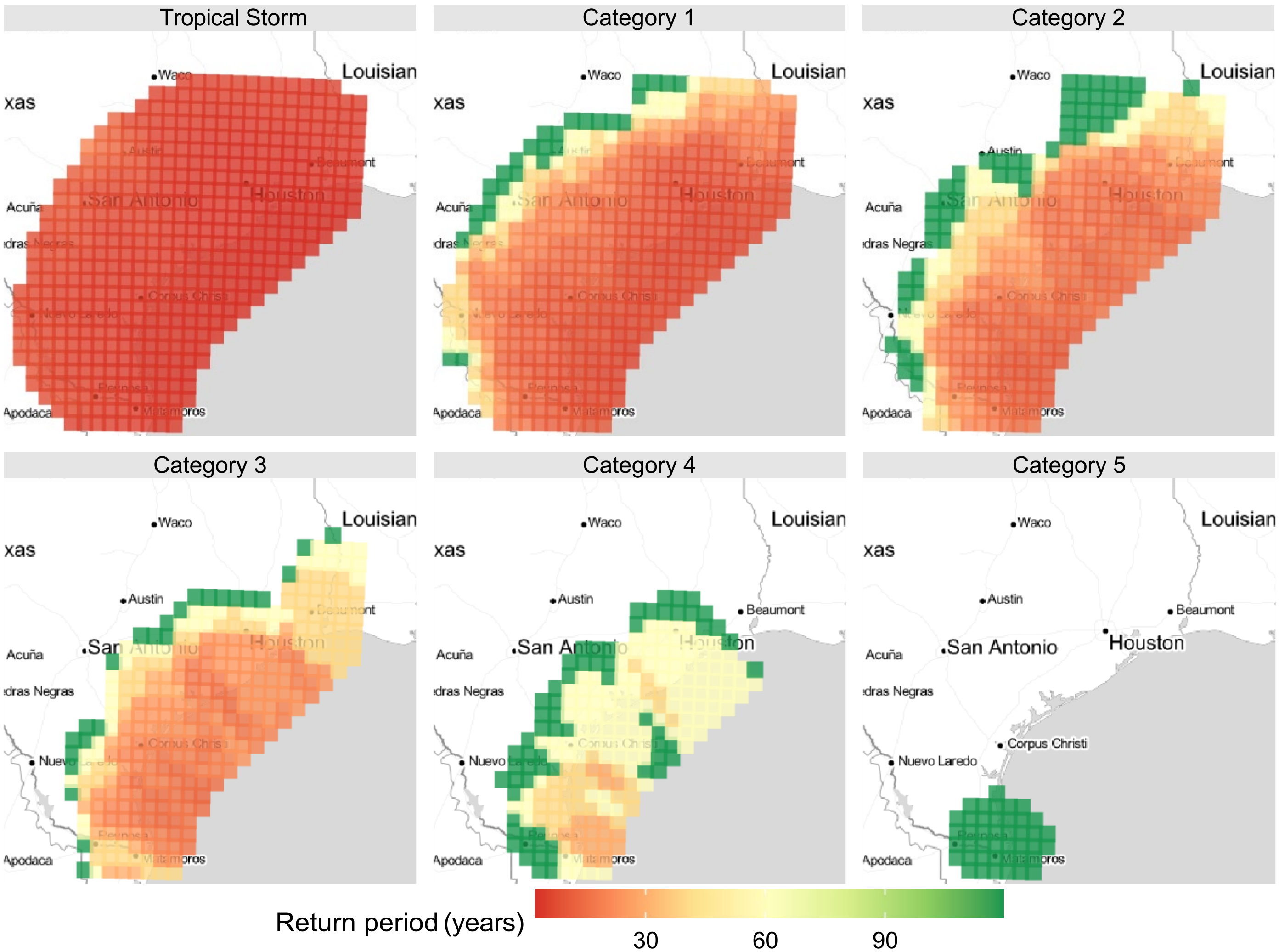


Figure 3.3 Estimated return periods of hurricanes of various intensities in different parts of Texas Coast

The expected sea level rise (SLR) impacts of climate change will exacerbate coastal flooding. As the average global temperature rises, sea water undergoes thermal expansion and land-based glaciers melt, releasing more water into the oceans. It is estimated that the Global Mean Sea Level (GMSL) has been rising at a rate of 4 mm/yr (Yi et al., 2015) and is expected to rise between 10-20 cm (4-8 inches) no later than 2050 (Vitousek et al., 2017). While these increments appear to be minor, the impacts may be wide reaching. High tide nuisance flooding will occur more frequently. According to Vitousek et al. (2017) coastal flooding events in tropical locations will double by 2050 under current SLR projections. Woodruff et al. (2013) states that SLR will result in increased extreme flooding in coastal regions and geomorphic changes (such as land subsidence) in populated areas will amplify storm flooding impacts.

Flood Data Sources

Flooding events analyzed for this study are storm surge events and SLR. The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model created by NOAA is used to simulate the flooding impacts of a selected intensity hurricane striking a specified location. Characteristics of an incoming storm are input and the model uses numerical-statistical methods to calculate and plot the predicted depth of water inundation along the impacted coastline (Jelesnianski et al., 1992). Storm surge data was obtained from the NHC as high tide SLOSH model results for the U.S. east coast from Texas to Maine. This dataset provides rasters of estimated inundation depth along the shoreline for each hurricane category. For SLR data, files for the online NOAA SLR viewer were downloaded. The files contain depth rasters for 0-10 m of SLR at 1 m intervals for the Gulf coast of Texas.

Flood Exposure Characterization

Storm surges have no specific rating system as they are typically a byproduct of a hurricane event. This is commonly cited as one of the biggest issues with the Saffir-Simpson Hurricane Wind Scale (Kantha, 2006). As the SSHWS category is determined solely from sustained wind speed, it does not indicate the expected severity of the hurricane's storm surge, which is determined from several factors as described above. Warnings for storm surge prone locations and potential surge heights are included in the NHC advisories posted every 6 hours during the approach of a tropical cyclone. Given that Texas is exposed to hurricanes, storm surges are likely to occur. Significant storm surges have impacted the Texas coast in the past: the deadly Galveston Hurricane of 1900 had an estimated 15 ft storm surge that was responsible for a large portion of the destruction and fatalities. More recently, Hurricane Ike struck the northern Texas coast in 2008 with a storm surge of 22 feet. A recent analysis modeled the return periods of the US Gulf Coast for storm surge height (Needham & Keim, 2012). The results indicate that, along the Texas coast, the region from Houston to the Louisiana border is most susceptible to storm surges with a 10-year exceedance probability of around 2.5 m (8 ft). Figure 3.4 shows the SLOSH model estimate for high tide storm surge impacts for various hurricane categories.

Currently, the U.S. NOAA and Environmental Protection Agency (EPA) provide online mapping tools to estimate the impact of SLR of U.S. coastlines. While the impacts vary by local geography and tides, SLR simulation estimates from NOAA Technical Report NOS CO-OPS 083 states that, for the western Gulf of Mexico coasts, SLR, "is projected to be greater than the global average for almost all future GMSL rise scenarios" (Sweet et al., 2017). This shows that Texas will experience impacts from SLR and necessary focus must be given to SLR in future vulnerability analyses. Figure 3.5 shows inundation estimates for the Brownsville, Texas region for 0, 1, and 4-foot SLR scenarios.

3.2.3 Tornadoes

Background

A tornado is a rotating column of air that is in contact with the ground, originating in the sky from a convective cloud such as a thunderstorm (Snow & Wyatt, 1997). Temperature and pressure variations between different storm fronts result in an updraft of warm air. This vertical movement of warm air interacts with horizontal wind forces, causing rotation. The current record for maximum- recorded wind speed on Earth is from a 1991 tornado in Oklahoma, in which wind speeds of up to 135 m/s (300 mph) were measured using a mobile Doppler radar (Snow & Wyatt, 1997). It is primarily this high wind speed which causes the most destruction, and as such, a direct hit on an urban area can be very damaging (E. M. Brooks, 1949). While there is no currently accepted methodology for precise tornado prediction, local weather agencies and the National Weather Service (NWS) issue warnings based on detection, where a tornado is visually spotted or tornado causing activity is recognized from algorithmically identified mesocyclones and wind shear levels detected by Doppler radar (Durage et al., 2013). Typically, a large geographic area spanning multiple states is placed under a "Tornado Watch," and when a visual identification of a funnel cloud is obtained, a "Tornado Warning" is issued for the proximity, although this gives an average lead time (time from issuance of a Tornado Warning to impact) of only 13 minutes (Stensrud et al., 2009).

Tornado Data Sources

Tornado data was accessed from the NWS Storm Prediction Center (SPC). This data contains both table and GIS formats containing historical tornado reports. The data gives tornado paths and intensities as well as estimated losses and tornado length and width.

Tornado Exposure Characterization

In the U.S., Tornadoes are rated by their wind speed and impacted area. Ted Fujita, at the University of Chicago, created the first rating system in 1971, known as the 'F scale' (Fujita, 1971). The F scale categorizes tornadoes into six groups, from F0 (gale) to F5 (incredible). The F scale was adopted for use by the NWS in 1974 and used until 2007, when it was replaced by the Enhanced Fujita, or EF scale, which uses a similar rating system. The EF rating system was adopted to address several shortcomings of the F scale, namely expanding the types of damages to be considered for wind speed estimation as an attempt to achieve more accurate maximum wind speed estimates (Doswell et al., 2009). Table 3.2 details the EF scale used to rate tornado intensity.

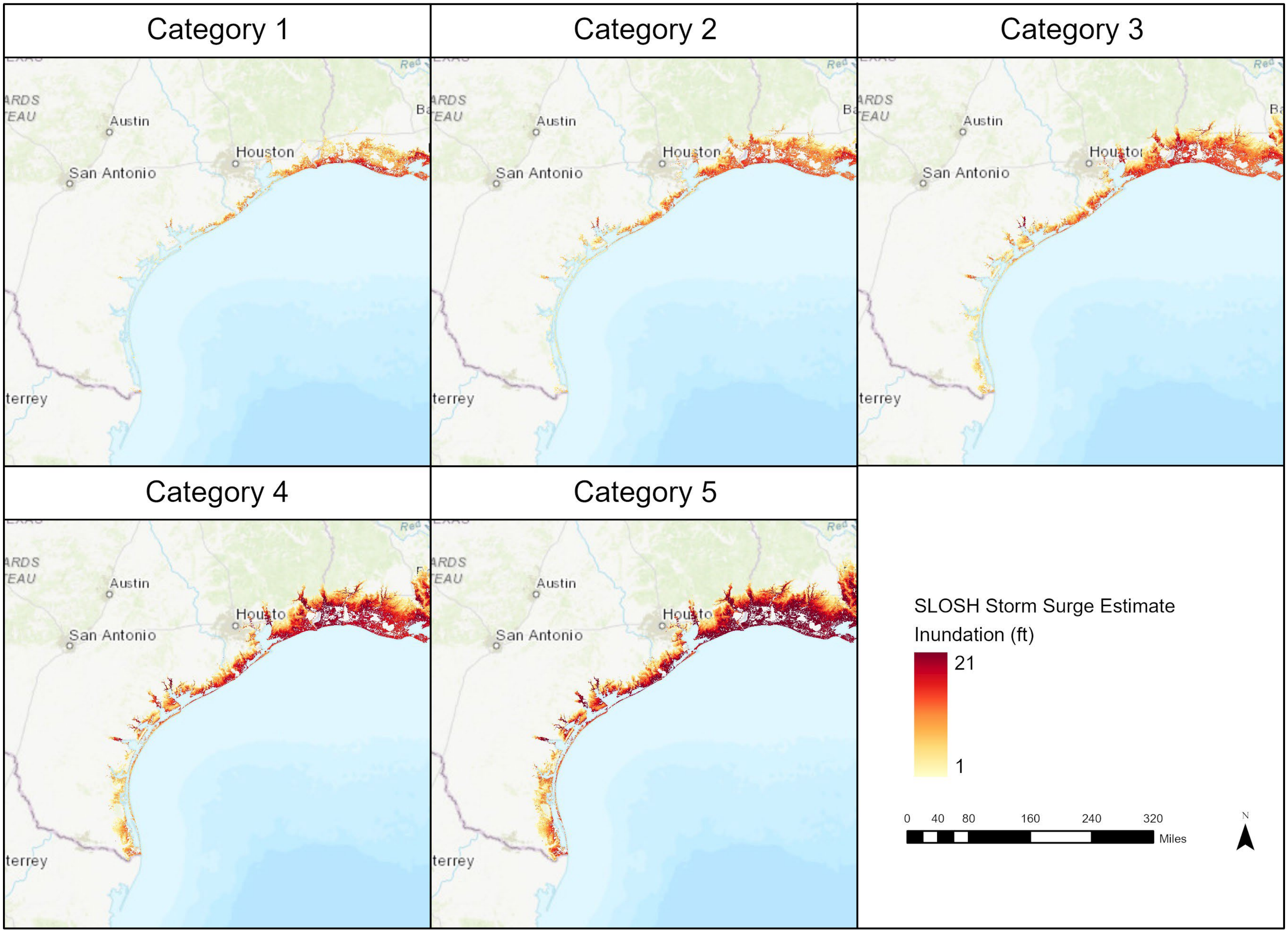


Figure 3.4 SLOSH model estimation of expected high tide storm surge for Texas coastal locations.

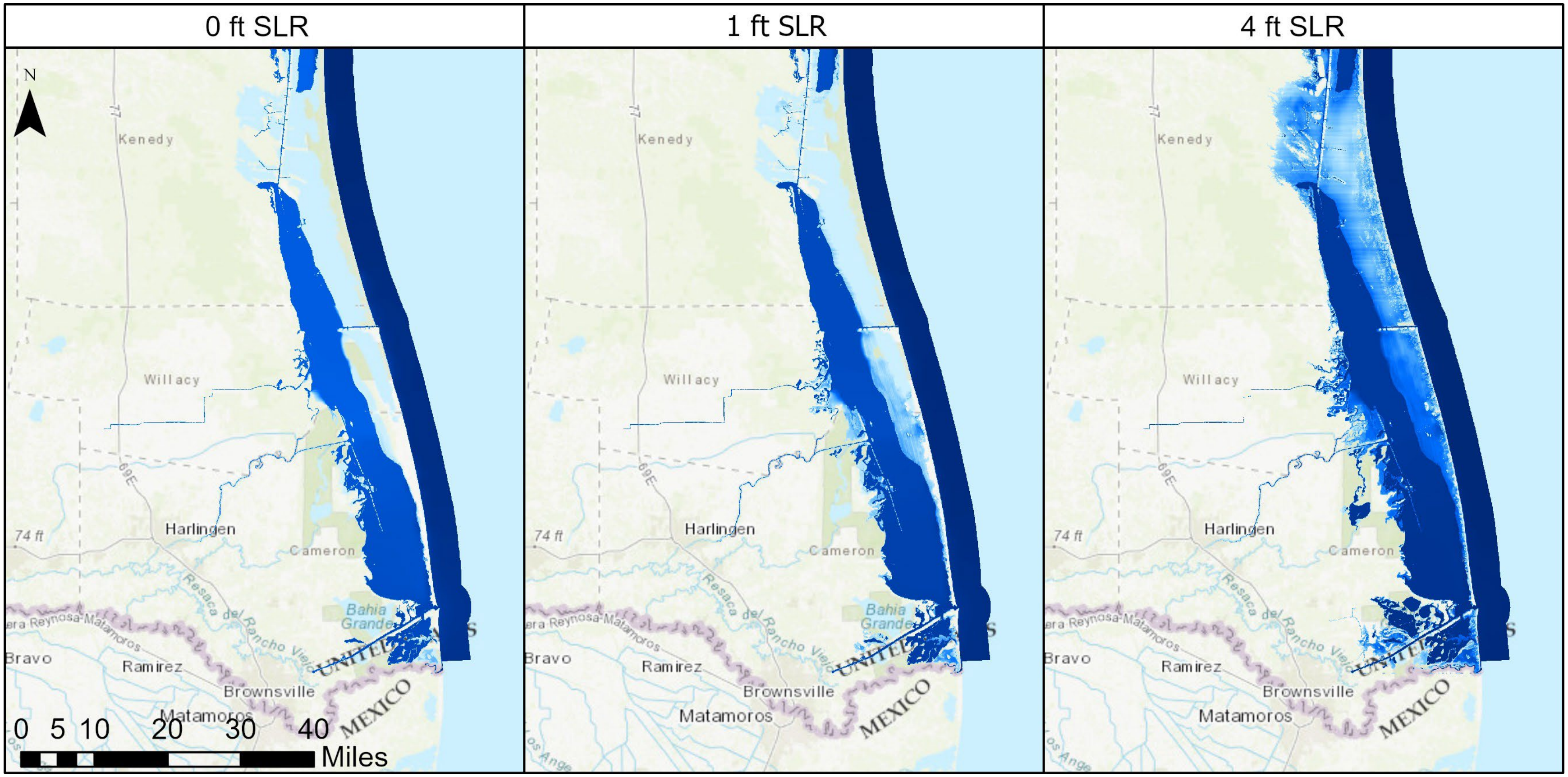


Figure 3.5 Inundation estimates for various sea level rise scenarios in southern Texas

While tornadoes may occur worldwide, they are most commonly found in North America, especially in the Great Plains region (Snow & Wyatt, 1997). The abundance of tornadoes in these states has led to the moniker “Tornado Alley.” While the exact location of Tornado Alley is continually debated, existing academic work examining all observed tornado events from 1921 to 1995 identified a region spanning from Texas to North Dakota, and as far east as Pennsylvania, to be most susceptible to tornadoes (Concannon et al., 2000). While Texas is included in most “Tornado Alley” regions, it is generally the northern and eastern areas of the state that experience the most frequent and severe events. Previous academic work has determined that, along the Gulf Coast, Jefferson County (containing ports at Beaumont, Port Arthur, and Port Neches) is the most vulnerable to tornadoes when societal indicators are combined with tornado frequency data (Dixon & Moore, 2012).

Table 3.2 Enhanced Fujita scale (National Weather Service)

EF-scale	Class	Wind speed (mph)	Description
EF-0	Weak	65-85	Gale
EF-1	Weak	86-110	Moderate
EF-2	Strong	111-135	Significant
EF-3	Strong	136-165	Severe
EF-4	Violent	166-200	Devastating
EF-5	Violent	> 200	Incredible

Tornado events are modeling using common statistical methods. Data is typically aggregated at the county level and expected occurrences are derived from historical tornado strike data. Typically, the expected number of strikes may be calculated as events per unit area (i.e., annual occurrences per 10,000 km) and presented per county (Elsner et al., 2016). Other common methods include the number of tornado days per year per county (Concannon et al., 2000). This representation accounts for storm events that spawn more than one tornado at a time. Other studies have focused on predictor variables including El Nino/La Nina (Northern/Southern Oscillation) impacts on US tornado occurrences. Elsner et al. (2016) found that, along the Texas coast, Brazoria County and the counties north to the Louisiana border have expected annual occurrences of between 2 and 4 tornadoes per 100 sq km. Galveston County has the greatest uncertainty regarding prediction, with a standard error of 0.9 tornadoes per year per 100 sq km. To portray the geographic distribution of tornadoes in Texas, kernel density estimation (KDE) techniques were employed with the SPC tornado data. Figure 3.6 displays the results of the density analysis. Northern regions along the Texas coast display a higher concentration of tornado events.

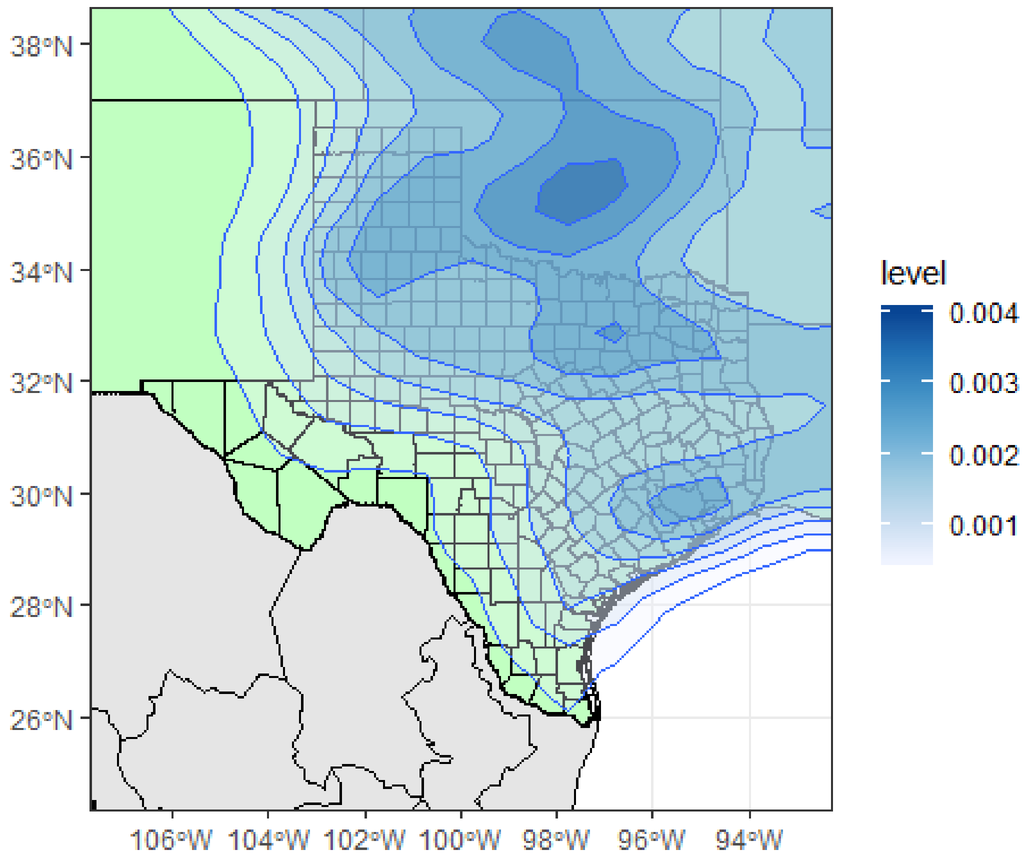


Figure 3.6 Texas reported tornado kernel density, 1950-2018

3.2.4 Wildfires

Background

Given that many ports in Texas support chemical, petrochemical, and plastic polymer production supply chains, fires are a risk. While the majority of wildfires are started from human-caused mechanisms, there are natural origin fires as well. Lightning strikes are the most common natural cause of forest fires, followed by fires in coal seams.

Wildfires may be characterized by the amount of land burned, type of vegetation consumed as fuel, or starting mechanism. Wet seasons followed by intense droughts are common climatic conditions conducive to wildfires. Soil moisture, heat waves, and El Niño oscillations also play a role in the creation of wildland fires. In recent decades, wildfires have become more prominent in North America and Australia as climate change alters traditional weather patterns and increases global temperatures.

Wildfire Data Sources

The National Interagency Fire Center (NIFC) coordinates fire response between the U.S. Forest Service, Bureau of Land Management, National Weather Service, National Park Service, Bureau of Indian Affairs, and the U.S. Fish and Wildlife Service. As part of its mission to strategically combat wildland fires, the NIFC maintains a public dataset of past fire perimeters. This dataset is composed of GIS files containing polygons of locations of past fires. Attributes for the data include the year, size, reporting agency, and occasionally the cause of the fire.

Wildfire Exposure Characterization

Texas is exposed to wildfires, especially in drought years. High temperatures and dry brush create an environment suitable for fires. Past wildfires have occurred throughout the state of Texas, although no major port disruptions have been widely reported due to these events. Figure 3.7 shows recent wildfires that occurred near the Texas coast. The region near Houston appears to be more heavily impacted by wildfire events, and Padre Island south of Corpus Christi has experienced significant burns.

Ports are prone to fire hazards themselves. In 2019, an explosion at a chemical plant in Port Neches, Texas forced the evacuation of surrounding communities, although it is currently unknown whether the fire was natural or man-made (Toal et al., 2019). In 1947, one of the largest non- nuclear explosions to ever occur on U.S. soil happened in Texas City, Texas when a vessel carrying ammonium nitrate fertilizer caught fire and detonated, resulting in over 500 deaths. Wildfires may indirectly impact port operations by disrupting the land-based intermodal infrastructure assets that link to the seaport.

3.2.5 Earthquakes

Background

An earthquake is the consequence of a sudden slip of a rigid block of land against another along a fault plane. Earthquakes occur due to several reasons, such as tectonic shifts, volcanic eruptions, explosions, mine-collapse, and reservoirs. The most common among the earthquakes are due to tectonic shifts. Earth's surface (lithosphere) consists of broken plates called lithospheric plates which are in constant motion due to dynamics in the earth's crust. The sudden movement in the lithospheric plates results in seismic waves which cause ground motion on the earth's surface.

In recent years, it has been found that earthquake intensity and frequency have increased in areas known for mining, dams, and petroleum extraction. The human-induced seismicity can be classified into four categories, namely, surface operations, extraction of mass from the surface, the introduction of mass into the subsurface and explosions.

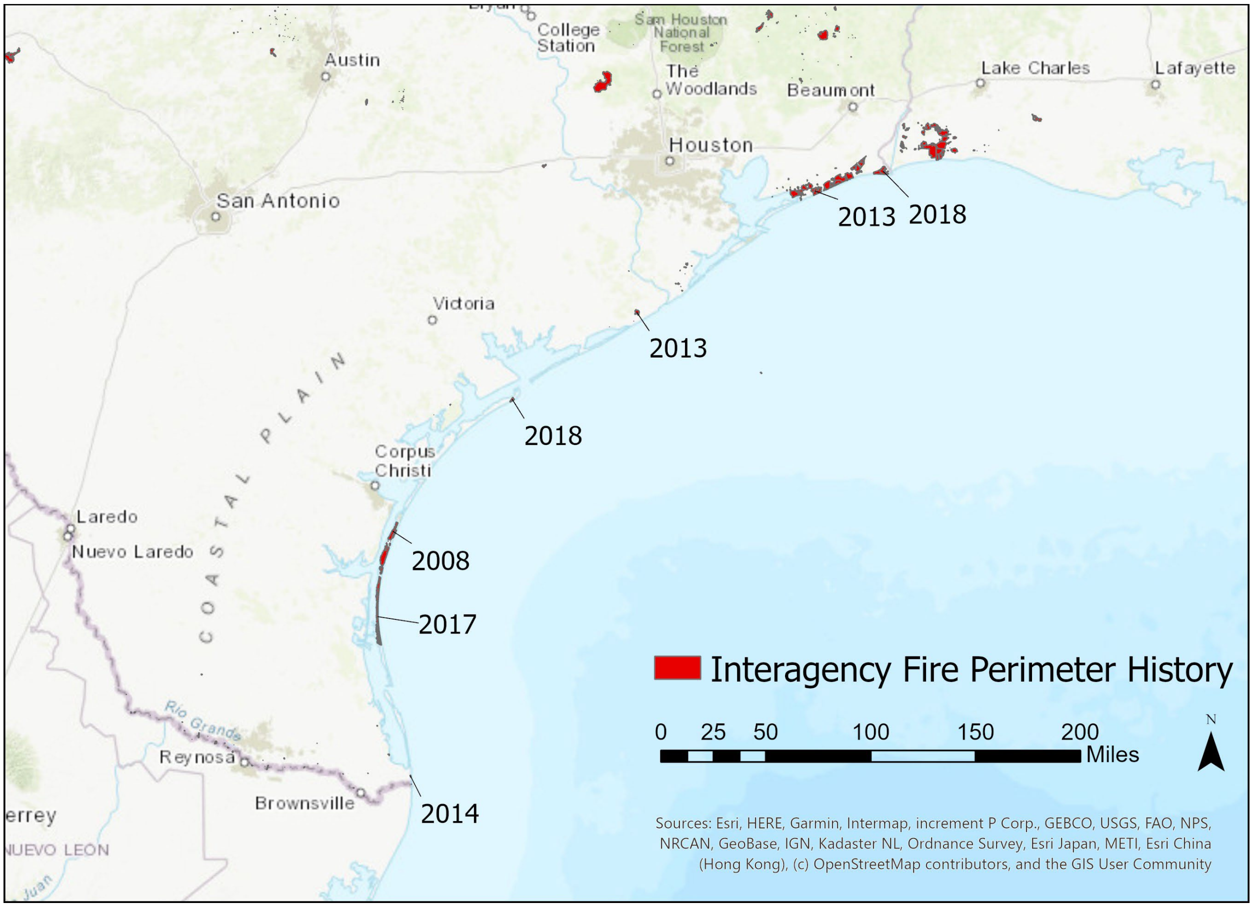


Figure 3.7 Recent wildfire events on the Texas coast, from NIFC

Earthquakes Data Sources

Data on Texas earthquakes was obtained from the UT-Austin Institute for Geophysics Texas earthquakes hazard website. The dataset contains records of all recorded earthquakes in Texas, dating to 1847. Attributes in the dataset include time, location, magnitude, and comments on reported damages and injuries.

Earthquake Exposure Characterization

The severity of an earthquake is measured in terms of its magnitude. The amplitude is often regarded as a standard as it is closely related to the energy dissipated during a hurricane event. The Richter scale developed by Charles Richter is the most widely adopted method for categorizing earthquakes. The Richter scale is logarithmic; therefore, an increase of one in magnitude represents a ten-fold amplification in the ground motion. Table 3.3 details the Richter scale system. In Texas, earthquakes are closely associated with activities related to petroleum production and those due to tectonic shifts are rare. The locations and magnitudes of earthquakes recorded in Texas between 1847 and 2013 are shown in Figure 3.8.

It was noticed that the magnitude of earthquakes in Texas are generally low (mostly belonging to Category 4 or lesser) and the majority are reported in the northern and western Texas. The earthquakes in the coastal region, which is of interest to the current study, are very rare. Therefore, characterization of earthquakes was not performed.

Table 3.3 Earthquake categories based on Richter scale (Encyclopedia Britannica)

Magnitude Level	Category	Effects	Earthquakes per Year
less than 1.0 to 2.9	Micro	Generally not felt by people, though recorded on local instruments	More than 100,000
3.0 - 3.9	Minor	Felt by many people; no damage	12,000 – 100,000
4.0 - 4.9	Light	Felt by all; minor breakage of objects	2,000 – 12,000
5.0 - 5.9	Moderate	Some damage to weak structures	200 – 2,000
6.0 - 6.9	Strong	Moderate damage in populated areas	20 – 200
7.0 - 7.9	Major	Serious damage over large areas; loss of life	3 – 20
8.0 and higher	Great	Severe destruction and loss of life over large areas	Less than 3

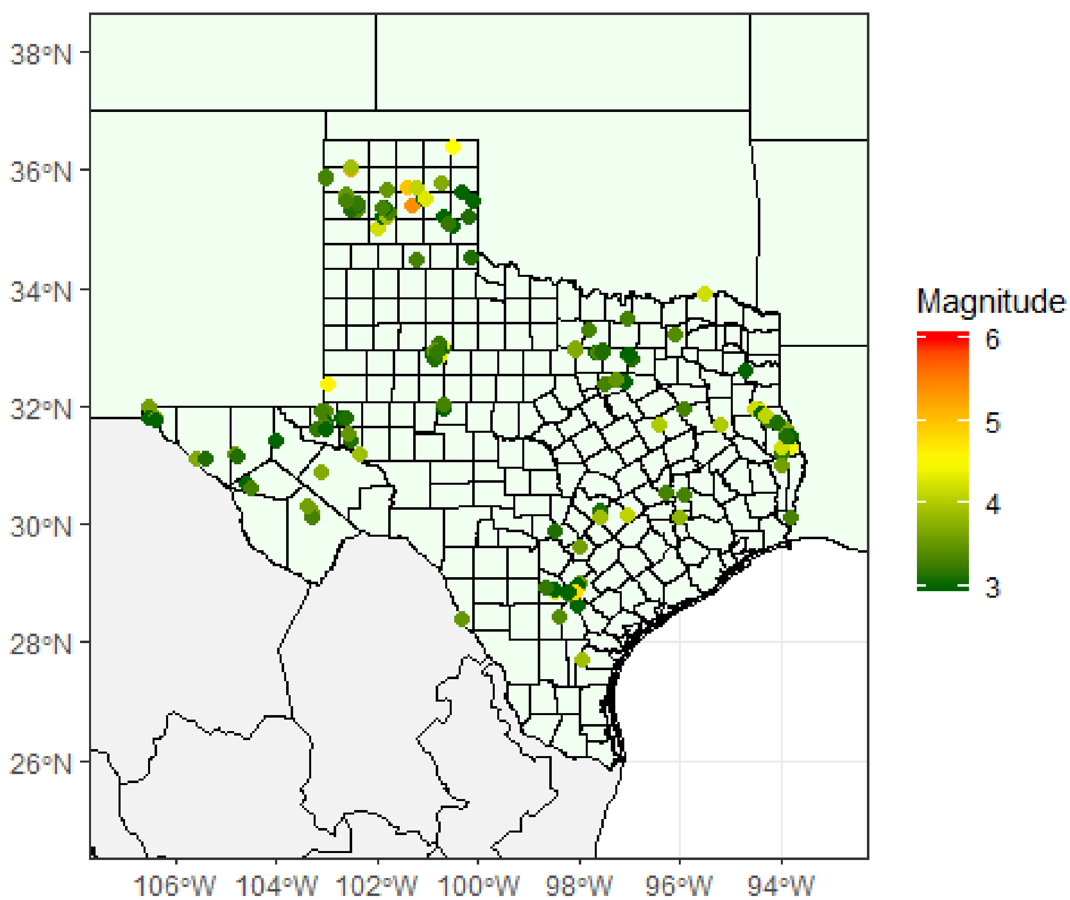


Figure 3.8 Recorded Texas earthquakes, 1847-2013

3.3 Summary

This chapter identified the major natural disasters that pose considerable threat to Texas. The notable natural disasters are tropical storms and hurricanes, storm surges and sea level rise, tornadoes, wildfires, and earthquakes. Among these, tropical storms, hurricanes, storm surges and tornadoes have significantly affected the coastal regions in the past. Therefore, their characterization in terms of magnitude and frequency was also performed.

As part of hazard characterization, at first, the data pertaining to occurrences of various hazards were retrieved from relevant databases and an integrated GIS database of the data sets was developed. Table 3.4 details the data sources used in this analysis. Later, historical occurrences of each hazard were analyzed, and their intensity and frequency were evaluated. To classify the disasters according to their intensity, standard classification methods were adopted. For example, for categorizing hurricanes and related storm surges, the well-known Saffir-Simpson scale was used. For characterizing the frequency of hazards, the concept of return periods was used. The intensity and frequency distributions will be used in the future project tasks for estimating the direct and indirect risks to ports due to the hazards discussed in this chapter.

Table 3.4 Hazard data sources

Hazard	Source	Content	Description	Link
Cyclone	NHC (NOAA)	Atlantic hurricane database	Six-hourly information on location, max winds, pressure, and size of all known tropical cyclones from 1851 to 2019	Link
Cyclone	NCEI (NOAA)	International Best Track Archive for Climate Stewardship (IBTrACS)	Most complete record of worldwide tropical cyclone best track data, dating to 1842. CSV and SHP files, contains location, time, intensity, etc.	Link
Flood	NHC (NOAA)	National Storm Surge Hazard Maps - V2	Extent of land exposure to storm surge resulting from various categories of hurricanes.	Link
Flood	NOAA	Sea Level Rise Inundation	GIS data from online NOAA SLR viewer, shows SLR inundation from 0 to 10 m depths, also flood frequency.	Link
Tornado	Storm Prediction Center (NWS/NOAA)	Past tornado tracks and data (SVRGIS)	Tornado events from SPC severe weather database. Gives start/stop points of past tornadoes, intensity, etc.	Link
Wildfire	National Interagency Fire Center	Wildfire perimeter dataset by National Incident Feature Service	Location and intensity details of wildfire incidents in the U.S.	Link
Earthquake	University of Texas Institute for Geophysics	Texas earthquakes >M3	Complete list of Texas earthquakes >M3 (1847-present)	Link

Chapter 4. Enhance Inventory of Port System and Supporting Infrastructure

4.1 Introduction

Understanding the existing port infrastructure in Texas and how it is connected to supporting infrastructure, as well as other utility systems, is vital for determining the threats that extreme weather hazards pose to the maritime trade system. Seaports are intermodal freight terminals, serving as a transfer point for items moving between land and sea transport modes. As such, the major infrastructure components of a seaport may be organized into two broad categories: maritime port facilities and landside systems, as shown by Figure 4.1. The landside infrastructure systems are dependent on major utility supply networks such as communications, water, electricity, etc. for their normal operations. The proper functioning of a seaport facility requires that all infrastructure assets are in satisfactory condition and provide sufficient access and connectivity.

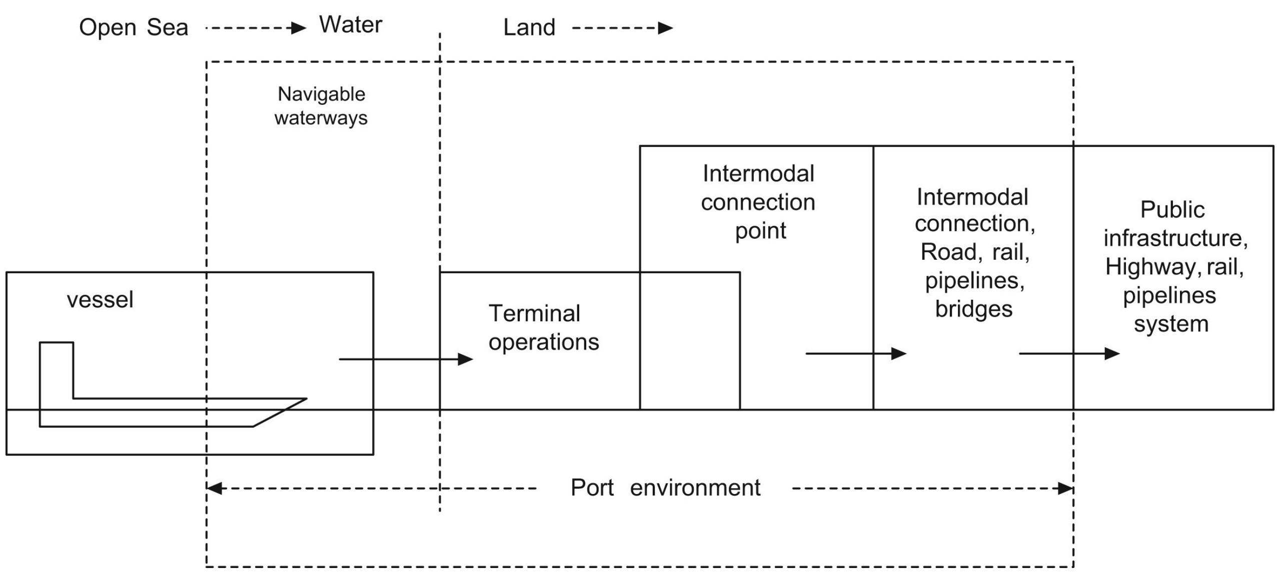


Figure 4.1 Typical components of a seaport, from (John et al., 2016)

This chapter serves to summarize the assembly of the port asset and trade dataset, created in ESRI ArcGIS Pro. This report is organized into three main categories: (1) port infrastructure, (2) supporting infrastructure, and (3) connected utilities. The port infrastructure section details the maritime navigation channels, port and dock equipment and operations, and trade data for ports in Texas. The supporting infrastructure section describes landside transportation modes that facilitate the movement of commodities in and out of the port facilities, such as freight highways, railroads, and pipelines. The connected utilities include the major infrastructure systems that provide basic infrastructure services that are required for the smooth functioning of the ports, such as electric grids. Within each subsection, basic uses and definitions are provided and existing facilities within Texas ports are summarized. Sources for all data used in this chapter are included throughout.

4.2 Port Infrastructure

Unlike other critical infrastructure systems, seaports are geographic regions with diverse physical infrastructure components to aid in the transfer of goods between land and sea. Key components at a port facility include berths, waterside access, channel, terminal, loading and unloading equipment, modal connections, and cargo/container storage and depots (Bureau of Transportation Statistics, 2017). The design and construction of the port structures and waterways are largely dependent on several factors, such as the type and size of cargoes and vessels handled at the port.

This section describes the key seaport infrastructure components by category and summarizes the inventory of Texas port facilities. The general methods employed to construct the database are provided and the data sources used to acquire all information are provided in each specific subsection. Also detailed is the general port information and trade volumes at each port.

4.2.1 General Information

For this analysis, the major deep draft and shallow draft ports in Texas were selected. Table 4.1 gives the port names, the project-specific Port IDs adopted for facility identification, port types, and principal port uses for the sites included in this study. The Port IDs will be used to link to additional port-related information throughout the database. The Texas ports are classified into various types based on their purpose, specifically breakbulk, bulk, container, cruise, energy, fishing, roll-on/roll-off (Ro/Ro), and vessel repair. Additionally, the U.S. Maritime Administration (MARAD) has designated the ports at Beaumont, Port Arthur, and Corpus Christi as strategic military ports in the National Port Readiness Network, meaning these sites support U.S. military mobilization for national defense purposes as a further typology. Figure 4.2 shows the location of ports and the navigation channels in Texas considered for the analysis.

4.2.2 Maritime Access

Access to port terminals from the water is limited by the depth of the approach channel and dock berth. To provide safe passage to shore for large vessels, the U.S. Army Corp of Engineers (USACE) excavates material through dredging to maintain navigable waterways. As sediment builds on sea and riverbeds, USACE is responsible for not only the initial dredging process but all routine maintenance dredging. Deep draft ports typically have navigation channels dredged to a depth of 30-45 ft, although the depth varies for each port. Deep draft ports can accommodate bigger vessels such as Panamax and Neo-Panamax cargo ships, cruise ships, and naval vessels. Therefore, deep draft ports generally serve larger cargo vessels used for international import and export trade. Deep draft ports also typically operate with higher trade volumes compared to shallow draft ports.

Table 4.1 Selected Texas port summarydetails

No.	Common Name	Port ID	Port Draft Type	Cargo Types
1	Beaumont	BPT	Deep	Breakbulk, Bulk, Energy, Ro/Ro
2	Brownsville	BRO	Deep	Breakbulk, Bulk, Energy, Fishing, Ship Recycling, Other
3	Calhoun	PCR	Deep	Breakbulk, Bulk, Energy
4	Corpus Christi	CRP	Deep	Breakbulk, Bulk, Energy, Ro/Ro
5	Freeport	FPO	Deep	Breakbulk, Bulk, Container, Energy, Ro/Ro
6	Galveston	GLS	Deep	Breakbulk, Bulk, Container, Cruise, Energy, Fishing, Ro/Ro
7	Houston	HOU	Deep	Breakbulk, Bulk, Container, Energy, Fishing, Ro/Ro
8	Orange	ORG	Deep	Other
9	Port Arthur	POA	Deep	Breakbulk, Bulk, Ro/Ro
10	Port Isabel	PIS	Deep	Bulk, Energy, Fishing, Other
11	Sabine Pass	NSS	Deep	Fishing, Recreation
12	Harlingen	HRL	Shallow	Bulk, Energy
13	Port Mansfield	RMV	Shallow	Bulk
14	West Calhoun	XLR	Shallow	Bulk, Fishing
15	Victoria	VCT	Shallow	Bulk

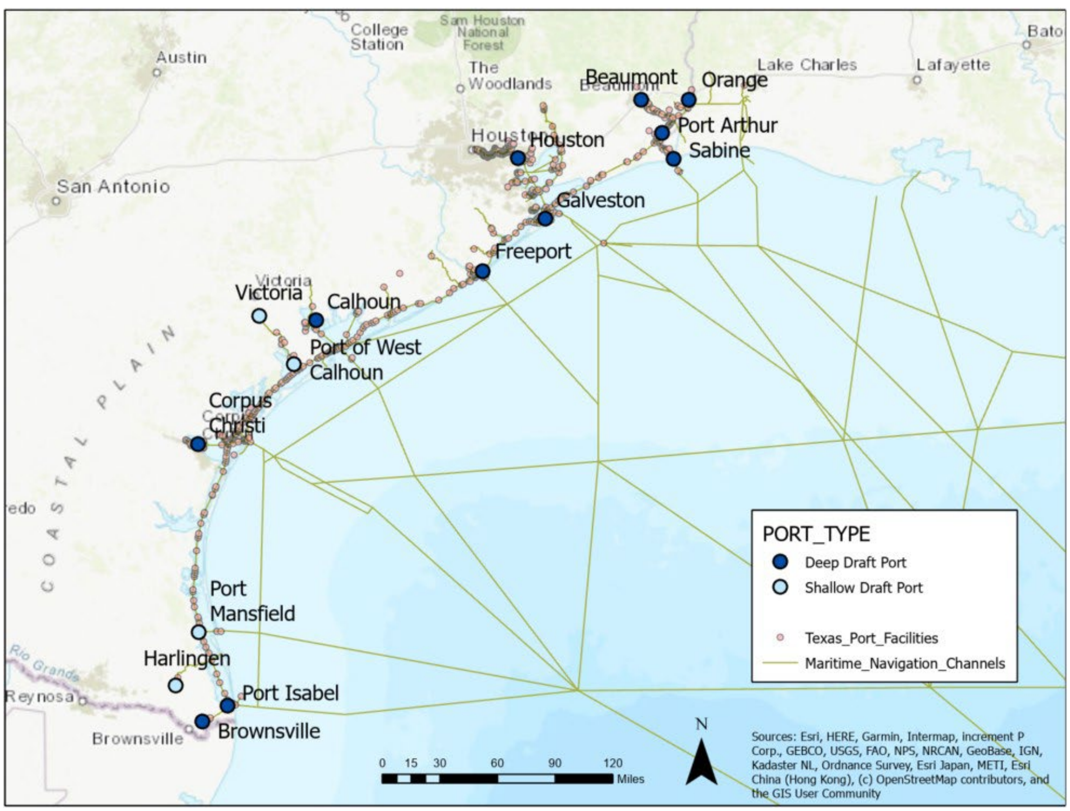


Figure 4.2 Texas port facilities GIS data.

Shallow draft ports have navigation channels dredged to 12 ft deep. Smaller vessels such as fishing fleets, recreational crafts, and bulk material barges commonly use shallow draft ports. Shallow draft ports play a crucial role in local and regional economies, serving as a transfer point for dry bulk, such as gravel and sand, and agricultural products. Texas' numerous shallow draft ports are connected to national trade sectors via the Gulf Intracoastal Waterway, a 12 ft deep navigable waterway stretching from Florida to Texas. The Gulf Intracoastal Waterway spans the entire Texas Gulf coast, from Beaumont to Brownsville, primarily serving barge traffic.

In addition to the entry channel depth, a port must have berth of a minimum depth for the ships to moor and unload cargo onto the port docks. The berth depth is similarly related to the types of vessels that can be accommodated at a facility. The berth length is also a critical dimension as this limits the size and type of vessel as well. For example, the Port of Galveston maintains a 40-45 ft channel and berth depths. It also has two 2,000 ft berths at Piers 25-27 that harbor cruise ships. The berth depth and length at dockside is also a determining factor for whether a port can service Panamax or Neo-Panamax vessels, the ships that are the maximum size that can fit through the Panama Canal locks. These ships are frequently used in trade routes with east Asian countries, and the ability to host these vessels is a major benefit to ports.

4.2.3 Port Terminal Facilities

Port terminals are interconnections between waterways, pipelines, freight highways and railroads. Once a ship has reached the port, it docks at a pier or berth. A dock consists of several berths which are designed based on the type and quantity of commodities loaded and unloaded. The auxiliary facilities near the berths will also vary depending upon the type of the berth. Cranes are used to unload containers and bulk solids, whereas liquids and gaseous materials are loaded and unloaded through elevators and pipeline terminals. Different types and sizes of gantry cranes are able to move different types and amounts of cargo. Often, crane operations are considered a bottleneck in port operations as crane efficiency (measured in terms of number of operations per unit time) is a common metric for port performance. Higher crane efficiencies mean that cargo can be unloaded faster, with ships requiring less berth time.

Dock storage space includes both covered and uncovered areas. Port authorities will lease dock storage areas to private enterprises which use the space as warehouses or short-term storage for goods awaiting loading onto trucks or trains. Some ports also have facilities for refrigerating perishable cargo, called 'reefer' storage. Uncovered, outdoor storage is typically used for dry bulk materials such as stone aggregate or sand. Large tank structures at a port can hold liquid bulk materials, typically petroleum or chemical products that are brought to the site via tanker ships or pipelines. Another important aspect of terminal operations is drayage, which refers to the short distance movement of cargo in the port, typically from the ships to the storage area or to the truck or train that will carry the cargo to its final destination. Drayage is commonly performed with trucks or forklifts used to move containers around a port terminal. For this study, the information related to port facilities such as terminals, docks, piers, cranes, and storage facilities were collated from several sources, such as port websites and TxDOT reports. The information collected are tabulated in Table 4.2.

4.2.4 Trade Data

Ports are essentially used by various economic sectors in the U.S. for either exporting finished goods or to import consumer goods as well as raw materials for domestic businesses. The USA Trade Online (U.S. Census Bureau, n.d.) portal provides detailed data on monthly imports and exports through major ports in the U.S. For developing the trade dataset for this study, the Performing Agency relied on the USA Trade Online datasets. The port-specific data related to imports and exports are available in terms of their monetary values (USD) and are classified into 6,093 different product groups using the 6-digit Harmonized System (HS). Since in the later stages of the project, the economic impact of disruptions to ports are to be analyzed using input-output models, the datasets were converted into ISIC Rev. 4 using the concordance table developed by OECD (Directorate for Science Technology and Innovation, 2019). While HS is based on industry products, ISIC Rev. 4 (International Standard Industrial Classification of All Economic Activities Revision 4) is based on economic activity. By doing so, the import and export loss for different product types resulting from port shutdown could be properly reflected in the final uses of each industry sector defined in the input-output table. The average port-wise daily import and export data corresponding to selected Texas ports are presented in Figure 4.3. The annual tonnage of commodities traded through Texas ports are illustrated in Figure 4.4.

4.3 Supporting Landside Connection Infrastructure

The primary objective of a port is to act as an interconnection between water-borne transportation modes and surface transportation modes like railroads, pipelines, and freight highways. The resilience of multimodal links to ports are essential for operations of the ports during normal conditions and extreme weather events. The reliability and quality of the landside connections is a determinant of the competitiveness of ports as they improve market access and facilitate uninterrupted flow of commodities. Given how ports are vital to state and national economies, the landside connections are important considerations in improving the resilience of port systems.

Therefore, identifying the most critical components of these landside connections to the ports is an important consideration in port resilience. This section describes key landside supporting infrastructure necessary for seaport operations. Data sources are also provided where applicable and data for Texas port supporting infrastructure is summarized.

4.3.1 Highways

While Texas has an extensive freight highway network, a major factor that determines the accessibility of ports to the statewide freight highways are the last-mile/first-mile connections between the port and the freight network. Access to major highway corridors, both US routes and

Interstate routes, is a key component to a port's competitiveness. Trucks require easy connections to the larger regional and national freight highway network. Locations farther from major highways require travel through local streets, which may experience greater delay due to lower speed limits and more frequent traffic signal stops.

Since these last-mile connections are extensively used by heavy trucks with large axle groups, it requires additional considerations with respect to design and maintenance. The 2020 TxDOT Port Connectivity Report identified five major issues that affect connectivity of ports to freight corridors, namely, incompatible roadway design, truck queuing, modal conflicts at ports serving multiple purposes, incompatible land uses around ports, and inadequate funding for port connectivity-related projects (Texas Department of Transportation, 2020). Out of the $210M proposed spending for the year 2020-2021, $48.5M is allocated for new interconnection links and $57.5M for capacity enhancement in 6 existing projects.

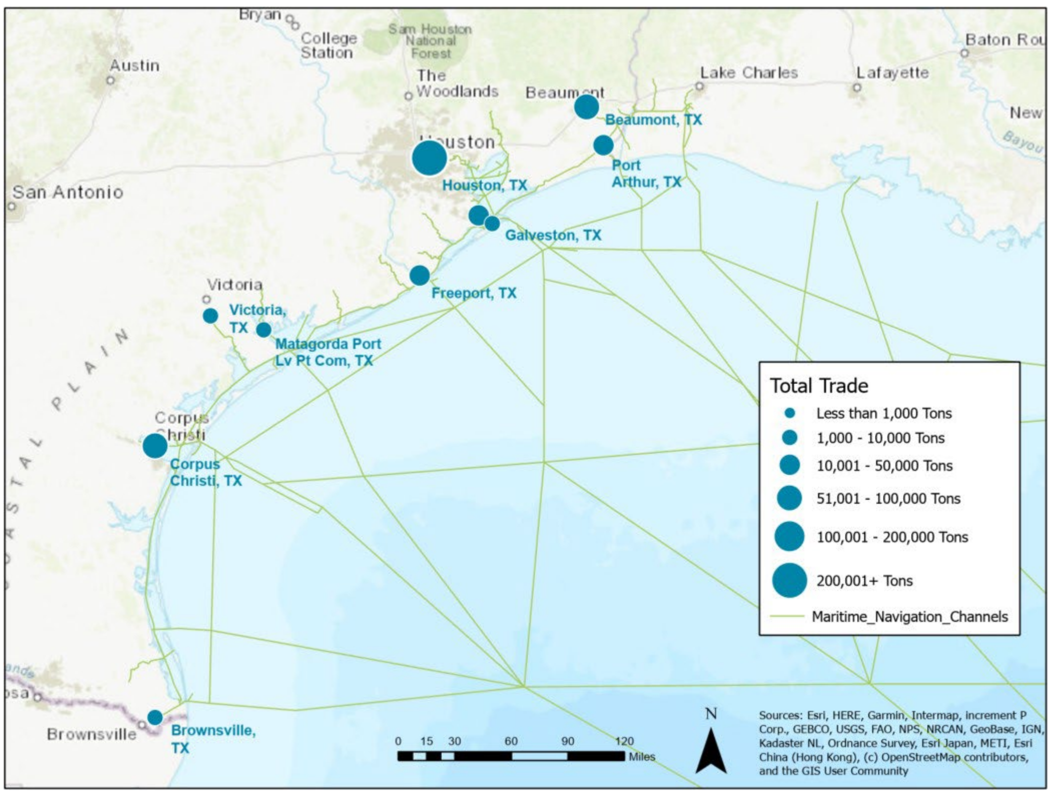


Figure 4.4 Total trade volume data, by tonnage, for selected Texas ports.

Table 4.2 Port terminal facilities

No.	Port Name	Port ID	Terminals	Piers/Dock information	Crane information	Storage information
1	Beaumont	BPT	8	8 deep draft, 2 barge docks, 3 layberths	1 Liebherr Mobile, 9460 American, 2 Grove GHC130 Crawler	560,000 sq. ft. covered storage; 90 acres open storage; 2.9 million barrel capacity liquid bulk storage
2	Brownsville	BRO	7	12 general cargo, 6 liquid cargo, 1 bulk cargo dock	1 Gottwalk HMK 300 E; 2 GHMK 6507	1 million sq. ft. of covered storage, 3 million sq. ft. open storage
3	Calhoun	CLN	3	12 public docks; 2 private	-	25,000 sq. ft. warehouse storage; 2.4 million bbl
4	Corpus Christi	CRP	5	48 liquid bulk; 23 dry cargo; 7 bulk materials	1 gantry crane	warehouse, open storage yards, rail storage
5	Freeport	FPO	8	4 general cargo; 1 barge berth; 1 bulk berth; 1 container vessel berth	1 ZPMC Post-Panamax Gantry Cranes, 1 Gottwalk Mobile Harbor Crane	warehouse and uncovered storage
6	Galveston	GLS	10	26 docks	-	98 acres laydown storage; general storage; breakbulk; refrigerated breakbulk; 2,100,000 barrels of liquid bulk commodity
7	Houston	HOU	8	56 general cargo, liquid bulk, dry bulk; 10 container	90 RTG, 13 NeoPanamax STS, 2 Panamax STS, 11 Post-Panamax STS	Transit sheds, warehousing
8	Orange	ORG	1	4 docks	-	8 warehouses, 345,000 sq. ft.
9	Port Arthur	POA	1	2 docks: 5 berths total, 1 Ro-Ro	1 90 ton gantry crane	518,400 sq. ft. covered storage, 17 acres open storage
10	Port Isabel	PIS	1	6 docks: cargo (2), RoRo, Barge, Fuel, Fishing Dock	-	50 acres of open storage
11	Sabine Pass	NSS	2	3 docks	-	-
12	Harlingen	HRL	1	5 docks	-	50,000 sq. ft. dry bulk handling
13	Port Mansfield	RMV	-	-	-	-
14	West Calhoun	WCN	2	3 docks	-	Land available for laydown yards, warehousing, tank terminals
15	Victoria	VCT	1	2 docks	-	17,000 sq. ft. covered storage; +3 acres uncovered storage; up to 2,000 acres available

NB: The port terminal details are compiled from multiple data sources, including individual port details and TxDOT reports.
Those fields marked with a "-" indicate that the information was not readily available.

45

46

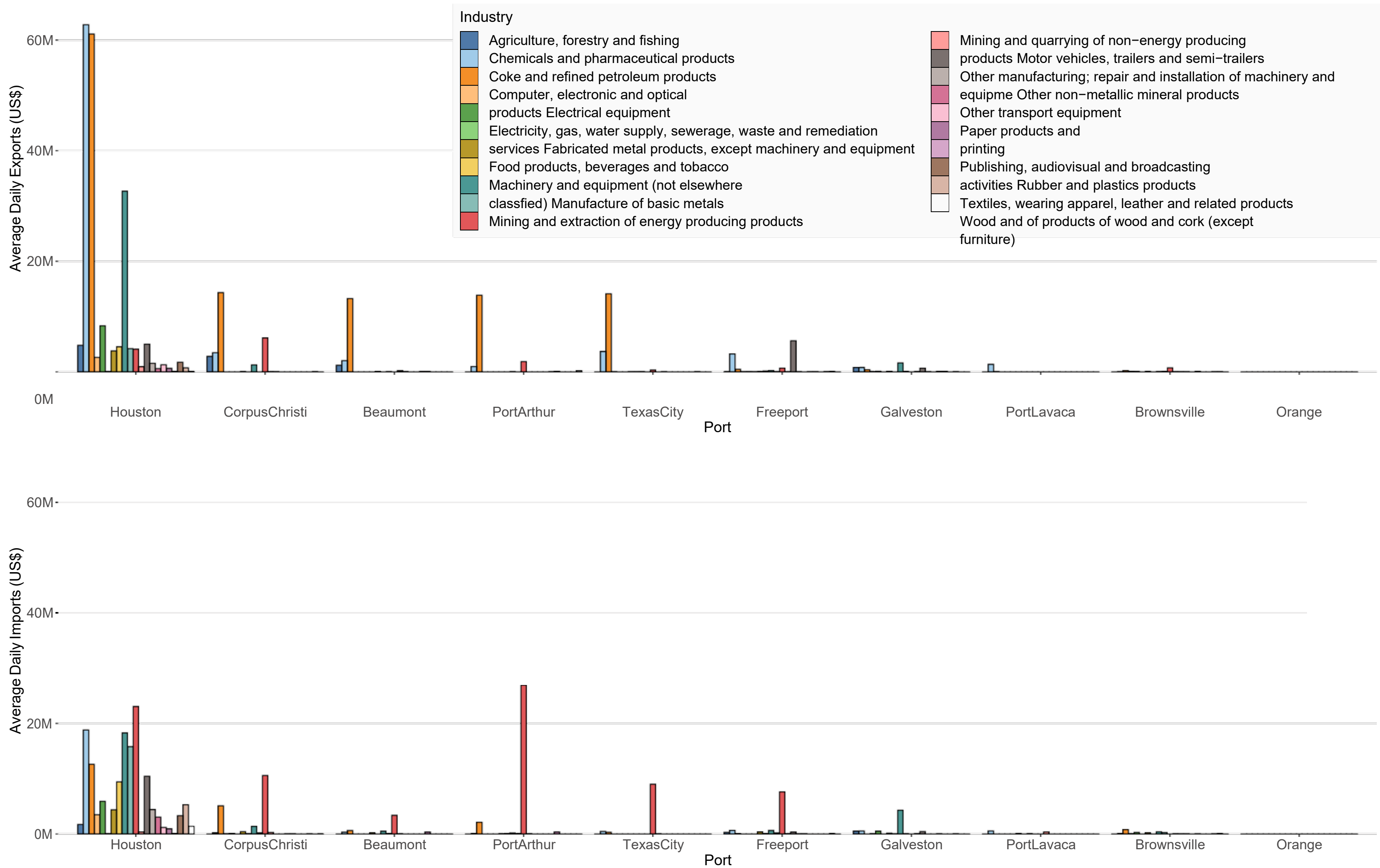


Figure 4.3 Port-wise average imports and exports in 2015 (Computed from U.S. Trade Online data)

At the port, trucks enter through gates, where they check in and receive information on the load they will be carrying. At larger ports, such as Houston, the number of gates can limit the efficiency of port trucking as semis may have to queue at the gates prior to entering. A larger number of gates, at multiple locations, can therefore provide better access for land-based freight operators. Port Houston leads all Texas ports with 25 gates, while many other ports have only one gate.

Some of the port authorities in border counties adjacent to Mexico and Gulf of Mexico have designated corridors for movement of oversize/overweight (OS/OW) trucks (Prozzi, 2016). The OS/OW permits allowed by these ports allow the private sector to transport goods without repackaging containers to meet the permissible domestic weight tolerance. Currently, the ports that have OS/OW permit capabilities are the Port of Brownsville, Port of Harlingen, Port of Freeport, Victoria County Navigation District, and the Port of Corpus Christi.

For the current study, the statewide connectivity corridor dataset compiled by the Texas Department of Transportation was utilized. In addition to this, the port connectivity details, such as the number of gates and annual truck traffic, corresponding to the ports were also obtained from the Receiving Agency. Additional datasets related to freight roads will be collected during the resilience analysis of supporting infrastructure. Figure 4.5 depicts the highway GIS dataset.

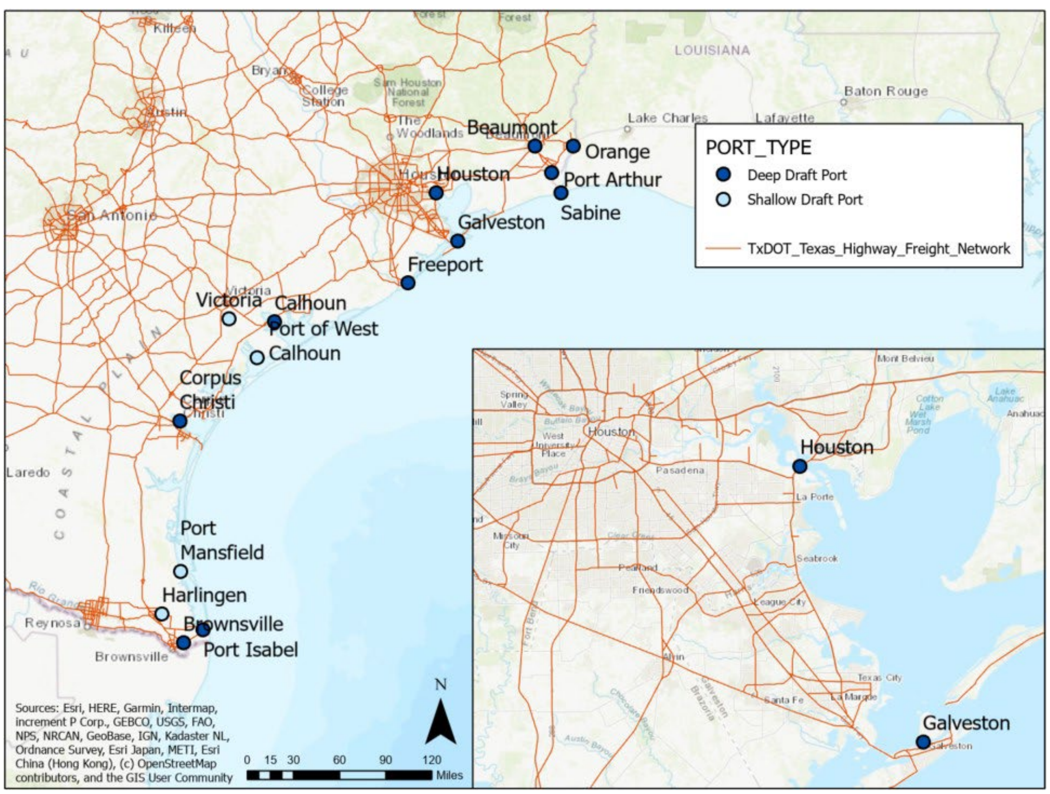


Figure 4.5 Landside highway connections for Texas ports, with inset Houston/Galveston region.

4.3.2 Railroads

Railroads are also a major landside mode at port facilities. Shipping companies may take advantage of the economies of scale provided by railroads to ship large quantities of bulk goods at lower costs per unit of cargo. A disadvantage of rail travel is that it is costly to construct rail lines and line capacity and routing is limited by the existing track structure. This gives railways less operational flexibility compared to highways. However, railways can ship much larger volumes of cargo per vehicle at a much lower unit cost as compared to highways. Therefore, ports that have rail access are at a competitive advantage over those which do not.

Railroad companies are categorized into one of three Classes, codified by the U.S. Surface Transportation Board (STB). Class I railroads are the largest, with annual operating budgets greater than $250 million in 1991 USD. This valuation is adjusted for inflation at regular intervals. In 2018, the threshold annual operating revenue for a Class I railroad classification was $489.9 million or higher (ASLRRA, 2019). Class II railroads are regional rail lines with operating revenues that fall below the Class I cutoff, and Class III railroads are local short lines and switching and terminal carriers. In the US, there are eight Class I railroads with trackage: seven freight railroads and Amtrak. In Texas, there are three Class I freight railroads: Union Pacific Railroad (UP), BNSF Railway, and Kansas City Southern Railway (KCS) (Texas Department of Transportation, 2016). Many ports in Texas have access to Class I railways. There are currently no Class II carriers in the state, but there are 43 Class III railroads (as of 2016). Class III railroads are common in port environments, where they provide terminal and switching rail service and interchanges with larger Class I lines.

For example, the Port Terminal Railroad Association at the Port of Houston provides rail access to harbor-side industries and maintains 154 miles of track with access to interchanges with BNSF, UP, and KCS lines. Other ports may have Class I rail access directly on site, such as the Port of Galveston, which has UP spur lines dockside. Roll-on/roll-off (Ro/Ro) cargo refers to docks that are structured in such a way that ships can back up to the dock and "roll" cars or train stock on or off of the ship. Some ports have rail tracks on their Ro-Ro docks, allowing for the direct shipment of train cars via maritime trade routes.

For the current study, the railroad GIS dataset prepared by the Transportation Planning and Programming Division of TxDOT was adopted. The dataset consists of the location of major railroad segments within Texas, the private operator who oversees operation and maintenance, and the railroad type (spur line, sidetrack, industrial lead, business lead, and main line). The railroad dataset is illustrated in Figure 4.6.

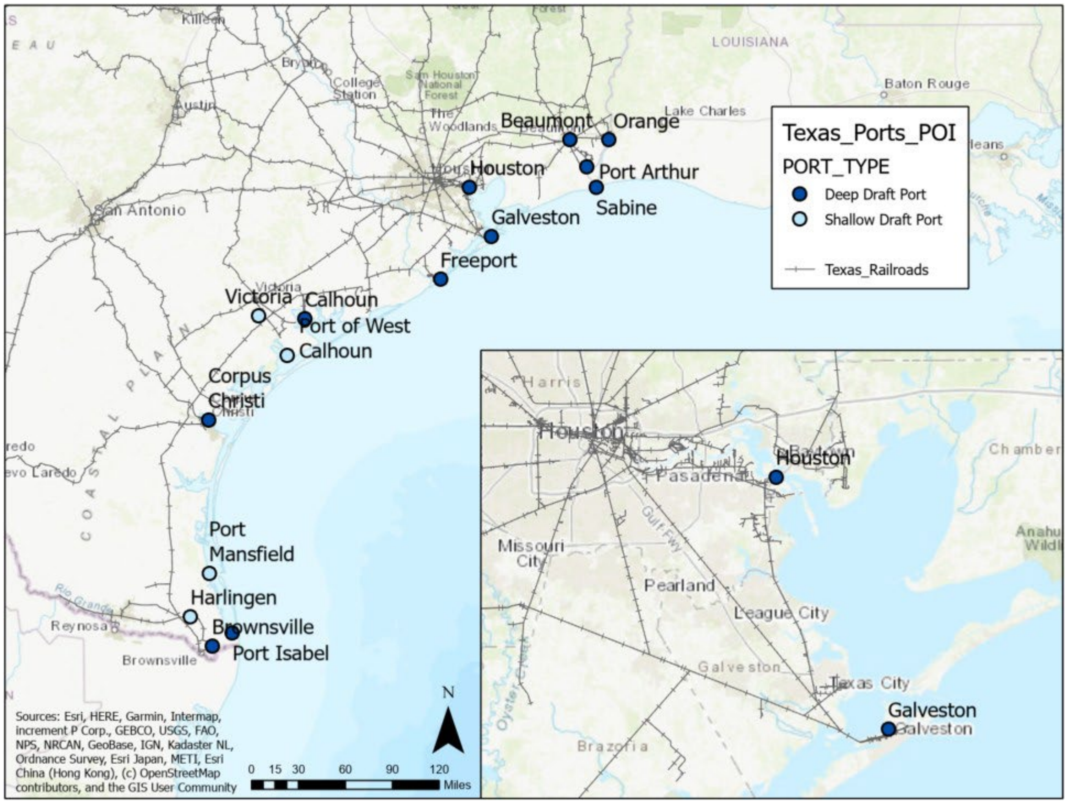


Figure 4.6 Landside railway connections for Texas ports, with inset Houston/Galveston region.

4.3.3 Pipelines

Pipelines are the most effective mode of long-distance transport for liquid or gas bulk products such as crude oil, refined petroleum products, chemicals, and industrial gases. Texas ports including ports at Beaumont, Port Arthur, Houston, Galveston, Freeport, Corpus Christi, and Brownsville, are known for import and export of petroleum products and petrochemicals which heavily depend on pipelines for transportation. The pipelines are mostly developed and maintained by the private sector and provide direct access to refineries and storage tanks. The surge in the demand for oil and gas produced in Texas has also led to the initiation of more pipeline projects in the Texas coast. For example, a 30-inch pipeline has been constructed to connection the Permian Basin in west Texas to the port of Corpus Christi (CITE).

For the current study, the dataset developed by the Railroad Commission of Texas was used. The dataset consists of the geographical location of various pipeline segments, the geometric details, operator details, and the types of commodities transported. Figure 4.7 displays the pipeline dataset in the Houston-Galveston region.

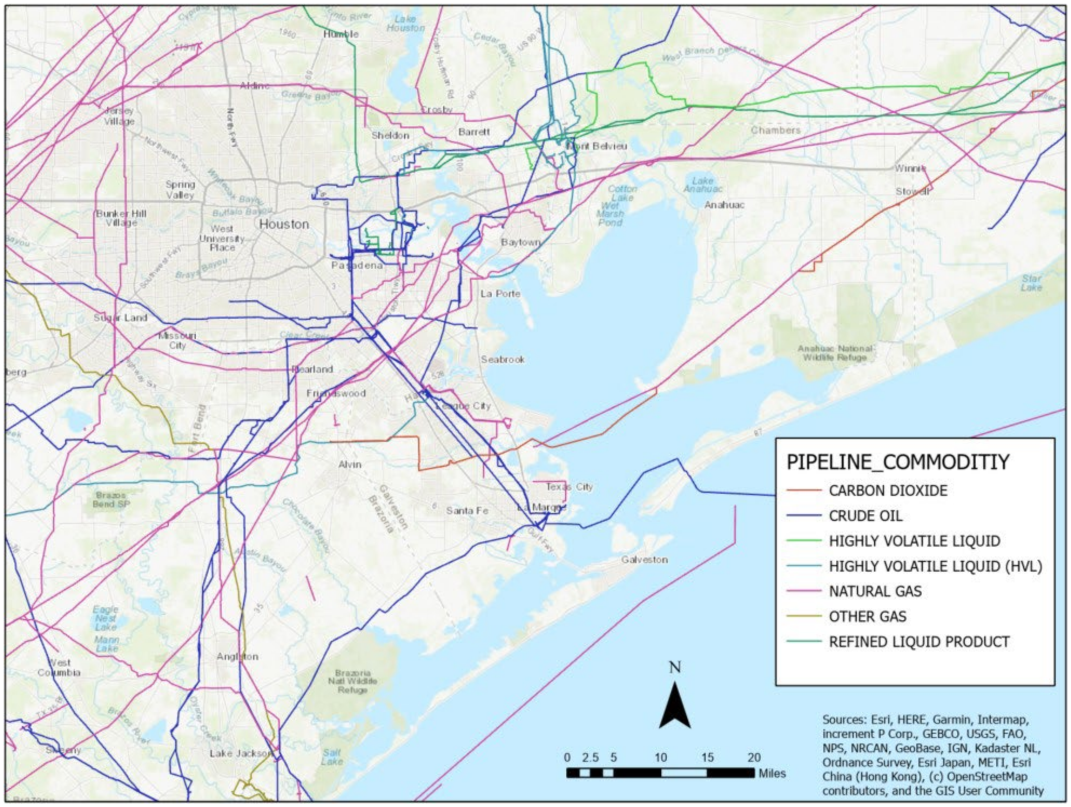


Figure 4.7 Houston/Galveston region pipelines greater than or equal to 24" in diameter, by commodity.

4.4 Connected Utilities

Utility services, such as electricity and water provided by third party operators, are essential for the normal operations of the ports. The disruptions to the utility services may partly or fully affect the functioning of ports. For example, electricity is required for crane operations and for air conditioning, refrigeration or heating, lighting in port buildings, storages, and open areas. Identifying critical utility services and provisions for backup systems can significantly improve the port operations during normal and inclement weather conditions.

4.4.1 Electric Grid

The electricity network dataset used in this study was obtained from Homeland Infrastructure Foundation-Level Data (HIFLD) database. The electricity grid that connects major ports in the Houston-Galveston region is presented in Figure 4.8. The dataset consists of the network topography, transmission line details, and operator information. This dataset will be used in the later chapters to identify any topographical vulnerabilities in the power network that may affect the resilience of ports during major weather-related hazards.

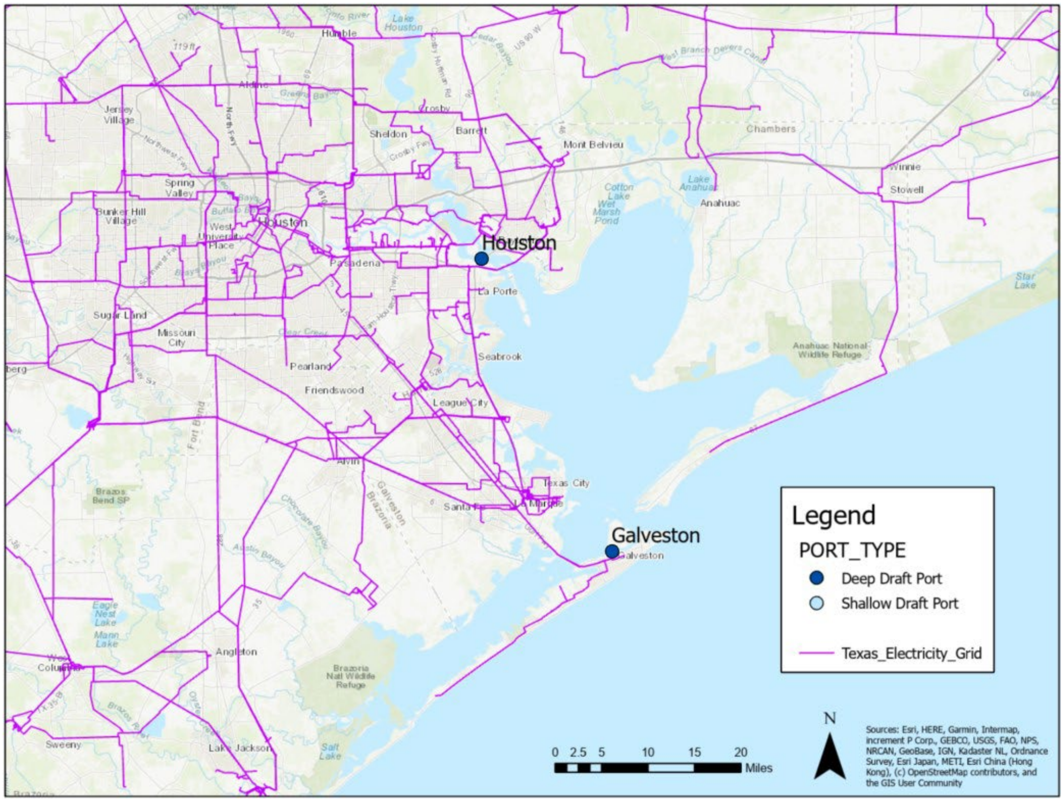


Figure 4.8 Coastal electric grid in Texas, showing Houston/Galveston region.

4.5 Development of the Integrated ArcGIS Infrastructure Dataset

The port and related infrastructure datasets were combined after processing to develop the integrated GIS dataset in ESRI ArcGIS. The integrated dataset developed is in its preliminary stage with basic information on major infrastructure components. The dataset will be enhanced as more port-specific information becomes available as the project progresses. Currently, the dataset consists of individual layers for ports, port facilities, navigation channels, freight highway network, railroad network, pipelines, and power grid. Tables corresponding to imports and exports at each port classified based on commodities are also incorporated. These tables will be linked to the ports layer later. The structure of the integrated GIS dataset is presented in Figure 4.9. The individual datasets used in the integrated database are stored in a geodatabase associated with the ArcGIS file. To open the integrated ArcGIS dataset, perform the following steps:

1. Download the "0-7055_GIS_Dataset_P1.zip" folder within the "P1: GIS Dataset" subfolder at: https://utexas.box.com/s/lnlpweb23wbrgbcydo6no6ucal8b8lk1
2. Click on the ArcMap file " 0-7055_GIS_Dataset_10.6.mxd" to open the integrated GIS dataset file. Once it opens, click "OK" if an error message ("System.NullReferenceException") is shown.
3. The port infrastructure layers can be selected on the left pane. By default, only the port layer is active when the dataset file is opened.

4.6 Summary

In this chapter, the various datasets and procedures used to develop the integrated GIS port infrastructure database are summarized. The infrastructure systems incorporated into the database can be broadly classified into three categories: (a) port infrastructure, (b) supporting connectivity infrastructure, (c) connected utilities, and (d) port trade data. The database currently includes only publicly available datasets from public agencies such as TxDOT and USDHS.

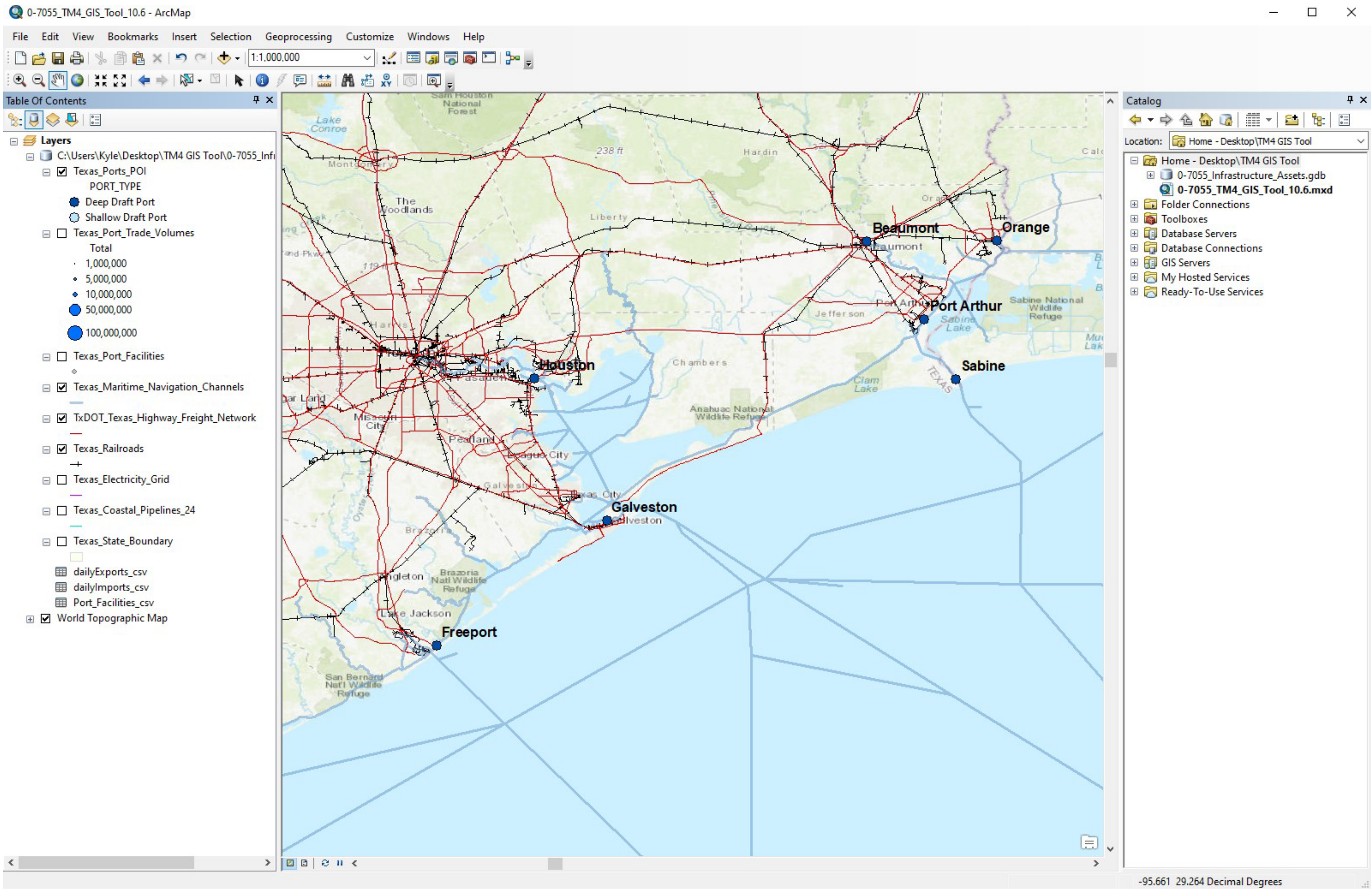


Figure 4.9 Illustration of the ESRI ArcGIS dataset developed for Texas port resilience assessment

Chapter 5. Gather Information on Port Vulnerability and Resilience

5.1 Introduction

This chapter summarizes the methodology and findings of Task 5 of this project, related to gathering information on port and connecting infrastructure vulnerability and resilience. The primary scope of work of this task encompasses contacting and communicating with current port stakeholders in an effort to further the understanding of current port vulnerability and resilience assessment practices. For this task, CTR established communication with several stakeholder groups, ranging from public agencies, such as port authorities, state DOT, and federal agencies, to private companies, such as railroad operators and trucking companies.

CTR conducted a virtual workshop on November 4, 2020, with relevant Texas port authority personnel. Additional virtual interviews were conducted on an individual basis with other port stakeholders, including those responsible for managing waterside and landside transportation modes.

Finally, CTR developed a web based Qualtrics survey to collect further quantitative information regarding port resilience. The survey was distributed to the port authorities in attendance at the workshop, as well as additional port authorities for which CTR had contact information but were not in attendance at the workshop. A total of eight responses were recorded for the survey out of 15 ports targeted for distribution. Specific organizations with participation in the port workshop and survey are shown in Figure 5.1.

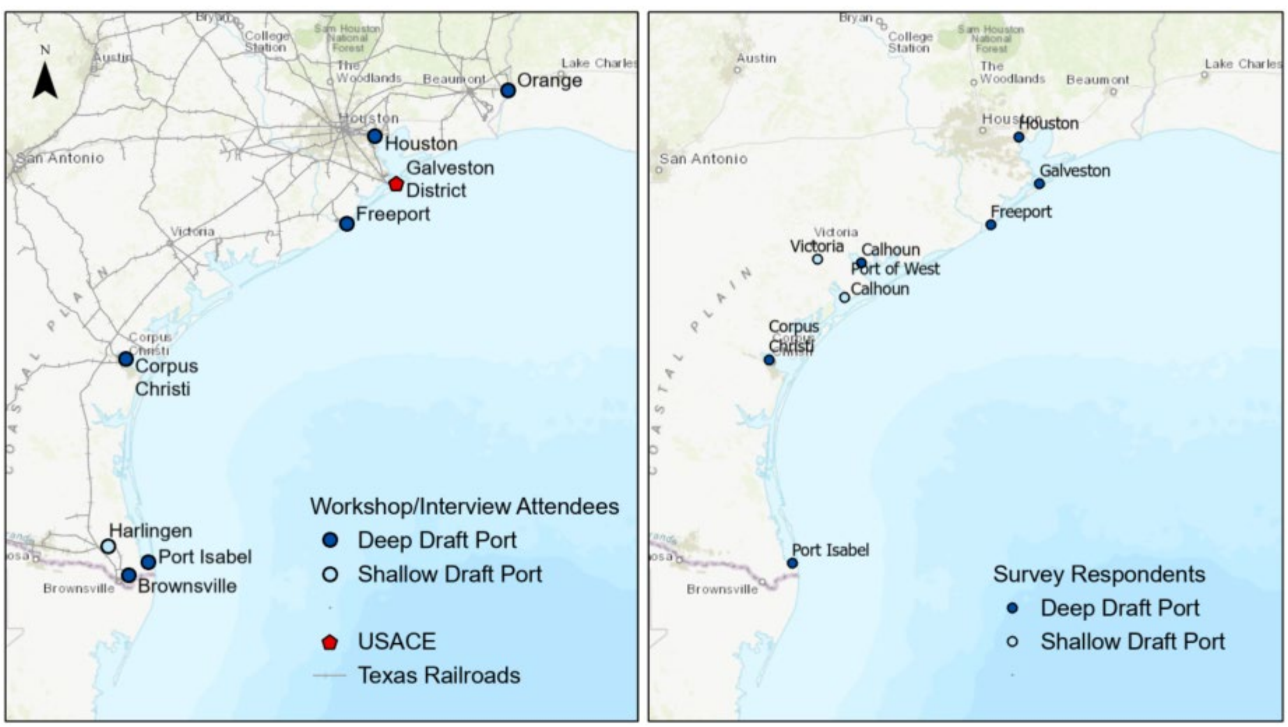


Figure 5.1 Map of participating stakeholders

Additionally, CTR distributed two online Qualtrics surveys to truckers and truck company employees. The surveys were developed to gain an understanding of the experiences of truckers when delivering goods to port facilities and in inclement weather. Some survey participants were also targeted for follow-up phone interviews, of which five individual phone interviews were performed.

The methodologies employed by CTR are summarized in this chapter. Results of the workshop, stakeholder interviews, and Qualtrics surveys are also detailed.

5.2 Participating Stakeholders

As the primary objective of this study is to assess the existing resilience of the Texas port system and provide recommendations for improvements, stakeholder input is an essential component, as those organizations are most able to affect change in engineering practice. Figure 5.2 shows the characterization of common port stakeholders and their influence in the port decision-making process. For this study, external, internal, and legislative/public policy stakeholders were incorporated into the analysis. Table 5.1 summarizes all stakeholders, public and private, that have participated in virtual workshops or interviews, or expressed interest, as of the writing of this memo.

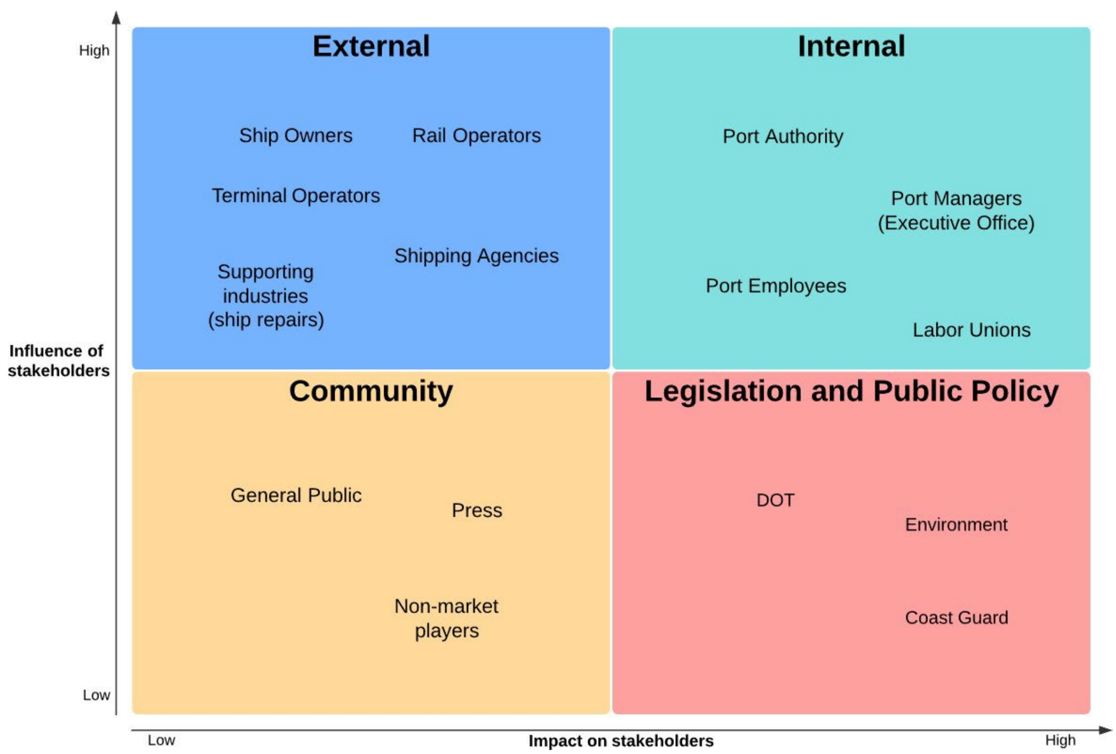


Figure 5.2 Stakeholder mapping, adapted from Henesey et al. (2003)

Table 5.1 Summary of workshop and interview participating agencies

Organization	Type	Status of participation
Brownsville Navigation District	Port Authority	Participated in the workshop held on November 4, 2020
Port of Corpus Christi Authority	Port Authority	Participated in the workshop held on November 4, 2020
Port Freeport	Port Authority	Participated in the workshop held on November 4, 2020
Orange County Navigation & Port District	Port Authority	Participated in the workshop held on November 4, 2020
Port Isabel-San Benito Navigation District	Port Authority	Participated in the workshop held on November 4, 2020
Port of Harlingen Authority	Port Authority	Participated in the workshop held on November 4, 2020
Port of Houston Authority	Port Authority	Individual interview held on August 10, 2021
US Army Corps of Engineers	Public Agency	Individual interview held on December 8, 2020
Union Pacific Railroad Company	Private Railroad	Individual interview on November 18, 2020
Trucking company employees	Private Companies	Five interviews conducted between June 21, 2021 and August 31, 2021

5.2.1 Port Authorities

As internal stakeholders, port authorities are often one of the most influential entities in the port environment. Given that they have jurisdiction over the ownership of the land and operations of the terminal, port authorities can implement rules or guidelines that may most directly affect changes in resilience practice.

CTR obtained contact information from port directors and employees at select ports in Texas from TxDOT. An initial email was sent to every provided port to establish contact. In this initial email, a one-page summary sheet detailing primary project objectives and contact information was attached. Table 5.2 lists all port governance entities contacted by CTR, requesting their participation in this project.

Table 5.2 Texas port commissions contacted by CTR

No.	Common Name	Port ID	Governance
1	Beaumont	BPT	Port of Beaumont Navigation District of Jefferson County, Texas
2	Brownsville	BRO	Brownsville Navigation District
3	Calhoun	PCR	Calhoun Port Authority
4	Corpus Christi	CRP	Port of Corpus Christi Authority
5	Freeport	FPO	Port Freeport
6	Galveston	GLS	Board of Trustees of the Galveston Wharves
7	Houston	HOU	Port of Houston Authority
8	Orange	ORG	Orange County Navigation & Port District
9	Port Arthur	POA	Port of Port Arthur Navigation District
10	Port Isabel	PIS	Port Isabel-San Benito Navigation District
11	Sabine Pass	NSS	Sabine Pass Port Authority
12	Harlingen	HRL	Port of Harlingen Authority
13	Port Mansfield	RMV	Port Mansfield/Willacy County Navigation District
14	West Calhoun	XLR	Port of West Calhoun
15	Victoria	VCT	Victoria County Navigation District

Of the 15 port authorities contacted by CTR, a total of six participated in the virtual workshop hosted via Microsoft Teams on November 4, 2020. The participants provided a representative sample of Texas ports: larger facilities such as Freeport and Corpus Christi were in attendance, while Brownsville is a typical medium-sized port, and Port Isabel and Harlingen represented smaller deep-draft and shallow-draft facilities, respectively. CTR also conducted an interview with emergency management personnel from the Port of Houston Authority on August 10, 2021.

5.2.2 Waterside Transportation Stakeholders

The U.S. Army Corps of Engineers (USACE) is responsible for maintaining navigable waterways for ship travel. As many channels and harbors are prone to seabed silting and shoaling of material on the sea floor, USACE is federally mandated to dredge any hazardous material to ensure that maximum allowable ship drafts are safely met. As hurricanes can result in large influxes of sand and other debris in channels and harbors, dredging is often a recovery action that is required in the aftermath of hurricane events. USACE is also responsible for overseeing the design and procurement of flood mitigation structures such as federally owned dams and levees. Currently, USACE is studying a flood gate structure that would protect Houston and Galveston from hurricane storm surges.

Given that USACE is responsible for such actions that play a role in resilience practice, CTR contacted USACE employees and conducted a virtual interview with an engineer of the USACE Galveston District Hydraulics and Hydrology Branch on December 8, 2020, via Microsoft Teams.

5.2.3 Landside Transportation Stakeholders

Landside transportation connections such as freight trucking and railroad companies have robust emergency management (EM) plans. Disruptions caused by a hurricane can impact road or rail lines and this can cascade to impacts at ports as the shipment of goods out of the port may be delayed.

To further the understanding of landside shipping resilience, CTR established contact with Union Pacific Railroad (UP), a prominent Class I freight railroad operator with many lines in Texas. A virtual interview with the UP General Director of Network Development was conducted on November 18, 2020, via Microsoft Teams.

CTR also conducted extensive outreach activities with trucking companies in Texas, other US states, Mexico, and Canada. An online Qualtrics survey was distributed to truckers in Texas and Mexico who are registered in the Federal Motor Carrier Safety Association (FMCSA) SaferSys database. A second Qualtrics survey was distributed to truckers in non-Texas US states to obtain the experiences of other US truckers who may operate at Texas ports or have past experiences with extreme weather events. A total of 255 valid surveys from Texas and 332 surveys from other US states were received. Survey respondents were given the option to volunteer to participate in a follow-up phone interview to give further information. A total of five of these interviews were completed. A comprehensive description of the survey methods and results is provided in section 5.4.

5.3 Methodology and Results

The workshops, one-on-one interviews, and online surveys were designed to understand the actions, plans, and challenges faced by the port stakeholders in terms of resilience management. Such information would help CTR to identify those factors that would influence the resilience of the port infrastructure or supporting transportation infrastructure, such as navigation channels and railroads. For data collection, CTR structured the workshop, interviews, and Qualtrics survey along the four phases of EM: (1) preparedness, (2) response, (3) recovery, and (4) prevention and adaptation. The resilience actions undertaken by the port stakeholders would have an impact on any of these stages of EM, which would improve the overall resilience of the ports against extreme weather events. The four phases of the EM cycle are shown in Figure 5.3.

Figure 5.3 Phases of EM cycle (Australian Council of Social Service, 2015)

CTR categorized the questions into these groupings to more easily communicate the resilience questions and concepts to the workshop participants. Questions were designed to cover the "4R's" of resilience: (1) robustness, (2) redundancy, (3) resourcefulness, and (4) rapidity, although this vocabulary was rarely used during the workshop as the EM cycle phases were thought to be better understood by the participants. This section summarizes the methods and results of the workshops, interviews, and surveys. Copies of presentation material, discussion summaries, and survey questions may be found in the appendices.

5.3.1 Workshop for Port Authorities

CTR conducted a virtual workshop via the Microsoft Teams platform on November 4, 2020, with active participation from six port authorities in Texas. Two weeks prior to the workshop, CTR invited all the major port authorities managing the 15 deep- and shallow-draft ports via email for participation in the workshop and to share their experiences regarding port resilience best practices. Representatives of the following six port authorities agreed to take part in the workshop and were present on the call: Port of Brownsville, Port of Corpus Christi, Port Freeport, Port of Orange, Port of Port Isabel, and Port of Harlingen.

The workshop was three hours long. CTR began by giving a brief presentation detailing the goals and objectives of the study, basic resilience vocabulary and definitions, and previous work that has been completed. Then, CTR guided a moderated discussion with the port representatives. A copy of the slides used during the workshop may be found in Appendix A.

For the moderated discussion, CTR posed pre-written questions intended to enhance understanding of vulnerability and resilience measures. As stated, the questions were split into three general topics, based on the four phases of the EM cycle shown in Figure 5.3. The specific focus of the workshop questions for each EM phase are listed below:

Prevention and Preparedness:

1. Definition of resilience and how COVID-19 has changed it
2. Type of trainings/exercises and frequency
3. Resilience criteria in new capital projects
4. Resilience measures and effects on insurance rates
5. Preparedness best practices

Response and Restoration:

1. Priority for restoring failed port components
2. Employee and resource mobilization issues, impacts of evacuation on staffing
3. Alternate utility (water, electricity, telecommunication) arrangements in case ofdisruption
4. Contract status for debris removal
5. Issues with landside connection disruptions
6. Challenges with perishable goods
7. Methods for communication with other agencies during response
8. Response and recovery best practices

Recovery and Adaptation:

1. How recovery projects are implemented and how funding sources factor in
2. Challenges with mobilizing resources
3. Incorporation of historical damage estimates in structural project design criteria
4. Sea level rise consideration for new projects
5. Incorporation of "lessons learned" into EM plan updates
6. Changes in resilience perspective, due to COVID-19 pandemic or other factors

The researchers guided the discussion by asking the target questions. For each individual question, every port authority representative was given a chance to respond. For some questions, only a few of the port authorities chose to respond, as their comments echoed those of other ports. The researchers augmented the scripted questions with follow-up questions or requests for further details or clarification.

The guided discussions revealed that though almost all the ports have a well-defined definition for resilience and the staff have a very good understanding of the resilience concepts, the key difference is in the availability of resources to implement resilience projects. While large ports have the capability of implementing major resilience projects, smaller ports were found to face difficulty in obtaining adequate resources for improving resilience. The major ports perform periodic vulnerability and risks assessment exercises as well as multi-jurisdictional tabletop exercises to prepare and coordinate among various stakeholders, including the Texas Division of Emergency Management, law enforcement, TxDOT, and local governments. The ports also make sure to incorporate the lessons learned from past events and update their emergency response plans accordingly.

While ports have an understanding of what resilience is, port authorities often act independently, on their own initiative, when implementing resiliency elements. For example, Port Freeport is implementing a resilience metric based on the Gulf of Mexico Alliance Port Resilience Index (PRI). The port decided to develop this metric of their own volition, indicating that resilience aspects are being considered by port authorities, but motivated only by leadership at individual ports, as there are currently no resilience codes or standards.

In terms of vulnerability to extreme weather, port authorities recognize that strength and robustness of infrastructure are important, but commonly emphasize other aspects, such as critical bottlenecks in recovery. Loss of aids to navigation and seabed shoaling are cited as two important aspects that can impact the speed of recovery, as these factors are out of the direct control of the port authorities. The US Coast Guard assists with navigational marker placement and USACE is responsible for channel dredging. Port authorities also indicate that workforce impacts can be disruptive to operations. Proper training, planning, and coordination for employees is necessary to ensure that port operations are restored in a timely manner. Communication between relevant port stakeholders is also commonly cited as an import resilience factor.

5.3.2 Interviews

CTR conducted individual interviews with additional stakeholders. These sessions were conducted in hour-long calls via Microsoft Teams. CTR began each interview with a brief presentation regarding the main objectives of the research project and then discussed prepared questions with the interviewees. Three interviews were completed: one with the Port of Houston Authority, one with UP, and one with USACE.

Port of Houston Authority

CTR held an interview with two Port of Houston Authority employees involved with risk and emergency management on August 10, 2021. The interview topics were formulated similarly to the workshop topics, with discussion topics organized by the EM cycle phases.

From the interview, CTR gained an enhanced perspective of some of the issues that are faced by a large port authority such as the Port of Houston in times of natural disaster. The interviewees mentioned that it is important to understand critical port components that are vital for operations, such as cranes and navigable waterways. They also stated that ports need to consider not only the worst historic disasters, but also future disasters that may not have occurred to determine the impacts of extreme weather events on port infrastructure and operations. One specific issue that the interviewees identified was the designation of port authorities as emergency management entities in the Texas government code. This discussion informed the creation of recommendation #8 in section 10.2.2. Additional findings from this interview were valuable in the creation of the resilience assessment tool described in Chapter 8 and in the formulation of other recommendations.

Union Pacific Railroad

CTR held an interview with two UP representatives on November 18, 2020. The participants worked in the network development and public affairs sectors in Texas. The interview questions were formatted similarly to the workshop questions, with topics derived from the EM cycle phases.

From the interview, it is clear that railroad companies are taking an active approach regarding resilience planning. The interviewee provided an extensive definition and examples of resilience measures that are routinely undertaken. UP has teams that take an active approach to emergency response in the days leading up to natural disasters. Days in advance, the teams move into areas forecast to be impacted by extreme weather and relocate locomotives and rolling stock out of flood areas. The railroad has a close working relationship with port authorities as they are in daily contact with port employees during times of typical operation. This builds a close working relationship between the railroads and the ports that can be leveraged during extreme weather response.

One factor that was emphasized is the importance of communication. Coordination between UP, port authorities, and other emergency response agencies was listed as an important aspect for restoration and recovery operations. Overall, the interview provided the researchers with a better understanding of how private landside freight operators view resilience and how they interact with other port stakeholders. As UP is a private company with a large operating revenue, they are able to recognize the importance of resilience operations and invest accordingly.

US Army Corps of Engineers

CTR conducted a virtual interview with an engineer from the USACE Galveston District Hydraulics and Hydrology Branch on December 8, 2020, via Microsoft Teams. The interview questions were formatted similarly to the port authority workshop questions, with three categories of topics derived from the EM cycle phases.

From the discussion, CTR was able to gain insight into the role that public agencies can play in resilience. USACE has a federally mandated mission to provide flood protection and maintain navigable waterways. Through these objectives, they are able to play an important role in coastal resilience in Texas. Large flood mitigation projects such as levees or floodgates are led by USACE. Coordination of post-hurricane dredging is also carried out by USACE and this can have a great impact on how rapidly ports may be reopened. USACE considers resilience in the design life of new facilities for flood management and the expected economic savings of each project. The U.S. Army Engineer Research and Development Center (ERDC), which is part of USACE, supports the Coastal System Resilience (CSR) initiative, a project that seeks to integrate three USACE sectors—Environmental Restoration, Navigation, and Flood Risk Management—to investigate resilience in coastal regions (Touzinsky & Rosati, 2018). USACE does not own any port infrastructure assets and is not directly in contact with port authorities on a frequent basis, yet they play a large role in port resilience through their flood management and navigation channel maintenance responsibilities.

5.3.3 Survey

CTR created and distributed a web-based survey via the Qualtrics platform to obtain further quantitative data regarding port vulnerability and resilience. The survey was distributed to Texas port authorities from December 7, 2020 through December 21, 2020. The researchers sent the survey to port authority representatives present at the November 4 workshop, as well as the additional contacts that CTR had obtained from TxDOT. In all, the survey was distributed to 16 port authorities and a total of eight responses were received.

The survey was organized into the same general sections as the workshop. An additional section asking for further port asset and trade details was included. Questions were given in the format of ranked choice, multiple selection, and text response. Questions seeking to determine the roles of various agencies in disaster response, training and planning frequency, and infrastructure criticality and weaknesses were asked in the survey. Appendix B gives the complete Qualtrics survey.

This chapter provides the results obtained through December 2020. Small and large ports, and deep- and shallow-draft ports were all represented in survey responses. The specific ports submitting responses were Victoria, Corpus Christi, Galveston, Port Isabel, Calhoun, West Calhoun, Freeport, and Houston.

Initial responses indicate that port authorities see funding shortages as common barriers to resilience, as shown in Figure 5.4. Funding for both non-revenue generating and revenue generating resilience projects were cited most frequently. A lack of standard resilience plans or codes and coordination conflicts are cited as other issues, but to a lesser degree.

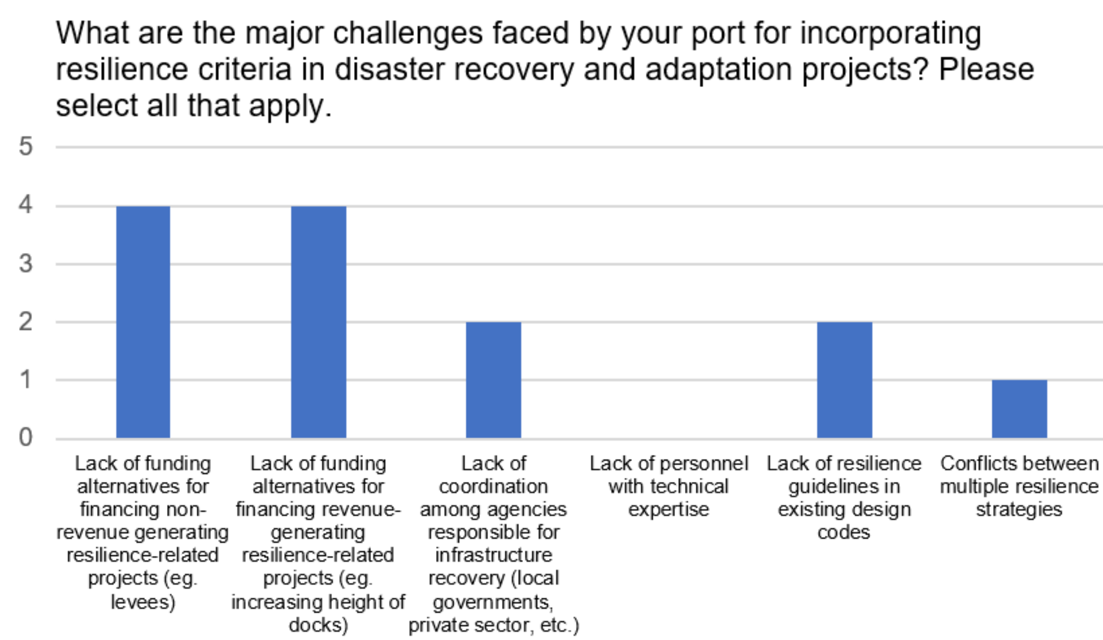


Figure 5.4 Survey responses for port resilience challenges

When asked about the top issues that would impact response and restoration activities, port authorities indicate that waterside access to the port (due to silted navigation channels) is the most important vulnerability impact as shown in Figure 5.5. This signifies that USACE dredging operations are critical for port recovery, echoing comments from port authority employees at the workshop, who cited dredging requirements as a barrier to restoration. Utility disruptions are also mentioned frequently, as are a lack of necessary labor force and landside access disruptions. Interestingly, delays in mobilizing emergency funds were not identified as being a frequent challenge, although funding for capital projects was listed as being a barrier in Figure 5.4. This suggests that emergency funding for disaster response is distributed adequately, but funding for capital projects for resilience is harder to come by.

Port authorities also tend to rank operational adjustments or improved coordination and communication higher than infrastructure retrofits to increase structural capacity when asked about the effectiveness of various measures for resilience. However, port authorities also indicated that they would allocate a majority of hypothetical funds to increasing the strength or robustness of port infrastructure. This suggests that current practices have focused on more flexible "soft" measures, such as communication or workforce enhancement, but perhaps ports would also invest in physical resilience projects if the necessary funding resources were available, in an ideal scenario.

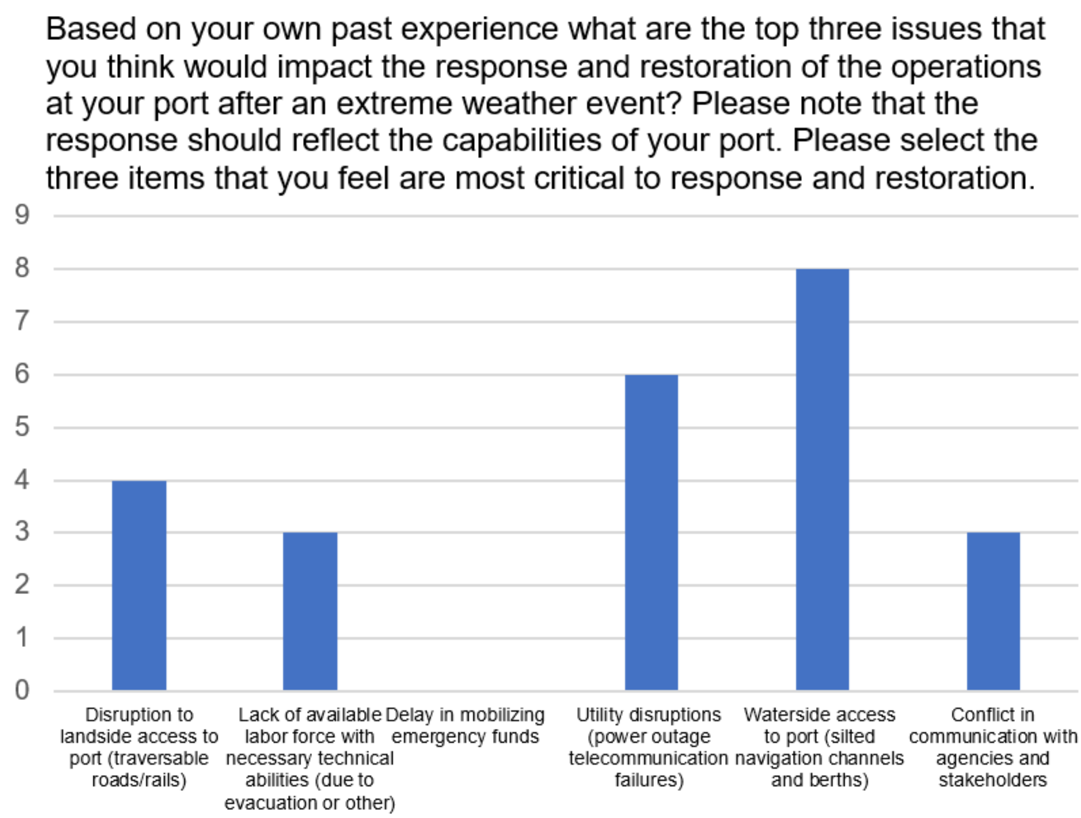


Figure 5.5 Survey responses for restoration bottlenecks

5.4 Trucking Data Collection Efforts

The following section discusses two email surveys distributed to truck drivers and trucking companies in 1) Texas and Mexico, and 2) all other continental US states and Canada. The purpose of these surveys was to learn about the experiences and insights of truck drivers, dispatchers, company managers and executive officers when traveling to/from and operating trucks at ports in Texas and across the US, Canada and Mexico. In addition to the survey questions, an invitation was included to participate in a telephone interview to discuss further the truck driver's experiences.

The goal of these surveys and telephone interviews was to learn how to improve the safety and operations of truck drivers and trucks during the trip to / from and while at coastal ports during severe weather conditions such as hurricanes, flooding, high winds and other emergencies. Improving trucker safety and truck operations will improve port resilience considering that approximately 6,000 to 7,000 trucks operate at Port Houston each day alone. Trucking and ports are essential elements to the Texas State economy. In Texas approximately 73% of manufactured goods are transported by truck. Texas is the largest exporting state and the second largest importing state in the U.S. (Texas Department of Transportation, 2021)

Disruptions to ports and truck operations can have a significant impact to the Texas and U.S. economy, jobs, and revenue. Hurricane Harvey alone caused over $17.6 billion in economic and infrastructure impacts. The following sections will discuss how impacts to trucking affect port resilience and recommendations for improvements.

5.4.1 Trucking Survey Development

The researchers distributed separate surveys to truck drivers operating in Texas and Mexico and truck drivers operating in all other continental US States and Canada. The purpose of the surveys was to:

1. Gain insights from truck drivers operating in Texas about Texas port operations during severe weather that support safe and efficient operations. Identify possible areas for improvement.
2. Estimate how many truck drivers operate at ports or do not operate at ports in Texas.
3. Estimate how many Texas truck drivers operate at ports in other states or countries and determine experiences at those ports.
4. Of Texas truckers who do not operate at ports, how many truckers identified impacts to their operations due to severe weather or other emergencies that affected freight delivery or pick-up?
5. Identify possible improvements to highway roadway networks, operations and related infrastructure that, though not directly related to the port, nevertheless affects freight deliveries / pick-up at ports.
6. Gain insights from truck drivers operating in other US states about port operations that support safe and efficient operations and identify possible areas for improvement.
7. Estimate how many truck drivers operate at ports or do not operate at ports in other US states
8. Obtain knowledge about sources used by truckers about route conditions and port gate

information.

9. Obtain knowledge about sources used by truckers about weather conditions, storm track and recommendations whether to proceed to the port, or where to stop until it is safe to proceed.

The surveys were developed in both English and Spanish using the University of Texas Qualtrics database software (Appendix C). The researchers obtained the Federal Motor Carrier Safety Administration (FMCSA) SaferSys database, which contains information about owner-operator truck drivers and trucking companies with a USDOT number (Federal Motor Carrier Safety Administration, n.d.). This information includes a contact email address, city and state business location and other data. The researchers extracted and sorted email addresses for further processing according to US state or country.

The researchers performed extensive email filtering since not every company with a USDOT number delivers freight. Removed emails included:

- Bus, taxi, limousine and charter tour companies
- Vocational truck companies such as ready-mix concrete, asphalt hot mix, construction, landscaping, and other non-freight operations
- Private companies with a USDOT number that provide compliance, permitting and/or training services to truck drivers or companies

In addition, researchers examined email addresses to correct spelling errors, add missing information such as a .com/.org extension and corrected other issues. If an email could not be corrected it was deleted from the database.

Through sorting and filtering researchers obtained approximately 800,000 email addresses for the survey distribution. Of these approximately 60,500 email addresses were for businesses located in Texas and Mexico. The remaining 739,500 email addresses were for other US states and Canada. The researchers distributed the surveys using the Word 'Mail Merge' feature and the Qualtrics™ email distribution feature. Each email invitation recipient received an email with the message in English and Spanish that explained the purpose of the survey and provided a survey link.

The researchers received 255 completed, valid surveys from truckers located in Texas and Mexico. The researchers note however that some trucking companies may have business locations in one or more states including Texas. Thus, we cited the trucking company as a Texas or Mexican company based on the zip code provided by the survey respondent as their business address. The researchers received 332 completed, valid surveys from truckers in other continental US states and Canada. Trucking companies in other states and Canada might also locate portions of their fleet in different states; the researchers also based the survey respondent's business location based on the zip code provided. Each survey was closely examined to identify inconsistencies that would suggest a 'careless' survey response. The literature provides some guidelines to identify careless surveys including time to complete the survey, consistently selecting the same response letter or response position for each question, providing information in one question that in some way contradicts or is not consistent with information provided in another question. The researchers deleted careless surveys from the survey analysis database.

In one instance however, the CTR researchers realized that question wording could be interpreted in more than one way and thus, these surveys were not considered careless responses if 'contradictory' with later information.

"*Do you operate a portion of your truck fleet at one or more coastal ports? Please select all responses that apply.*"

- *Yes, this is our primary business*
- *Yes, this is a percentage of our primary business*
- *Yes, though rarely, this is 10% of our primary business*
- *We do not operate or trucks at a Texas Port*
- *We operate our trucks at one or more ports in another US state*
- *We operate our trucks at one or more ports in another country*
- *We do not operate our trucks at any port in Texas, another US state or country*
- *I prefer not to answer*

A selection of surveys contained the response 'Yes, this is our primary business' but did not provide the names of ports at which they operated. Further, in responding to later questions, the survey taker indicated they did not operate their trucks at a port.

However, based on a review of trucking terminology, the researchers learned that a trucking company may be 'for hire' and thus will accept business from other companies that need freight transported. Other companies, such as Walmart, COSTCO and Coca Cola operate their own private truck fleets, which only transport freight for that company (not for hire). Thus, if a trucker answered 'Yes, this (transporting freight) is our (company's) primary business,' would not apply to a truck driver for Walmart or Coca Cola since their primary business is retail or selling soft drinks. However, this would apply to an owner operator or a driver for a truck company that exclusively transports freight for other companies as its 'primary' business. Thus, surveys with this 'seeming contradiction' were included in the analysis database.

Of the 255 Texas surveys, 229 were in English and 26 were in Spanish. Of the Spanish surveys, 4 were from cities in Mexico, the remaining 22 were from cities in Texas. The Qualtrics™ survey software automatically records the Spanish responses for questions with multiple answer options in English since both English and Spanish surveys and response options are identical except for the language. However, the database records comments in Spanish. Thus, the CTR researchers used an online Spanish to English translator to interpret the Spanish comment responses. Of the 332 US state and Canadian surveys, 11 were completed in Spanish. Of the 332 surveys, 23 were from cities in Canada. The researchers received a few emails asking why other languages such as French were not available in the survey. However, we could not have known what other languages potential survey respondents might have preferred. Multiple language versions of the survey and invitation email would have complicated the email invitation and survey response process.

The following sections discuss the results of the two surveys and interviews to provide information to understand how to improve the safety and operations of truckers operating at ports during severe weather.

5.4.2 Trucking Survey and Interview Results

The following summary provides basic information from each survey regarding truck fleet size, types of trailers operated and other factors. The Texas and Mexico, and other US States and Canada survey results are presented in adjacent tables to help the reader better understand similarities and differences between these two groups. Tables 5.3 and 5.4 provide the number of surveys received based on truck fleet size.

Table 5.3 Texas and Mexico number of surveys by truck fleet size

Truck Fleet Size	Number of Surveys	Size Description	% of Total Surveys
Very Small	117	<6 power units	45.9%
Small	56	6–20 power units	22.0%
Medium	28	21–100 power units	11.0%
Large	9	101–1,000 power units	3.5%
Very Large	2	>1,000 power units	0.8%
Owner Operator	42	Assume 1 truck	16.5%
Prefer Not to Answer	1		0.4%
Total Number of Surveys	**255**		**100.0%**

Table 5.4 Other US continental states and Canada number of surveys by truck fleet size

Truck Fleet Size	Number of Surveys	Size Description	% of Total Surveys
Very Small	162	<6 power units	48.8%
Small	51	6–20 power units	15.4%
Medium	40	21–100 power units	12.0%
Large	19	101–1,000 power units	5.7%
Very Large	0	>1,000 power units	0.0%
Owner Operator	59	Assume 1 truck	17.8%
Prefer Not to Answer	1		0.3%
Total Number of Surveys	**332**		**100%**

The truck fleet size distribution of the survey is generally in proportion to statistics provided by the American Trucking Association (ATA) which indicates that about 97% of trucking companies operate 20 or fewer trucks compared to the survey which contained approximately 84% from the Texas and 81% from the US state survey samples (very small, small and owner operators) (*Economics and Industry Data*, n.d.). The number of medium and large trucking companies make up a larger proportion of Texas and US state survey respondents than does the ATA national truck-company fleet size distribution.

Since the majority of surveys were from companies with multiple trucks and possibly different business locations, it is possible that different trucks and truck drivers might or might not be affected by a specific hurricane or other severe weather event depending on where they are operating during that event. For example, for a company with 6 trucks, 2 trucks might be delivering cargo to a port, 2 trucks might be located at warehouses in a large city picking up freight and 2 trucks might be traveling along a highway to yet a third destination within 50 miles of the coast. Thus, 4 of the 6 trucks might be affected by the hurricane while the remaining 2 trucks might not. Thus, the researchers note that a given survey might provide multiple responses regarding how hurricanes or other severe weather affected their company operations. Further, in some cases, a survey respondent might not have chosen to answer a specific question, thus resulting in total numbers / percentages of answers different from the total number of surveys.

Tables 5.5 and 5.6 provide the number and percentages of survey respondents who answered the question Question 7 "*Which of the following actions did you take during the hurricane or other emergency?*"

Table 5.5 Texas and Mexico responses to hurricane or severe weather

Question Responses	Number of Responses	Percentage of Responses
The hurricane affected our trucking operations even though we do not operate at a port	62	19.2%
We temporarily delivered cargo at locations other than a port	39	12.1%
The hurricane had no effect on our trucking operations since we do not operate at a port	79	24.5%
We temporarily stopped cargo deliveries until the port was back in operation	69	21.4%
Diverted normal truck operations to deliver relief supplies in the affected port city	50	15.5%
We temporarily delivered cargo to a different Texas port	10	3.1%

Question Responses	Number of Responses	Percentage of Responses
We temporarily delivered cargo to a different port in my state	3	0.9%
We temporarily delivered cargo to a port in another state	11	3.4%
Total Number of Responses	**323**	**100.0%**

Table 5.6 Other US states and Canada's responses to hurricane or severe weather

Question Responses	Number of Responses	Percentage of Responses
The hurricane affected our trucking operations even though we do not operate at a port	82	21.8%
We temporarily delivered cargo at locations other than a port	50	13.3%
The hurricane had no effect on our trucking operations since we do not operate at a port	107	28.5%
We temporarily stopped cargo deliveries until the port was back in operation	78	20.7%
Diverted normal truck operations to deliver relief supplies in the affected port city	43	11.4%
We temporarily delivered cargo to a different Texas port	0	0.0%
We temporarily delivered cargo to a different port in my state	6	1.6%
We temporarily delivered cargo to a port in another state	10	2.7%
Total Number of Responses	**376**	**100.0%**

Regarding the response in Table 5.5 indicating that 3 trucking companies delivered freight to a different port in 'my state' during the hurricane or severe weather, this is an example of trucking companies that have business locations in more than one state including Texas. In each of these cases, the survey respondent indicated that their company operated at ports in Texas and other US states. In one case, a respondent simply indicated that they were a large (100 – 1000 power units) tank truck fleet and operated at every Gulf and Atlantic port that handles bulk chemicals.

During Federal Emergency Management Agency (FEMA) operations, trucking companies may participate in relief efforts in the areas affected by the hurricane. Based on responses approximately 50 Texas or Mexico (15.5%) of truck company surveys and 43 (11.4%) of other US state and Canadian truck companies indicated they participated in the relief effort. One survey respondent indicated that FEMA relief efforts can affect the amount to time it takes to return to normal truck freight operations since FEMA relief deliveries take priority over other types of deliveries. Other survey respondents indicated that a hurricane or other severe weather event can disrupt the supply chain well beyond the state in which the main hurricane impacts occur. Supply chain disruptions will include deliveries or pickups at the port until normal operations resume but can also affect deliveries at factories that produce manufactured goods that, in turn, are delivered to the port. Thus, a truck freight company that deliveries computer chips to a factory in Texas that assembles computers, might not directly make deliveries to the port however its business is affected by the hurricane since the factory making computers cannot deliver them to the port until normal operations resume. In this way, the number of trucking companies and truckers affected by a hurricane or other severe weather event is significantly larger than just those truckers who operate directly at ports. Based on responses shown in Table 5.3 approximately 19.2% of Texas or Mexico survey respondents indicated that the hurricane or severe weather affected their operations even though they do not operate at a port. Table 5.4 indicates that hurricanes, or other severe weather events, affected 21.8% of respondents trucking operations in other US states and Canada even though they do not operate at a port.

Based on an assessment by FTR Transportation Intelligence, a consulting firm that provides information to the trucking industry, Hurricane Harvey disrupted up to 10% of the US truck fleet due to four primary impacts (Truck News, 2017):

1. Disruption due to idle trucks waiting for water to recede from roads and loading docks
2. Additional relief shipments including construction supplies
3. Lower productivity due to out of cycle shipments and extra shipments
4. Slow operations due to congestion and backed up loading docks.

These do not include other factors that were identified during the literature review, survey and interviews regarding impacts due to loss of power and access to fuel that will be discussed in a later section.

Tables 5.7 and 5.8 summarize responses regarding the information sources cited by truckers, which are used during trips to a port or other destination during severe weather. In most cases, multiple information sources are used. Owner operators tend to have fewer information sources likely due to lack of a company dispatcher, or more sophisticated in cab equipment including a Qualcomm (aka Omnitracs). A Qualcomm is an onboard computer system that provides a messaging system, GPS navigation and an integrated electronic logging device. These units allow trucking companies to track where a truck is located and other information relative to the freight shipment.

Table 5.7 Texas and Mexico trucker information sources about travel during a hurricane or other severe weather

Texas and Mexico Truckers – sources that provided information during travel	Number of Surveys	Percentage of Responses
My wife, husband, or partner kept me informed about what I should do	56	15.9%
The port authorities informed me about what I should do	31	8.8%
The port tenant to whom I was making the delivery informed me about what I should do	16	4.5%

Texas and Mexico Truckers – sources that provided information during travel	Number of Surveys	Percentage of Responses
I had direct communications with the ship that was going to carry the cargo I was transporting	8	2.3%
I obtained information from the city police where the port is located	17	4.8%
I obtained information from the county where the port is located	16	4.5%
I obtained information from a State – Travel Information Center	82	23.3%
I obtained information from the State Highway Patrol	12	3.4%
I obtained information from the Department of Motor Vehicles	47	13.4%
My trucking company dispatcher informed me about what I should do	67	19.0%
Total Responses (some truckers cited multiple sources)	**352**	**100.0%**

The highest percentage of Texas truckers indicated that they obtained information from Travel Information Centers. Based on interviews with TxDOT Travel Division – Travel Information Center Supervisors and travel center employees, many phone calls are answered each day from Texas and out of state truckers approaching the Texas border requesting route information, information about Texas State Laws, construction work zones, traffic congestion and other information. The TIC employees only provide direct answers to questions about construction work zones, traffic congestion, crashes and other information available through DriveTexas.org. TIC employees provide contact information to truckers directing them to the appropriate state agency or law enforcement on other types of questions. (Murphy et al., 2018)

Table 5.8 Other US state and Canada trucker information sources about travel during a hurricane or other severe weather

Other US States and Canada – sources that provided information during travel	Number of Surveys	Percentage of Responses
My wife, husband, or partner kept me informed about what I should do	57	12.9%
The port authorities informed me about what I should do	27	6.1%
The port tenant to whom I was making the delivery informed me about what I should do	22	5.0%
I had direct communications with the ship that was going to carry the cargo I was transporting	7	1.6%
I obtained information from the city police where the port is located	19	4.3%
I obtained information from the county where the port is located	9	2.0%
I obtained information from a State – Travel Information Center	97	22.0%
I obtained information from the State Highway Patrol	86	19.5%
I obtained information from the Department of Motor Vehicles	56	12.7%

Other US States and Canada – sources that provided information during travel	Number of Surveys	Percentage of Responses
My trucking company dispatcher informed me about what I should do	61	13.8%
Total Responses (some truckers cited multiple sources)	**441**	**100.0%**

The highest percentage of other US state and Canada truckers also indicated that they obtained information from Travel Information Centers. However, there is a distinct difference between the two sets responses regarding information obtained from other sources such as the State Highway Patrol; Texas and Mexico 3.4%, other US states and Canada 19.5%; and information provided directly by the port, tenant, or ship; Texas and Mexico port authority 8.8%, port tenant 4.5%, direct communications with ship 2.3% (total 15.6%). Other US states and Canada, port authority 6.1%, port tenant 5.0% and direct communications with ship 1.6% (12.7%). Thus, a relatively low percentage of truckers indicate that they receive information directly through communications with the port or related party. It may seem unusual that a trucking company would have direct communications with a ship on which cargo is loaded or which the cargo they are carrying will be loaded. However, based on experience, project cargo, which can include large pieces of equipment for the petroleum industry, generators and other items that constitute oversize/overweight loads are very high value and require special communications to ensure delivery or pickup. In addition, the 'ship' that is transporting the cargo can be a tugboat pushing a large barge or special unit that is carrying the large piece of equipment. Port Houston, Port of Corpus Christi and Port of Brownsville specialize in project cargoes of this type.

Regarding the reliability of the information received from these sources, 13 Texas or Mexico respondents indicated that the information was inconsistent, while 77 respondents indicated the information was consistent. In addition, 4 respondents indicated the information they received resulted in the trucker making a bad decision about route travel, while 87 respondents indicated they were able to make good decisions. Regarding US state, or Canada respondents, 26 indicated they received inconsistent information, and 143 indicated they received consistent information, while 4 indicated they made a bad decision based on the information and 160 made a good decision.

Based on survey responses truckers experienced adverse conditions and impacts due to the hurricane or other severe weather event. Table 5.9 summarizes the various experiences by Texas and Mexico truckers, Table 5.10 summarizes experiences by other truckers in other US States and Canada.

Table 5.9 Adverse conditions experienced by Texas and Mexico Truckers during a hurricane or other severe weather event

Adverse Conditions on Route Due to Severe Weather	Number of Surveys	Percentage of Surveys
Roadways and bridges were flooded	86	30.4%
Could not buy fuel locally	65	23.0%
Downed power lines had to be removed	8	2.8%
Debris blocked route	21	7.4%
Had to turn around due to flooding, debris, or power lines	57	20.1%
My truck broke down and repair services were unavailable	15	5.3%
High winds damaged my truck or cargo	21	7.4%
High winds turned my truck over	2	0.7%
Flooding damaged my truck or cargo	7	2.5%
I had to be rescued from my truck	1	0.4%
Total Number of Responses	**283**	**100.0%**

Table 5.10 Adverse conditions experienced by truckers from other US states and Canada during a hurricane or other severe weather event.

Adverse Conditions on Route Due to Severe Weather	Number of Surveys	Percentage of Surveys
Roadways and bridges were flooded	91	31.9%
Could not buy fuel locally	69	24.2%
Downed power lines had to be removed	19	6.7%
Debris blocked route	15	5.3%
Had to turn around due to flooding, debris, or power lines	55	19.3%
My truck broke down and repair services were unavailable	12	4.2%
High winds damaged my truck or cargo	14	4.9%
High winds turned my truck over	1	0.4%
My truck and cargo were damaged by flooding	2	0.7%
My truck and cargo were destroyed by flooding	1	0.4%
I had to abandon my truck to seek safety	6	2.1%
Total Number of Responses	**285**	**100.0%**

There are several results shown in these two tables that bears further examination. First, the largest impact to truckers is flooding of roadways and bridges, which is consistent with information contained in the literature. However, damage to trucks and cargo is more often attributed to high winds than due to flooding. Flooding can mean that a trucker must turn around and seek a different route or abandon the trip destination altogether. However, impacts due to high winds can occur near the port city during hurricane landfall and can persist as the hurricane moves inland. Though documented information about the relationship between wind speed and truck overturning was not obtained from an official source, unofficial sources provided through a trucker's forum indicated the following:

1. The potential for truck roll over is related to 'sail factor' that is, the area of trailer based on trailer height x width. This is because high winds will typically pick up the rear of the trailer first and progressively roll the trailer over due to lack of structural rigidity.
2. The definition of 'high winds' can vary – however, usually 60 mph wind speeds are dangerous and can roll a loaded truck depending on direction and duration.
3. A loaded truck is safer to drive in high winds than an unloaded truck.
4. A double 28-1/2 foot tractor-trailer unit is safer to drive than a tractor with 53' trailer due to the greater rigidity of the shorter, double 28-1/2 trailers. However, unloaded double 28-1/2 foot trailers are also less able to withstand high winds.
5. Even if high wind speeds are not of sufficient force to roll the trailer, the stability of the tractor-trailer is still affected and can push the truck into another truck or car in the adjacent lane or can push the adjacent traffic into the truck.

The researchers were not able to find documented information on wind speed and truck safety in the literature. However, as mentioned the following chart is posted on a trucker's forum as an indicator when it is ok to operate a truck with a specified minimum load and when the trucker should seek shelter and park the truck. This does not constitute a recommendation by the CTR research team on safe truck operations at these wind speeds.

Constant Wind Speed (mph)	Wind Gusts (mph)											
	10	15	20	25	30	35	40	45	50	55	60	65 or >
10	OK	OK	OK	OK	OK	OK	2	2	3	3	3	4
15		OK	OK	OK	OK	OK	2	2	3	3	3	4
20			OK	OK	OK	OK	2	2	3	3	3	4
30					OK	OK	2	2	3	3	3	4
35						OK	2	2	3	3	3	4
40							2	2	3	3	3	4
45								2	4	4	4	4
50									4	4	4	4
55										4	4	4
60 or >											4	4

2	Minimum of 25,000 lbs. NO empty trailers
3	Minimum of 40,000 lbs. NO empty trailers
4	NO GO! PARK IT or STAY PARKED

All minimum trailer weights are in addition to the empty trailer weight

Wind direction should be considered when using this chart. Wind hitting you at 90° will have a greater effect than directly from the front or rear.

Note: This information has no formal citation and is presented in this document for illustrative purposes only to emphasize the potential effects of wind speeds on trucks.

Figure 5.6 Relationship between loaded truck operations and wind speed (no citation, this figure is presented for illustration purposes only and is not a recommendation from this research)

Though Figure 5.6 is not based on cited literature, the general information provided is consistent with advice from experienced truckers who routinely operate along highway corridors with high winds. In Texas, high wind speeds do occur during hurricanes and other types of severe weather and can occur at locations other than a port such as the highway between Laredo and Nuevo Laredo, and along routes crossing the Franklin Mountains near El Paso. A survey respondent indicated that their truck was flipped by high winds due to a sudden thunderstorm that occurred in March 2021 along the highway between Laredo and Nuevo Laredo.

Comments from the truck survey and the literature indicated that there is no clear guidance about where a trucker can safely park if caught in a severe weather event with high winds. A selection of comments from the literature and survey include:

1. Truckers from my company chain their trucks to the ground if caught in Houston when a severe storm or hurricane is coming ashore.
2. Park your truck with the windshield away from the major wind direction so that debris is not blown through the windshield and injure you.
3. Truckers reported that high winds, can damage a truck and its cargo even if the truck

remains upright

4. I am unsure what is considered safe parking – can I park under a highway overpass for example?
5. In general, ‘safe parking’ means you are not parked along a travel lane carrying traffic, or along a freeway / interstate ramp or entrance / exit to a roadside park. However, it is often difficult to find parking places during severe weather due to the high demand for spaces.

Tables 5.9 and 5.10 also show that truckers often are faced with power outages and the inability to buy fuel locally during severe weather. There are two states, Florida and Louisiana, which have laws requiring gas stations along hurricane evacuation routes to have a backup power supply in case of a power outage. However, though efforts have been made to pass legislation in New Jersey, New York and Connecticut to require gas stations to have backup power supplies, these efforts have not been successful. The reasons cited by industry representatives for gas stations and convenience stores is that the problem is not lack of electric power, it is the difficulty the fuel trucks have getting loaded at their fuel supply location and being able to drive and deliver fuel to gas stations under severe weather conditions.

It has been further been pointed out by opponents of backup power that during an evacuation order from the local city officials, residents will fuel up at stations quickly draining the stations storage tanks. This situation occurs across the city and especially along hurricane evacuation routes. However, fuel tank trucks, even if loaded can have a difficult time reaching fuel stations with empty storage tanks due to the traffic on the routes leading to the stations. Thus, even if these stations had backup power, they still would not have fuel to pump. The estimated cost to install backup power generators at a gas station or convenience store ranges from $10,000 to $30,000 dollars or more. If installing backup power does not solve the problem these stations have made a major investment that does no good.

Additional unedited key comments from the truck survey are given in the following summary:

Texas and Mexico

1. Quit trying to beat the storm and just stay away and safe. No freight is worth a life and I tell the young drivers that all the time.

2. Use highway (ITS) signs to provide information the way that Amber Alerts are done.

3. Need to educate trucking companies more on how to monitor highway conditions during these (severe weather) events.

4. It revolves around pay, a lot of independent (truckers) rely on the next delivery to pay the mortgage or truck payment. So ANY downtime is detrimental.

5. Parking (is needed) for trucks stranded by storms. Shopping center parking lots, industrial plant parking lots and other places could be places to park.

6. Need more high visibility markings on the roadways. All of them. Even for normal rain events on highways you can't see the lines to tell if you are in the lane or not.

7. Load and unload (trucks) quickly, spending 3 – 4 hours at a port to unload is (not acceptable). Stop all truck loading when the hurricane is within 24 hours of landfall if the port has to stay open. I would close (the port) 2 days out and prepare buildings and loose stuff tied down to make reopening faster.

8. Blitz AM radio, Satellite Radio and highway signage with warnings about significant hazards on highways and at ports WAY before the hazard is to take place. Truckers have a long time horizon built in so (it) can be 600 miles since they last heard accurate information in a dawn report.

9. Expand hours and streamline the delivery and gate process. The lines after the (February Texas) freeze were 3 miles long. It's absolutely unacceptable to expect people to wait an entire day for free. Port employees should be incentivized to move the line quickly and get the loads in and out. Expand the normal business hours of the ports to allow companies to catch up before a severe weather condition and move the freight out of the affected area faster - and the same for after the event.

10. Send automatic updates to trucking companies

11. Access information DIRECTLY from the Port. We are fortunate to have direct contact with the stevedores at our ports and thus we have reliable information upon which to base our decisions. That is why we have not had any of the catastrophic experiences listed above.

12. Perhaps an APP on phones for updated information on ports like the amber alert system – but for hurricane type events.

Continental US states and Canada

1. (Truckers need) automatic alert notices: (email, social media groups), centralize resource links. Ensure every state has a link to DOT alert notice page from their state website and/or 511 alert notices.

2. DOT should provide parking for trucks during weather events since (under normal circumstances) parking is already an issue.

3. Do not reverse the interstates so soon, this limits the ability for home based trucks to get back to their terminals/homes.

4. Keep the painted lines of the highways maintained. At night and (during) rain there are many areas that the lines are not visible. There should be way more funds to keep these visible. I don't think most maintenance engineers are aware (of this): meaning they don't survey safety at night or in rain conditions.

5. Better paint for highway lines for lane control. In most states under adverse weather conditions you cannot see the lines……this is extremely unsafe.

6. Need more rest areas and authorized truck parking areas (always, year-round! Massive shortage!!); but especially in times of active storms. There simply are not enough authorized spaces to put all the trucks on a daily basis, much less during a disaster or serious storm.

7. Fuel is difficult if not impossible to find in the aftermath of a hurricane, so initiating some sort of emergency fueling stations in critical areas would be beneficial. Truck stops are frequently full or closed during the aftermath of a hurricane - so temporary emergency truck parking in critical areas - so drivers can take required breaks. State Departments of Transportation for areas affected by a particular storm should restrict loads to critical emergency relief loads for a set time after the storm (time parameters would depend on the severity of the storm.)

8. Truck operators should restrict loads to critical freight / emergency loads until areas are reopened for normal operations. Many truck operators and 3rd party (Freight Logistics Companies) are trying to dump non-critical loads into affected areas so they can move on to the next load. This causes capacity issues in warehouses and docks in storm-damaged areas.

9. The best response from DOT is a timely and accurate one. Overhead highway signs, warnings at state ports of entry, and notifications at truck stops are all helpful.

10. Carry emergency food and water in case a trucker gets stranded. Know your driving abilities. If you don't feel safe then park! That way you don't cause accidents that affect others and distract emergency responders from their other tasks related to the storm.

11. More information posted online as we are a Canadian carrier that does most of our business between Texas and Alberta (Canada) and don't have access to local (Texas) news, TV or weather warnings.

12. During times of severe emergency open more parking areas. Lack of parking is largest reason why most trucks try to go to the delivery.

Certain survey respondents agreed to conduct a separate telephone interview to provide more detail about their experiences operating during hurricanes and other severe weather events. A total of five of these phone interviews were conducted with employees from freight trucking companies in Texas, Louisiana, South Carolina, and Illinois. The phone interviews offered CTR the opportunity to discuss extreme weather issues with truckers who had prior experience with operations during these events. An outline of the questions typically discussed in the trucking phone interviews may be found in Appendix D. The following summary provides key responses from 5 telephone interviews.

Illinois

1. We operate trucks in the Chicago area at rail intermodal yards. Each railway company has their own rules and methods regarding how they operate gate openings and deliveries. It takes anywhere from 2 – 5 hours to enter the rail yard, get loaded and exit the rail yard. It seems that most rail company's procedures are outdated.

2. We previously picked up containerized cargo using container chassis pool equipment, but we were getting too many fines because the container chassis pools were not maintaining their equipment. Sometimes we get the ticket and sometimes the chassis pool gets the ticket. We decided to operate our own trailers – and we maintain our own equipment now – this has significantly improved safety and decreased traffic fines.

3. The problems we are experiencing at the rail yards are a) too many containers arriving from the west coast; b) too few cranes at the rail yards, c) lack of container chassis – slows down the entire operation; d) differences in operating procedures by the different rail roads.

4. Intermodal facilities send an email if they will be closed due to weather– so we know in advance not to travel. A trucking company must be enrolled to get the emails. Our

drivers have the choice not to operate in bad weather in any case they can make their own decision.

5. We've only had one serious accident with one of our trucks, it was a roll over in Iowa.

6. We've found that social media sites are a good source of information because information is often posted there before it is posted on the official site.

7. I am not aware of a manual that provides information about what to do or how to drive in severe weather. Perhaps the FMCSA Manual has some information – but it is over 2,000 pages thick, so no one is going to carry it with them in a truck.

Texas

1. One of the problems at ports when a hurricane is approaching is that the port allows employees to go home, leaving most operations short-handed. There does not seem to be a sense of urgency to get trucks loaded and out of the port.

2. I had live load at the port when a hurricane was on the way, I waited several hours and finally went back to my business location which is over an hour away. I had one of my employees who is a driver wait 9 hours at a Texas port to have 3 pieces of equipment loaded. It seems that the port should just close the gates and stop loading if they are going to let that many employees go home. I understand that they want to be with their families and shelter – but the ports need to consider how long the truckers are having to wait.

3. I think TxDOT should create some type of an alert system about port terminal gates closing like the Amber Alert system.

4. I also pick up loads at drayage – cross-docking facilities – they are a lot better than the ports, but still, it seems they take too long. We sit in our trucks without so much as a glass of water for hours waiting to be loaded – it seems that the trucker and his family should be given some consideration.

5. I don't think it's a good idea to have heavy trucks operating on contraflow lanes – truckers need to get to safety. There is a big problem with truckers not being able to find a place to park – they need to have access to food and a restroom.

6. I don't think it would help to have backup power for gas stations within an area subjected to heavy rain. The underground storage tanks will get infiltrated with water

and the fuel will cause problems. Perhaps requiring back up power at stations well away from the coast – say as far out as we are in Tomball would work.

7. I haven't been involved in FEMA relief work because I've heard it takes too long to get paid.

8. Commercial Driver License classes don't cover driving in bad weather and I can't think of a manual or other reference that provides that type of information. There are requirements about operating in inclement weather on oversize/overweight permits that could help.

9. Companies need to treat their drivers better and not expect them to drive in unsafe conditions. If a trucker has a rig that gets flooded, that decision was made 3 or 4 people up the chain of command but the driver will be blamed.

Texas

1. We are a Less than Truck Load (LTL) operation – we rarely operate at ports unless it is less than container load deliveries. We do deliver to cities and hurricanes do affect our operations.

2. An Amber Alert type system for ports is a good idea – but other types of businesses should be included. The state is the only agency big enough to handle a project like this.

3. We need to know if a port is going to close its gates. However, the same type of information is needed for a variety of businesses as well. Especially after a hurricane, it can be quite difficult to know where to deliver a load; we might show up to a business and find it is closed and a small sign has been posted indicating where they are taking deliveries during the hurricane aftermath. Having a system that would allow companies to indicate if they are open or closed or where they are taking deliveries would really help truckers after a hurricane.

4. We saw the winter storm approaching in February and moved to cut long haul operations so we wouldn't have truckers away from home base. When hurricanes are approaching, we have drivers fill up at our yard with quality fuel and require them to keep at least ½ tank at all times – standard procedure is to fill up again in San Antonio if driving to Houston with a hurricane approaching.

5. A mobile mechanic to help truckers with mechanical problems in a port city would not be complicated – but likely expensive. The mechanic is likely going to charge premium rates and will only be able to help repair certain types of problems.

6. Planning ahead is critical. We have our drivers carry extra clothes, food, and blankets in their truck cab in case they have to stop at some isolated location due to bad weather.

7. FEMA relief supply work is cumbersome and requires a lot of redundant paperwork. The paperwork could be done once electronically and save truckers a lot of time. It can take up to 6 months to be paid for FEMA relief work.

8. One of the problems with truckers and trucking is that our image with the public is not good. Back in the 1970s truckers wore their company's uniform and were considered a professional. These days, truckers don't take as much pride in their appearance – but it also has to do with the way truckers are treated by the businesses to which they deliver.

9. Travel Information Centers are useful – TIC employees are very knowledgeable and informative.

Louisiana

1. Before and after a hurricane fuel is a big issue. We have our truckers leave with a full tank and keep our trips shorter than usual, say around 100 miles so that we don't risk having to fill up at a location with questionable fuel or no fuel.

2. We also don't want to send our trucks into areas that we aren't sure are safe. There is a lot of debris on the road after a hurricane and we need to ensure the trucker and truck are delivering to a location that is safely accessible (no downed power lines, flooding or debris such as tree limbs in the road).

3. We have a range of truck sizes at my facility – we do run double 28-1/2' trailers, but also have 53', 48' and 45' single trailers depending on load size. We are an LTL operation.

4. There is a lot of work necessary to repair highway infrastructure after a major hurricane – if this work could be completed within 3 to 5 days, that would be ideal. That would allow regular freight deliveries to resume by the end of the first week. However, typically relief operations and deliveries of water, generators and other essentials are still being made during that time frame. If relief supply deliveries are

operating at the same time as regular freight – this causes congestion and problems for the relief supply deliveries.

5. Twenty to twenty-five years ago, a truck driver was expected to make a freight delivery as long as the road was open, regardless of the weather. That has changed and now the trucker has more say in whether they think it is safe to drive. I haven't seen any manuals on safe driving procedures during severe weather.

6. Parking is always a big problem – even during regular weather – there are never enough parking spaces. This becomes worse during severe weather – and at times a trucker has to park in an unsafe or dangerous location because there is nowhere else to go; and there are hours of service (HOS) rules.

7. It would be helpful to provide information to truckers using (ITS) signs such as the Amber Alert system or if there was a number truckers could call to get up to date information – this would be extremely helpful. Other ways to communicate to the trucker when the port gates will close could include the internet or radio.

8. Not knowing if a particular company is open or closed can be a big problem before or after a hurricane – this is similar to not knowing if the port is open or closed.

9. We have vendors who are mobile mechanics that provide service to our truckers if they break down.

South Carolina

1. We operate at container and break-bulk terminals in Charleston, SC. and Savannah, Ga. I think these ports have one of the best systems for communicating with truckers I know of. The same system that is used to issue a number to pick up or drop off a load at the port is also used to communicate weather information to truckers. Therefore, if a trucker is registered to operate at the port, they automatically receive information about port terminal gate closing times if a hurricane is approaching.

2. This system is not limited to truck drivers though – anyone who wants these messages can register using the same system. This is the same at Savannah. We receive messages 24 to 48 hours in advance of a hurricane landfall that the port will be closing its gates or will stop receiving freight. Thus, we can make decisions about moving our staff and fleet further inland and away from danger.

3. My company primarily operates at the break bulk terminal since we typically transport heavy project cargo. However, the port has two large container terminals, a Roll on –

Roll off terminal and the break bulk terminal located in different parts of the town. There are other types of operations at the port, which have their own dock facilities – one is steel production and the other coal.

4. In addition to the automatic messages received through the electronic registration system, the port posts notifications on its website.

5. Annually, the highway patrol will perform an exercise simulating a hurricane and establishing contraflow lanes. However, there are no truckers involved in that exercise. Ports are not part of the state's emergency management team since they are a quasi-public / private entity.

6. We do not have a lot of information in our company manuals regarding operations during severe weather, maybe a couple of pages. We rely on our managers to know the weather conditions and how to work with drivers to keep them safe.

7. We also receive messages if the port has stopped receiving empty containers due to high wind advisories. The ideal situation would be if we received notification 72 hours in advance of the time the port will be closing its gates – most ports close their gates 24 – 48 hours before a hurricane makes landfall. However, having a 72 hour notification would give a trucker enough time to know whether they can make it to the port or not. This would be particularly helpful for truckers who are on the road, out of state traveling to the port.

8. Smaller trucking companies are at a greater risk due to severe weather since often the owner is also one of the truck drivers. Also, they may not have more advanced communications equipment in their trucks to keep up to date on conditions. The driver must find a place to stop to check conditions, which in itself can be difficult. Since the smaller companies don't have the same access to equipment or perhaps a dispatcher, the ITS signs might be more helpful to them.

9. Hours of Service rules are suspended for truckers making relief supply deliveries after a hurricane, but drivers delivering normal freight or oversize/overweight loads should not be given any special considerations. There is enough information available for planning ahead regarding weather conditions.

10. South Carolina has a roadside assistance program for passenger vehicles – however, there is no similar program for heavy trucks.

5.4.3 Trucking Survey and Interview Conclusion

Section 5.4 provided an extensive overview of information obtained through two surveys and five interviews with truckers. A summary of the responses and comments was presented including similar themes that point to agreement among truckers about needed improvements regarding port operations. These improvements can help improve resilience by keeping truck drivers, their trucks and cargo safe. In addition, these improvements can potentially help the port resume normal operations with less disruption to normal freight operations and improved operations at port truck gates.

5.5 Limitations

The COVID-19 pandemic presented the researchers with unexpected challenges. Originally, CTR was to host multiple, in-person workshops to gather data on port vulnerability and resilience from relevant stakeholders. An online survey was originally intended to be sent out to port stakeholders who were unable to attend the in-person workshop. Given the challenges that arose due to the pandemic, CTR had to adjust the original scope. Rather than hosting multiple in-person workshops with multiple attendees, CTR hosted one workshop with multiple port authorities and then individual interviews with other stakeholders. All interviews and workshops were conducted virtually on Microsoft Teams. CTR also intended to conduct site visits at actual port facilities to observe operations and meet with stakeholders in person. These site visits were not possible due to COVID-19 precautions.

5.6 Summary

This chapter presents the methods and results employed in Task 5 of this study. As part of the scope of work to gather information on port vulnerability and resilience from relevant stakeholders, CTR conducted multiple virtual and web-based activities to collect stakeholder input:

- Workshop with port authorities: November 4, 2020
- Interview with UP Railroad officials: November 18, 2020
- Interview with USACE district chief engineer: December 8, 2020
- Interview with Port Houston employees: August 10, 2021
- Web-based Qualtrics survey targeted to port authorities: December 7–21, 2020
- Web-based Qualtrics survey targeted to truckers and trucking company employees in Texas and Mexico, 1/20/2021
- Web-based Qualtrics survey targeted to truckers and trucking companies in U.S. states other than Texas and Canada, 2/15/2021
- Phone interviews with trucking company employees, 6/21/2021–8/31/2021 (five total interviews)

Results show that port authorities have an understanding of resilience concepts, yet currently only larger ports take an active approach to resilience planning as they have more resources available. Ports commonly speak of employee flexibility or operational impacts when discussing resilience measures, although survey results seem to indicate that port authorities would invest in physical resilience improvements if funding were available. One-on-one interviews with additional stakeholders reveal that inter-stakeholder communication is vital for a resilient port environment.

Efforts to communicate with truckers provided a better understanding of the issues that are faced by truckers in port and other delivery environments during times of inclement weather. The trucker interviews provided more detailed information and anecdotes regarding past extreme weather experiences and gave truckers a chance to offer suggestions regarding improvements to extreme weather trucking operations.

The results of this analysis are incorporated into future tasks, specifically the vulnerability assessment in Chapter 6 and the economic assessment in Chapter 7.

Chapter 6. Quantify Physical Risks on Texas Port System

6.1 Introduction

The methods and techniques used to perform the quantification of the physical risks on the Texas port system are detailed in this chapter. The general processes involved include determining the criticality, vulnerability, exposure, and risk at the network-level analysis scale, as shown in Figure 6.1.

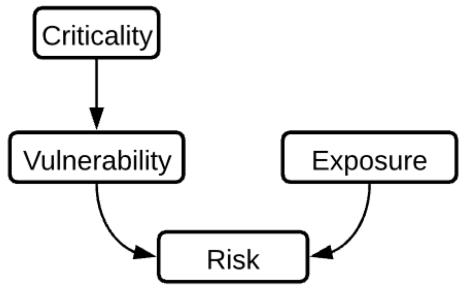


Figure 6.1 Conceptual framework for extreme weather physical risk assessment.

The overall objective of this project is to examine the resilience of the Texas port system to extreme weather events. To achieve this objective, it is crucial to understand what inherent inadequacies and potential exposures to climate disasters are present in the physical infrastructure of port system. Therefore, assessing the vulnerability of port systems to extreme weather hazards is crucial for a full understanding of the resilience of the physical systems. Additionally, understanding which assets have higher levels of risk may aid decisionmakers in budget allocation and capital project selection when choosing projects to mitigate risk and increase system resilience.

The data acquired in previous tasks are employed for this analysis to demonstrate the risk framework using a case study—namely, the hazard data detailed in Task 3 and the infrastructure data described in Task 4 and used to perform the analysis. Information gained from stakeholder input in Task 5 is also incorporated where applicable, particularly in the criticality assessment, where input from stakeholders is important to accurately determine which infrastructure components are most critical for port system operations. Similarly, vulnerability characteristics as recorded from the port authority workshop and survey were incorporated into that respective component of the analysis. The assessment framework was formulated using best available datasets and was contrived to be simple and straightforward to serve as a baseline for implementation in real-world applications. The framework presented herein may be enhanced by the inclusion of additional datasets, further expert engineering opinion, or other factors.

A case study is performed in the Houston-Beaumont region to demonstrate the applicability of the framework. The general methodology is inspired by the FHWA Gulf Coast Study methods. First, criticality of Texas ports, roadways, waterways, pipelines, and railways are determined. Next, the vulnerability of each of these systems is quantified using the results of the criticality assessment plus an additional indicator. Exposure to hurricane storm surge and sea level rise was performed, although additional hazards may be incorporated into the analysis framework if required data is available. Finally, risk is found as a product of vulnerability and exposure.

6.2 Theoretical Background

The concepts and theory used to formulate the risk assessment framework are provided in this section. Basic definitions and terminologies are presented along with relevant examples and citations. Figure 6.2 details the theoretical relationships between the quantities.

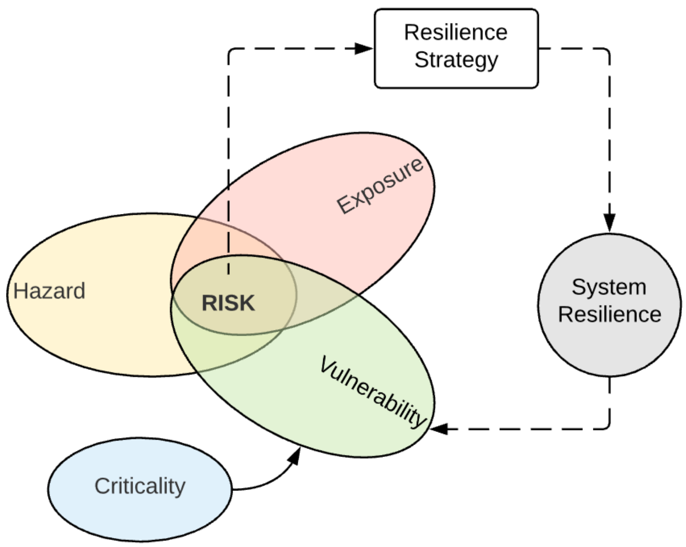


Figure 6.2 Conceptual relationship between risk factors and resilience, adapted from Field et al. (2012) *and Srijith Balakrishnan.*

6.2.1 Criticality

The term *criticality* refers to items that are of the highest importance. Regarding infrastructure systems, "critical infrastructure" refers to those systems that are vital for the proper functioning of society, which would result in debilitating effects if disabled or damaged (Rinaldi et al., 2001). The U.S. Cybersecurity and Infrastructure Security Agency (CISA) lists 16 sectors as critical infrastructure systems. Included in these 16 systems are transportation, communication, chemical, and energy sectors, among others, which are present in some form in a port environment (CISA, n.d.-a). Therefore, assessing the criticality of the infrastructure systems at port facilities is vital for identifying specific assets, structures, or equipment that are most important for uninterrupted operations and require special attention to ensure that they are adequately designed to avoid failure.

6.2.2 Vulnerability

In this study, *vulnerability* refers to the susceptibility of an element to physical damage or harm at a given level of exposure. In infrastructure systems, vulnerabilities may also represent inherent inadequacies that are present in the system, such as a structure designed to withstand lower loads than it may experience in practice. The interdependencies present between multiple infrastructure systems may result in vulnerabilities that exist in infrastructure systems other than those that are directly impacted due to cascading or escalating failures (Rinaldi et al., 2001). Other vulnerability characteristics may involve operation measures that are taken by port stakeholders. Breakdown in communication practices or a failure to properly train employees in disaster response procedures may be other examples of vulnerability.

Given that criticality refers to infrastructure assets that are most vital for proper system functioning, incorporating criticality into vulnerability assessment is an important consideration (Jenelius et al., 2006; Theoharidou et al., 2009; Tu et al., 2013). Current frameworks for assessing vulnerability with criticality include those presented in the FHWA Gulf Coast Study.

6.2.3 Exposure

Exposure refers to the presence of an infrastructure facility in a place that may be impacted by extreme weather. Exposure is quantified as frequency and severity of extreme weather impacts on a given infrastructure facility. As described in Chapter 3.2.1 (as provided in Tech Memo 3), hurricane exposure may be calculated as a return period, representing the approximate interval between subsequent events of a specified intensity (Needham & Keim, 2012). This concept is also applied to flooding, where terminology such as “a 100-year flood” is commonly used (Benn, 2013). For sea level rise, the estimated depth and extent of inundation at some future time period is typically reported, such as a map showing estimated flooding depths and extents for the year 2100. When determining the exposure of infrastructure assets, it is important to account for both magnitudes, or severity, and frequency to provide a temporal scale for the predicted exposure levels.

6.2.4 Risk

Risk refers to the level of potential losses or impacts that may occur from exposure to a specific hazard event (Moteff, 2005). Risk is often quantified as a likelihood measure, using probabilistic techniques or a value of estimated economic impact in currency amounts, or may be reported as a scalar ‘score’ depending on whether the analysis is qualitative or quantitative in its approach (Tagg et al., 2016). From a quantitative perspective, risk may be computed as the product of the exposure and vulnerability of an infrastructure component, with criticality reflected as a vulnerability aspect of the infrastructure system. Figure 6.3 shows an example of risk levels for given inputs of vulnerability and exposure.

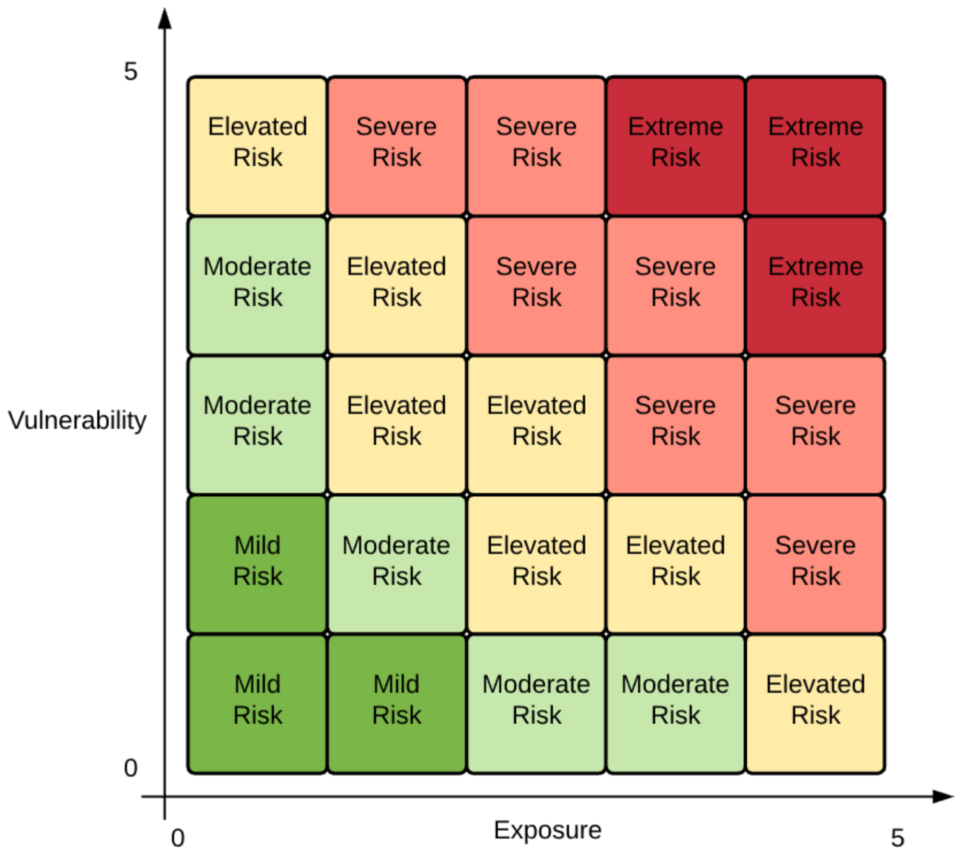


Figure 6.3 Risk matrix from exposure and vulnerability inputs

6.3 Risk Analysis Framework Methodology

To assess the criticality, vulnerability, exposure, and risk of a port infrastructure system, the following conceptual framework is proposed. The framework focuses on using available datasets to perform the analysis and is conceived to be easily implemented in a real-world setting. As such, the overarching objective is to create a scoring system for the criticality, vulnerability, exposure, and resultant risk that is easy for port and other freight stakeholder employees to intuit and calculate.

The overall approach is based on empirical analysis using subjective weights to account for past professional experience. This allows for experts and engineers familiar with the study site to make rankings based on their past observations about port assets and damages that were incurred during hurricane or other extreme weather events. The general methodology is aligned with that presented in the FHWA Gulf Coast study, which uses tables and a straightforward ranking system to determine asset criticality and vulnerability. The proposed framework builds on the Gulf Coast methods by expanding the analysis to include exposure as a separate indicator, rather than treating it as a component of vulnerability. This framework also determines vulnerability as an intermediate step, with the final result giving the risk for each asset in the study area. The conceptual framework and data sources are shown in Figure 6.4.

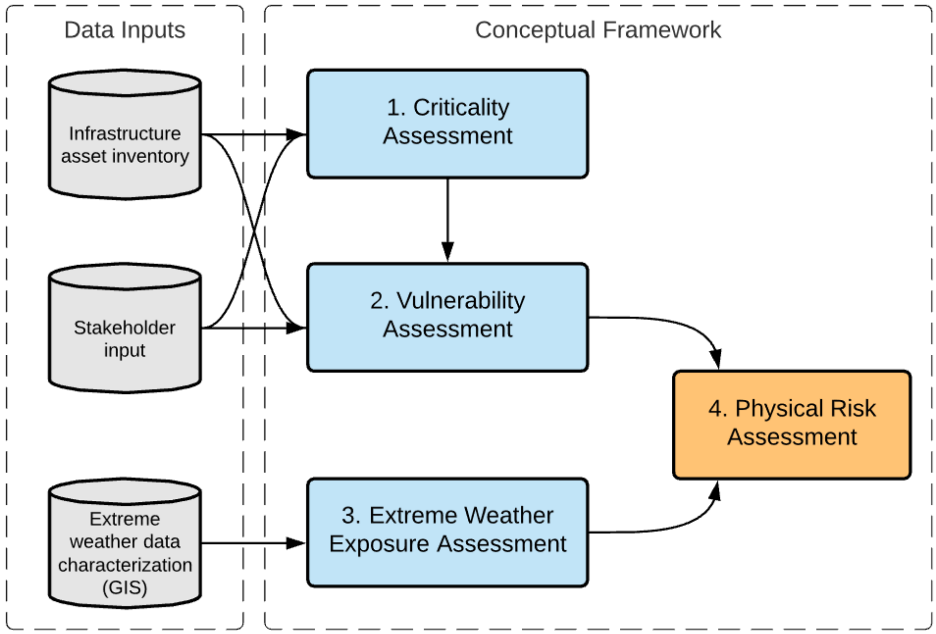


Figure 6.4 Conceptual risk assessment framework with corresponding data needs.

6.3.1 Data Requirements

The framework is conceived to make use of the data described in previous chapters. Namely, the hazard data detailed in Task 3 and the infrastructure data described in Task 4 are used to perform the criticality, vulnerability, and exposure analyses. Information gained from stakeholder input in Task 5 is also incorporated into the criticality assessment, as input from stakeholders is important to accurately determine which infrastructure components are most critical for port system operations. Similarly, vulnerability characteristics as recorded from the port authority workshop and survey were incorporated into that respective component of the analysis.

The assessment framework was formulated using best available datasets and was contrived to be simple and straightforward to serve as a baseline for implementation in real-world applications. The framework presented herein may be enhanced by the inclusion of additional datasets, further expert engineering opinion, or other factors deemed to be important to the decision maker. The framework may be implemented using standard tools such as GIS programs or spreadsheet-based software.

6.3.2 Study Area Selection

The conceptual framework is intended to be applied to a regional port network at the multi-port scale. This requires that, for a full implementation of the framework, stakeholder buy-in is required from multiple entities and should be spearheaded by an overarching organization such as the state DOT or local MPOs. Input from port authority employees, local shipping companies, and other local officials is necessary.

At this geographic scale, the impacts of an extreme weather event such as a hurricane may be more accurately assessed given that these events span a large area. Therefore, the study area should be selected so as to include multiple ports, a regional highway network, main line and short line rail networks, and pipeline system assets.

The general framework may be adapted for use at an individual port level. For example, the formulation of the criticality, vulnerability, exposure, and risk may be adjusted and augmented with localized port data and information and the geographic scope may be reduced to a single port and the immediate local supporting infrastructure assets depending on the level of analysis desired.

6.3.3 Criticality

First, for each system, the objective of the criticality must be defined. This ensures that the criticality assessment is performed for the desired use case and that available data is employed in the correct manner. Table 6.1 provides an example of criticality definitions for each system. It is important to note that these objectives may be altered depending on the specific scenario, region, and weather hazards being studied.

Table 6.1 Example criticality objectives.

System	Criticality Definition
Ports	Ports responsible for larger trade volumes are more critical
Navigable waterways	Channels serving a higher volume of vessels and used by larger freight vessels are more critical
Highways	Road links that support port-based truck traffic are more critical
Railroads	Rail links that support port-based operations are more critical

Next, the criticality indicators are determined based on available data. The indicators should represent data attributes that may best describe the defined objectives. Using expert opinion to reflect past experiences that have occurred in previous extreme weather events, a weight should be given to each data attribute to account for the perceived differences in importance between the different attributes shows an example for the data attributes and weights for a hypothetical roadway network in a port region.

Once criticality score values are determined for the each of the ports, navigable waterways, freight highways, and railroads in the selected study region, the values should be normalized to obtain values that fall within the range of a predetermined scale, such as 0 to 5, with values in the range of 0 to 1 being "mild criticality," 1 to 2 being "moderate criticality," 2 to 3 being "elevated criticality," 3 to 4 being "severe criticality," and 4 to 5 being "extreme criticality." This will allow for easy comprehension of the results and integration in the later vulnerability and risk calculation steps.

Since the criticality objectives in Table 6.1 define critical roadway assets as roadways that support freight trucking operations, the data selected and scored in Table 6.2 is intended to emphasize typical roadway characteristics that influence the efficiency of trucking operations. For example, functional class, NHS designation, evacuation route status, and truck AADT percentage are all roadway data characteristics that may indicate the importance of a roadway link to port trucking operations. In the given example, truck AADT percentage and NHS classification are weighted the highest to further emphasize the importance of these data attributes. Finally, the data is normalized according to Equation 6.1 to result in final scores that range from 0 (low) to 5 (high) as described.

The criticality scores presented in Table 6.2 would be used to determine a criticality value for every roadway link in the selected study area. A similar table would be created for the other systems as well, to determine the criticality of navigable waterways, railroads, pipelines, and ports using different data attribute characteristics for each system. The final output is criticality scores for all links and points of each asset of the systems being analyzed.

$$Score = \left(\frac{x - x_{min}}{x_{max} - x_{min}}\right) * 5 \qquad (6.1)$$

Table 6.2 Sample criticality scoring criteria for a roadway dataset.

Attributes	Values	Criticality Score	Notes	Weight
Functional classification	1=Interstate 2=Other Freeway 3=Principal Arterial 4=Minor Arterial 5=Major Collector 6=Minor Collector 7=Local	5 5 4 3 2 1 1	Criticality decreases as functional class decreases	1
National Highway System (NHS) classification	0=Not on the NHS 1=On NHS, not Intermodal Connector *2–9=On the NHS, is Intermodal Connector:* 2=Major Airport 3=Major Port Facility 4=Major Amtrak Station 5=Major Rail / Truck Terminal 6=Major Inter-city Bus Terminal 7=Major Public Transit Passenger Terminal 8=Major Pipeline Terminal 9=Major Ferry Terminal	1 1 2 5 1 4 1 1 4 5	NHS routes that serve ports, ferries, pipeline terminals, or truck/train terminals (freight systems) are more critical	3
Evacuation route status	0=Is not Evacuation Route 1=Is an Evacuation Route	1 5	Evacuation routes are critical	2
AADT	<20,000 <50,000 <100,000 <175,000 <330,000	1 2 3 4 5	Higher AADT roadways are more critical	1
Percentage of trucks in AADT	< 5% < 10% < 15% < 25% > 25%	1 2 3 4 5	Roads with higher truck percentages are more critical	3

6.3.4 Vulnerability

Vulnerability assessment quantifies the susceptibility of infrastructure to disruptions from extreme weather events. Vulnerability assessment also focuses on determining the inherent inadequacies or shortcomings that exacerbate the severity of extreme weather impacts. The criticality determinations performed in the previous step comprise an important factor of the vulnerability assessment, as criticality is tied to greater impacts and disruptions. Other indicators of vulnerability are adaptive capacity and sensitivity. According to CISA, vulnerability assessments may also identify "interdependencies, capabilities, and cascading effects" (CISA, n.d.-b).

Like the criticality assessment, the vulnerability of the infrastructure systems is scored using available data. Vulnerability assessment is especially dependent on input from professionals with experience working in the study location. Professional judgement regarding the vulnerabilities of the infrastructure components is paramount for accurate scoring. For example, in the workshop conducted with port authorities, described in Chapter 5, stakeholders mentioned that waterway dredging requirements and loss of aids to navigation were bottlenecks in post-storm recovery. Therefore, when assessing the vulnerability of the navigable waterway system, attributes such as time to recovery, dredging depth, and construction costs should be incorporated.

A similar scoring system is employed for vulnerability, where 0 to 1 is "mild vulnerability," 1 to 2 is "moderate vulnerability," 2 to 3 is "elevated vulnerability," 3 to 4 is "severe vulnerability," and 4 to 5 is "extreme vulnerability." Table 6.3 provides a sample of a potential scoring method that may be used to determine the vulnerability of roadways in a hypothetical port region.

The data attributes for replacement cost, detour length, and disruption duration represent adaptive capacity of the roadway system. Interdependencies between the roadway and other infrastructure systems are determined from stakeholder input and high interdependencies are given high vulnerability scores, as this results in a higher potential for cascading and escalating failures. The vulnerability criteria is also weighted to further emphasize specific data attributes.

An issue with the proposed vulnerability assessment method is that it requires a high level of data collection and a high degree of stakeholder input to verify that the scoring system and data attributes are accurately selected. The vulnerability framework should be altered for each system and each specific case study that is performed.

Table 6.3 Sample vulnerability scoring criteria for a hypothetical roadway.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Location in flood plain	0=No 1=Yes, located in flood plain	1 5	Roads in floodplains are more vulnerable	3
Interdependency	1=Low 2=Medium 3=High	1 3 5	Determined from stakeholder input	1
Replacement cost	*Low* *Medium* *High*	1 3 5	Ranges for values may be determined from stakeholders or from past projects in study area	2
Detour length if closed	< 10 mins 10 mins < t < 1 hr > 1 hr	1 3 5	Longer detours lead to more vulnerability	3
Disruption duration	< 6 hours 6 hours < t < 1 day > 1 day	1 3 5	Determined from past stakeholder experience	3

6.3.5 Exposure

The exposure of the infrastructure assets must be determined to quantify the impact that extreme weather events will have on the systems in question. Hurricane storm surge and long-term sea level rise are the two hazards used for hazard exposure analysis in this example, as these were listed as being the most critical in the case study performed for the FHWA Gulf Coast Study (Federal Highway Administration, 2019).

Storms of specified intensities are used to determine the level of exposure of the infrastructure assets. For hurricane storm surge, the estimated high tide storm surge extents shown in Figure 6.5 are employed. GIS layers of the storm surge flooding inundation extent for Category +0 (tropical storm and higher intensity), Category +1 (all hurricane), and Category +3 (major hurricane) storms are used to characterize the exposure. These storm surge inundation extents are shown in Figure 6.5. By intersecting the flood extent layers with the infrastructure layers in GIS, the port system assets that are exposed to the various intensities of hurricane storm surge are identified. Assets that are inundated by flooding during tropical storm or greater intensity events are given the highest exposure score, as they are susceptible to storm surge flooding at even relatively low intensity cyclone storms. The assets that are inundated by only Category +3 events are given a low exposure score, as they are flooding only during the most severe events, which are relatively rare in occurrence. These concepts are portrayed in Table 6.4.

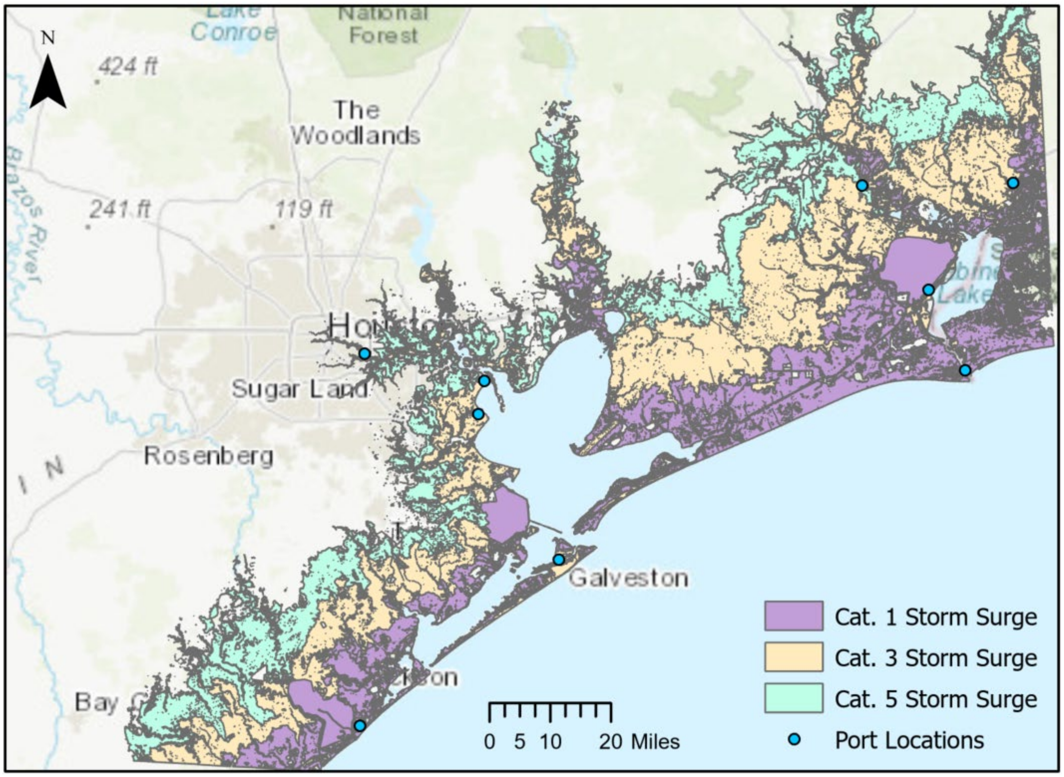


Figure 6.5 Hurricane storm surge exposure datasets

For sea level rise exposure, different inundation depths are used to determine what amount of sea level rise is necessary for infrastructure assets to be exposed to inundation. In the sample data shown in Table 6.4, the sea level rise exposure is determined at levels of 0, 1, 4, and 8 feet. These values were selected because it is estimated that, by 2100, the global sea level will rise by an estimated 1 to 8 feet (Lindsey, 2021; Sweet et al., 2017). Therefore, a value of 1 foot was selected as a best-case scenario for sea level rise, while 4 feet and 8 feet were selected as most likely and worst-case scenario levels. Figure 6.6 shows the sea level rise extents used in the exposure analysis. As with hurricane storm surge, the sea level rise exposure scores are highest for the assets that are inundated by the lowest levels of rise, as this indicates that they will become exposed to flooding earlier, at lower sea level rise levels.

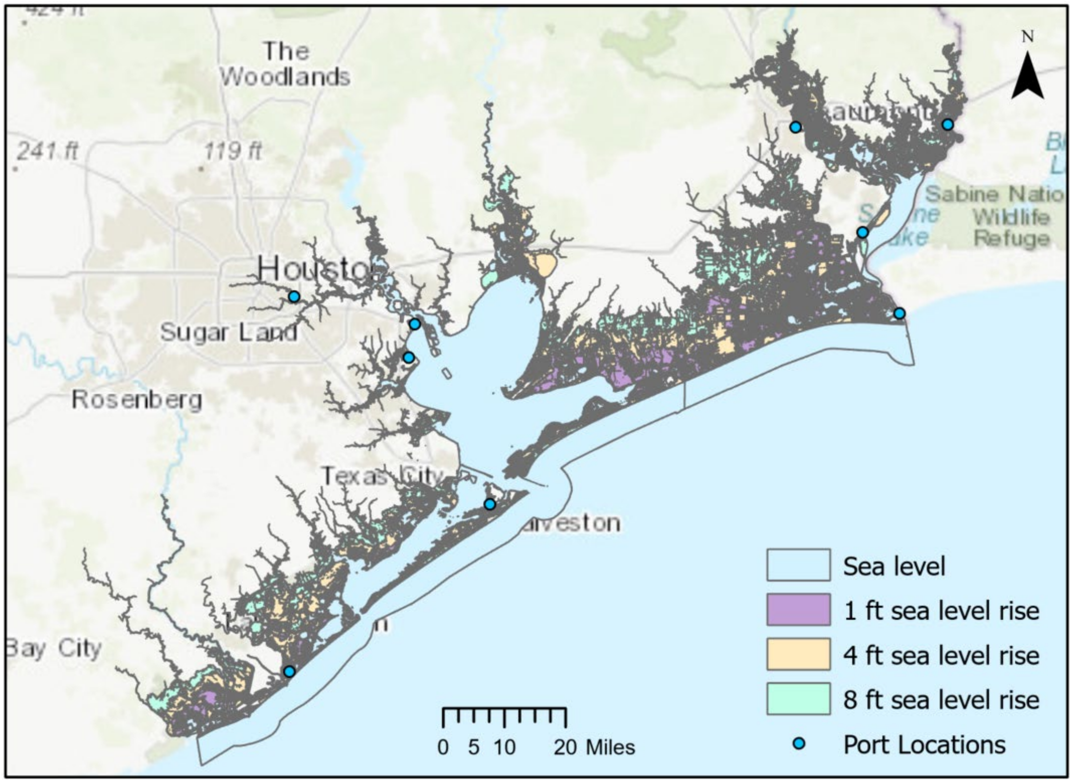


Figure 6.6 Sea level rise exposure datasets

Table 6.4 Sample hazard exposure scoring criteria.

Hazard	Severity	Exposure Score	Hazard Notes
Hurricane storm surge	None Cat +0 – Tropical storm Cat +1 – Hurricane Cat +3 – Major hurricane	1 5 4 3	High tide storm surge extents for each SSHWS Category hurricane
Sea level rise	None 1 ft by 2100 4 ft by 2100 8 ft by 2100 0 ft	1 5 4 3 5	Sea level rise estimates for best, most likely, worst-case, and current scenarios

The exposure analysis is to be performed for all infrastructure systems included in a given analysis.

6.3.6 Risk

The final risk scores of the infrastructure assets are calculated by taking the product of the vulnerability and exposure scores of each hazard for each infrastructure asset, using Equation 6.2.

$$R_{ij} = V_i \cdot E_{ij} \qquad (6.2)$$

where R_{ij} is the risk of infrastructure asset i to hazard j, V_i is the vulnerability of infrastructure asset i, and E_{ij} is the exposure of infrastructure asset i to hazard j. This means that the risk of each infrastructure asset within each infrastructure system (roadway, railroad, pipeline, etc.) is given a risk score for each hazard. For example, using the previous sample tables, a specific roadway link will have two risk values: one for risk of exposure to hurricane storm surge and one for risk of exposure to sea level rise. The total risk for each asset in the system may be found by weighting the risk due to each hazard and summing, shown in Equation 6.3. A system-level risk score can be computed by taking the weighted average of the risk scores and shape length or other measure, as in Equation 6.4.

$$R_{i_{Total}} = \sum_{j} W_j R_{ij} \tag{6.3}$$

$$R_{i_{Network}} = \sum_{k} W_L R_{ik} \tag{6.4}$$

This final risk score is given on a scale of 0 to 25, as the vulnerability and exposure scores in this sample framework are given in the range of 0 to 5. Table 6.5 gives sample risk values in the format that results from this methodology. To characterize the calculated asset physical risk as mild, moderate, elevated, severe, or extreme, the matrix classification shown in Figure 6.2 is used. This results in values for "mild risk" ranging from 0 to 1, "moderate risk" ranging from >1 to 4, "elevated risk" ranging from >4 to 9, "severe risk" ranging from >9 to 16, and "extreme risk" ranging from >16 to 25.

Table 6.5 Hypothetical physical risk calculation results.

Sample Asset	Exposure Score	Exposure Level	Vulnerability Score	Vulnerability Level	Risk Score	Risk Level
#1	3.2	Severe	0.6	Mild	1.92	Mild
#2	1.6	Moderate	3.5	Severe	5.60	Elevated
#3	4.1	Extreme	2.7	Elevated	11.07	Severe

6.4 Case Study

To demonstrate the application of the presented conceptual framework, a case study is presented using available datasets collected in previous project tasks. The case study is performed at a regional network level and primarily focuses on road, rail, and pipeline systems, although waterway channels and the electric grid are also included. Infrastructure inventory data, as collected in Task 4, is employed along with extreme weather hazard data (Task 3) and port stakeholder input (Task 5) to perform the analysis. Calculations were performed using ESRI ArcGIS Pro software and MS Excel.

Due to a lack of active stakeholder participation while conducting this analysis, some attributes required for a full implementation of the framework were unavailable. This is specifically an issue when conducting vulnerability assessments, as this process requires detailed input from local experts and stakeholders. Therefore, in this case study, vulnerability attributes mentioned in Table 6.3 are not used and instead a "distance to port" measurement method is used. If performing a complete analysis using this framework, the Table 6.3 attributes should be included in the vulnerability assessment.

The methods used to perform the case study are presented in this section and results are shown in Section 6.5.

6.4.1 Study Area Selection

To demonstrate the risk assessment framework, a case study for the Houston-Galveston-Beaumont region was conducted. Figure 6.7 shows the location of the case study. This region was chosen for the case study as a total of seven port authorities (Houston, Galveston, Beaumont, Port Arthur, Orange, Sabine, and Freeport) are included within the area of interest (AOI). Additional port facilities, such as that of Texas City, are contained in the AOI as well but are not included in the analysis.

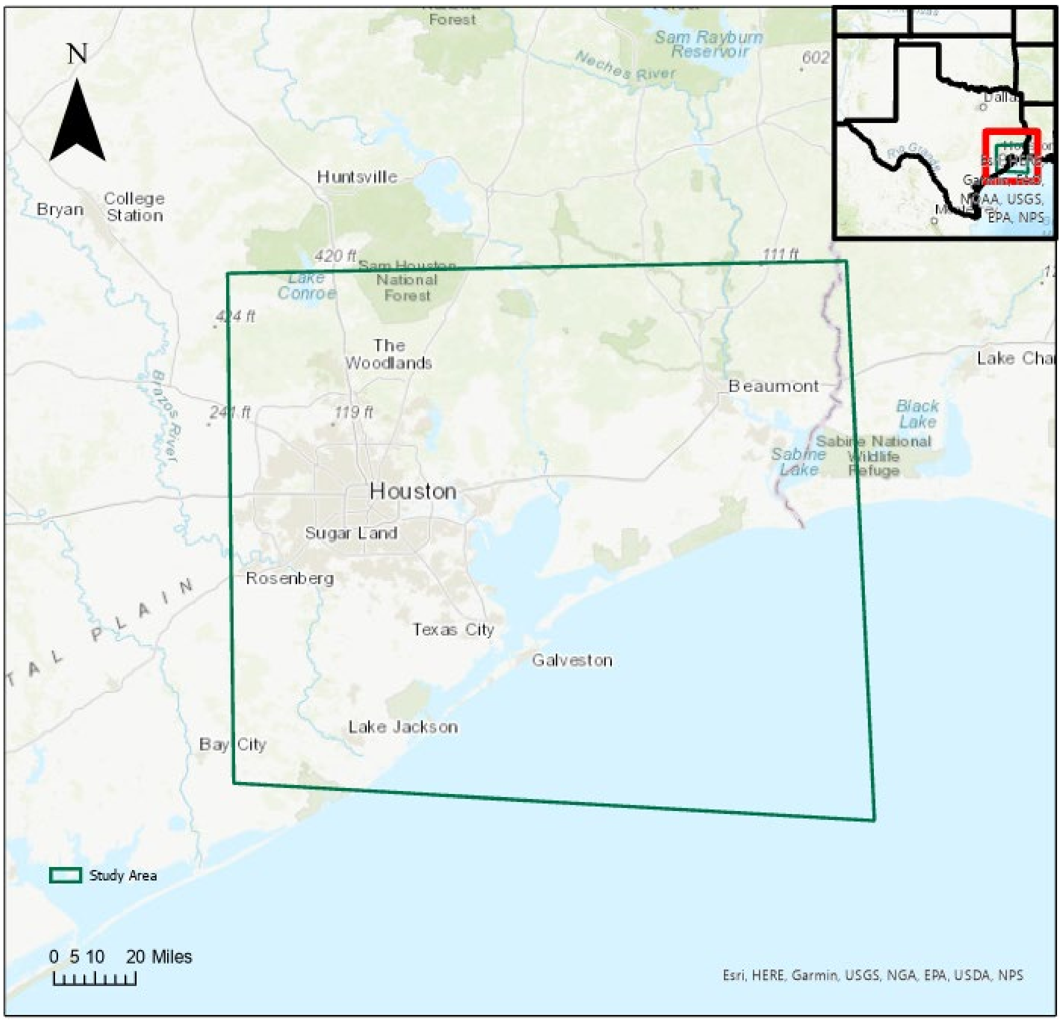


Figure 6.7 Location of study area

The specific infrastructure systems selected for analysis are roadway, railroad, and pipeline. Additionally, the navigable water channels and electric grid components are assessed for criticality and risk, respectively.

As mentioned, when formally performing this analysis, stakeholder input is needed for complete criticality and vulnerability assessment in addition to the attributes used in this analysis.

6.4.2 Roadway

The roadway network of the greater Houston and Beaumont area provides access to seaport facilities for freight trucking purposes. Many cargo types, but specifically container and automotive cargo, are reliant on highway and roadway access to ports. Congestion and pavement condition can also lead to operational difficulties for highway freight traffic (Texas Department of Transportation, 2020). For this study, the publicly available TxDOT roadway asset inventory GIS dataset was employed. The roadway data was filtered to include only those roads that are located near ports and provide port access, and those roadways that have functional classification of arterial or higher.

Criticality

Critical roadways were those links that have the most impact on freight trucking operations. The criticality attributes and scoring methods used for this case study are described in Table 6.2. The specific data attributes used for criticality were functional classification, NHS designation, STRAHNET status, evacuation route status, current AADT, and percent truck traffic. These attributes were selected as they provide details regarding the importance of roadway links on trucking operations. After each roadway was assigned a score for each selected data attribute, the final criticality was determined by first weighting the data with the selected factors and then normalizing to achieve final criticality scores ranging from 0 to 5.

Vulnerability

As mentioned, the attributes shown in Table 6.3 are required for a full assessment of system vulnerability. Given data availability constraints regarding stakeholder input, vulnerability was instead calculated as criticality combined with asset distance to port, as shown in Table 6.6. While these components are indicators of infrastructure vulnerability, further data requirements dependent on stakeholder input are needed for a formal vulnerability assessment, such as information regarding interdependencies, replacement costs, and adaptive capacity.

Table 6.6 Vulnerability scoring for case study roadway network.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Distance to port	< 5 5 < *distance* < 10 10 < *distance* < 15 15 < *distance* < 20 > 20	5 4 3 2 1	Roads closer to ports have higher vulnerability	1

As with the criticality scoring, the final vulnerability scores are assigned by weighting the scores of each attribute and normalizing the values using Equation 6.1 to give final scores ranging from 0 to 5.

Exposure

Based on the exposure definition and quantification methodology described in Section 6.3.5 and the data attributes available, a spatial intersection analysis was performed for both sea level rise and hurricane storm surge for the selected roadway network features. Table 6.4 shows the exposure criteria and exposure scores of each disaster. In this study, any roadway link that intersected with the hazard impact area was considered exposed to the given hazard. The result of this analysis was an exposure score for each roadway link for both sea level rise and hurricane storm surge at differing levels of intensity.

Risk

Finally, the risk of the roadway assets to sea level rise and hurricane storm surge is calculated by taking the product of the vulnerability and exposure as shown in Equation 6.2. This results in risk scores ranging from 0 to 25 for the roadway network for both sea level rise and storm surge. The total risk for the road network is found by averaging the two scores to achieve one final risk score that incorporates the criticality, vulnerability, and exposure to both sea level rise and hurricane storm surge using Equation 6.3. Finally, a singular risk score for the entire roadway network is found by weighting each road link based on its length and its total risk score, shown from Equation 6.4.

6.4.3 Railway

Railway infrastructure plays a critical role in port-related intermodal freight transportation. In this case study, criticality, vulnerability of the railway infrastructure, and exposure were assessed and then combined into the final risk score. This study used the railroad GIS layer from TxDOT and only the active railways were considered.

Criticality

Based on the criticality definition and quantification methodology described in Section 6.3.3 and the attributes available in the TxDOT railroad GIS layer, three factors—the owner of the rail track infrastructure, the type of the rail track, and location criticality—were selected to be the key indicators of railway network criticality. Table 6.7 shows the weights and criticality scores of the three indicators. Among the three key indicators, railroad type was most critical with weight 3, followed by location with weight score 2, and railroad company with weight score 1. For railroad company, those directly owned by the ports were considered most critical and Class I freight railroads were slightly less critical, with a score of 4. For railroad type, mainline routes are most critical, and spur lines slightly less, while the remaining small connectors have low criticality. Location criticality is measured by the closeness of railway section to significant railway hubs, as identified from the stakeholder interview performed in Task 5 (e.g., the Union Pacific Englewood Yard of Houston). In this case study, any railway link that was either entirely or partially within 10 miles of the Union Pacific Englewood Yard of Houston was considered to have a more critical location. The final criticality score is computed using Equation 6.1.

Table 6.7 Criticality score and weights.

Attributes	Value	Score	Weight
Railroad Company	BNSF Railway Company	4	1
	Galveston Railroad L.P.	5	
	Kansas City Southern Railway	4	
	Port Terminal Railroad Association	5	
	Sabine River & Northern Railroad	1	
	Texas City Terminal Railway	5	
	Timberrock Railroad Company	1	
	Union Pacific Railroad Company	4	
	West Texas & Lubbock Company	1	
	Other	1	
Railroad Type	Business Lead	1	3
	Industrial Lead	1	
	Main Line	5	
	Sidetrack	1	
	Spur Line	3	
	Other	1	
Location	Hub	3	2
	None	1	

Vulnerability

Based on the vulnerability definition and quantification methodology described in Section 6.3.4 and the attributes available in the TxDOT railroad GIS layer, criticality and distance to port were selected to be the key indicators of railway network vulnerability. Criticality of the network was obtained from the previous step, and the distance-to-port value was measured using the shortest point-to-point distance of the railroad link to the ports. Maximum shortest distance was set to be 20 miles; railroads further away than 20 miles have low vulnerability. The distance score was given by classifying the distance scores using the Jenks natural break, as shown in Table 6.8. The final vulnerability scores were calculated by averaging the criticality score and distance score.

Table 6.8 Vulnerability scoring for case study rail network.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Distance to port	< 5 5 < *distance* < 10 10 < *distance* < 15 15 < *distance* < 20 > 20	5 4 3 2 1	Railroads closer to ports have higher vulnerability	1

Exposure

Based on the exposure definition and quantification methodology described in Section 6.3.5 and the attributes available in the TxDOT railroad GIS layer, a spatial intersection analysis was performed for both sea level rise and hurricane for the railroads. Table 6.4 shows the exposure criteria and exposure scores of each disaster. In this study, any railway link that intersects with the hazard impact area was considered exposed.

Risk

Based on the risk definition described in Section 6.3.5, risk scores were calculated using Equations 6.2, 6.3, and 6.4.

6.4.4 Pipeline

Criticality

Based on the criticality definition described in Section 6.3.3 and the attributes available in the TxDOT pipeline network GIS layer, the pipeline diameter was selected to be the only indicator of pipeline criticality. Therefore, the criticality of a pipeline section is measured by normalizing the diameter value based on the maximum and minimum values of all pipeline sections.

Vulnerability

According to the vulnerability definition and quantification methodology described in Section 6.3.4 and the attributes available in the TxDOT pipeline network GIS layer, criticality and distance to port were selected to be the key indicators of pipeline network vulnerability. Criticality of the network was obtained from the previous step, and the distance-to-port values were measured using the shortest point-to-point distance of the pipeline link to the ports. Maximum shortest distance was set to be 20 miles; pipeline sections beyond that distance have low vulnerability. The distance and the corresponding distance scores are presented in Table 6.9. The final vulnerability score was calculated by averaging the criticality score and distance score.

Table 6.9 Vulnerability scoring for case study pipeline network.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Distance to port	< 5 5 < *distance* < 10 10 < *distance* < 15 15 < *distance* < 20 > 20	5 4 3 2 1	Pipelines closer to ports have higher vulnerability	1

Exposure

Based on the exposure definition and quantification methodology described in Section 6.3.5 and the attributes available in the TxDOT pipeline network GIS layer, a spatial intersection analysis is performed for both sea level rise and hurricane for the pipeline sections. Table 6.4 shows the exposure criteria and exposure scores of each disaster. In this study, any pipeline link that intersects with the hazard impact area is considered exposed.

Risk

From the risk definition described in Section 6.3.5, risk score is calculated using Equation 6.2.

6.4.5 Water Channels

Criticality

Based on the criticality definition described in Section 6.3.3 and the attributes available in the TxDOT water channel GIS layer, the functional class of the water channel, the control depth of the water channel, and the channel waterway type were selected to be the key indicators of waterway network criticality. Table 6.10 shows the weights and criticality score of the three indicators. All three indicators are equally weighted. For functional class of the water channel, those for both shallow and deep draft vessels were considered most critical, while those channels used only for shallow draft vessels were least critical. The special-vessels-only waterways were not considered as important waterways for port operation. For control depth, the criticality was measured by normalizing the value based on the maximum and minimum values. For waterway types, harbor, bay, and channel were considered the most critical, with the intracoastal waterway being less important.

Table 6.10 Criticality Score and weights.

Attributes	Value	Weight	Score
Functional class	Deep Draft Vessels	1	4
	Shallow Draft Vessels		2
	Both Shallow and Deep Draft Vessels		5
	Special Vessels Only (fishing, pleasure craft, etc; no freight traffic)		0
Control depth	Control depth of link, in feet, US Army Corps of Engineers links only	1	Equation 6.1
Waterway type	Intracoastal Waterway	1	3
	Harbor (including harbor channels), Bay		5
	Channel (not including harbor channels)		5
	Sea Lane		1
	Sea Lane with Separation Zone		1
	River, Creek, Thoroughfare, Lake		1
	Open Water Routes		1

Attributes	Value	Weight	Score
	Corps of Engineers Lock		1

Vulnerability

According to the vulnerability definition and quantification methodology described in Section 6.3.4 and the attributes available in the TxDOT water channel GIS layer, criticality and distance to port were selected to be the key indicators of waterway network vulnerability. Criticality of the network was obtained from the previous step, and the distance-to-port values were measured using the shortest point-to-point distance of the waterway link to the ports. The maximum shortest distance was set to be 20 miles; waterway channels beyond that distance have low vulnerability. The distance and the corresponding distance scores are presented in Table 6.11. The final vulnerability score was calculated by averaging the criticality score and distance score.

Table 6.11 Vulnerability scoring for case study waterway network.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Distance to port	< 5 5 < *distance* < 10 10 < *distance* < 15 15 < *distance* < 20 > 20	5 4 3 2 1	Waterways closer to ports have higher vulnerability	1

Exposure

Since the water channels are not directly impacted by sea level rise or hurricanes, which are the two disasters considered in this case study, the exposure analysis and risk analysis were not conducted for waterway channels. Waterways are impacted by sediment deposits that require channel dredging and debris removal, but data regarding locations and depths of sediment deposits are not used in this case study analysis.

6.4.6 Electric Grid

Criticality

Based on the criticality definition described in Section 6.3.3 and the attributes available in the TxDOT electric grid GIS layer, the line voltage was selected to be the only indicator of criticality. Therefore, the criticality of an electric transmission line section is scored solely by voltage, as shown in Table 6.12. It was assumed that electric lines with higher voltage are more critical, as they are used for transmission rather than local distribution.

Table 6.12 Criticality score for electric grid.

Attribute	Value	Score
Voltage	500	5
	345	5
	230	4
	138	3
	69	2
	Unknown	1

Vulnerability

Vulnerability was calculated as criticality combined with asset distance to port, as shown in Table 6.13. Electric lines that are over 20 miles away from a port are given the lowest vulnerability score, while those within 5 miles of a port are given the highest vulnerability score. The final vulnerability score is taken as an equal weight between the criticality and the port distance.

Table 6.13 Vulnerability scoring for case study electric grid network.

Attributes	Values	Vulnerability Score	Notes	Weight
Criticality	1=Mild 2=Moderate 3=Elevated 4=Severe 5=Extreme	1 2 3 4 5	Determined in previous step	1
Distance to port	< 5 5 < *distance* < 10 10 < *distance* < 15 15 < *distance* < 20 > 20	5 4 3 2 1	Electric lines closer to ports have higher vulnerability	1

Exposure

Based on the exposure definition and quantification methodology described in Section 6.3.5 and the data attributes available, a spatial intersection analysis was performed for both sea level rise and hurricane storm surge for the selected roadway network features. Table 6.4 shows the exposure criteria and exposure scores of each disaster. In this study, any roadway link that intersected with the hazard impact area was considered exposed to the given hazard. The result of this analysis was an exposure score for each roadway link for both sea level rise and hurricane storm surge at differing levels of intensity.

Risk

Finally, the risk of the electric grid assets to exposure to sea level rise and hurricane storm surge is calculated by taking the product of the vulnerability and exposure as shown in Equation 6.2. This results in risk scores ranging from 0 to 25 for the electric network for both sea level rise and storm surge. The total risk for the road network is found by averaging the two scores to achieve one final risk score that incorporates the criticality, vulnerability, and exposure to both sea level rise and hurricane storm surge.

6.5 Results

The results of the framework case study example are described in this section. The final risk of each system is portrayed graphically using maps of the study area.

6.5.1 Roadway

The total risk scores for the roads in the study area are illustrated in Figure 6.8. The roadways that are identified as most at-risk are interstates or arterials. The roads that lay in coastal areas and close to ports have the highest risk of extreme sea weather events. The total system risk score is 3.75, which is at the "Moderate" level.

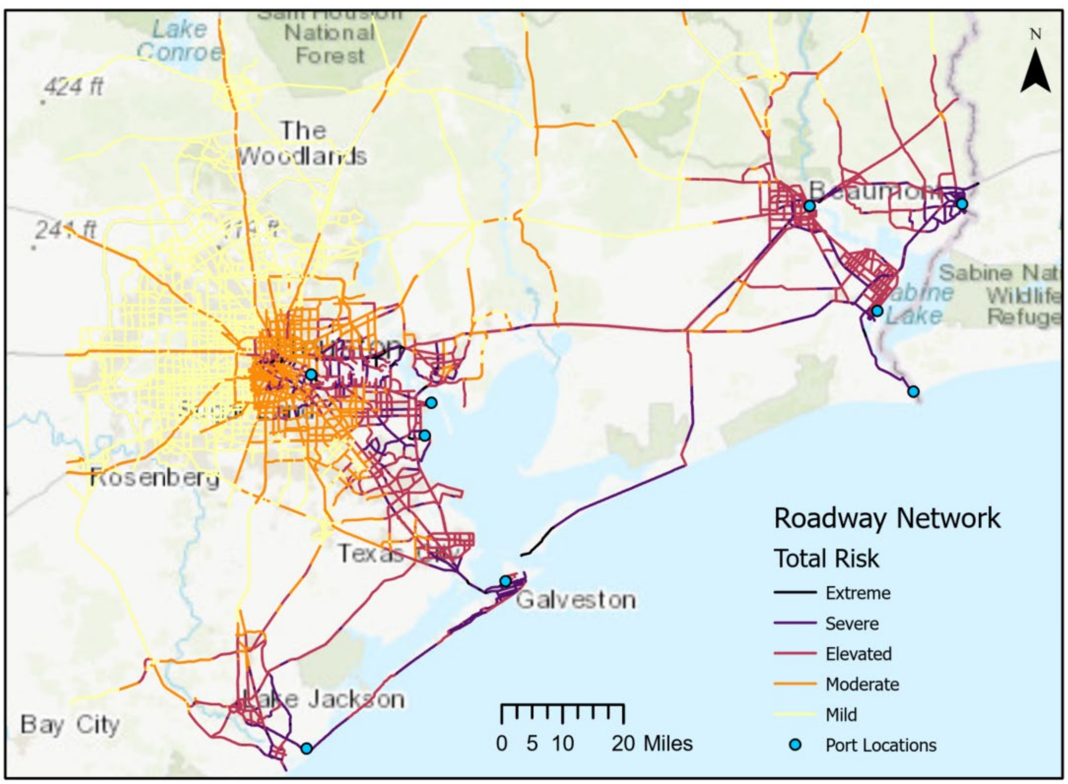


Figure 6.8 Final risk results for roadway network

6.5.2 Railway

The total risk scores for the railroads in the study area are illustrated in Figure 6.9. In general, the railroads that are either close or directly connected to the ports face higher risks and those far from the coastal lines face lower risks. Using the system risk score assessment method described in Section 6.3.6, the system risk score of railway for sea level rise and hurricane storm surge is 5.90 (Elevated) and 8.80 (Elevated), respectively. The total risk score is 7.38 (Elevated).

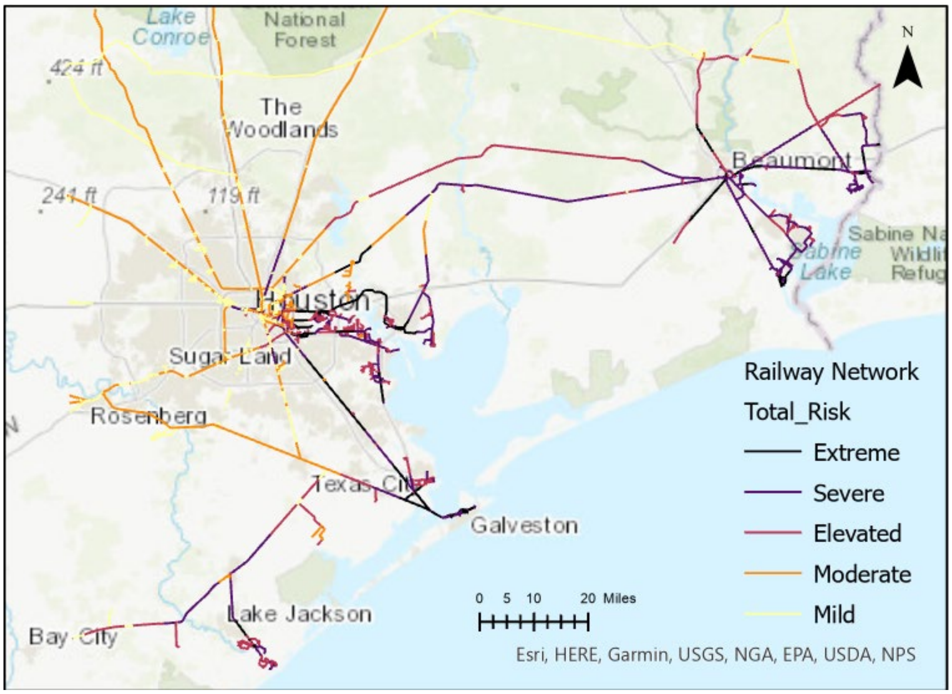


Figure 6.9 Final risk results for railway network

6.5.3 Pipeline

Figure 6.10 illustrates the resulting risk scores for pipelines in the study area. In general, the pipeline sections that are either close to the ports or close to the coastal area have greater risks. The total risk score of pipeline system is 7.09, which is at the 'Elevated' level.

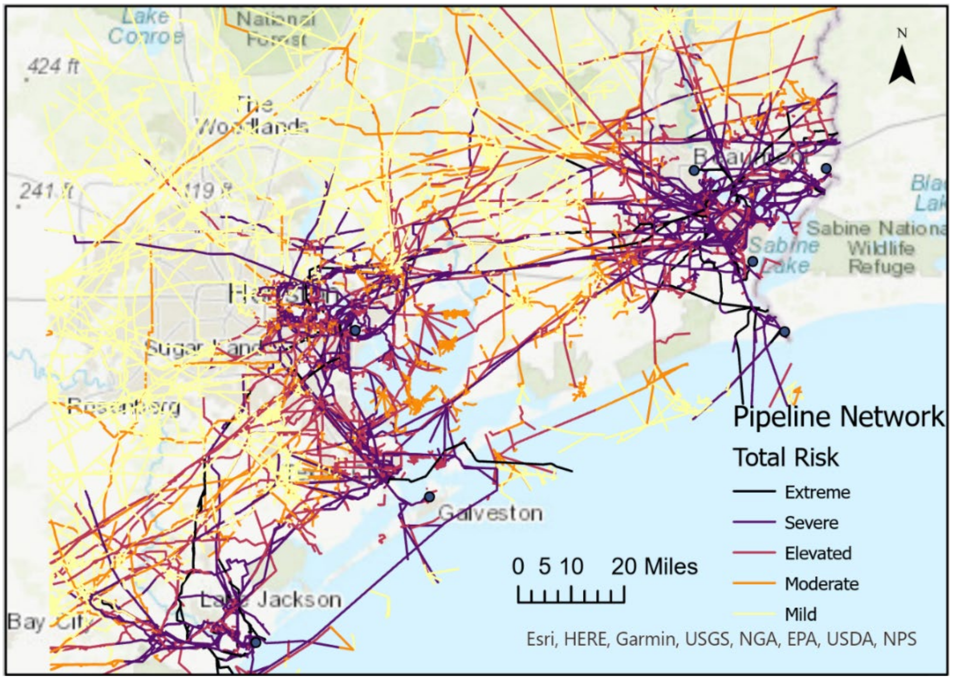


Figure 6.10 Final risk results for pipeline network

6.5.4 Water Channels

According to previous discussion, the exposure and risk calculations of water channels are not feasible for the two types of disaster selected for this case study. Thus, this section presents only the criticality and vulnerability of the water channels. Figure 6.11 and 6.12 show the criticality and vulnerability scores for waterway channels in the study area. In general, the waterway channels that are either close to the ports or have deeper control depth received higher vulnerability scores.

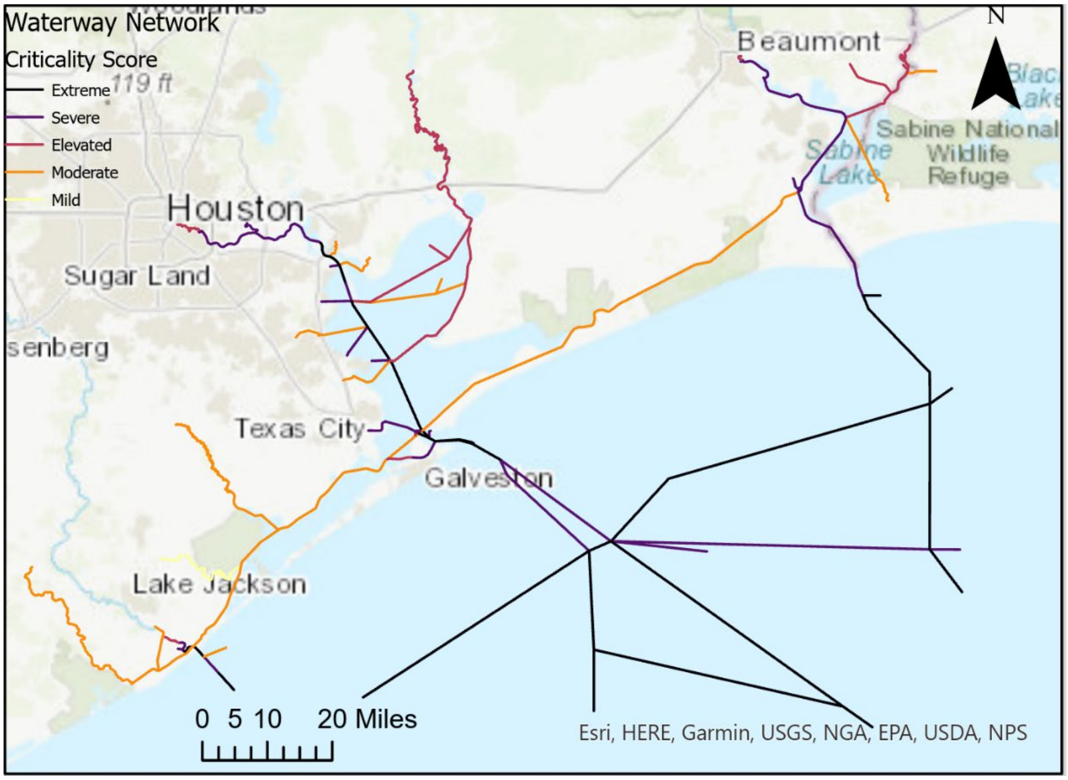


Figure 6.114 Criticality scores for water channels

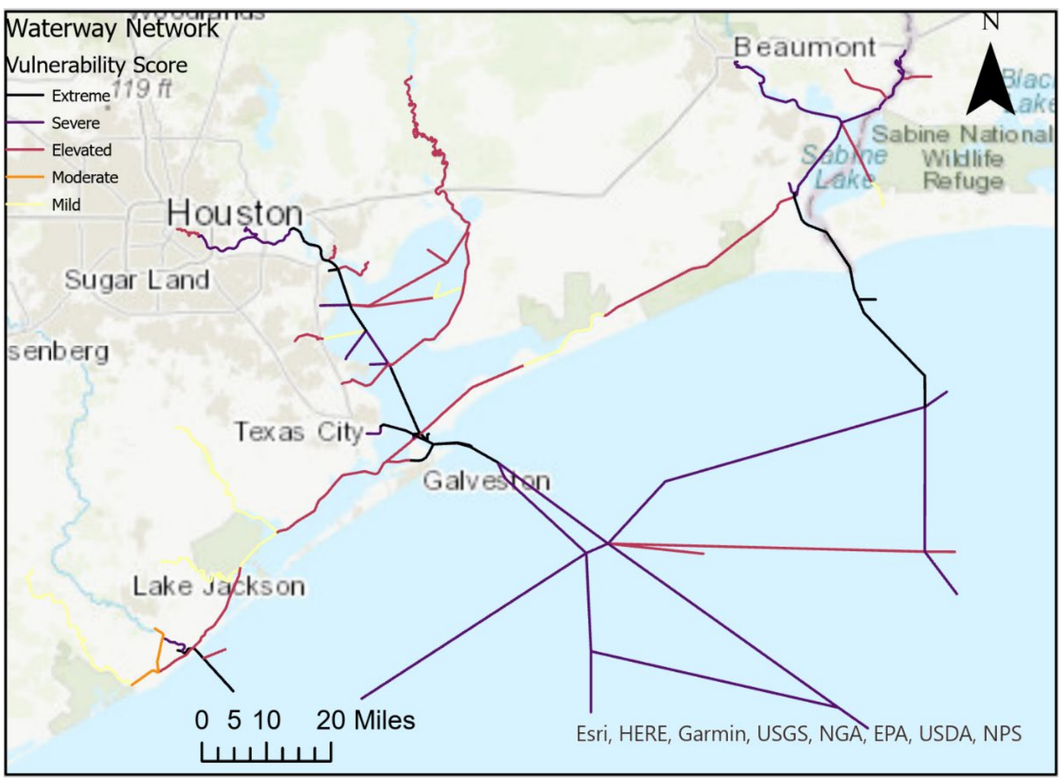


Figure 6.125 Vulnerability scores for water channels

6.5.5 Electric Grid

The total risk scores for the electric grid components in the study area are illustrated in Figure 6.13. The power lines that lay in coastal areas and close to ports have the highest risk of extreme sea weather events. The total system risk score is 9.57, which is at the "Severe" level.

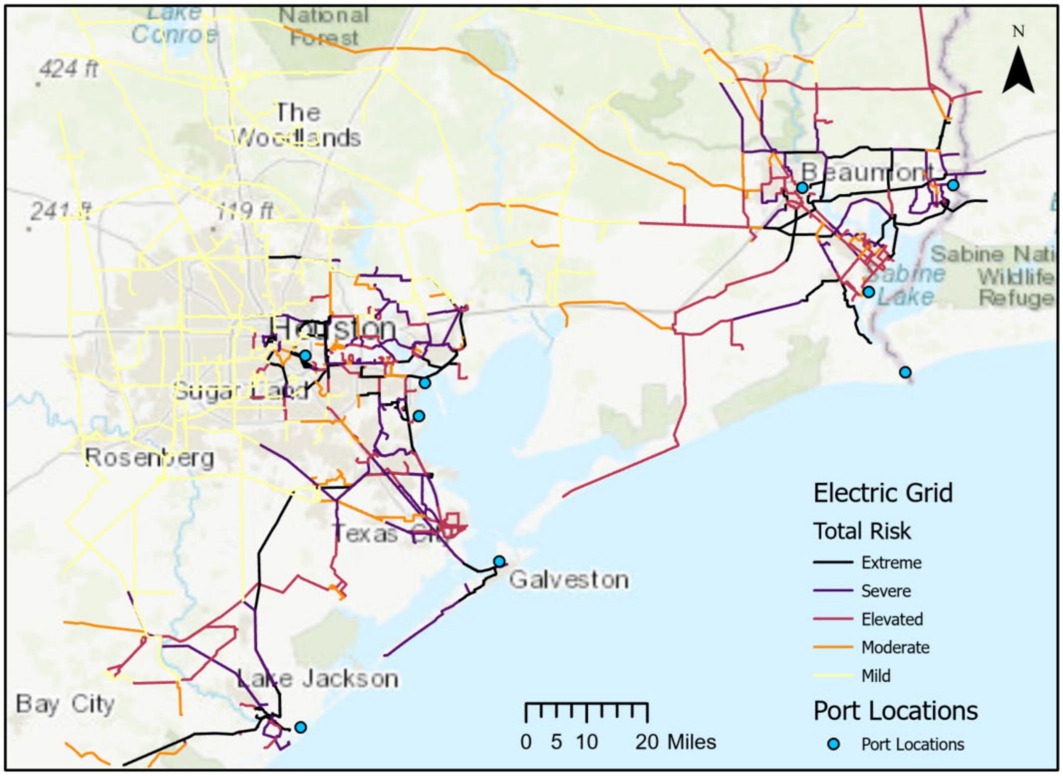


Figure 6.136 Final risk results for electric grid network

6.5.6 Summary of Results

The overall network-level risk for all supporting infrastructure systems is presented in Table 6.14. The electric grid system faces relatively higher risks in terms of both disasters compared the other systems, whereas the roadway system faces relatively low risks.

Table 6.14 Total system-level risk results

Infrastructure System	Sea Level Rise Risk Score	Sea Level Rise Risk Level	Storm Surge Risk Score	Storm Surge Risk Level	Total Risk Score	Total Risk Level
Roadway	2.76	Moderate	4.74	Elevated	3.75	Moderate
Railway	5.90	Elevated	8.80	Elevated	7.38	Elevated
Pipeline	5.68	Elevated	8.52	Elevated	7.09	Elevated
Electric Grid	8.48	Elevated	10.66	Severe	9.57	Severe

6.6 Port-Level Analysis

The given conceptual framework may be adjusted to the scale of a single port for use by individual port authorities. This may be done by retaining the same general process of calculating 1) criticality, 2) vulnerability, 3) exposure, and 4) risk. However, the data attributes used in each step of this process should be changed to reflect the reduced scale. For example, instead of using AADT or evacuation route status, the roadway criticality could be determined by using the number of access points and redundant routes providing direct ingress and egress into the port. Similarly, the port could incorporate their own hazard data and vulnerability information collected from past natural disasters to have a better understanding of the specific issues that are common at their own facility. The data could be further augmented by including operational and functional information, such as frequency of staff training exercises or mock drills.

The research team has been in contact with representatives from the Port of Corpus Christi to discuss additional port asset data access. The research team would like to perform an in-depth sea level rise exposure analysis on the port's assets. This was discussed with representatives from the port during a virtual meeting on April 13, 2021. The port representatives are interested in the study; ongoing work to quantify the sea level rise vulnerability at an individual port-level scale will proceed in the coming months.

6.7 Comments on Hazus-MH Use

Initially, the research team sought to use FEMA's Hazus-MH software to perform the physical risk assessment given that this program is widely used for extreme weather risk assessments. However, the research team realized that this program would not be adequate for this analysis as Hazus-MH is primarily meant to assess the risk of buildings and critical infrastructure facilities to extreme weather events. Transportation systems are included in the analysis but are not used for risk assessment for hurricane wind events. In flooding analyses, transportation assets are included but are analyzed only for scour that may occur on bridges. Roadway and railway links are only included in the analysis for earthquakes, and port assets are also not included as needed. Therefore, the research team decided to draw from the FHWA Gulf Coast study and develop a new framework for the physical risk assessment of port and supporting infrastructure systems rather than use the existing Hazus-MH software.

6.8 Summary

This chapter presents a conceptual framework that assesses the physical risk to seaport system infrastructure from extreme weather events. The general methodology is inspired by the FHWA Gulf Coast Study methods. First, criticality of Texas ports, freight highways, waterways, and railways are determined. Next, the vulnerabilities of the Texas port systems are quantified using the results of the criticality analysis and other indicators. Exposure to hurricane storm surge and sea level rise were used as an example, although additional hazards may be incorporated into the analysis framework if required data is available. Finally, risk is found as a product of vulnerability and exposure. The conceptual framework is intended to be simple and straightforward for ease of implementation and common tools such as GIS programs can be employed to perform the analysis.

A case study of the Houston-Galveston-Beaumont region is provided to demonstrate the application of the conceptual framework. Roadway, railway, and pipeline infrastructure systems are included in case study, and waterway and electric grid system are partially assessed. The infrastructure systems are assessed for exposure to sea level rise and hurricane storm surge. Finally, the risk of each system for each hazard is computed, as is a final "total risk" score.

The results of the analysis show that the Houston-Galveston-Beaumont area freight system is at elevated risk for sea level rise and storm surge. The results of this study may be used to identify infrastructure components that are at greater risk to harm from natural disasters, to increase system resilience in future infrastructure investment.

Chapter 7. Quantify Economic Risks of Port System Disruptions

7.1 Introduction

Understanding the economic risks of hazard disruptions helps to frame the importance of resilience in the Texas port system environment. By quantifying monetary losses, the impacts of specific resilience improvement measures may be compared, and the optimal alternatives may be selected. Therefore, an in-depth understanding of the tools, techniques, and data sources needed to perform an economic risk analysis of the Texas port system is necessary to fully understand the port system's resilience.

This chapter serves to present the results of an economic assessment of the risks that hurricanes present to Texas ports. First, theoretical background information relevant to port economic assessments is described. An analysis framework, shown in Figure 7.1, is developed to estimate the direct and indirect impacts of hurricanes on the Texas port system. The analysis framework is used to provide estimates for the expected losses due to port disruptions from hurricanes of varying intensity.

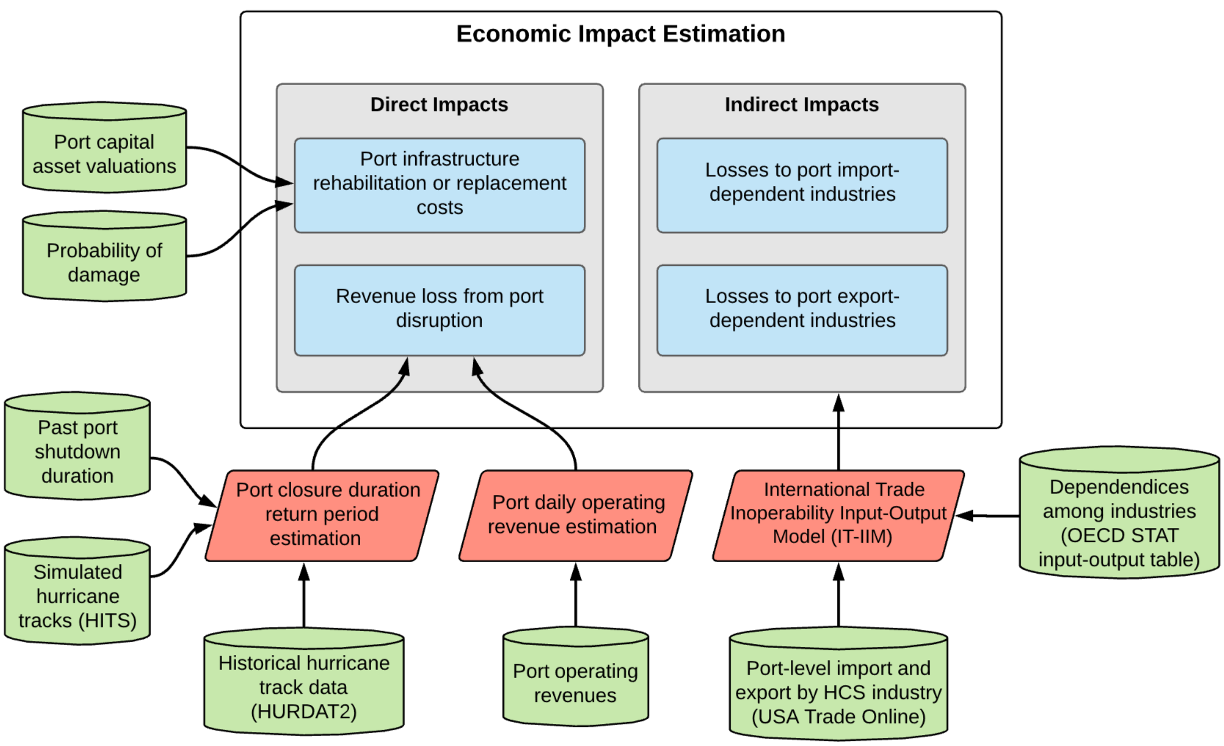


Figure 7.1 Methodology for estimating economic risks of port disruptions from hurricanes.

The data sources used in this analysis are detailed, as are the methods used to perform the analysis. Primary sources where data is obtained include the U.S.A. Trade Online database, Organization for Economic Cooperation and Development (OECD) input-output tables, port authority financial reports, National Hurricane Center (NHC), and TxDOT; additional supplement data is also gathered from other publicly accessible sources. The methods employed range from quantifying asset repair and replacement costs and revenue losses for direct impacts, to conducting input-output analysis for estimating the indirect losses experienced across multiple port-dependent industries.

7.2 Background

To fully estimate the economic impacts experienced by Texas ports due to hurricane events, both direct and indirect impacts must be quantified. This results in a more complete analysis, with estimates for losses experienced by the port authority and losses experienced by the industries dependent on port import and export commodities resulting from the hurricane disruptions. Table 7.1 details the types of economic impacts and the specific estimation techniques that are considered for this analysis.

Table 7.1 Economic impact estimation methods and data requirements

Type	Specific Impact	Estimation Method	Data Requirements
Direct impacts	Port infrastructure damage costs	*Probability of damage* × *Capital asset cost*	Hazard-wise failure probabilities, component capital costs
	Losses from disruptions to port revenues	*Disruption duration (days)* × *Average daily port revenue*	Port operating revenues, closure durations by storm intensity
Indirect impacts	Disruption of import commodity flows	*Input-output models*	Port-specific import data by industry type, input-output tables
	Disruption of export commodity flows	*Input-output models*	Port-specific export data by industry type, input-output tables

7.2.1 Direct Impacts

Direct impacts refer to the losses incurred at a port level due to damaged infrastructure components that require replacement or repair. Additional losses encompassed by the direct impacts are those resulting from lost revenue experienced due to port closure.

Damaged infrastructure results from exposure of port structures, equipment, and other assets to extreme weather. During hurricane events, high winds, storm surge, flooding, lightning, and more may fully or partially destroy port infrastructure components. High winds may topple cranes, blow over unanchored port equipment, damage or destroy roofing, and shatter windows by launching debris. Storm surge results from elevated water uplift that is blown to shore and may damage objects due to impact force and inundation. Extreme precipitation volumes cause inland or flash flooding, which may damage buildings or block road and rail links to a port.

Damaged buildings, cranes, warehouses, laydown pads, food or other perishable product refrigeration systems, generators, fencing, berth areas, and site security components may all reduce a port's ability to operate at a full capacity. Damaged components require repair or rehabilitation activities to fully restore functionality. Similarly, fully destroyed components require complete reconstruction or replacement to achieve complete functional requirements. These repair and replacement costs place a burden on the owning authority and may result in a bottleneck in storm recovery. Therefore, understanding the economic impacts that may occur to port infrastructure is crucial to quantify the direct impacts that ports may experience from hurricanes and other extreme weather events.

To quantify losses resulting from destroyed infrastructure components, an in-depth understanding of the infrastructure's exposure to expected storm intensities is needed. Along with this, knowledge of the vulnerability or allowable capacity of the assets is required to determine the probability of damage or destruction. For cranes, docks, buildings, and other structures, fragility curves may be developed to relate the probability of a specific asset's failure to hazard levels of a specified severity, such as wind speed to probability of collapse. The total direct losses due to damaged infrastructure is the sum of repair and replacement costs for all damaged components.

A second type of direct economic impact is experienced due to loss of revenues that port authorities collect by charging shipping companies for using the port facilities and handling cargo. When a hurricane approaches, ports may shut down preemptively for a multi-day period to remove vessels from the path of danger and preserve human life. These shutdowns result in the port authority losing fees that they would typically collect as operating revenue from vessels using the port facility to load and unload cargo. The port shutdown duration may also be affected by employee availability shortages post-storm due to evacuation orders, blocked roads into the port, or damaged housing.

7.2.2 Indirect and Macroeconomic Impacts

In this study, *indirect impacts* refer to the economic losses that industry sectors, other than the ports themselves, suffer due to the disruption of port operations. This includes the indirect impact, which is the linkage effects of the disruptive event to all industry sectors in the supply chain. These indirect impacts are macroeconomic in nature, as the scale of the impacts may be felt at a regional or national level and across multiple industry sectors.

Damaged port infrastructure or partial loss of functionality of the port infrastructure may impact port-dependent industry sectors. Some industries may rely heavily on imported raw material or intermediate products, while others may require certain key components, and still others need imported power sources to continue operations. The impact of port closures on the regional or national economy due to supply chain disruptions may be assessed by analyzing the dependencies and interdependencies between various port-dependent industries. Such dependency may be understood and quantified using economic-related statistics and ensuring that forward and backward linkage effects are accounted for. In addition, assessment of disruption events is also required to understand the extent and duration of the disruption.

In this case study, to quantify and study the dependencies and interdependencies among industry sectors, the International Trade Inoperability Input-Output Model (IT-IIM) (Jung et al., 2009) was used to analyze the economic losses of a single-day port disruption. Input-output models are a family of linear matrix operations that consist of various economic entities in a region that has interdependencies among themselves. Input-output tables illustrate the flow of sales and purchases and describe the relationship between economic sectors. The Inoperability Input-Output Model (IIM) studies products and services within a country with gross domestic product (GDP) as input and thus has the capability to study domestic economic issues. The IT-IIM was developed to account for import- and export-related losses due to disruption by introducing the concept of *gross trade economy* (GTE). The formulation of GTE is expressed in Equation 7.1.

$$GTE = GDP + M = DD + X + M \tag{7.1}$$

where M is the import value, DD is the domestic product value, X is the export value.

7.3 Direct Impacts to Texas Ports

Direct economic impacts to the port authorities include the replacement cost or repair cost of the damaged facility and the revenue loss during the shutdown. Therefore, for this study, these two quantities are used to estimate the direct economic impacts to Texas ports. Analysis results are presented for a total of eight ports in Texas. The ports selected are primarily the large, deep-water ports that experience the highest freight volume tonnages and for which data was available, as shown in Figure 7.2.

7.3.1 Port Infrastructure Damage Costs

The infrastructure damage costs to the port agencies—the cost to repair or replace the infrastructure facilities—are calculated based on the depreciated asset values of the infrastructure facilities in the port and the probability of damage. Since detailed data, such as facility inventory and asset unit depreciated cost, is not available, this chapter considers the capital assets (excluding land assets) from port financial reports (Brownsville Navigation District, 2019; City of Port Lavaca, Texas, 2019; Orange County Navigation and Port District, 2020; Port Freeport, 2020; Port of Beaumont, 2020; Port of Corpus Christi Authority, 2020; Port of Galveston, 2020; Port of Houston Authority, 2020) as the depreciated asset values that are vulnerable to the disasters. The asset values are collected and organized in Table 7.2.

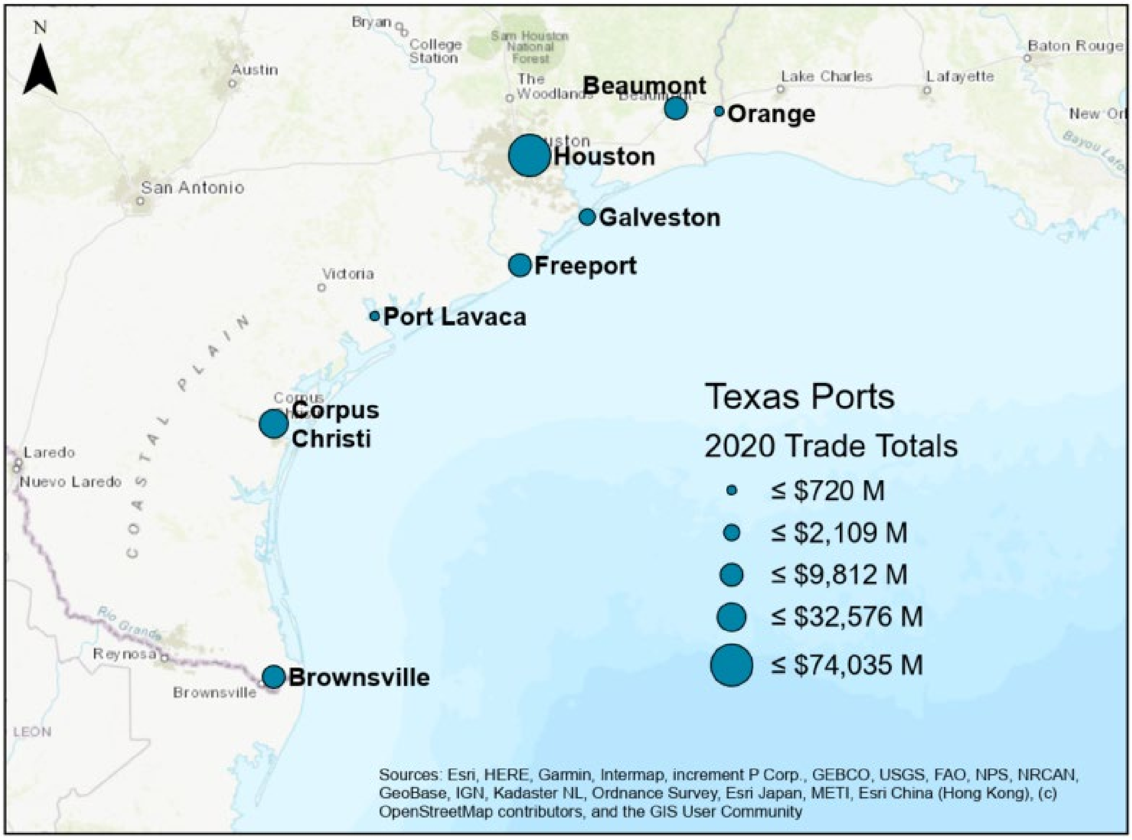


Figure 7.2 Study port locations and 2020 trade volumes

Table 7.2 Total capital assets by port

Port	**Reported Capital Asset Valuation ($ Millions)**
Corpus Christi	624.2
Freeport	161.2
Galveston	142.3
Houston	1,890.8
Port Lavaca	23.1
Brownsville	182.7
Beaumont	103.8
Orange	11.5

After determining the capital asset values, a port agency could estimate the probability of damage for a specific disaster and multiply that by the vulnerable asset value. The port infrastructure damage costs could be expressed by Equation 7.2.

$$\textit{Infrastructure Damage Cost} = \textit{Capital Assets} * \textit{Probability of Damage} \quad (7.2)$$

This chapter does not provide the values of the port infrastructure damage costs as the probability of damage varies based on the types and magnitude of the natural disaster severity. The researchers do not have access to the required data—fragility curves or failure probabilities for actual port assets—to offer complete results. However, with an estimated probability of damage, the values of the port infrastructure damage costs could easily be calculated. The infrastructure asset damage costs for individual components may also be determined by adjusting Equation 7.2 to account for the cost of a single asset and the probability of damage for that specific asset as determined from a fragility curve or other method. The total economic impact for a port may be found by summing the individual asset losses due to a given event.

7.3.2 Losses from Disruption to Port Operations

Another source of direct economic loss to port agencies is the losses from port operation disruptions. During a disaster, such as a hurricane, ports are not able to maintain their normal functionalities. As a result, operating revenues are lost during this period of disruption. This chapter collects the annual operating revenues from Texas ports' financial reports (City of Port Lavaca, 2019; Orange County Navigation and Port District, 2020; Port Freeport, 2020; Port of Beaumont, 2022; Port of Brownsville, 2019; Port of Corpus Christi Authority, 2020; Port of Galveston, 2020; Port of Houston Authority, 2020). The operating revenues include service fees, building and land rental, facilities use charges, and more. Operating revenues from taxes, investments, and non-business sources are not included, as these cash flows would not typically be disrupted during hurricane events. The daily operating revenue of each port is estimated by dividing the annual operating revenue by 365 and is summarized in Table 7.3.

Table 7.3 Estimated daily operating revenue

Port	Daily Operating Revenue (USD)
Corpus Christi	310,242
Freeport	91,981
Galveston	74,953
Houston	1,070,499
Port Lavaca	4,159
Brownsville	29,665
Beaumont	70,541
Orange	6,057

To obtain the total operating revenue loss in a disaster, it is necessary to estimate the shutdown duration during that disaster. This study uses hurricanes as an example to illustrate how different

Categories—as established by the Saffir–Simpson hurricane wind scale (SSHWS)—lead to different shutdown durations, and therefore different economic losses.

To determine the expected port shutdown duration for a hurricane of a given intensity, past hurricane disruptions were used to create a logistic regression. Nine recent hurricanes—Barry (2019), Dorian (2019), Nate (2019), Florence (2018), Michael (2018), Harvey (2017), Irma (2017), Matthew (2016), and Sandy (2012)—were used for the analysis. The shutdown durations of 46 U.S. ports along the Atlantic and Gulf Coasts for these nine hurricane events were determined from U.S. Department of Energy emergency situation reports. Figure 7.3 shows the hurricanes and ports used for the logistic regression.

Specific data attributes related to ports, such as port type, harbor type and size, and depth of approach channel, were collected, as were hurricane characteristics such as wind speed, distance from port to storm eye, distance from port to nearest landfall, and more. These data attributes were used to create regression models.

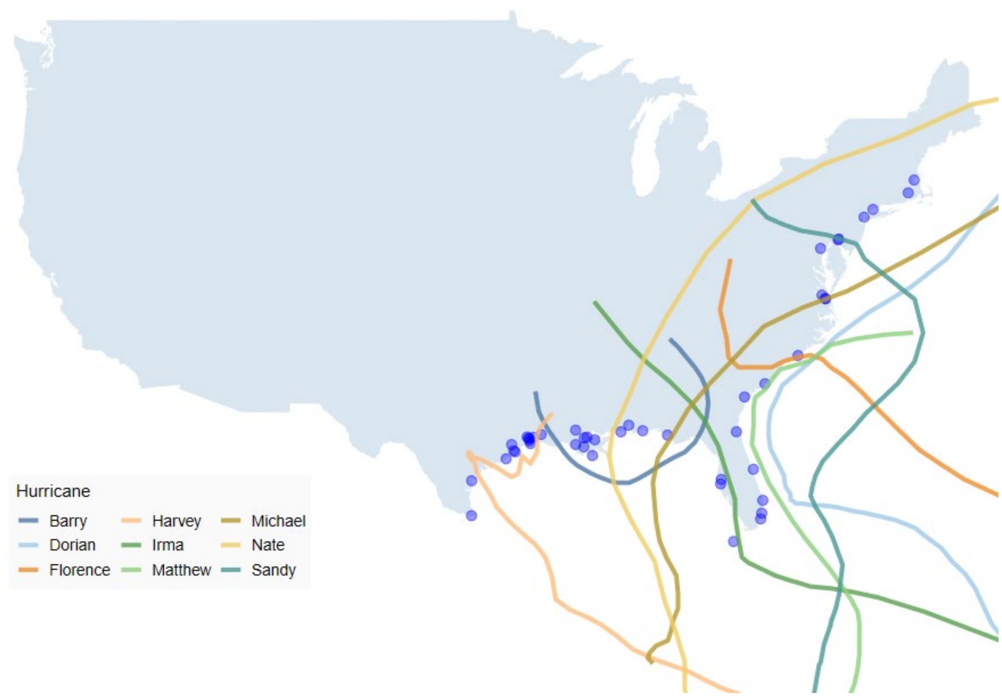


Figure 7.3 Hurricane events and port facilities used to determine port shutdown durations.

Through further analysis, it was determined that the shutdown durations follow the Poisson distribution. Two models were created: one for events where the hurricane makes landfall prior to reaching the port (landfall model), and one where the hurricane makes landfall after passing by the port (non-landfall model). In populating the landfall model, the research team found many instances where the port did not shut down in response to the hurricane's arrival. Therefore, a hurdle model was used for this scenario, employing two different processes to first determine whether a port is shut down or not, and then estimate the shutdown duration. A binary logit model was used to determine if a port will be shut down using distance from landfall position and the port as a variable. A Poisson regression model was used to determine the number of shutdown days based on duration of high-speed wind gusts. For the non-landfall model, Poisson regression models were used to model the duration of the port shutdown. For both models, the desired parameters were solved for by maximizing log-likelihood functions of the probability mass functions of the Poisson distributions.

Next, simulated hurricane tracks from the Hurricane Interactive Track Simulator (HITS) for the North Atlantic Basin (Nakamura et al., 2015) were employed. The HITS database is created using stochastic Markov processes to imitate the North Atlantic HURDAT2 dataset over a larger timespan. For this study, 5,000 hurricane seasons (a total of 76,577 unique hurricane events) were used. The simulated hurricanes were used in the previously described shutdown duration model to acquire the shutdown durations for storms of specified intensity of return period. The results of this process are shown in Table 7.4.

Next, the return periods for historical storms by SSHWS Category are calculated using the process described in Chapter 3, Section 3.2.1.3. Data from the HURDAT2 North Atlantic track archive was used along with points representing the location of Texas ports. Then, calculations for the number of hurricane strikes and return periods were performed. A hurricane is considered to be a strike if it passes within 50 nautical miles (58 statute miles) of a port, as mentioned by the National Hurricane Center (National Hurricane Center, n.d.). Tracks from 1901 to June 2021 were used in the analysis. Return periods by SSHWS Category were found by dividing the time period (120.4548, representing the years between January 1, 1901, and June 16, 2021) by the number of recorded strikes at each port. As return periods represent exceedance rates, the return periods were calculated for a given storm category *and higher*. For example, the return period for a Cat +3 strike at the port of Corpus Christi represents the number of years that may occur between successive events that are of Category 3 intensity or higher. The results of this analysis are in Table 7.5.

Table 7.4 Calculated port shutdown durations (days) by hurricane return period

Port	**Return Period (years)**				
	10	**20**	**50**	**100**	**200**
Corpus Christi	3.1	3.7	4.8	5.6	6.4
Freeport	3.6	4.5	5.7	6.9	8
Galveston	3.7	4.6	5.6	6.6	7.8
Houston	3.1	3.6	4.3	5	6.1
Port Lavaca	3.1	3.7	4.7	6	7.2
Brownsville	3.4	4.1	4.8	5.4	6.1
Beaumont	3	3.4	4.1	4.6	5.3
Orange	3	3.4	4.1	4.8	5.4

Table 7.5 Hurricane return period occurrences at Texas ports

Port	Storm Intensity (SSHWS Category)					
	Cat +0	Cat +1	Cat +2	Cat +3	Cat +4	Cat +5
Corpus Christi	4.15	10.95	20.08	24.09	60.23	200.00
Freeport	2.94	6.34	13.38	24.09	60.23	200.00
Galveston	2.74	6.69	13.38	24.09	60.23	200.00
Houston	2.74	6.34	13.38	24.09	60.23	200.00
Port Lavaca	4.02	12.05	24.09	30.11	60.23	200.00
Brownsville	4.15	9.27	15.06	30.11	40.15	120.45
Beaumont	3.01	9.27	17.21	30.11	120.45	200.00
Orange	3.35	10.95	17.21	30.11	120.45	200.00

After the return period of different categories of hurricanes in each port and the shutdown duration of each return period are estimated, the next step is to derive the shutdown duration corresponding to each hurricane category. The research team assumed a linear relationship for the shutdown duration between two return periods in Tables 7.4 and 7.5. For example, according to Table 7.5, the shutdown duration in Port Corpus Christi during a hurricane with a return period of 10 years is 3.1 days. Therefore, a Category 0 cyclone, which has a return period of 4.15 years, is estimated to cause a 1.29-day shutdown duration in Port Corpus Christi. The estimated port shutdown durations by hurricane category are summarized in Table 7.6.

Table 7.6 Calculated port shutdown durations (days) by hurricane category

Port	Storm Intensity (SSHWS Category)					
	Cat +0	Cat +1	Cat +2	Cat +3	Cat +4	Cat +5
Corpus Christi	1.29	3.16	3.70	3.85	4.96	6.40
Freeport	1.06	2.28	3.90	4.66	5.95	8.00
Galveston	1.01	2.48	4.00	4.74	5.80	7.80
Houston	0.85	1.97	3.27	3.70	4.44	6.10
Port Lavaca	1.24	3.22	3.84	4.04	4.97	7.20
Brownsville	1.41	3.15	3.75	4.34	4.57	5.54
Beaumont	0.90	2.78	3.29	3.64	4.74	5.30
Orange	1.00	3.04	3.29	3.64	4.92	5.40

With the shutdown durations estimated, the operating loss due to hurricanes is found by multiplying the shutdown duration by the daily operating revenue, and the estimated total operating loss by hurricane category for each port is summarized in Table 7.7.

Table 7.7 Estimated total operating loss by hurricane category

Port	Daily Operating Revenue ($ Thousands)	Losses from disruption to port operations ($ Thousands)					
		Cat +0	Cat +1	Cat +2	Cat +3	Cat +4	Cat +5
Corpus Christi	310.24	399.47	979.44	1148.76	1194.43	1539.93	1985.55
Freeport	91.98	97.28	209.93	359.14	428.97	546.87	735.85
Galveston	74.95	75.92	185.59	300.15	355.01	435.07	584.64
Houston	1070.50	908.49	2103.87	3499.67	3955.98	4756.42	6530.04
Port Lavaca	4.16	5.18	13.40	15.95	16.79	20.65	29.94
Brownsville	29.67	41.89	93.46	111.36	128.63	135.58	164.44
Beaumont	70.54	63.73	196.08	231.96	256.49	334.59	373.87
Orange	6.06	6.08	18.40	19.92	22.02	29.81	32.71

7.4 Indirect/Macroeconomic Impacts to Texas Ports

Indirect economic loss includes the linkage effect on domestic products as well as the disruption to exports and imports during the port shutdown. As noted earlier, indirect economic loss was quantified using the IT-IIM. The economic impact for a given disruption was quantified by multiplying the losses due to a single day disruption by the anticipated days of disruption, as determined in Section 7.3.2.

7.4.1 Data Collection

The data used in this study includes:

1. *The input-output table, which describes the flow of commodities between industries within a nation*. In this study, the latest data from OECD (2015) is used (Organization for Economic Cooperation and Development, n.d.). The OECD input-output table categorizes industries into 36 industry clusters based on the International Standard Industrial Classification of All Economic Activities (ISIC Rev.4). The industry clusters are shown in Table 7.8. The Leontief inverse matrix obtained from OECD was directly used for the analysis.

2. *The port disruption perturbation vector, which represents the one-day loss of imports and exports*. The 2015 import and export trade values for each port were obtained from U.S.A. Trade Online, with products categorized into 6,093 groups based on the Harmonized System (U.S. Census Bureau, n.d.) The disruption of port operation was assumed to be a one-day shutdown during June 1 and November 30, which is the official Atlantic hurricane season. Daily average monetary value was used for the one-day shutdown purpose.

The import and export product values for each of the ports was then converted and clustered to be consistent with the OECD cluster for input-output analysis following the concordance table developed by OECD (Directorate for Science Technology and Innovation, 2019).

Table 7.8 Industry ISIC Rev.4 code and cluster

Industry	Cluster	Industry	Cluster
TTL_01T03: Agriculture, forestry, and fishing	1	TTL_30: Other transport equipment	19
TTL_05T06: Mining and extraction of energy producing products	2	TTL_31T33: Other manufacturing; repair and installation of machinery and equipment	20
TTL_07T08: Mining and quarrying of non-energy producing products	3	TTL_35T39: Electricity, gas, water supply, sewerage, waste, and remediation services	21
TTL_09: Mining support service activities	4	TTL_41T43: Construction	22
TTL_10T12: Food products, beverages, and tobacco	5	TTL_45T47: Wholesale and retail trade; repair of motor vehicles	23
TTL_13T15: Textiles, wearing apparel, leather, and related products	6	TTL_49T53: Transportation and storage	24
TTL_16: Wood and of products of wood and cork (except furniture)	7	TTL_55T56: Accommodation and food services	25
TTL_17T18: Paper products and printing	8	TTL_58T60: Publishing, audiovisual and broadcasting activities	26
TTL_19: Coke and refined petroleum products	9	TTL_61: Telecommunications	27
TTL_20T21: Chemicals and pharmaceutical products	10	TTL_62T63: IT and other information services	28
TTL_22: Rubber and plastics products	11	TTL_64T66: Financial and insurance activities	29
TTL_23: Other non-metallic mineral products	12	TTL_68: Real estate activities	30
TTL_24: Manufacture of basic metals	13	TTL_69T82: Other business sector services	31
TTL_25: Fabricated metal products, except machinery and equipment	14	TTL_84: Public administration and defense; compulsory social security	32
TTL_26: Computer, electronic and optical products	15	TTL_85: Education	33
TTL_27: Electrical equipment	16	TTL_86T88: Human health and social work	34
TTL_28: Machinery and equipment n.e.c.	17	TTL_90T96: Arts, entertainment, recreation, and other service activities	35
TTL_29: Motor vehicles, trailers, and semi-trailers	18	TTL_97T98: Private households with employed persons	36

7.4.2 Methodology

The indirect losses consist of impacts on GDP and losses due to disruptions of port import and export functionality. The model used in this study—the IT-IIM—includes a variety of industry/economic sectors at the national and regional level. The data sources have been updated regularly by government and international organizations. In the IIM, GDP was used as a measure of economic impact and considers perturbations of domestic infrastructures and the secondary effects. For impact on disruptions on import and export, GTE (the combined value of GDP and import value) was used as the measure of analyses.

The general format of the matrix operations of the IT-IIM process is described in Equation 7.3.

$$X = (I - A)^{-1}C \tag{7.3}$$

where C is the change in port-side final demand (the one-day port import/export values), $(I\text{-}A)^{-1}$ is the Leontief Inverse Matrix (Input-Output Table), and X is the change in total output. The IT-IIM assumes two extreme scenarios to perform the analysis. The two scenarios, Case A and B, are defined based on the distribution and usage of imported commodities. Case A assumes all imported goods become input or are used as intermediary goods while Case B assumes all the imported goods are consumed directly. In Case A, all the imported goods impact domestic production as the flow of intermediate goods are interrupted due to port disruption. In Case B, domestic production is not impacted by imports. The real-world usage of imported goods is a mix of domestic industry use and final consumption. Therefore, the real-world loss value will be a fraction of Case A and a fraction of Case B values. The Case A and B models could also serve as lower and upper bounds.

The one-day disruption loss was computed for each of the ports for both cases. The result was then multiplied by the duration of the disruption at all hurricane levels estimated in Section 7.3.2. to obtain the final disruption loss. The loss values were then converted into 2019-dollar value by adjusting for inflation from 2015 to 2019.

7.4.3 Results and Discussions

Tables 7.9 and 7.10 show the indirect losses by port and by SSHWS Category. Port Houston, which operates multiple facilities and terminals, has the largest indirect losses due to port shutdowns for all storm categories. Port Houston sees a significant volume of cargo across many different industry clusters, ranging from container cargo to liquid petrochemical product and more. Therefore, disruptions to Port Houston will have the most severe impacts. Corpus Christi is estimated to have the second-highest shutdown losses, followed by the remaining six ports. It should also be noted that many port facilities are located in close proximity to each other (for example, Houston, Galveston, and Freeport), which means that multiple ports may be shut down simultaneously for the same hurricane events depending on the exact locations of hurricane landfall. Therefore, extensive indirect losses may occur across multiple industry sectors for hurricanes of high intensity and large geographic coverage. The results for the Port of Orange are identical for both cases, as the U.S. Trade Online dataset indicates that this site dealt only with exports in 2015. Therefore, the results for both Case A and Case B, which compare *import* use, are the same.

Table 7.11 shows the top industry sectors that suffer the most indirect losses due to the disruption of port operations. The results indicate that different ports suffer from losses under hurricane events, and, for different ports, the most-impacted industry sector may also be different. Table 7.11 indicates that industry clusters 9 and 10 are commonly among the most impacted sectors in Texas ports. These sectors are coke and refined petroleum products (Cluster 9) and chemicals and pharmaceutical products (Cluster 10). Given that a large portion of the Texas export economy is based on the production of petrochemical goods, the impacts to these clusters may result in impacts felt at a national or even international level. Therefore, the presented analysis results include dimensions of a macroeconomic analysis.

Table 7.9 Estimated indirect loss by port by hurricane category for Case A

Port	Case A Indirect Losses (in $Million)					
	Cat +0	Cat +1	Cat +2	Cat +3	Cat +4	Cat +5
Corpus Christi	113.13	277.12	324.48	337.63	434.98	561.26
Freeport	92.96	199.95	342.02	408.67	521.80	701.58
Galveston	26.81	65.84	106.19	125.83	153.97	207.07
Houston	636.56	1,475.32	2,448.88	2,770.91	3,325.09	4,568.25
Port Lavaca	6.06	15.73	18.76	19.74	24.28	35.18
Brownsville	10.25	22.91	27.27	31.56	33.23	40.29
Beaumont	40.76	125.89	148.98	164.83	214.65	240.01
Orange	0.001	0.002	0.003	0.003	0.004	0.004

Table 7.10 Estimated indirect loss by port by hurricane category for Case B

Port	Case B Indirect Losses (in $Million)					
	Cat +0	Cat +1	Cat +2	Cat +3	Cat +4	Cat +5
Corpus Christi	96.68	236.84	277.31	288.55	371.75	479.68
Freeport	38.66	83.16	142.24	169.96	217.01	291.77
Galveston	18.32	44.98	72.55	85.97	105.20	141.48
Houston	499.44	1,157.52	1,921.36	2,174.02	2,608.82	3,584.19
Port Lavaca	4.91	12.74	15.20	15.99	19.67	28.49
Brownsville	6.54	14.61	17.39	20.13	21.19	25.69
Beaumont	37.22	114.98	136.07	150.55	196.04	219.20
Orange	0.001	0.002	0.003	0.003	0.004	0.004

Table 7.11 Industry clusters mostly indirectly impacted by port disruption

Port	Industry clusters most indirectly affected	
	Case A	**Case B**
Corpus Christi	Cluster 9	Cluster 9
Freeport	Cluster 18	Cluster 18
Galveston	Cluster 17	Cluster 17
Houston	Cluster 10	Cluster 10
Port Lavaca	Cluster 10	Cluster 10
Brownsville	Cluster 9	Cluster 9
Beaumont	Cluster 9	Cluster 9
Orange	Cluster 10	Cluster 10
Port Arthur	Cluster 2	Cluster 2

7.5 Summary

In this chapter, the economic impacts of hurricane events on Texas port facilities are examined. The assessment accounts for both direct and indirect economic impacts that may result from hurricane hazards. Direct impacts are determined from the repair or replacement costs for port infrastructure assets and lost operating revenue that results from loss of fees charged for berthing and cargo handling, which are interrupted while ports are closed. Indirect impacts are calculated for import and export commodities that are not shipped to port-dependent industries due to the port closure. These indirect impacts are macroeconomic in nature, as the losses are felt by industry sectors that may play a significant role in the regional or national economy.

The analysis is performed for eight port facilities in Texas: Beaumont, Orange, Houston, Galveston, Freeport, Port Lavaca, Corpus Christi, and Brownsville. The selected ports encompass the large, deep-water facilities that are most prominent and have trade data publicly available. Methods for the damaged infrastructure losses are presented, but final results are not presented, as detailed data on probability of damage were not available. Lost operating revenues were calculated using data acquired from port financial statements and the estimated port shutdown durations for each storm SSHWS category. The methods and data sources used to estimate the shutdown durations are described. The indirect impacts are calculated using input-output tables and import/export trade data from OECD and USA Trade Online. The indirect impact assessment indicates that Port Houston is most critical in terms of economic impact, owing to the large amount of freight that moves through the port and the many different industry clusters served by the goods traveling through the port.

The methods and results presented show the far-reaching economic consequences of tropical cyclone events on the Texas port system. These disruptive events require a comprehensive assessment and understanding to frame the importance of port system resilience in Texas.

Chapter 8. Develop Port Resilience Metric

8.1 Introduction

The development of PortRESECO, the port resilience metric and related spreadsheet-based scoring tool, is detailed in this chapter. Data collected in previous tasks were employed in the identification of resilience indicators and development of test questions. An outline of the overall methodology employed in this Chapter is shown in Figure 8.1.

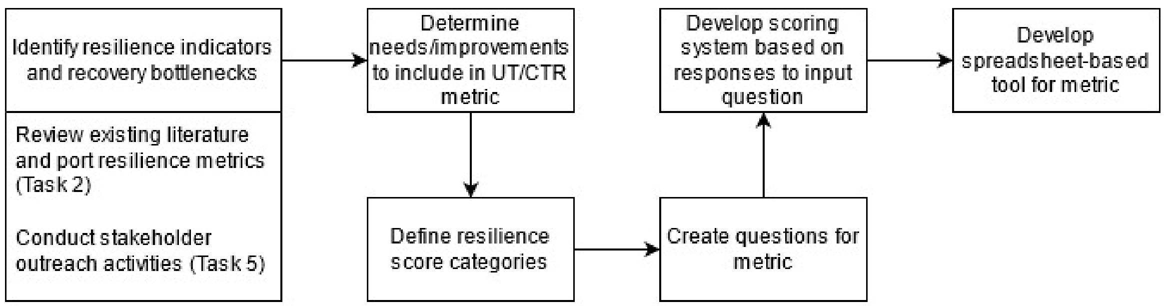


Figure 8.1 Methodology for development of PortRESECO resilience metric

As described in Chapter 2, there exists a general lack of widespread and accessible tools for the purpose of resilience assessment of port infrastructure facilities. Metrics and scores to assess resilience are crucial for improving the existing resilience levels of an infrastructure system as a score allows for stakeholders to identify areas requiring additional investment or operational adjustments to improve disaster response and recovery.

The most widely known existing resilience metric for use in Texas ports is the Port Resilience Index (PRI), developed by the Gulf of Mexico Alliance. This metric is divided into eight subsections with questions formatted in a yes/no response type. The metric is designed for port authority employees to use as a rough gauge of their facility's resilience. The PRI provides a baseline for port resilience scoring but is qualitative in its approach and attempts to span all aspects of port operations, from financial to physical, and all hazards, both manmade and natural in origin.

Therefore, the UT/CTR research team seeks to build on previous efforts to develop a new port resilience metric suited for use in Texas ports. The focus of the new metric is natural disasters, specifically extreme weather events such as hurricanes, and operational and physical aspects are primarily considered. The resilience assessment module of the tool also incorporates quantitative questions, requiring numerical input from the end user. Thus, the tool seeks to provide a more data-driven approach to assessing extreme weather resilience in Texas ports.

Additionally, the results of the economic impact quantification discussed in Chapter 7 is incorporated into the tool as a stand-alone module. This module provides quantitative monetary values for Texas port systems and may help users to better understand the economic risks and port systems' resilience.

8.2 Background

The criteria for measuring port resilience in the developed metric is based on the four dimensions of resilience (Bruneau et al., 2003) and the standard emergency management (EM) processes. The four dimensions of resilience, applied in the context of a port, include robustness, redundancy, resourcefulness, and rapidity. Robustness refers to the strength of the port's infrastructure and its ability to withstand major flooding and wind damage. Redundancy considers the availability of systems, tools, or other needs that can be substituted during a disaster event. Resourcefulness covers the ability of the port to properly identify deficiencies, plan for, and respond to a disruptive disaster event. Rapidity addresses the ability of the port to respond and meet its needs in a timely fashion.

Evaluation of the four resilience dimensions is then applied to each step of the hurricane EM process. In chronological order, the hurricane EM process consists of preparedness, response, recovery and adaptation. Different ports may have varying interpretations or definitions tailored to their unique response, but the principles remain largely the same. Preparedness, response, recovery, and adaptation refer to actions taken before, during, and after a storm, as well as in the long term, respectively.

Resilience metrics serve the necessary purpose of allowing stakeholder groups to assess the existing resilience capabilities of a system and identify areas for improvement. By using established techniques to score or rate the resilience of a port facility, stakeholders such as the port authority, state DOT, local officials, and more may comprehensively determine the current resilience capacity in light of expected natural hazards. Similarly, a scoring tool allows for the identification of specific areas for future improvement. The regular use of a resilience assessment tool allows stakeholder groups to compare different investment strategies, prioritize targeted capital improvements, or implement operational adjustments to increase workforce response capacity.

8.2.1 Port Resilience Assessment

Existing methods for the assessment of port resilience are available. Both academic and practical measures have been developed using a variety of approaches. Academic studies typically approach the issue from an analytical standpoint, using simulation or modeling techniques to portray port conditions and measure resilience. While the discussions in this section are focused on measures for academic research, practical measures are summarized in the Section 8.2.2.

One of the most basic methods to measure the resilience of an infrastructure system is that proposed by Henry and Ramirez-Marquez (2012), which defines the time-dependent resilience of a system as the ratio of the recovered functionality to the total lost functionality resulting from the disruption. This metric is quantitative in nature and is best applied to measure the changes in system state due to a disruptive event.

For port-specific applications, a number of metrics and assessment techniques exist. One assessment technique, published by Omer et al. (2012), establishes a three-phase framework consisting of network construction, metric identification, and network analysis techniques including a systems dynamics model. The metrics identified were tonnage resiliency, time resiliency, and cost resiliency. These metrics provide a measurement for the resilience of the port throughout time during a disruptive event by quantifying the ratio of the port's capacity for each indicator before the disruption to after the disruption.

Another framework, developed by Nair et al. (2010), uses network modeling to develop a framework for resilience assessment at the intermodal component level. The framework consists of three steps: network construction, development of disruption scenarios, and evaluation of recovery tools. The cost and time efficiency of each recovery action is assessed to determine the total benefit to the intermodal system. The framework is then applied in a case study of a port in Poland to demonstrate its use.

Dhanak et al. (2021) developed a framework to assess the resilience of a port for use in planning. The framework employs microscopic traffic simulation to model port vessels and their interactions. The performance of both regional and local systems is quantified using time-dependent resilience plots, along the lines of those introduced by Henry and Ramirez-Marquez.

8.2.2 Port Resilience Indices

While resilience assessment frameworks provide methods for the measurement of system or component resilience using modeling or simulation tools to represent past or future disruptions, other efforts focus on scoring the existing resilience capacities of ports. These studies seek to develop tools or metrics that may be used by port authority employees or other stakeholders to determine the resilience capabilities of a given port facility. These tools are typically developed using significant input from said port stakeholders as the identification of port resilience indicators and recovery bottlenecks is necessary for developing specific questions used in the tool. A majority of port resilience scoring tools take a qualitative approach, where users input answers to yes/no questions. Many existing port resilience scorecards seek to provide ports with a rough understanding of their current resilience status and identify major shortcomings that require action to address.

The Port Resilience Index (PRI) developed by the Gulf of Mexico Alliance is one common metric created in coordination with ports along the U.S. Gulf Coast (Morris, 2016). The PRI is a self-assessment tool consisting of yes/no questions intended for use by a port authority or port management association. The index is intended to be used by port authority administrative employees to conduct high-level assessments of the existing resilience at the port. The primary goal of the tool is not to provide a granular, detailed score, but rather begin a discussion regarding resilience and the improvements that are necessary. The PRI is intended to be revisited every few years so that port officials will regularly discuss resilience issues and determine if improvements are being made.

The Gulf of Mexico Alliance PRI was developed through outreach to a wide group of stakeholders. Officials at the ports of Pascagoula (MS), Corpus Christi (TX), New Orleans (LA), Morgan City

(LA), Pensacola (FL), Port of West St. Mary (LA), Lake Charles (LA), and other private and public entities, were involved in interviews and discussions to identify questions for inclusion in the PRI tool. The Association of American Port Authorities "Emergency Preparedness and Continuity of Operations Planning Manual for Best Practices" was used as a starting point for identifying specific issues worth developing questions for. The stakeholder group then met to provide feedback regarding the structure of the proposed questions and refine the question topics. Finally, three ports (Corpus Christi, Tx; Jackson County, MS; and Lake Charles, LA) were selected as case study locations to use the PRI to score their resilience and relate the experience back to the Gulf of Mexico Alliance and other participating ports.

León-Mateos et al., (2021) also created a port resilience index. The goal of this index was to ensure that all stakeholders were involved in the resilience process. The index was then applied to the port of A Coruña in Galicia, Spain, for demonstration. The index was developed using the Delphi process to establish risk scenarios and risk indicators based on stakeholder input. Then, the results of these processes were used to normalize the (weight values of the index. The index was designed to address the resilience dimensions of governance, society, infrastructure, operations, and risk management. Table 8.1 summarizes the existing port resilience assessment frameworks and index tools developed in academic and practitioner settings as discussed in this report.

Table 8.1 Existing port resilience assessment studies and indices

Study	Use	Infrastructure system	Methodology
(Omer et al., 2012)	Resilience assessment	Port network	Systems dynamics modeling, network analysis
(Nair et al., 2010)	Resilience assessment	Intermodal network components	Network analysis
(Dhanak et al., 2021)	Resilience assessment	Regional port system	Microscopic simulation, time dependent resilience metrics
Gulf of Mexico Alliance PRI (2016)	Resilience scoring index	Port	Stakeholder assessment, Delphi process
(León-Mateos et al., 2021)	Resilience scoring index	Port	Stakeholder assessment, Delphi process, weights

8.3 Development of PortRESECO (Resilience and Economic impact Assessment) Tool

The goal in developing the PortRESECO tool is to have a working system automated for assessing resilience in the face of natural disasters by expanding on existing metrics with the inclusion of data driven analysis and diverse stakeholder input. The resilience assessment module of PortRESECO Tool differs from existing port resilience scoring methods by focusing on two primary characteristics of port response: physical infrastructure ("hard" components) and operational capabilities ("soft" factors).

In the port resilience assessment module, the questions also focus primarily on the EM procedures in place at a port and the infrastructure management techniques that port stakeholders employ. The specific hazards that the tool is designed to address are weather-based events, specifically hurricanes. Finally, the UT/CTR research team wanted to create a tool with data-driven input compared to existing metrics, such as the PRI. Therefore, the question types vary from qualitative questions in a yes/no format or multiple selection list to quantitative questions requiring the input of numerical values.

As discussed in Chapter 7, the economic impact assessment module focuses on understanding the economic risks of hazard disruptions and thus enhance the understandings

8.3.1 Port Resilience Assessment module

As described in Section 8.2, existing studies were reviewed to determine topics of focus for the tool. Similarly, the results of existing port stakeholder surveys and interviews were reviewed to ensure that all critical aspects of port hurricane response were incorporated into the spreadsheet tool. Task 5 of this project involved collecting information from port stakeholders to better understand Texas port resilience. The port authority workshop, interview, and survey results influenced the development and selection of question topics for the Port Resilience Assessment Tool.

Review of other Metrics and Studies

The Gulf of Mexico Alliance PRI served as a valuable resource to understand the perspective of port management agencies and offered guidance in the construction of the new assessment tool. The Port Resilience Assessment Tool utilized the approach of the PRI by incorporating a majority of the questions as yes/no format. Unlike the PRI, the developed metric focuses primarily on infrastructure, operations, and risk management factors. Another differentiating aspect between the Port Resilience Assessment Tool and the PRI is that the Port Resilience Assessment Tool is created specifically with hurricane emergency management factors in mind, while the PRI is designed to cover all types of hazards, such as terrorist attacks, ship collisions, and more.

A review of existing literature, such as those sources listed in Section 8.2 and Chapter 2, was also integral in the creation of this metric for identifying common issues with port disruptions and recovery from widespread impact.

Stakeholder Input Considerations

To identify and consider stakeholder priorities, workshops were conducted with port authorities and other stakeholders. Diverse input is necessary in order for the tool to address the needs of stakeholders beyond port management agencies, such as tenants, freight companies, and public agencies. The complete port stakeholder outreach efforts are detailed in Chapter 5 of this report.

During a phone interview, the Port of Freeport indicated that they were in the process of using the Gulf of Mexico Alliance PRI to perform a resilience assessment of the port and had identified additional questions regarding documentation of construction activity, critical communications, emergency operations, and GIS data acquisition. The researchers decided to include some of these aspects in the Port Resilience Assessment Tool by asking questions regarding backup communication systems and emergency response.

Overall, the workshops and interviews with stakeholder parties resulted in the identification of targeted issues that stakeholders described as being bottlenecks for recovery or critical for sustained port operations. The UT/CTR research team structured survey questions such that the identified points were included within the Port Resilience Assessment Tool. The specific critical issues are:

- Loss of navigable waterways and approach channels due to increased dredging requirements or other obstructions
- Loss or displacement of aids to navigation (AtoNs)
- Loss of power supply and lack of backup systems
- Communication failure and the lack of alternative communication methods
- Employee availability for response and recovery operations
- Site security post-storm when fencing and other infrastructure is damaged
- Leveraging FEMA and other relevant funding sources for post-disaster recovery
- Coordination with tenants and other stakeholders
- Securing dockside infrastructure and equipment such as ship-to-shore cranes
- Communication of suspension of trucking operations to relevant parties
- Interconnections with landside modes such as truck, train, and pipelines
- Maintaining employee training and awareness of emergency management procedures

Question Development

Once critical issues for port resilience and recovery were determined, questions were developed to include these aspects within the Port Resilience Assessment Tool. A majority of the questions are in qualitative yes/no or multiple selection input. However, a few questions require numerical input from the end user. Considering factors such as availability of critical resources or frequency of response actions can identify tangible steps for improvement or allocation of resources. Questions were crafted such that each dimension of resilience was analyzed along each step of the emergency management process, resulting in a holistic evaluation of port resilience. Care was also taken to address the needs of both of physical infrastructure ("hard" factors such as cranes and channels) and operational response ("soft" factors such as chain of command and communication). Appendix E contains a complete list of the questions included within the tool.

Input Requirements

There are three types of questions in the Port Resilience Assessment Module: (1) yes/no questions, (2) quantitative questions, and (3) multiple choice questions. Questions belonging to the same type share the same method to convert the question answer to a quantitative score that characterizes the contribution of this question to the port resilience score:

1. Yes/no response: This type of question gives a statement, and the answer indicates whether this statement applies to the port. The resulting score from this question is either zero (if the response is "no") or one (if the response is "yes").
2. Quantitative response: This type of question often starts with 'How many' or 'How often' and requires an answer with a quantitative value. The score from this question is between zero and one. All questions are designed that the port resilience increases with that answered value, a value (Q_{max}) is determined and act as the value that is enough to give a full score to this question. Therefore, any value beyond that will yield a score of one, while a value (Q) below that will result in a score less than one (Q/Q_{max}).
3. Multiple choice response: In this type of question, the user is asked to select all applicable answers using checkboxes. First, the number of selected answers that will result in a score of one for this question is determined. The number of selected answers and this pre-determined number are used to calculate the score for this question. If the number of selected answers is greater than the pre-determined number, the score of this question is one, otherwise, the score is the ratio of the number of selected answers to that pre-determined number.

Altogether, the user is asked to provide input for a total of 44 questions. The questions are divided into four groups based on the emergency management cycle: preparedness, response, recovery, and adaptation. Each question is also categorized into one of the four resilience dimensions: robustness, redundancy, resourcefulness, and rapidity, although this question categorization is hidden from the end user and occurs in back-end calculations. Some questions serve as sub-questions, building off the previous question. These questions are treated independently, and the score is calculated the same for them as for all other questions.

Backend Calculations

For each question, answers are normalized to values ranging from 0 to 1. Each question is given a weight, and then the total score for each dimension or phase is normalized by dividing the weighted score by the total weight and multiplying by 10 as shown in Equation 8.1.

$$Score = \frac{\sum_i A_i * W_i}{\sum_i W_i} * 10 \quad (8.1)$$

Where A_i is the normalized answer and W_i is the weight of the question.

The user is provided with the option of adjusting the weights of each question if they desire to place a greater priority or emphasis on certain questions. Assigning a weight of zero to a question will completely remove it from score calculation. The maximum recommended weight is five, which will add a significant emphasis to the question. It is recommended that the user does not change any weights unless they have a strong reason for doing so. The final score results are calculated and available for review in the "Resilience Assessment Module" sheet tab.

Output Interpretation

After each question has been answered, the user is provided a score ranging from 1 to 10 for each resilience dimension (Robustness, Resourcefulness, Redundancy, and Rapidity), as well as a score from 1 to 10 for each phase of the emergency management process (Preparedness, Response, Recovery and Adaption). A cumulative score representing overall resilience is also provided. These scores are calculated by score and relative importance, or weight, of each question. To compliment the numerical scores, the results are visualized on two spider charts, as shown in Figure 8.2, providing the user with an intuitive display of their port's strengths and weaknesses.

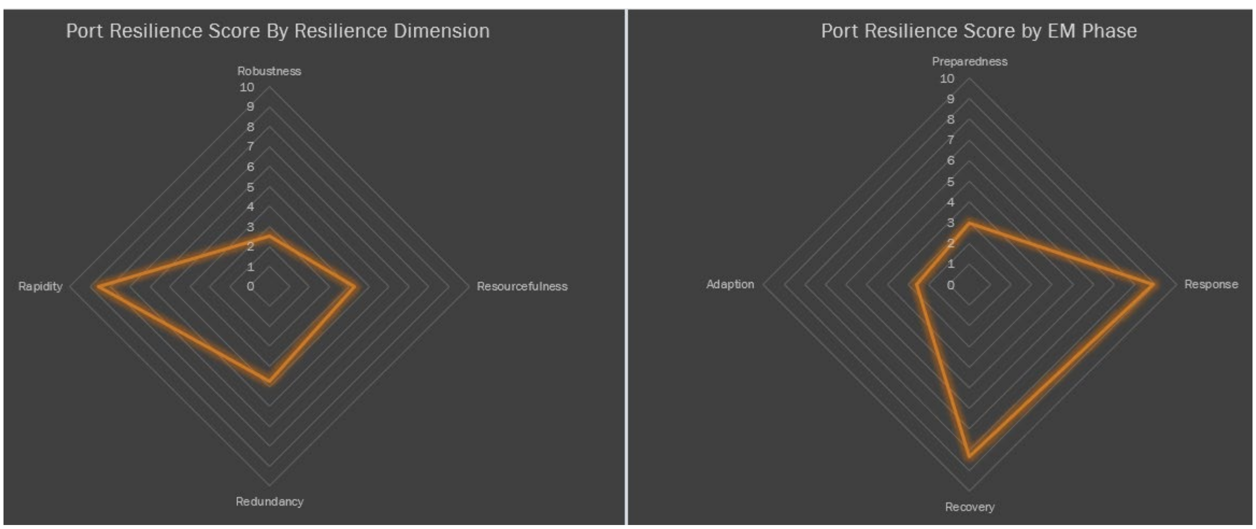


Figure 8.2 Spider charts representing the resilience score of the port.

8.4 Development of Economic Impact Assessment Module

The goal in developing the Economic Impact Assessment Module is to have a working system automated for assessing the economic risks of hazard disruptions. The need, methodologies and backend calculations for this module is discussed in Chapter 7, this module implements the methodology and provides the users flexibility of selecting hurricane category, daily operation revenue and target analysis year.

8.4.1 Input Requirement

The input for economic impact module includes: (1) Port of interest, (2) Hurricane Category, (3) Daily Operational revenue (Optional, for target year) and (4) Target year.

8.4.2 Output Interpretation

After all input have been filled, the user is provided estimated monetary losses for both direct and indirect loss. The definition as well as backend methodology details is discussed in Chapter 7.

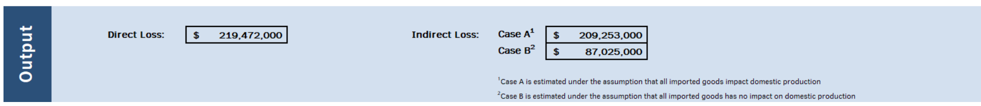


Figure 8.3 Economic Impact Values.

8.5 Tool Construction

The developed resilience questions and economic impact methodologies are implemented into a spreadsheet-based tool for ease of use by stakeholders. The spreadsheet editing software Microsoft Excel was used to build the Port RESECO Tool. End users require access to Excel in order to use the tool. Given the prevalence of Excel in technical business applications, this ensures that the tool is readily accessible to those in industry and results in optimal ease of use.

8.6 User Instructions for Port Resilience Assessment Tool

This tool consists of three main parts: a “Instruction” sheet, a “Front Page” that provides buttons for navigation to the Module sheets and module sheets which includes the operation buttons of the two modules and displays the output results. Macros are used in navigation to provide the user with a seamless experience using the tool.

8.6.1 Port Resilience Assessment Module

The Port Resilience Assessment Module consists of three parts: the main page, four question sheets, and one sheet containing a set of weight adjustment tables. The “Port Resilience Assessment Module” page includes the input area and the output report area; as shown in Figure 8.4. The user left clicks on the buttons to activate each of the question sheets or the weight adjustment sheet. After reviewing all the questions and answers, the user should click the “Calculate Score” button to update the results in the output area.

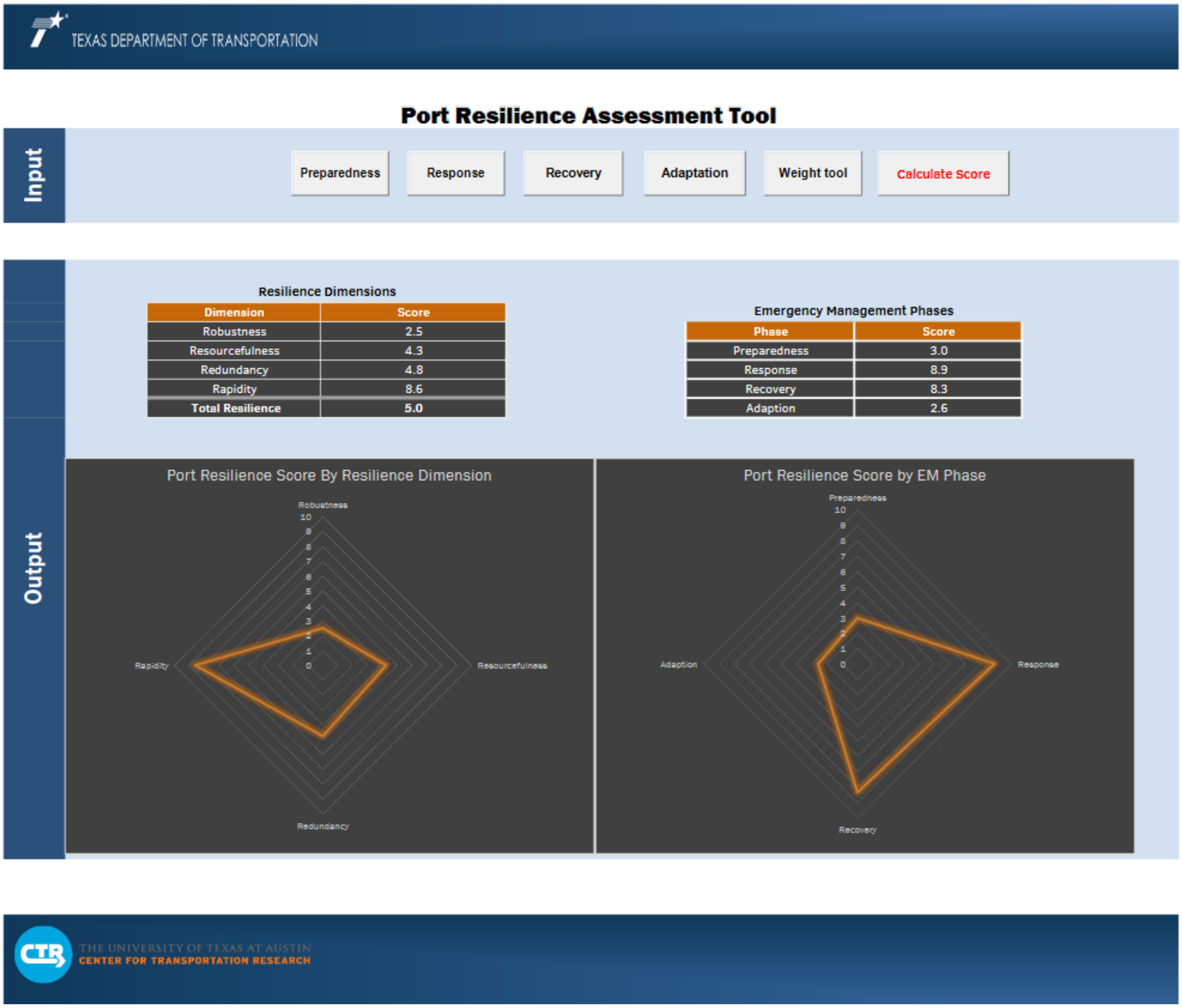


Figure 8.4 Main page showing both "Input" and "Output" of the Module

The output area consists of an output table giving scores for resilience by each dimension and for each emergency management phase as described in Section 8.3.

The four question sheets are organized by emergency management phase: preparedness, response, recovery, and adaptation. As shown in Figure 8.5 a) to 8.5 c), the user should check or uncheck the corresponding boxes for the multiple-choice questions, use the dropdown box to select answers for yes/no questions, or type in number for quantitative response questions. The user should click the "Submit" button upon finishing each EM phase question sheet.

1	Does the port authority have methods to tie down or restrain equipment and items on dock, rail, and truck pads prior to the arrival of tropical force winds? Select all that apply:	☐Ship to shore Cranes ☐Lighting towers ☐Radio towers ☐Container moving equipment ☐Vehicles including tractor trailer units, empty containers, empty truck trailers, and automobiles ☐Utility equipment (generators, additional cabling, water pumps, etc.)

a) Multiple-choice question

2	Is it feasible to secure every critical piece of equipment that can be moved (portable, mobile)?	Yes

b) Yes/no question

3	What percentage of essential equipment can be secured? (Provide an estimate **(Integer using 0-100)** with 0 if no plan)	100

c) Quantitative response question

Figure 8.5 Example of question types present in Port Resilience Assessment Module

The weight adjustment tool grants the user the flexibility of changing the relative weight of each question as shown in Figure 8.6. The user could either eliminate questions by changing the weight to 0 or put significant importance on questions by setting the weight up to 5 based on their professional judgement.

Question #	Weight
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1

Figure 8.6 Example: Weight Adjustment

8.6.2 Economic Impact Assessment Module

The Economic Impact Assessment Module consists of two parts: the Input area and Output area as shown in Figure 8.3. The user left clicks on the buttons to select the port of interest and hurricane category. The user could select the boxes and input numbers for daily operational revenue and target year. Upon the finish of all user inputs, the user gets the estimated monetary loss values in the output area.

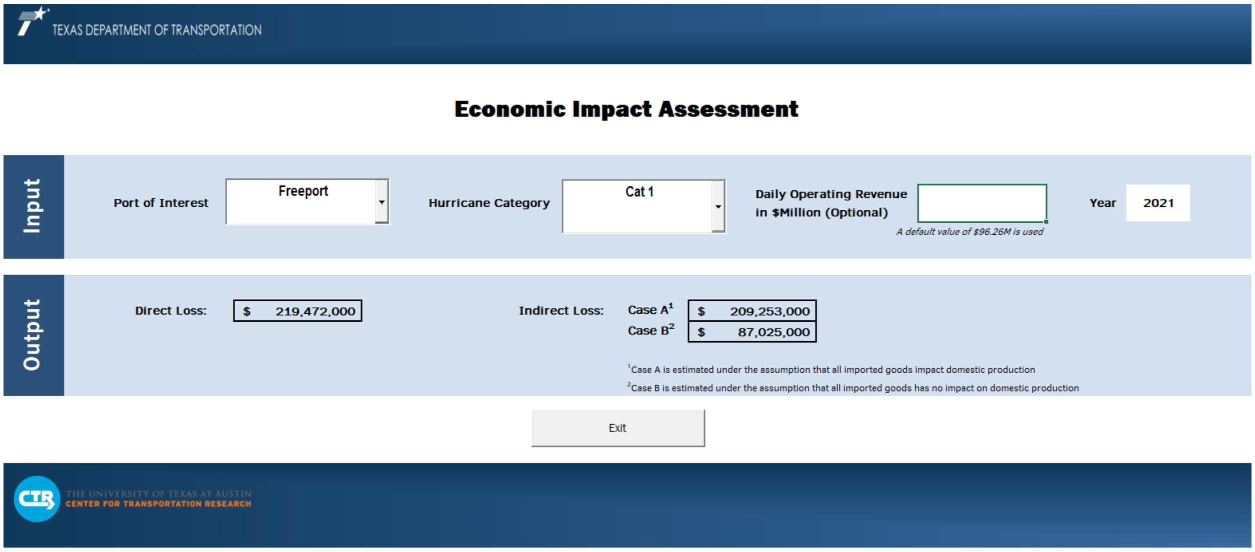


Figure 8.7 Input and Output areas of Economic Impact Assessment Module

8.7 Accessing the Tool

The Port Resilience Assessment Tool is developed in Microsoft Excel, a common spreadsheet editing and viewing software platform. The tool contains Excel Macros for user input and score calculation and may be accessed using the following steps:

1. Navigate to the shared UT Box link at: https://utexas.box.com/s/lnlpweb23wbrgbcydo6no6ucal8b8lk1
2. Download the tool from the UT Box “P2: PortRESECO Excel Tool” subfolder onto a local folder
3. Open the “UT-CTR_PortRESECO_Tool_1.0.xlsm” file
4. Dialog boxes will appear. Click “Enable Content” for the Protected View warning and click “Enable Content” for the Security Warning
5. If file is in Read-Only mode, save the file locally to remove this restriction and save the input and output values
6. Begin using the tool

8.8 Summary

This chapter provides an overview of how the resilience metric was established and how the Port Resilience Assessment Tool was developed. The framework of the tool is rooted in the four dimensions of resilience (robustness, resourcefulness, redundancy, and rapidity) applied to each step of the emergency management process (preparedness, response, recovery, and adaptation). Care was also taken to consider the capabilities of both physical infrastructure (“hard” factors) and organizational response (“soft” factors).

Existing metrics for assessing port resilience were examined, specifically with a focus on the Ports Resilience Index (PRI) developed by the Gulf of Mexico Alliance. The UT/CTR research team, taking advantages of previous work in existing literature and capitalizing on information gathered from ports in Texas through workshops, interviews, and online surveys, aims at creating a tool that incorporates quantitative and qualitative analysis specifically for Texas ports to prepare for hurricane events. Reviewing existing studies in addition to working closely with port stakeholders provided insight that directed the construction of each question. The 44 total questions consist of yes/no, quantitative, and multiple choice/select all that apply response formats.

After results are calculated, the user is provided with the score of their port's resilience along each resilience dimension and EM phase in both a numerical and visual format. An overall resilience score is also provided. The user is then free to evaluate the results of the resilience assessment and identify deficiencies under a specific resilience dimension or EM phase for their specific port.

Overall, the developed Port Resilience Assessment Tool provides a novel method for Texas ports and port stakeholders to assess their own physical and operational resilience and emergency management capabilities for hurricanes and other extreme weather events. Use of the tool will allow for the identification of specific areas of improvement and result in enhanced extreme weather resilience of the Texas port system.

Chapter 9. Assess Port-Level and Network-Level Resilience

9.1 Introduction

The resilience assessment of the Texas port system is presented in this chapter. Understanding the factors and tools that may be employed to assess the resilience of physical systems is crucial for developing resilient operations and practices in application. While Chapter 6 describes the development of a risk assessment framework for the Texas port system at the network level, this chapter takes a theoretical approach by determining the criticality and vulnerability of the coastal freight transportation network using network theory metrics. Rather than considering the road, rail, and waterway networks as individual, isolated systems, the methodology constructs the network model in such a way that physical interdependencies between the systems are accounted for.

The topological criticality is determined for the overall, combined network of different transportation networks via the graph metric of betweenness centrality. The topological vulnerability is determined for each of the transportation networks via the graph metric of total graph diversity (TGD). The calculation of these metrics is described in detail, as is the construction of the combined interdependent network. The network construction was performed using ArcGIS for layer editing and the NetworkX Python package was used for the network metric assessment. Results of the analysis are given in tabular and map format.

Discussion is also provided regarding the applicability of the network topology metrics to the previously developed risk assessment framework in Chapter 6. The topological criticality and topological vulnerability can be added to the network level criticality and vulnerability scoring methodology. This will result in a more comprehensive coastal transportation criticality, vulnerability, and risk indicator score as each score is now derived from link attributes, such as roadway classification and traffic volumes, as well as topological calculations related to the structural layout and connections present in the physical network.

9.2 Background

A network, also referred to as a graph, is represented by links and nodes. Links, also known as edges, provide connections between nodes in the network, while nodes serve as points where links converge and connect. Due to this simple layout, network graphs are commonly used to represent transportation networks such as road or rail systems. The links and nodes may represent different features depending on the scale of the network model: at a large scale, nodes may represent cities and links may represent the major interstate highways connecting the cities. At a city-level scale, nodes may represent intersections or interchanges and links may represent local streets. Network models can be directed, where constituent items flow in specified directions between nodes, or undirected where items can flow in both directions along the links (Milanovic & Zhu, 2018). A one-way street would be represented by a directional link, while a bi-directional or undirected link would represent a two-way road.

This simple level of abstraction allowing complex real-world networks to be represented with easily interpreted symbolic models has resulted in an abundance of research examining transportation networks and network topology. Topology refers to the physical layout of nodes and links in a network. The topology of a physical system network is thought to have a significant impact on its resilience (X. Zhang et al., 2015). The layout of the existing streets and connections between routes can impact the ability of the system to maintain performance levels during disruptions as the presence or lack of redundant routes can affect the evacuation of civilians and the transport of recovery and relief cargo to affected areas. Therefore, it is important to understand the critical and vulnerable links and nodes within the transportation system network.

9.2.1 Topological Criticality

Critical links and nodes are those which offer the greatest importance to the functioning of the network. For example, critical links may represent roadways or railways which transport the greatest amount of traffic. Another measure of criticality may be related to the network topology. The links and nodes that offer the most connectivity in the network may be seen as being more important than links that only provide connections to a smaller number of nodes or an isolated series of links. One common way to measure topological criticality is the betweenness centrality metric (Liu et al., 2019). Betweenness centrality measures criticality by portraying how much connectivity is provided by each link and node by relating the number of shortest paths in the network that use the a given link or node to the total number of shortest paths possible in the network (Bešinović, 2020). Since the shortest paths between two nodes is typically the most desirable route, calculating the ratio of the number of shortest paths that use a network element to the total number of shortest paths offers a view of the importance of a given node or link relative to all other links and nodes in the network. Equation 9.1 shows the specific calculation used to determine betweenness centrality:

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{9.1}$$

This equation presents how the betweenness centrality of node *v* is calculated. It is the ratio of shortest paths in the network passing through *v* to total number of shortest paths. Similarly, the betweenness centrality of the links of the network may be calculated by taking the ratio of the number of shortest paths passing through a given link to the total number of shortest paths in the network.

9.2.2 Topological Vulnerability

Vulnerable links and nodes are those which are most sensitive to disruptive events and are predisposed to loss of function compared to the other links and nodes in the network. When a disruptive event occurs, these are the network components that, if impacted, will create the most damaging impacts for the overall network. If there is only one link that connects two nodes with no alternative, redundant route access, then this link is considered to have a higher vulnerability as the network would lose connectivity to some of its nodes if this link were to fail.

One way to measure the vulnerability of a network is path diversity, which is calculated for each node pair, and the total graph diversity (TGD) which is calculated for the entire network (Alenazi & Sterbenz, 2015). Path diversity determines the number of disjoint links in an alternate path between a given node pair as compared to the shortest path for the given node pair. This calculation is shown in Equation 9.2 (Rohrer & Sterbenz, 2011).

$$D(P_k) = 1 - \frac{|P_k \cap P_0|}{|P_0|} \tag{9.2}$$

Where P_k represents path k between a given node pair and P_0 is the shortest path between the node pair. A path diversity of zero indicates that the shortest path and the alternate path share the exact same route, while a path diversity of 1 indicates that the paths are completely disjoint—they do not share any of the same links or nodes.

The TGD is first calculated from the effective path diversity (EPD). The EPD is calculated as shown in Equation 9.3.

$$EPD = 1 - e^{-\lambda k_{sd}} \tag{9.3}$$

Where λ represents an experimentally fitted constant, and k_{sd} is the sum of the minimum diversity value for the current paths and all previously evaluated paths between for the node pair. For ease of implementation, a subset of the paths between each node pair is selected. There are three common methods typically used for path selection: the number of paths, a diversity threshold, and the stretch limit (Rohrer et al., 2009).

Finally, TGD is computed as the mean of the EPD for all node pairs of the network. The TDG offers a view of the overall path diversity, and therefore the route redundancy, present in a network. The TGD value ranges from 0 to 1, with a value of zero representing no diversity in the network and 1 representing a highly diversity network with many redundant routes.

9.2.3 Multi-Layered Complex Network Theory

For complex systems, multi-layered networks are used to model the interactions between the disparate components (L. Zhang et al., 2019). This technique is commonly used in fields where systems have multiple levels of interactions, such as a system that operates with its own components but also has physical or logical connections with the other systems present in the same geographic setting (Viljoen & Joubert, 2018). These interdependent networks may rely on each other for the transfer of goods or information in order for the individual systems themselves to properly function. In these complex environments, it is important to consider these relationships between systems rather than just evaluating each system independently (Sterbenz et al., 2014). Therefore, the use of complex multi-layered networks allows for a more accurate assessment of real-world systems via the incorporation of interdependencies. Figure 9.1 shows a visual interpretation of a multi-layered network.

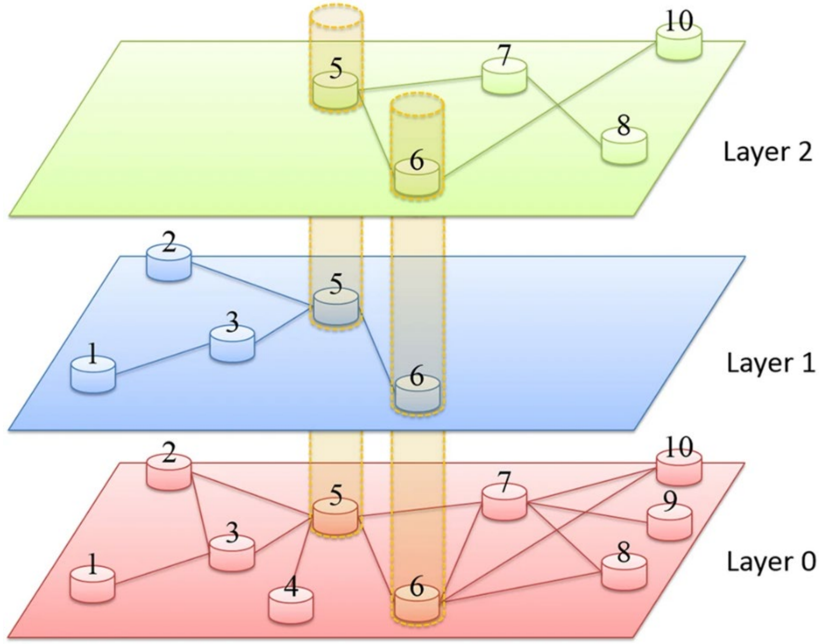


Figure 9.1 Visual interpretation of a complex multi-layered network, where each layer is a physical system and connections between systems are represented by hollow tubes (Klein, 2021).

9.3 Port System Resilience Assessment Framework

To evaluate the resilience of the Texas port system from a topological standpoint, a framework is presented and illustrated in Figure 9.2. The objective of the proposed framework is to assess the port system resilience by network topology and system attributes (including traffic, function class, etc.) while including infrastructure interdependencies between different freight systems. The system attributes are collected and calculated as detailed in Chapter 6. Therefore, this task focuses on incorporating the interdependent effects among infrastructure systems and evaluating the network topology of the physical system. The interdependent effects can be combined with the system attributes to better characterize the port system resilience.

Due to on the data availability, the interdependencies between the networks are measured with network topology metrics. Two metrics are used to represent different aspects of the effects of interdependencies on the system resilience: (1) the criticality of each node and link in the integrated network using betweenness centrality and (2) the vulnerability of each independent infrastructure system using total graph diversity to measure link redundancy.

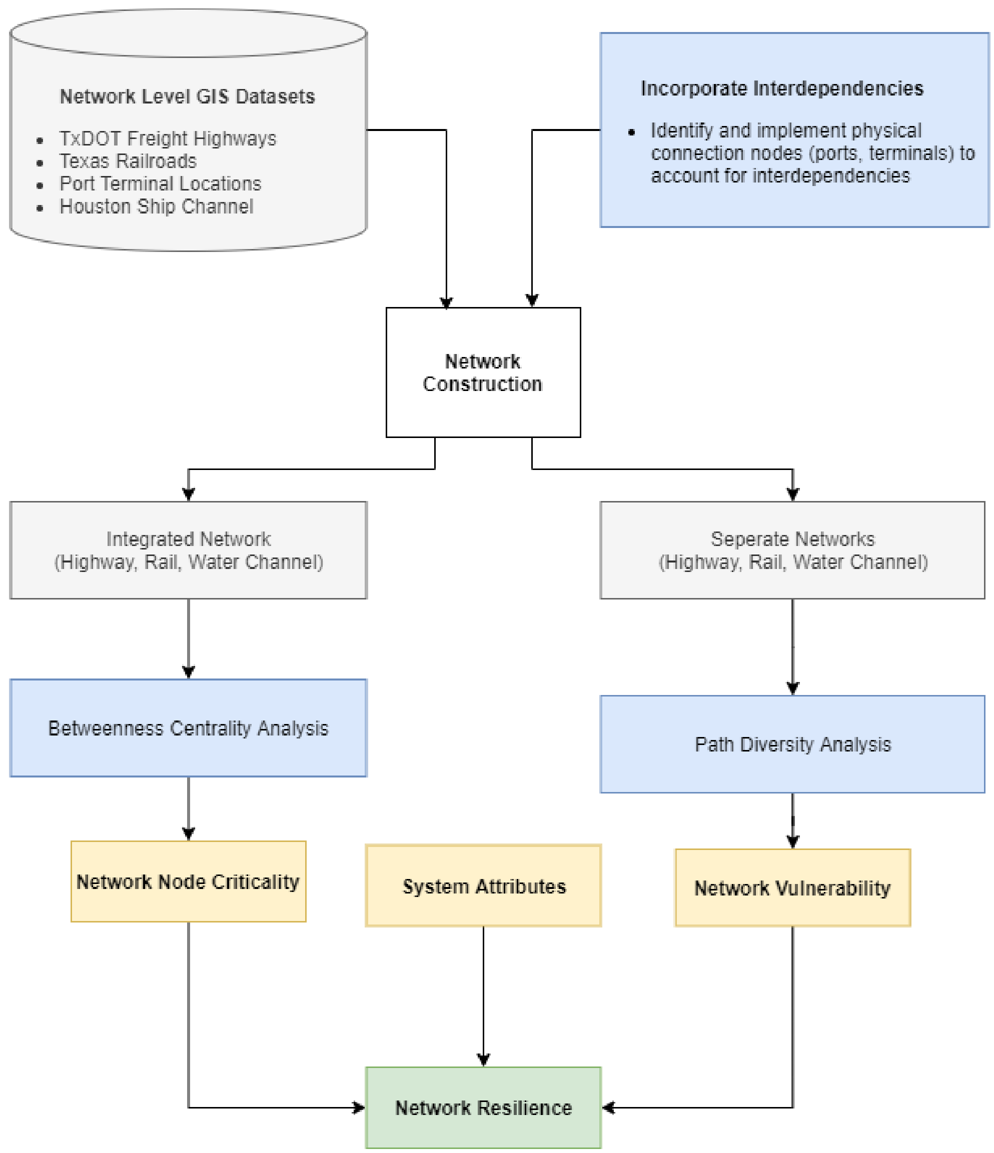


Figure 9.2 Proposed resilience assessment framework

9.3.1 Network Node Criticality

Network node criticality implies how critical an infrastructure facility (represented by a node in the network) is to the infrastructure network. In this framework, it is measured by betweenness centrality, a term in graph theory, which is calculated by Equation 9.1.

Before calculating the betweenness centrality, different infrastructure system networks are connected by terminals. Therefore, the betweenness centrality of a node could reflect the interdependent effects among different transportation systems. In this framework, the betweenness centrality of a node indicates the impact of the failure of that node to the integrated network during disasters. As a result, the betweenness centrality measures the criticality of the nodes in the network considering interdependencies.

Similarly, the betweenness centrality of the multi-layered network can be calculated for each link. Therefore, the criticality of each road, rail, and water channel in the network can be determined.

9.3.2 Network Vulnerability

Network vulnerability is measured by path diversity. Path diversity quantifies the degree to which alternate paths share the same nodes and links. With less degree of shared nodes and links, the network is considered more diverse. When a network is diverse, failures in nodes or links will have less impact on the functionality of the whole network. Thus, the network is considered less vulnerable to disasters. In the proposed framework, the path diversity of each individual infrastructure system is calculated and estimated as the vulnerability of that infrastructure network. The vulnerability is assessed for each network individually rather than the combined, interdependent network.

9.3.3 Network Resilience

Combined with the infrastructure network attributes collected and calculated in Chapter 6, the criticality of the infrastructure facilities and the vulnerability of the infrastructure networks then contribute to the resilience assessment of port system resilience. The network topology indicators can serve as additional scoring components for the framework presented in Chapter 6, for the criticality and vulnerability scores, respectively. Since the resilience of the port system is the ability of the port system to withstand reduce the magnitude and duration of disruptive events, the actual resilience of the port system cannot be calculated without a disruptive event being defined and introduced into the system model through simulation. However, the results of this Chapter produce the topological criticality and vulnerability of the combined port transportation system, which are key contributors to port system resilience.

9.4 Resilience Assessment Case Study

The framework is conducted with a case study of the ports and transportation systems in the Houston area to demonstrate the link and node criticality assessment methodology with interdependencies considered. Three types of transportation systems are included in the analysis: the freight highway system, railroad system, and water navigation channels. These systems converge and contain physical connections for goods transfer at seaport and intermodal terminals. As this component of the study focuses on network topology, the system resilience is assessed through the lens of criticality and vulnerability scores. This section describes the network construction for the graph used in the analysis and the analysis results.

9.4.1 Study Area

The case study is performed at a regional scale, such that multiple port and intermodal facilities are included within the analysis area. The specific region was selected such that it includes multiple port terminals, intermodal road-to-rail facilities, considerable road, rail, and waterway components, and has a manageable complexity to ensure that the network algorithms are feasible to implement in a timely manner. The specific study area was chosen for the Port Houston area and is shown in Figure 9.3.

9.4.2 Network Construction

In this case study, three types of networks are included: the freight highway system, railroad system, and water navigation channels. The regional networks were obtained in shapefile format from the TxDOT online GIS data repository. The GIS layers were clipped to fit the study area and each layer underwent considerable cleaning and editing to create layers with line breaks at all intersecting streets and railroad junctions. The individual systems also connect into the same nodes at seaport and intermodal terminal locations. In this way, the interdependencies between the systems are represented. In this case study, the transportation systems all converge at seaport and intermodal terminal nodes and direct connection links are used to represent locations of physical good transfer between each transportation system. In this case study, container and breakbulk cargo were the primary cargo types considered as tanker facilities and pipeline infrastructure was not considered in the analysis.

After the initial construction of the three individual networks, the layers were exported from GIS applications into Python, where the NetworkX library was used to combine the networks to construct the regional connected network. The final infrastructure network and terminal nodes are shown in Figure 9.3, where different infrastructure systems are represented in different colors.

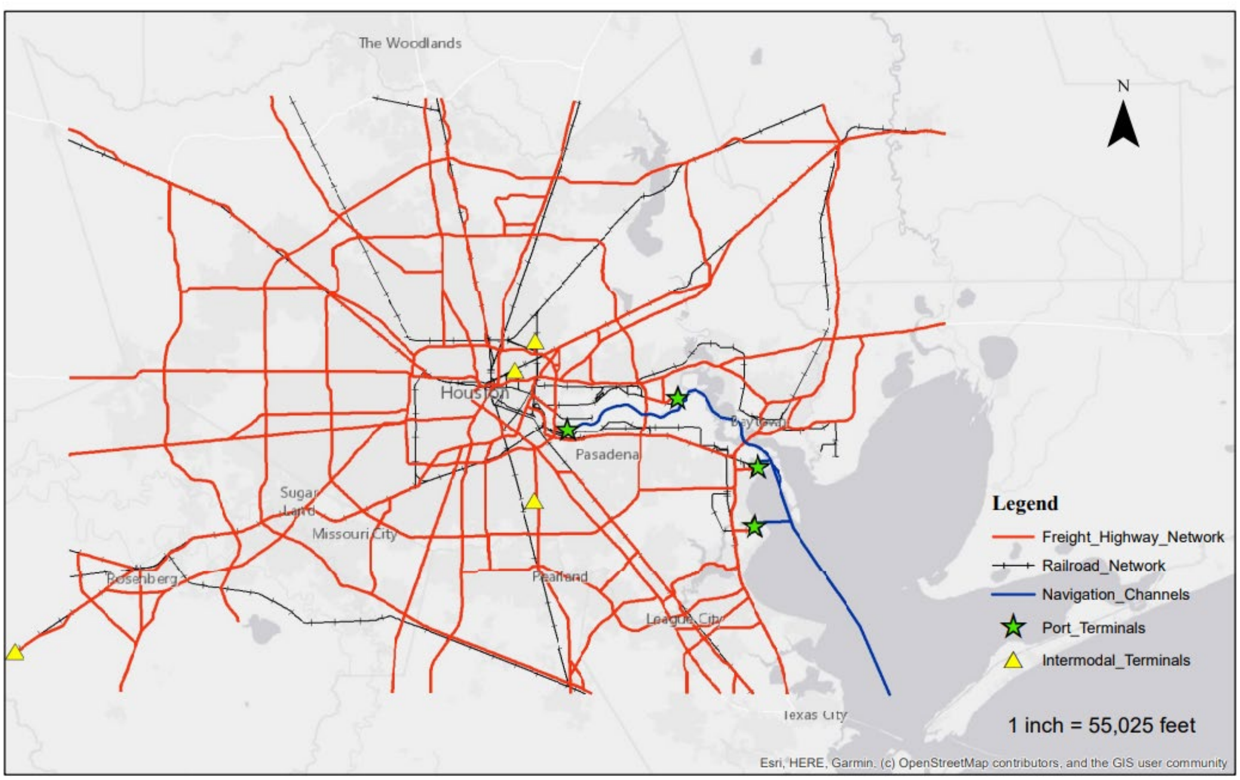


Figure 9.3 TxDOT GIS layers for freight highways, railroads, and water ways used in the topology analysis

Freight Highway Network

The roadway network is an important component of overall network analysis. For this case study, the "TxDOT Texas Highway Freight Network" shapefile was obtained from the TxDOT Online Data Portal. Rather than using the complete roadway network or a subset of the roadway network, the research team decided to use the freight highway network as the focus of the project is on Texas ports and coastal freight logistics. By selecting the freight roadway network, the computational complexity of the problem is reduced while still maintaining roadway links and nodes that are representative of the routes taken by port truck traffic in real-world scenarios. Necessary manual corrections were made to the freight network shapefile in order to verify full connectivity and the correct location of nodes for usability in the analysis.

Railroad Network

The railroad network is another important component in the port area as many goods are transported to and from ports and vessels in massive volumes via rail transportation. The railroad network shapefile, "Texas Railroads," was obtained from the TxDOT Online Data Portal. The shapefile was filtered to only include active Class I railroad mainline tracks, active spur lines and Port Terminal Railroad Association-owned tracks to provide necessary connections to and from the port terminals and intermodal transportation centers. Some necessary manual corrections were applied to make the network file fully connected and usable, as with the roadway network.

Navigation Channel Network

In this study, the water navigation channels are included in the analysis. These links are highly important to the proper functioning of the port system as ships are not able to access port facilities if the approach channels are blocks or out of service. In this case study, the Houston Ship Channel, which runs from the Gulf of Mexico into the port terminals in the Houston area, is included. A GIS shapefile for Texas waterways was clipped to the project extents and the desirable links representing the Houston Ship Channel were extracted for use in the analysis.

Port and Intermodal Terminals

The transportation systems all converge at port and intermodal terminal locations, where container and breakbulk cargo is physically transferred from one freight mode to another. At seaport terminals, shipping container, breakbulk, and roll-on/roll-off cargo is transferred between waterborne vessels and trucks or trains. Therefore, the waterway, roadway, and railway networks are all interconnected at these seaport terminal locations. In this analysis, three Port Houston terminals are included: Barbour's Cut container terminal, Bayport container terminal, and the Jacintoport Terminal, which is a privately owned and operated breakbulk terminal located along the Buffalo Bayou waterway.

Intermodal terminals are inland locations where cargo is transferred between trains and trucks. Therefore, in the model, the road and rail networks are also connected at these intermodal terminal locations, which are typically owned by railroad operators. In this case study, the intermodal terminals of Union Pacific (UP) Englewood, UP Settagast Yard, BNSF Houston (Pearland) terminal, and KCS Rosenberg Intermodal terminal are included in the model.

9.4.3 Criticality Results

As discussed in Section 9.4.2., the final combined intermodal network was imported into Python for the betweenness centrality analysis using the NetworkX library. The complete, multi-layered network as created by combining all transportation systems was used for the criticality assessment to account for interdependencies between the systems. Both node centrality and link centrality were assessed. The centrality scores were categorized into five groups using the Jenks break (Jenks, 1967), which minimizes variance within each class and maximizes the variance between different classes to find a natural classification grouping for the data.

The result of the betweenness centrality of nodes is shown in Figure 9.4. The port terminal locations and notable intermodal centers clearly have higher criticality scores, and other nodes also have relatively high criticality values based on their locations in the combined interdependent network. Other than the critical locations such as port and intermodal terminals, the centrality analysis also identified other critical locations such as interchanges in the freight road network with a high betweenness centrality score. Nodes located near downtown Houston and along the western and southern portions of Route 8, the Sam Houston Tollway, also have higher levels of criticality.

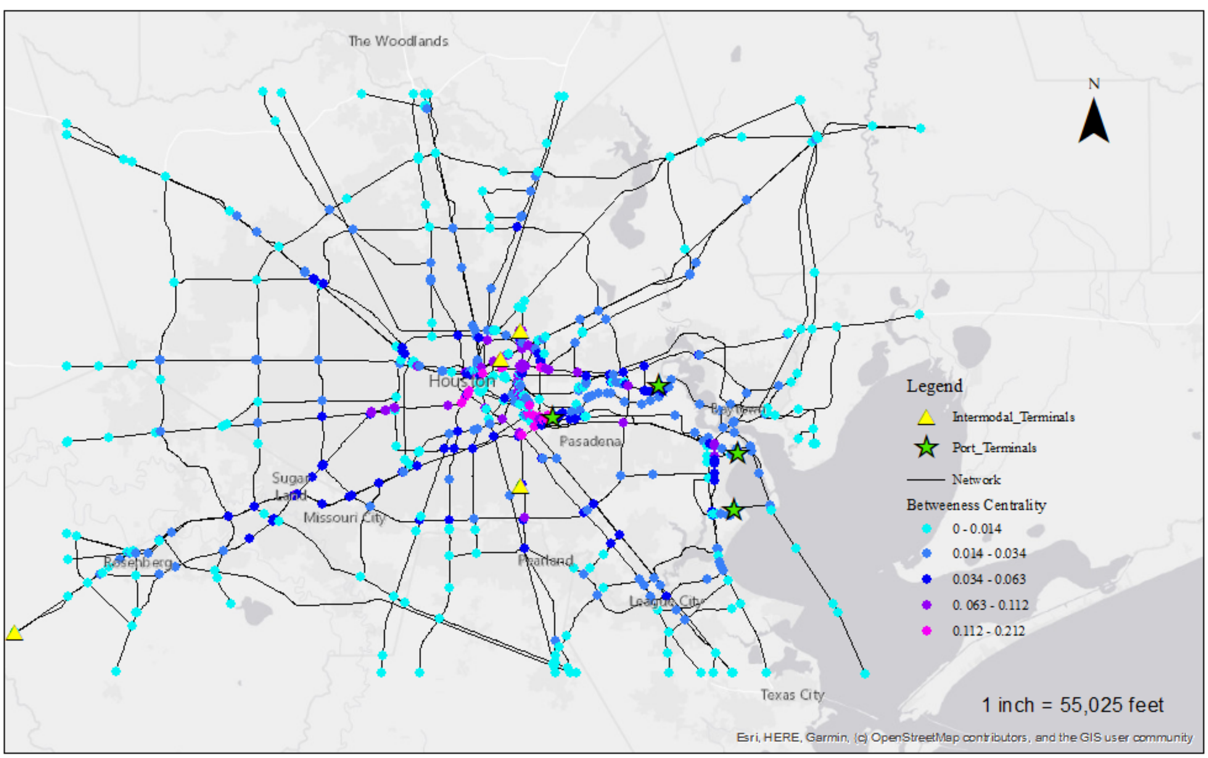


Figure 9.4 Node centrality scores for the combined multi-layered network

The result of the betweenness centrality for the network links is shown in Figure 9.5. The links near or between port and intermodal centers have higher criticality scores and other links directly connecting to those locations also have high centrality. There are further links that have relatively high centrality based on the graph topology, which indicates they are also highly critical to the combined network. These link criticality scores can be used as an additional attribute for the risk assessment framework for the criticality score calculated in Chapter 6.

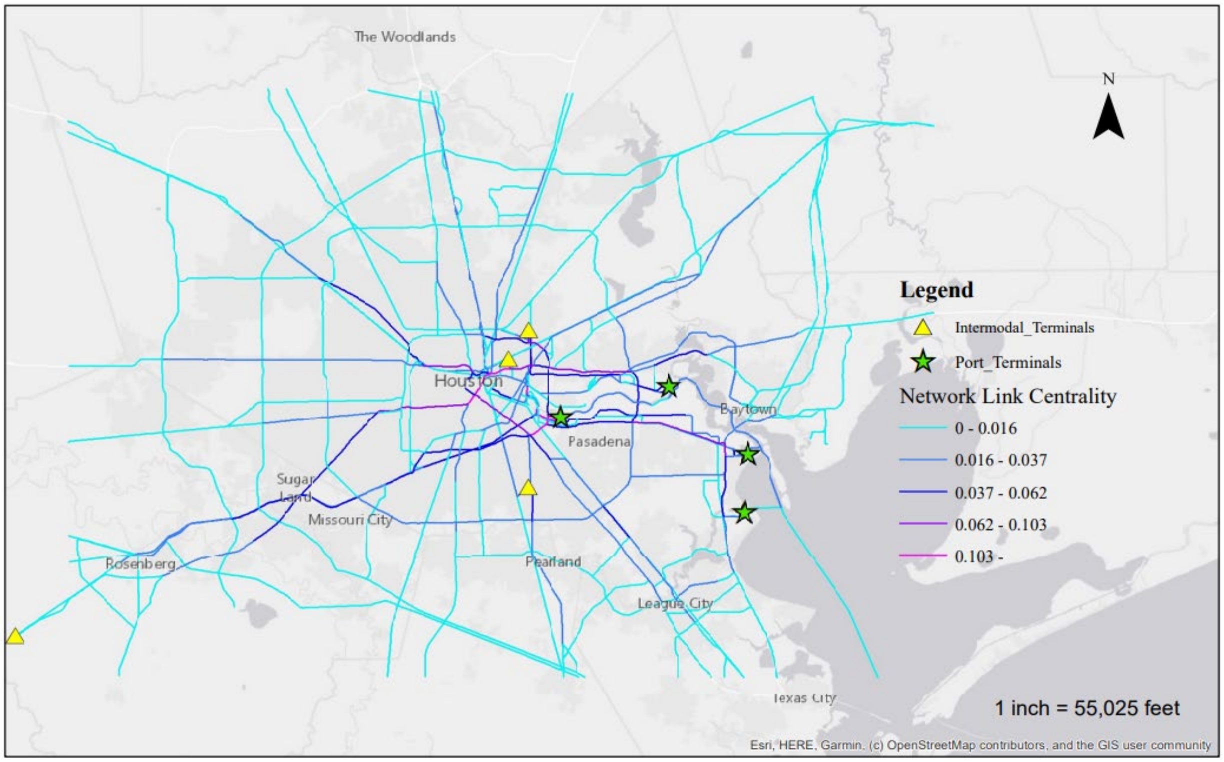


Figure 9.5 Link centrality scores for the combined multi-layered network

9.4.4 Vulnerability Results

As described in Section 9.3, path diversity is a path-based factor. As the connection between the different modes of transportation are sometimes logical and abstract while the connection within each mode is physical, the path diversity analysis is conducted on each of the three networks separately. Table 9.1 shows the network level total graph diversity (TGD) scores for each network. The roadway network system has a relatively high graph diversity which indicates that it is less vulnerable against disasters based on its topology. Road users are more likely to find an alternate route to take when a link is out of service as the structural layout of the road network provides the opportunity for several redundant routes for each node pair.

The railroad network system has a smaller TGD score compared with the roadway network system which indicates it is more vulnerable to disasters. This is to be expected when visually inspecting the two systems, as the railway network has less overall connectivity and therefore contains less redundant routes between node pairs. In reality, this is also observed. Due to the higher cost of constructing rail corridors, railways typically provide direct, long-range connections between shipping hubs, whereas a road system is designed to provide a greater amount of coverage and access to more local businesses. Therefore, if a main rail line goes out of service during a disaster, the impacts can be severe on the rail network.

The navigation channel system has a diversity score of zero because the selected channel is a linear network of only one single route to and from the port terminals. This linear topology is extremely vulnerable such that the system completely shuts down if any interruption on key component occurs. This result is intuitive as the Houston Ship Channel is critical for uninterrupted port operations. If the channel is closed, it would bring all ship-based trade in the Houston region to a halt. Additionally, the channel is vulnerable as it is constrained by the geography and geometry of the waterways. There is no possibility of adding a secondary alternate route as the Houston Ship Channel follows existing rivers and harbors. Therefore, recovery efforts post-hurricane must prioritize reopening the Houston Ship Channel as rapidly as possible to restore full port functions in a timely manner.

Table 9.1 Network TGD results

Network	Total Graph Diversity
Roadway	0.66
Railroad	0.40
Navigation Channel	0.00

9.5 Risk and Resilience Implications

While the methods presented in this chapter and case study provide calculations for network topology criticality and vulnerability, these factors may provide an indirect view of the resilience of the port system at a network level. As discussed in Chapter 6, criticality and vulnerability are factors that influence the risk of a system to disruptions. In turn, this risk influences the resilience strategies that decision makers and stakeholders may employ by seeking to minimize the risk present in the system by reducing vulnerabilities. Therefore, the results of this analysis may allow stakeholders and decision makers to identify highly important (critical) or susceptible (vulnerable) system components and determine potential solutions. For example, investing in capital projects to create a greater degree of network redundancy may increase the TGD of a system network.

The results of this analysis can be incorporated into the risk assessment framework developed in Chapter 6 of this report. Using a score of 1-5 to rank the betweenness centrality, the results may be added to the network link criticality score as an additional attribute to incorporate the network topology into the attribute-based criticality score.

Similarly, the vulnerability score as derived in Chapter 6 may be augmented with the results of this topological analysis. The TGD score, which ranges from 0 to 1, may be used as a weight for the vulnerability score or replace the proxy "distance to port" variable which was used as a vulnerability indicator in the Chapter 6 case study.

While betweenness centrality and path diversity are common graph metrics used to assess the resilience of transportation networks, additional network metrics such as clustering coefficients, degree centrality, efficiency, and transitivity may also be implemented to further examine the criticality, vulnerability, and resilience of a network.

9.6 Summary

This chapter provides an overview of how the topological, network-level resilience assessment was performed for a case study of the Houston port area. The analysis uses betweenness centrality to measure link and node criticality of the multi-layer, interdependent network and total graph diversity to measure the graph vulnerability of each independent system.

Significant efforts are required for construction of the complex multi-layered network. The GIS layers must be cleaned and examined to verify connectivity and proper node placement. Then, the individual networks must be connected at port and intermodal terminal nodes to create the links representing the physical interdependencies present in the system where physical goods are passed between the transport modes. Once the network is imported to Python for analysis, the betweenness centrality and TGD is calculated, and the results are plotted. This work provides a framework for the topological assessment of a complex, multi-layered freight transportation network and ties into the risk assessment framework previously developed in Chapter 6. This framework has implications in real-world interdependent transportation systems as it allows stakeholders and decision makers to identify inherent weaknesses within the network structure to prioritize potential improvements that may reduce vulnerabilities and increase resilience.

To directly measure the resilience of the system, detailed data with a high level of granularity on the impacts of past disasters is required. Time-dependent resilience measurement requires data on the level of reduced cargo throughput or system traffic over the time of the disruption as compared to levels during typical operations. As this level of data was not available, these efforts focused on assessing the resilience characteristics of the network from a topology standpoint.

Chapter 10. Assess Port-level and Network-level Resilience

10.1 Introduction

The final component of the study is to provide recommendations for potential actions to improve the resilience of the Texas seaport system. This chapter draws from the key findings of the project to identify specific actions that UT/CTR recommends TxDOT to implement to enhance the resilience of Texas ports and the Texas port system. The recommendations are provided for physical infrastructure improvements, operational adjustments, and employee characteristics that should be implemented for expected increases in the resilience of the Texas port system to extreme weather events.

The recommendations are targeted for feasible improvements that TxDOT can seek to implement considering current and future budget constraints. In some instances, the recommendations are intended for future implementation and are recommended as innovative or novel methods to spur discourse and increase technological factors at port facilities. Some recommendations are intended to provide extreme weather relief to landside supporting infrastructure systems, such as trucking or rail connections to ports, while others target the ports themselves. In most port industry settings, operational adjustments are preferred over physical or regulatory measures as operational adjustments tend require less capital and offer a greater ease of implementation. In some cases, TxDOT may use its leverage as a state executive agency to facilitate the implementation of legal or governance regulation changes to increase emergency response and preparedness among port environment stakeholders.

10.2 Recommendations

The proposed improvement recommendations as determined from the project findings are presented in three priority categories: (1) Recommendations for TxDOT to Act on, which are recommendations intended for implementation by the Texas Department of Transportation; (2) Recommendations for Texas Legislature to Act on, which are recommendations that require legal or lawmaking action; and (3) Recommendations for Port Authority and Tenant to Act on, which are recommendations related to actions that are to be completed by port authorities and their tenants. A final category describes general recommendations, which are related to port hurricane emergency management and primarily apply to port authorities. Table 10.1 summarizes the recommendations and intended responsible stakeholders. The remaining sections describe the recommendations in detail, organized by category.

Table 10.1 Summary matrix of recommendations

	Recommendation Number	TxDOT	Texas Legislature	Port Authorities	Port Tenants	Other Stakeholders
Prioritized Recommendations	1	✓		✓		
	2	✓				
	3	✓		✓		✓
	4	✓		✓		✓
	5	✓		✓		
	6	✓				
	7	✓				
	8		✓			
	9		✓			
	10			✓		
	11			✓		
	12			✓		✓
	13			✓		
General Recommendations	14	✓		✓	✓	✓
	15	✓		✓		
	16	✓		✓		
	17			✓	✓	
	18			✓		
	19			✓		
	20			✓		
	21			✓		
	22			✓		
	23			✓		
	24			✓		
	25			✓		
	26			✓		
	27			✓	✓	
	28			✓		
	29			✓	✓	
	30			✓		
	31			✓		
	32			✓		
	33			✓	✓	✓

10.2.1 Recommendations for TxDOT

1. TxDOT should encourage port authorities to use resilience assessment tools, such as the Port Resilience Index (PRI) or the UT/CTR developed PortRESECO tool, to assess the resilience of their facilities and operations to extreme weather events or other disruptions. TxDOT should facilitate the use of these assessment tools on a recurring basis to grade the resilience of port facilities and measure the expected resilience improvements of potential improvements. With support from the Texas legislature, additional funding for port resilience enhancement could be provided for projects with the greatest expected increases in resilience scores.
2. TxDOT should consider implementing the methodology UT/CTR developed for network-level resilience assessment in Chapter 9 of this project. The network-level topological resilience assessment has a broad impact on the Texas economy and its impact is felt across highway, railway, and port systems. The complex interdependencies between these systems should be examined in a more complete manner, providing decision makers at various levels in Texas with reliable information on its transportation resilience, and in turn business resilience, in order to keep Texas' economic competitiveness.
3. TxDOT should encourage port authorities to improve communications with trucking companies and individual truckers (owner-operators) by developing a port emergency email or cell phone notification system. Truckers and other individuals desiring these notifications will register for the emergency system notifications through an online registration system on the port website. This recommendation requires collaboration between TxDOT, port authorities, and other stakeholders such as trucking companies.
4. Notifications should be sent to truckers and other interested parties not less than:
    - 72 hours before a hurricane makes landfall
    - At least 24 hours in advance of the date and time that the port will close truck terminal entry gates due to a hurricane or other emergency
    - At least 24 hours advance notification of when the port will reopen truck terminal gates. These notifications should contain specific information about restrictions or other operational conditions truckers should consider.

    This recommendation may require collaboration between TxDOT, port authorities, and other stakeholders such as trucking companies.
5. TxDOT Travel Information Centers (TICs) should maintain multiple, up to date contact information for port authorities or information hot lines that truckers can call to get information about the status of port terminal gates.
6. TxDOT should coordinate with the port(s) and monitor the port emergency notification system information.
7. As agreed with the port authority, TxDOT should explore the possibility of displaying port emergency notifications on ITS signs along all freight routes leading to affected ports as one of the emergency message types. To ensure timely notification to truckers who might not be aware of or have access to direct notifications from the port, the TxDOT notifications should

be placed on ITS signs along freight routes from the nearest sign to the state border to ITS signs in the affected port cities.

10.2.2 Recommendations for Texas Legislature

8. The Texas legislature should designate the larger port authorities as agencies responsible for emergency management in Texas Government Code Chapter 418. This would allow for these ports to take an active role in natural disaster response and recovery and enable the port authorities to access additional funds for preparation and response activities.
9. The Texas legislature should consider appropriating funds to be disbursed to Texas port authorities for the purpose of investing in resilience projects to enhance the response to port disruptions and mitigate the economic and social impacts that result from port disruptions.

10.2.3 Recommendations for Port Authorities and Tenants

10. Ports should consider climate change and extreme weather events in the planning, design, and construction of new port facilities. Long term impacts should be forecast to ensure that any new construction is adequate for sustained long-term use.
11. Port authorities should prioritize the preservation of life following a storm event by first conducting window assessments to gauge safety conditions, followed by an initial damage assessment of port facilities and finally formal damage assessment as per FEMA regulations. Window assessments refer to the practice of visually inspecting conditions from the safety of a building or vehicle to ensure that conditions are safe for employees to return to affected areas. Port authorities should communicate with port tenants to ensure that expectations regarding the return to impacted areas are understood.
12. Port authorities should establish means to communicate with the U.S. Army Corps of Engineers (USACE) to discuss navigable water channel dredging operations and priority and establish a means to communicate with the U.S. Coast Guard (USCG) to discuss aids to navigation (AtoN) repairs for the rapid restoration of unrestricted vessel operations.
13. Port authorities should not only utilize data from past disruptive weather events to identify risks for both urgent hazards (e.g., hurricanes, fires) and long-term hazards (e.g., sea level rise, seafloor shoaling), but also consider "worst-case" scenarios that have not occurred to assess the port's preparedness for these extreme cases.

10.2.4 General Recommendations

In addition to the previously listed TxDOT, Texas legislature, and port authority/tenant recommendations, a number of general port-hurricane resilience recommendations are provided:

14. Low-lying port roads, train tracks and other port infrastructure components should be studied to determine if raising the elevation of these assets is feasible and cost effective for long-term

capital project planning. This recommendation may require collaboration between TxDOT, port authorities, port tenants, and other port stakeholders.

15. TxDOT and port authorities should seek to increase the robustness of electric and utility infrastructure in coastal environments through actions such as burying power lines and increasing transmission tower structural capacity.
16. Port authorities and coastal TxDOT offices should invest in backup computer storage services, (cloud-based or physical storage devices such as hard drives) to maintain critical information and data during and after disruptive events if they have not done so yet.
17. Port authorities and port tenants should invest in back up power supply systems, such as generators, with the ability to provide electricity to critical facilities for a minimum of 48 hours of self-sufficiency during power loss if they have not already done so.
18. Port authorities should invest in backup communication systems that will remain operational when telephone lines, electricity, and cell towers are out of service in the immediate aftermath of an extreme weather disruption.
19. Port authorities should assess cranes use to load / unload container ships for structural capacity against wind loading to increase understanding of the susceptibility of individual components to hurricane-force wind speeds.
20. Port authorities should identify land suitable for future expansion by considering locations that are less exposed to storm surge, flooding, and the impending effects of climate change.
21. Port authorities should determine a location for a backup emergency operations center (EOC) for use in coordinating disaster response and recovery actions during and after extreme weather events.
22. Port authorities should develop prioritization lists identifying critical facilities and infrastructure components to be restored for the port to resume normal operations as rapidly as possible after encountering disruptions.
23. Port authorities should have a plan to implement temporary housing needs of the port staff, other first responders, or other recovery assistance staff using temporary housing structures or emergency trailers.
24. Port authorities should coordinate to “embed” employees with other responses agencies such as the USCG or local first responders during times of disaster for improved inter-agency communication.
25. Port authorities should conduct emergency response exercises for hurricane hazards with port management staff and essential personnel to prepare for future extreme weather incidents and conduct these training exercises frequently.
26. Port staff should be trained to properly document all damaged infrastructure via photographs and written reports, in accordance with FEMA or other agency guidelines.
27. Port authorities and port tenants should maintain emergency food and drinking water supplies for employees remaining on site during extreme weather instances. This recommendation may require collaboration with port tenants.

28. Port authorities should have contracts or other means for evaluating buildings that have sustained water damage to ensure that molds and mildew, which are dangerous to humans, are not present after a flooding event.
29. Port tenants should have agreements to share resources and supplies with each other or the port authority during the recovery process for a disaster event.
30. Port authorities should understand disaster assistance programs (i.e., FEMA Public Assistance, FEMA Hazard Mitigation Grant Program) and how to ensure compliance with all requirements to secure necessary funding needed for recovery and reconstruction post-disaster.
31. Port authorities should implement hurricane preparedness plans following the USCG hurricane condition levels (or similar), with conditions assigned by time to hurricane landfall and specific action items assigned at each condition. This plan should be readily available to port employees and other stakeholders.
32. Port authorities should record and implement lessons learned from past disasters and frequently update preparedness manuals with new information collected from lessons learned.
33. Port authorities should conduct regular stakeholder meetings to review the port's hurricane preparedness policies with local officials, customers, public agencies, and tenants.

10.3 Summary

This chapter provides the specific recommendations that the research team proposes for implementation to increase the resilience of the ports and port system to extreme weather events. A total of 33 recommendations are provided, and the recommendations are divided into two main groups: priority recommendations and general recommendations. The priority recommendations are divided into three groups based on the intended stakeholders: (1) TxDOT, (2) Texas legislature and (3) port authority and port tenants. The general recommendations are provided for port authorities as general measures for hurricane preparedness and response. The recommendations are summarized in the matrix table, where the category and intended stakeholders are provided for each recommendation.

References

Alenazi, M. J. F., & Sterbenz, J. P. G. (2015). Comprehensive Comparison and Accuracy of Graph Metrics in Predicting Network Resilience. *2015 11th International Conference on the Design of Reliable Communication Networks, DRCN 2015*, 157–164. https://doi.org/10.1109/DRCN.2015.7149007

Arnold, B., Cammarata, C., Farmer, D., Kowalewski, K., Ladipo, F., Lasky, M., & Moore, D. (2006). *The Economic Costs of Disruptions in Container Shipments*. www.cbo.gov

ASLRRA. (2019). *Railroad Definitions*. American Short Line and Regional Railroad Association. https://www.aslrra.org/web/About/Short_Line_Definitions.aspx

Australian Council of Social Service. (2015). *Emergency Management: Prevention, Preparedness, Response & Recovery*. Resilient Community Organisations. https://resilience.acoss.org.au/the-six-steps/leading-resilience/emergency-management-prevention-preparedness-response-recovery

Averett, A., Agrawal, S., Lee, R., Borchard, B. L., Essig, H., Harker, H., Lachance, C., Miller, G., Morgan, S., Odeyemi, E., Shi, Y., Shi, Z., Smith, A., Rivero, R., & Mcclenning, L. (2014). *Hazard and Resilience Plan for the Coast of Georgia*.

Bagchi, A., Sprintson, A., & Singh, C. (2009). Modeling the impact of fire spread on the electrical distribution network of a virtual city. *41st North American Power Symposium, NAPS 2009*. https://doi.org/10.1109/NAPS.2009.5484082

Becker, A., & Caldwell, M. R. (2015). Stakeholder Perceptions of Seaport Resilience Strategies: A Case Study of Gulfport (Mississippi) and Providence (Rhode Island). *Coastal Management*, *43*(1), 1–34. https://www.tandfonline.com/doi/pdf/10.1080/08920753.2014.983422?casa_token=9z-rOtI4370AAAAA:5Dv1IpCru7nNRXF8gh7B0Grem8ib0BMCEVL-mm8HNrmo7W6TJSDQuiu0d9nCTbx_RlFYaIqL3QU8og

Benn, J. (2013). Railway Bridge Failure During Flooding in the UK and Ireland. *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, *166*(4), 163–170. https://doi.org/10.1680/feng.2013.166.4.163

Bešinović, N. (2020). Resilience in Railway Transport Systems: A Literature Review and Research Agenda. *Https://Doi.Org/10.1080/01441647.2020.1728419*, *40*(4), 457–478. https://doi.org/10.1080/01441647.2020.1728419

Bigger, J. E., Willingham, M. G., & Krimgold, F. (2009). Consequences of critical infrastructure interdependencies: lessons from the 2004 hurricane season in Florida. *International Journal of Critical Infrastructures*, *5*(3), 199–219.

Bradbury, J., Allen, M., & Dell, R. (2015). *Climate Change and Energy Infrastructure Exposure to Storm Surge and Sea-Level Rise Acknowledgements*.

Brancucci Martínez-Anido, C., Bolado, R., de Vries, L., Fulli, G., Vandenbergh, M., & Masera, M. (2012). European power grid reliability indicators, what do they really tell? *Electric Power Systems Research*, *90*, 79–84. https://doi.org/10.1016/J.EPSR.2012.04.007

Brooks, E. M. (1949). The Tornado Cyclone. *Weatherwise*, *2*(2), 32–33. https://doi.org/10.1080/00431672.1949.9930047

Brooks, H. E., Doswell III, C. A., & Kay, M. P. (2003). Climatological Estimates of Local Daily Tornado Probability for the United States. *Weather and Forecasting*, *18*, 626–640.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A Framework to

Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

Bureau of Transportation Statistics. (2017). *Port Performance Freight Statistics Program: Annual Report to Congress 2017*.

Chen, L., & Miller-Hooks, E. (2011). Resilience: An Indicator of Recovery Capability in Intermodal Freight Transport. *Https://Doi.Org/10.1287/Trsc.1110.0376*, *46*(1), 109–123. https://doi.org/10.1287/TRSC.1110.0376

Chhetri, P., Corcoran, J., Gekara, V., Maddox, C., & McEvoy, D. (2015). Seaport Resilience to Climate Change: Mapping Vulnerability to Sea-Level Rise. *Journal of Spatial Science*, *60*(1), 65–78. https://doi.org/10.1080/14498596.2014.943311

Choate, A., Dix, B., Kuna, J., Rodehorst, B., Snow, C., Beucler, B., Hyman, R., & Kafalenos, R. (2014). *The Gulf Coast Study, Phase 2: Assessing Transportation System Vulnerability to Climate Change: Synthesis of Lessons Learned and Methods Applied: Final Report, Task 6*.

CISA. (n.d.-a). *Critical Infrastructure Sectors*. Cybersecurity & Infrastructure Security Agency. Retrieved April 14, 2021, from https://www.cisa.gov/critical-infrastructure-sectors

CISA. (n.d.-b). *Critical Infrastructure Vulnerability Assessments* . Cybersecurity & Infrastructure Security Agency. Retrieved April 14, 2021, from https://www.cisa.gov/critical-infrastructure-vulnerability-assessments

City of Port Lavaca. (2019). *Comprehensive Annual Financial Report*. https://portlavaca.org/wp-content/uploads/2020/07/2019-CAFR.pdf

Concannon, P. R., Brooks, H. E., & Doswell III, C. A. (2000). Climatological Risk of Strong and Violent Tornadoes in the United States. *Second Conference on Environmental Applications*. https://www.nssl.noaa.gov/users/brooks/public_html/concannon/

Dhanak, M., Parr, S., Kaisar, E. I., Goulianou, P., Russell, H., & Kristiansson, F. (2021). Resilience Assessment Tool for Port Planning. *Https://Doi.Org/10.1177/2399808321997824*, *48*(5), 1126–1143. https://doi.org/10.1177/2399808321997824

Directorate for Science Technology and Innovation. (2019). *HS to ISIC to End-Use Conversion Key Spreedsheet*. OECD.

Dixon, R. W., & Moore, T. W. (2012). Tornado Vulnerability in Texas. *Weather, Climate, and Society*, *4*(1), 59–68. https://doi.org/10.1175/WCAS-D-11-00004.1

Doswell, C. A., Brooks, H. E., & Dotzek, N. (2009). On the Implementation of the Enhanced Fujita Scale in the USA. *Atmospheric Research*, *93*(1–3), 554–563. https://doi.org/10.1016/j.atmosres.2008.11.003

Du, J., Park, K., Dellapenna, T. M., & Clay, J. M. (2019). Dramatic hydrodynamic and sedimentary responses in Galveston Bay and adjacent inner shelf to Hurricane Harvey. *Science of the Total Environment*, *653*, 554–564. https://doi.org/10.1016/j.scitotenv.2018.10.403

Durage, S. W., Wirasinghe, S. C., & Ruwanpura, J. (2013). Comparison of the Canadian and US Tornado Detection and Warning Systems. *Natural Hazards*, *66*(1), 117–137. https://doi.org/10.1007/s11069-012-0168-7

Economics and Industry Data. (n.d.). American Trucking Associations. Retrieved November 26, 2021, from https://www.trucking.org/economics-and-industry-data

Elsner, J. B., Jagger, T. H., & Fricker, T. (2016). Statistical Models for Tornado Climatology: Long and Short-Term Views. *PLoS ONE*, *11*(11). https://doi.org/10.1371/journal.pone.0166895

Federal Highway Administration. (2019). *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study*. U.S. Department of Transportation.

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/gulf_coast_study/index.cfm
Federal Motor Carrier Safety Administration. (n.d.). *Safety Measurement System – Motor Carrier Census Information*. Census Database File Available in Text Format. Retrieved November 25, 2021, from https://ai.fmcsa.dot.gov/SMS/Tools/Downloads.aspx
Field, C. B., Barros, V., Stocker, T. F., Dahe, Q., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., & Midgley, P. M. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*.
Fog Delays Houston-area Ports for Seventh Day. (2019, March 13). *Argus Media*. https://www.argusmedia.com/en/news/1865543-fog-delays-houstonarea-ports-for-seventh-day
Frohlich, C. (2013). *Texas Earthquakes*. University of Texas Institute for Geophysics and Texas Division of Emergency Management. http://www-udc.ig.utexas.edu/external/TXEQ/
Fujita, T. T. (1971). *Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity*. https://archive.org/details/nasa_techdoc_19720008829/mode/2up
Ganin, A. A., Kitsak, M., Marchese, D., Keisler, J. M., Seager, T., & Linkov, I. (2017). Resilience and Efficiency in Transportation Networks. *Science Advances*, *3*(12). https://doi.org/10.1126/SCIADV.1701079/SUPPL_FILE/1701079_SM.PDF
Garvey, M. D., Carnovale, S., & Yeniyurt, S. (2015). An analytical framework for supply network risk propagation: A Bayesian network approach. *European Journal of Operational Research*, *243*(2), 618–627. https://doi.org/10.1016/J.EJOR.2014.10.034
Goff, J. A., Allison, M. A., & Gulick, S. P. S. (2010). Offshore transport of sediment during cyclonic storms: Hurricane Ike (2008), Texas Gulf Coast, USA. *Geology*, *38*(4), 351–354. https://doi.org/10.1130/G30632.1
Gultepe, I., Pearson, G., Milbrandt, J. A., Hansen, B., Platnick, S., Taylor, P., Gordon, M., Oakley, J. P., & Cober, S. G. (2009). The fog remote sensing and modeling field project. *Bulletin of the American Meteorological Society*, *90*(3), 341–359. https://doi.org/10.1175/2008BAMS2354.1
Henesey, L. E., Notteboom, T. E., & Davidsson, P. (2003). Agent-based Simulation of Stakeholders Relations: An Approach to Sustainable Port Terminal Management. *Proceedings of the International Association of Maritime Economists Annual Conference*, 99–126.
Henry, D., & Emmanuel Ramirez-Marquez, J. (2012). Generic Metrics and Quantitative Approaches for System Resilience as a Function of Time. *Reliability Engineering & System Safety*, *99*, 114–122. https://doi.org/10.1016/J.RESS.2011.09.002
Hossain, N. U. I., Nur, F., Jaradat, R., Hosseini, S., Marufuzzaman, M., Puryear, S. M., & Buchanan, R. K. (2019). Metrics for Assessing Overall Performance of Inland Waterway Ports: A Bayesian Network Based Approach. *Complexity*, *2019*. https://doi.org/10.1155/2019/3518705
Hsieh, C. H. (2014). Disaster Risk Assessment of Ports Based on the Perspective of Vulnerability. *Natural Hazards*, *74*(2), 851–864. https://doi.org/10.1007/s11069-014-1214-4
Hundreds killed, thousands injured in Texas City disaster of 1947. (2020, April 16). ABC13 Houston. https://abc13.com/disaster-fire-explosion-texas-city/1865491/
Ibrahim, M. W. (2018). Level of resilience measure for communication networks. *Journal of Information and Communication Technology*, *17*(1), 115–139. https://doi.org/10.32890/JICT2018.17.1.6
Institute for Water Resources. (2020). *Waterborne tonnage for principal U.S. ports and all 50 states and U.S. territories*. USACE Digital Library. https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/7447

Islam, T., Merrell, W., Seitz, W., & Harriss, R. (2009). Origin, Distribution, and Timing of Texas Hurricanes: 1851–2006. *Natural Hazards Review*, *10*(4), 136–144. https://doi.org/10.1061/(ASCE)1527-6988(2009)10:4(136)

Jelesnianski, C. P., Chen, J., & Shaffer, W. A. (1992). *SLOSH: Sea, Lake, and Overland Surges from Hurricanes - NOAA Technical Report NWS 48*. https://slosh.nws.noaa.gov/slosh/pubs/SLOSH_TR48.pdf

Jenelius, E., Petersen, T., & Mattsson, L. G. (2006). Importance and Exposure in Road Network Vulnerability Analysis. *Transportation Research Part A: Policy and Practice*, *40*(7), 537–560. https://doi.org/10.1016/j.tra.2005.11.003

Jenks, G. (1967). The Data Model Concept in Statistical Mapping. *International Yearbook of Cartography* , *7*, 186–190.

John, A., Yang, Z., Riahi, R., & Wang, J. (2016). A Risk Assessment Approach to Improve the Resilience of a Seaport System Using Bayesian Networks. *Ocean Engineering*, *111*, 136–147. https://doi.org/10.1016/J.OCEANENG.2015.10.048

Jung, J., Santos, J. R., & Haimes, Y. Y. (2009). International trade inoperability input-output model (IT-IIM): theory and application. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *29*(1), 137–154. https://doi.org/10.1111/J.1539-6924.2008.01126.X

Kafalenos, R. S., Leonard, K. J., Hunt, D. T., Hyman, R. C., Maynard, M. K., Fritsche, B., Henk, R. H., Seymour, E. J., Olson, L., Potter, J. R., & Savonis, M. J. (2012). What Are the Implications of Climate Change and Variability for Gulf Coast Transportation? In *Impacts of Climate ChangeTransportation and Infrastructure - A Gulf Coast Study*. U.S. Department of Transportation. https://www.researchgate.net/publication/237430346_40_What_Are_the_Implications_of_Climate_Change_and_Variability_for_Gulf_Coast_Transportation

Kano, C. H., Blos, M., Junqueira, F., Filho, D. S., & Miyagi, P. (2014). Modeling and Analysis of Global Supply Chain Disruption based on Petri Net. *ABCM Symposium Series in Mechatronics*.

Kantha, L. (2006). Time to replace the Saffir-Simpson Hurricane Scale? *Eos*, *87*(1), 3–6. https://doi.org/10.1029/2006eo010003

Keim, B. D., Muller, R. A., & Stone, G. W. (2007). Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricane Strikes from Texas to Maine. *Journal of Climate*, *20*(14), 3498–3509. https://doi.org/10.1175/JCLI4187.1

Kim, Y., & Ross, L. (2019). *Ports: An Industry Guide to Enhancing Resilience*.

Klein, B. (2021, May). *jkbren/matplotlib-multilayer-network: Small Template Code to Create a Multilayer Network using Matplotlib and NetworkX*. GitHub. https://github.com/jkbren/matplotlib-multilayer-network

Kong, D., Setunge, S., & Zhang, G. (2013). *Structural Resilience of Core Port Infrastructure in a Changing Climate*. https://www.researchgate.net/publication/282809637

Lam, J. S. L., & Su, S. (2015). Disruption Risks and Mitigation Strategies: An Analysis of Asian Ports. *Http://Dx.Doi.Org/10.1080/03088839.2015.1016560*, *42*(5), 415–435. https://doi.org/10.1080/03088839.2015.1016560

Lam, J. S. L., & Yip, T. L. (2012). Impact of Port Disruption on Supply Chains: A Petri Net Approach. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *7555 LNCS*, 72–85. https://doi.org/10.1007/978-3-642-33587-7_5

Landsea, C. W. (1999, October 21). *Why do Hurricanes Hit the East Coast of the U.S. but Never the West Coast?* Scientific American. https://www.scientificamerican.com/article/why-do-hurricanes-hit-the-east-coast-of-the-u-s-but-never-the-west-coast/

León-Mateos, F., Sartal, A., López-Manuel, L., & Quintás, M. A. (2021). Adapting Our Sea Ports to the Challenges of Climate Change: Development and Validation of a Port Resilience Index. *Marine Policy*, *130*, 104573. https://doi.org/10.1016/J.MARPOL.2021.104573

Lewis, B. M., Erera, A. L., & Chelsea C. White, I. (2006). Impact of Temporary Seaport Closures on Freight Supply Chain Costs: *Https://Doi.Org/10.1177/0361198106196300109*, *1963*(1), 64–70. https://doi.org/10.1177/0361198106196300109

Lindell, M. K., Prater, C. S., & Peacock, W. G. (2007). Organizational Communication and Decision Making for Hurricane Emergencies. *Natural Hazards Review*, *8*(3), 50–60. https://doi.org/10.1061/(ASCE)1527-6988(2007)8:3(50)

Lindsey, R. (2021, February 25). *Climate Change: Global Sea Level*. NOAA Climate.Gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

Littlejohn Mann & Associates. (2019). *Florida Seaports Resiliency Report*. http://scdn.flaports.org/wp-content/uploads/2019-09_FPC_LittleJohnMann_Resiliency_Report-v6-web.pdf

Liu, W., Li, X., Liu, T., & Liu, B. (2019). Approximating Betweenness Centrality to Identify Key Nodes in a Weighted Urban Complex Transportation Network. *Journal of Advanced Transportation*, *2019*. https://doi.org/10.1155/2019/9024745

Loh, H. S., & Thai, V. van. (2015). Cost Consequences of a Port-Related Supply Chain Disruption. *The Asian Journal of Shipping and Logistics*, *31*(3), 319–340. https://doi.org/10.1016/J.AJSL.2015.09.001

Maloney, M. C., & Preston, B. L. (2014). A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications. *Climate Risk Management*, *2*, 26–41. https://doi.org/10.1016/j.crm.2014.02.004

Martin Associates. (2019). *The Economic Impacts of the Texas Ports on the State of Texas, 2018*. www.texasports.org

McLeod, G. M., Allen, T. R., & Behr, J. G. (2019). Geospatial Risk Assessment of Marine Terminal Infrastructure to Storm Surge Inundation and Sea Level Rise. *Transportation Research Record*, *2672*(11), 19–29.

Milanovic, J. v., & Zhu, W. (2018). Modeling of Interconnected Critical Infrastructure Systems Using Complex Network Theory. *IEEE Transactions on Smart Grid*, *9*(5), 4637–4648. https://doi.org/10.1109/TSG.2017.2665646

Morris, L. L. (2017). *Ports Resilience Index: Participatory Methods to Assess Resilience*. https://digitalcommons.lsu.edu/gradschool_dissertations/4474

Morris, Lauren. L. (2016). Ports Resilience Index: Three Case Studies in the Gulf of Mexico. *Unpublished Manuscript*.

Moteff, J. (2005). *CRS Report for Congress - Risk Management and Critical Infrastructure Protection: Assessing, Integrating, and Managing Threats, Vulnerabilities and Consequences*.

Murphy, M., Han, Z., Jiang, N., Hazlett, D., Ahsan, A. S., Cooper, A., Baumanis, C., Zhang, Z., Machemehl, R., & Harrison, R. (2018). *Evaluating Safety and Economic Impacts of Texas Travel Information Centers*.

Nair, R., Avetisyan, H., & Miller-Hooks, E. (2010). Resilience Framework for Ports and Other Intermodal Components. *Https://Doi.Org/10.3141/2166-07*, *2166*, 54–65. https://doi.org/10.3141/2166-07

Narendran, K. (2001). Forest Fires: Origins and Ecological Paradoxes. *Resonance*, *6*(11), 34–41. https://doi.org/10.1007/bf02868242
National Hurricane Center. (n.d.-a). *Saffir-Simpson Hurricane Wind Scale*. NOAA. Retrieved March 26, 2020, from https://www.nhc.noaa.gov/aboutsshws.php
National Hurricane Center. (n.d.-b). *Tropical Cyclone Climatology*. NOAA. Retrieved March 26, 2020, from https://www.nhc.noaa.gov/climo/
National Oceanic and Atmospheric Administration. (2021, February 26). *What is the Difference Between a Hurricane Watch and a Warning?* Ocean Facts.
Needham, H. F. (2014). *A Data-Driven Storm Surge Analysis for the U.S. Gulf Coast*. https://digitalcommons.lsu.edu/gradschool_dissertations/3250
Needham, H. F., & Keim, B. D. (2012). A Storm Surge Database for the US Gulf Coast. *International Journal of Climatology*, *32*(14), 2108–2123. https://doi.org/10.1002/joc.2425
Office of the Press Secretary. (2013, February 12). *Presidential Policy Directive - Critical Infrastructure Security and Resilience*. The White House. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil
Omer, M., Mostashari, A., Nilchiani, R., & Mansouri, M. (2012). A Framework for Assessing Resiliency of Maritime Transportation Systems. *Http://Dx.Doi.Org/10.1080/03088839.2012.689878*, *39*(7), 685–703. https://doi.org/10.1080/03088839.2012.689878
Orange County Navigation and Port District. (2020). *Annual Financial Report*. https://www.portoforange.com/financial-reports?task=download.send&id=37&catid=8&m=0
Padgett, J. E., Spiller, A., & Arnold, C. (2012). Statistical analysis of coastal bridge vulnerability based on empirical evidence from Hurricane Katrina. *Structure and Infrastructure Engineering*, *8*(6), 595–605. https://doi.org/10.1080/15732470902855343
Pant, R., Barker, K., Ramirez-Marquez, J. E., & Rocco, C. M. (2014). Stochastic measures of resilience and their application to container terminals. *Computers & Industrial Engineering*, *70*(1), 183–194. https://doi.org/10.1016/J.CIE.2014.01.017
Peduzzi, P., Chatenoux, B., Dao, H., de Bono, A., Herold, C., Kossin, J., Mouton, F., & Nordbeck, O. (2012). Global Trends in Tropical Cyclone Risk. *Nature Climate Change*, *2*(4), 289–294. https://doi.org/10.1038/nclimate1410
Phillips, E. E., & Calfas, J. (2016, August 2016). California Reopens Some Commercial Routes as Wildfire Rages. *The Wall Street Journal*. https://www.wsj.com/articles/california-reopens-some-commercial-routes-as-wildfire-rages-1471558542
Port Freeport. (2020). *Comprehensive Annual Financial Report*. https://f.hubspotusercontent20.net/hubfs/1537475/About/Financial%20Information/2021/Port%20Freeport%20CAFR%209-30-20.pdf
Port of Beaumont. (2022). *Financial Report 2020*. https://www.portofbeaumont.com/download/financial-report-2020/
Port of Brownsville. (2019). *Comprehensive Annual Financial Report*. https://www.portofbrownsville.com/wp-content/uploads/2020/07/BND-CAFR-2019.pdf
Port of Corpus Christi Authority. (2020). *Annual Comprehensive Financial Report*. https://www.portofcc.com/images/pccpdfs/annual/2020_ACFR_Final.pdf
Port of Galveston. (2020). *Annual Comprehensive Financial Report*. https://www.portofgalveston.com/DocumentCenter/View/2876/2020-GW-ACFR
Port of Houston Authority. (2020). *Comprehensive Annual Financial Report*. https://porthouston.com/wp-content/uploads/PHA-CAFR-2020.pdf

Port of Long Beach, & AECOM. (2017). *Port of Long Beach Climate Change Adaptation and Coastal Resiliency Plan (CRP)*. https://www.cakex.org/documents/port-long-beach-climate-change-adaptation-and-coastal-resiliency-plan-crp

Prozzi, J. (2016). *Potential Metrics for Designating and Monitoring Oversize/Overweight Corridors Final report*.

Rice, J., & Trepte, K. (2012). *The MIT CTL Port Resilience Survey Report*.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems Magazine*, *21*(6), 11–25. https://doi.org/10.1109/37.969131

Rohrer, J. P., Jabbar, A., & Sterbenz, J. P. G. (2009). Path Diversification: A Multipath Resilience Mechanism. *Proceedings of the 2009 7th International Workshop on the Design of Reliable Communication Networks, DRCN 2009*, 343–351. https://doi.org/10.1109/DRCN.2009.5339988

Rohrer, J. P., & Sterbenz, J. P. G. (2011). Predicting Topology Survivability Using Path Diversity. *2011 3rd International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*. https://ieeexplore.ieee.org/abstract/document/6078849

Rose, A., & Wei, D. (2013). Estimating the Economic Consequences of a Port Shutdown: The Special Role of Resilience. *Economic Systems Research*, *25*(2), 212–232. https://doi.org/10.1080/09535314.2012.731379

Rosoff, H., & von Winterfeldt, D. (2007). A risk and economic analysis of dirty bomb attacks on the ports of Los Angeles and Long Beach. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *27*(3), 533–546. https://doi.org/10.1111/J.1539-6924.2007.00908.X

Roth, D. (2010). *Texas Hurricane History*.

Schiff, A. J., & Holzer, T. L. (1997). *The Loma Prieta, California, Earthquake of October 17, 1989-Lifelines* .

Schneider, P. J., & Schauer, B. A. (2006). HAZUS—Its Development and Its Future. *Natural Hazards Review*, *7*(2), 40–44. https://doi.org/10.1061/(asce)1527-6988(2006)7:2(40)

Sebastian, A., Proft, J., Dietrich, J. C., Du, W., Bedient, P. B., & Dawson, C. N. (2014). Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC model. *Coastal Engineering*, *88*, 171–181. https://doi.org/10.1016/j.coastaleng.2014.03.002

Shafieezadeh, A., & Ivey Burden, L. (2014). Scenario-Based Resilience Assessment Framework for Critical Infrastructure Systems: Case Study for Seismic Resilience of Seaports. *Reliability Engineering and System Safety*, *132*, 207–219. https://doi.org/10.1016/j.ress.2014.07.021

Shepard, C. C., Agostini, V. N., Gilmer, B., Allen, T., Stone, J., Brooks, W., & Beck, M. W. (2012). Assessing future risk: Quantifying the effects of sea level rise on storm surge risk for the southern shores of Long Island, New York. *Natural Hazards*, *60*(2), 727–745. https://doi.org/10.1007/s11069-011-0046-8

Sietfhoff, B. ten, Grose, T., Sudhalkar, A., Bonham-Carter, C., & Smith, J. (2017). *Post-Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut*. https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/hurricane_sandy/index.cfm

Snow, J. T., & Wyatt, A. (1997). Back to basics: The Tornado, Nature's Most Violent Wind: Part 1—World-Wide Occurrence and Categorisation. *Weather*, *52*(10), 298–304. https://doi.org/10.1002/j.1477-8696.1997.tb05525.x

Soberanis, D., & Elizabeth, I. (2010). An extended Bayesian network approach for analyzing supply chain disruptions. In *undefined*. https://doi.org/10.17077/ETD.E4HW0B69

Southworth, F., Hayes, J., McLeod, S., & Strauss-Wieder, A. (2014). Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains. *Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains*. https://doi.org/10.17226/23428

State of the Climate: Tropical Cyclones for Annual 2017. (2018). National Centers for Environmental Information. https://www.ncdc.noaa.gov/sotc/tropical-cyclones/201713/

Stensrud, D. J., Ming, X., Wicker, L. J., Kelleher, K. E., Foster, M. P., Schaefer, J. T., Schneider, R. S., Benjamin, S. G., Weygandt, S. S., Ferree, J. T., & Tuell, J. P. (2009). Convective-Scale Warn-on-Forecast System: A Vision for 2020. *Bulletin of the American Meteorological Society*, *90*(10), 1487–1499. https://doi.org/10.1175/2009BAMS2795.1

Sterbenz, J. P. G., Hutchison, D., Çetinkaya, E. K., Jabbar, A., Rohrer, J. P., Schöller, M., & Smith, P. (2014). Redundancy, Diversity, and Connectivity to Achieve Multilevel Network Resilience, Survivability, and Disruption Tolerance Invited Paper. *Telecommunication Systems 2014 56:1*, *56*(1), 17–31. https://doi.org/10.1007/S11235-013-9816-9

Storm Surge. (2020, March 25). U.S. Climate Resilience Toolkit. https://toolkit.climate.gov/topics/coastal/storm-surge

Sweet, W. v., Dusek, G., Obeysekera, J., & Marra, J. J. (2018). *NOAA Technical Report NOS CO-OPS 086: Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold*.

Sweet, W. v., Kopp, R. E., Weaver, C. P., Obeysekera, J., Horton, R. M., Thieler, E. R., & Zervas, C. (2017). *NOAA Technical Report NOS CO-OPS 083: Global and Regional Sea Level Rise Scenarios for the United States*. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

Tagg, A., Raïkkönen, M., Mäki, K., & Collell, M. R. (2016). Impact of Extreme Weather on Critical Infrastructure: The EU-INTACT Risk Framework. *E3S Web of Conferences*, *7*. https://doi.org/10.1051/e3sconf/20160707007

Tan, X. M., Lam, J. S. L., & Zhang, Y. (2015). Economic Impact of Port Disruptions on Industry Clusters: A Case Study of Shenzhen. *ICTIS 2015 - 3rd International Conference on Transportation Information and Safety, Proceedings*, 617–622. https://doi.org/10.1109/ICTIS.2015.7232069

Tannehill, I. R. (1956). *The Hurricane* (94th–956th ed., Vol. 30). U.S. Department of Commerce, Weather Bureau. https://books.google.com/books/about/The_Hurricane.html?id=7CtyxwEACAAJ&hl=en&output=html_text

Texas Department of Transportation. (2016). *2016 Texas Rail Plan Update - Chapter 2: Texas' Existing Rail System*. https://ftp.dot.state.tx.us/pub/txdot-info/rail/2016-rail-plan/chapter-2.pdf

Texas Department of Transportation. (2020). *Port Connectivity Report: 2020-2021 Texas Port Mission Plan*. moz-extension://66649f0f-6a49-4810-8cba-b2f75d2f8438/enhanced-reader.html?openApp&pdf=https%3A%2F%2Fftp.dot.state.tx.us%2Fpub%2Ftxdot-info%2Ftpp%2Fgiww%2F2020-21-connectivity-report.pdf

Texas Department of Transportation. (2021). *Texas Freight Mobility Plan – Texas Trucking Quick Facts*.

The Port Authority of NY & NJ. (2018). *Engineering Department Manual: Climate Resilience Design Guidelines (v1.2)*. https://doi.org/10.1111/nyas.2015.1336.issue-1/issuetoc

Theoharidou, M., Kotzanikolaou, P., & Gritza-Lis, D. (2009). Risk-Based Criticality Analysis. *IFIP Advances in Information and Communication Technology*, *311*, 35–49. https://doi.org/10.1007/978-3-642-04798-5_3

Toal, M., Bogel-Burroughs, N., & Fernandez, M. (2019, November 27). Thousands Evacuated in Texas After Explosion at Port Neches Chemical Plant. *The New York Times*. https://www.nytimes.com/2019/11/27/us/texas-explosion-port-neches-tpc.html

Touzinsky, K. F., & Rosati, J. D. (2018). *USACE-ERDC Coastal System Resilience Research*. https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/31353/1/ERDC-CHL SR-18-4.pdf

Touzinsky, K. F., Scully, B. M., Asce, M., Mitchell, K. N., & Kress, M. M. (2018). Using Empirical Data to Quantify Port Resilience: Hurricane Matthew and the Southeastern Seaboard. *Article in Journal of Waterway, Port, Coastal and Ocean Engineering*. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000446

Truck News. (2017, August 17). *Hurricane Harvey to disrupt nearly 10% of U.S. trucking*. https://www.trucknews.com/transportation/hurricane-harvey-disrupt-nearly-10-u-s-trucking/1003080506/

Tu, Y., Yang, C., & Chen, X. (2013). Road Network Topology Vulnerability Analysis and Application. *Proceedings of the Institution of Civil Engineers: Transport*, *166*(2), 95–104. https://doi.org/10.1680/tran.10.00007

U.S. Census Bureau. (n.d.). *USA Trade Online*. Retrieved March 21, 2021, from https://usatrade.census.gov/

U.S. National Park Service. (2019, May 30). *Galveston Hurricane of 1900*. Series: Coastal Geomorphology—Storms of Record. https://www.nps.gov/articles/galveston-hurricane-of-1900.htm

Viljoen, N. M., & Joubert, J. W. (2018). *The Road most Travelled: The Impact of Urban Road Infrastructure on Supply Chain Network Vulnerability*. *18*, 85–113. https://doi.org/10.1007/s11067-017-9370-1

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., & Storlazzi, C. D. (2017). Doubling of Coastal Flooding Frequency within Decades due to Sea-Level Rise. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-017-01362-7

Wei, D., Chen, Z., & Rose, A. (2016). *Development and Application of an Economic Framework to Evaluate Resilience in Recovering from Major Port Disruptions*.

Weisberg, R. H., & Zheng, L. (2006). Hurricane storm surge simulations for Tampa Bay. *Estuaries and Coasts*, *29*(6), 899–913. https://doi.org/10.1007/BF02798649

Woodruff, J. D., Irish, J. L., & Camargo, S. J. (2013). Coastal Flooding by Tropical Cyclones and Sea-Level Rise. In *Nature* (Vol. 504, Issue 7478, pp. 44–52). Nature Publishing Group. https://doi.org/10.1038/nature12855

Yi, S., Sun, W., Heki, K., & Qian, A. (2015). An Increase in the Rate of Global Mean Sea Level Rise Since 2010. *Geophysical Research Letters*, *42*(10), 3998–4006. https://doi.org/10.1002/2015GL063902

Yuen, C. L. A., Zhang, A., & Cheung, W. (2012). Port Competitiveness from the Users' Perspective: An Analysis of Major Container Ports in China and its Neighboring Countries. *Research in Transportation Economics*, *35*(1), 34–40. https://doi.org/10.1016/J.RETREC.2011.11.005

Zhang, L., Du, H., Zhao, Y., de Maeyer, P., Dessein, B., & Zhang, X. (2019). Drawing Topological Properties from a Multi-Layered Network: The case of an Air Transport Network in "the Belt and Road" Region. *Habitat International*, *93*, 102044. https://doi.org/10.1016/J.HABITATINT.2019.102044

Zhang, X., Miller-Hooks, E., & Denny, K. (2015). Assessing the Role of Network Topology in Transportation Network Resilience. *Journal of Transport Geography*, *46*, 35–45. https://doi.org/10.1016/J.JTRANGEO.2015.05.006

Zhang, Y., & Lam, J. S. L. (2015). Estimating the Economic Losses of Port Disruption due to Extreme Wind Events. *Ocean & Coastal Management*, *116*, 300–310. https://doi.org/10.1016/J.OCECOAMAN.2015.08.009

Zhang, Y., & Lam, J. S. L. (2016). Estimating Economic Losses of Industry Clusters due to Port Disruptions. *Transportation Research Part A: Policy and Practice*, *91*, 17–33. https://doi.org/10.1016/J.TRA.2016.05.017

Appendix A. Texas Port Authority Workshop Presentation Material

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

0-7055- Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events

Port Authority Workshop

Microsoft Teams Virtual Meeting

November 4, 2020

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Agenda

1. Self-Introductions (1:00 – 1:10 pm)
2. Project background (1:10 – 1:45pm)
3. Session I: Moderated discussion (1:45 pm – 2:45 pm)
   1. Topic A: Prevention and Preparedness4.

Break (2:45 - 2:50 pm) - 5 mins

5. Session II: Moderated discussion (2:50 pm – 3:50 pm)
   1. Topic B: Response and Restoration
   2. Topic C: Recovery and Adaptation
6. Questions and comments (if needed) (3:50 - 4:00 pm)

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

1. Self-Introduction

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Project Management and Advisors (TxDOT)

- Project Manager:
  - Joanne Steele, RTI
- Project Advisors:
  - Emily Shelton, Maritime Program Coordinator, MRD
  - Sherry Pifer, Branch Manager, Freight Planning Section

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Research Team (UT Austin/CTR)

- Research Supervisor:
  - Zhanmin Zhang, Professor
- Researchers:
  - Mike Murphy, Senior Research Engineer
  - Lisa Loftus-Otway, Senior Scientist Associate
  - Zhe Han, Research Associate
  - Srijith Balakrishnan, Postdoctoral Fellow
  - Kyle Bathgate, Graduate Research Assistant

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Participants (Port Authorities)

- Port of Brownsville: **Eduardo Campirano, Donna Eymard**
- Port of Corpus Christi: **Leslie Ruta, Danielle Hale**
- Port of Freeport: **Chris Hogan, Stephanie Cribbs**
- Port of Harlingen: **Walker Smith**
- Port of Houston: **Bruce Mann**
- Port of Orange: **Lorrie Taylor**
- Port of Port Isabel: **Steve Bearden**

COLLABORATE. INNOVATE. EDUCATE.

2. Project Background

COLLABORATE. INNOVATE. EDUCATE.

Project Summary

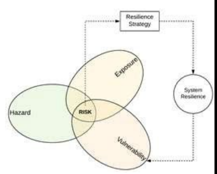
- The coastal regions of Texas are exposed to extreme weather events frequently.
- Hurricanes and flooding-related events cause significant physical, operational and economic costs to Texas ports.
- This study will analyze the exposure and vulnerabilities of Texasports to extreme weather events and recommend measures to improve the current resilience capabilities.

Flooding due to Hurricane Harvey in Houston in 2017 (Source: Associated Press)

COLLABORATE. INNOVATE. EDUCATE.

Research Objectives

- Systematic investigation of the resilience of the Texas Port System by assessing network-level and port-level exposure,risks, vulnerabilities, and resilience capacity
- The specific objectives are:
  - Identify and characterize potential extreme weather events
  - Identify the network- and port-level vulnerabilities of Texas ports and supporting infrastructure
  - Quantify the physical and economic risks posed by extreme events to Texas ports.
  - Develop metrics and evaluate the resilience of Texas ports
  - Provide recommendations for improving Texas port system resilience

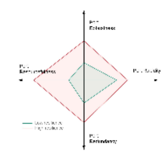


Relationship between hazard, exposure, vulnerability, risk and resilience.

COLLABORATE. INNOVATE. EDUCATE.

Expected Outcomes

- Online survey will be sent post-workshop to collect quantitative data
- A resilience metric will be developed to 'score' each port based on the vulnerability and risk factors, as determined from workshops/survey
- Identification of port vulnerabilities and resilience capabilities will enable ports to make more informed decisions on future planning and expenditures regarding extremeweather impacts

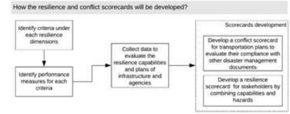


Potential structure of the port resilience metric

How the study plan to collect data regarding resilience dimensions?

Data collected from	Present Resiliece				Future Resilience
	Robustness	Redundancy	Resourcefulness	Rapidity	Adaptiveness
Vulnerability analysis of physical infrastructure	✓	✓			
Survey of resilience stakeholders	✓	✓	✓	✓	✓

How the resilience and conflict scorecards will be developed?

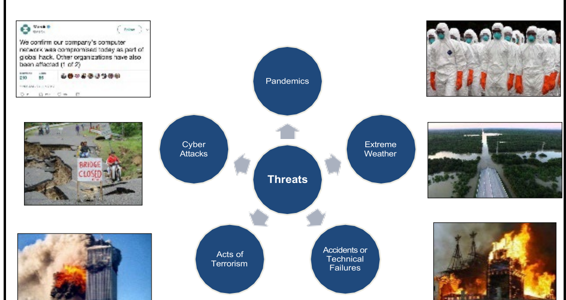


COLLABORATE. INNOVATE. EDUCATE.

3. Resilience Concepts

COLLABORATE. INNOVATE. EDUCATE.

Hazards



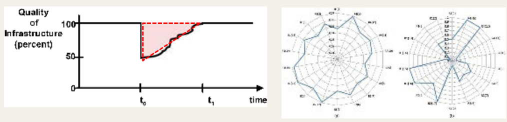
Source: Strategic National Risk Assessment

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

What is Resilience?

- **System Resilience** is the ability of a system to
  - reduce the chances of a shock
  - absorb such a shock if it occurs (abrupt reduction of performance)
  - recover quickly after a shock (re-establish normal performance)



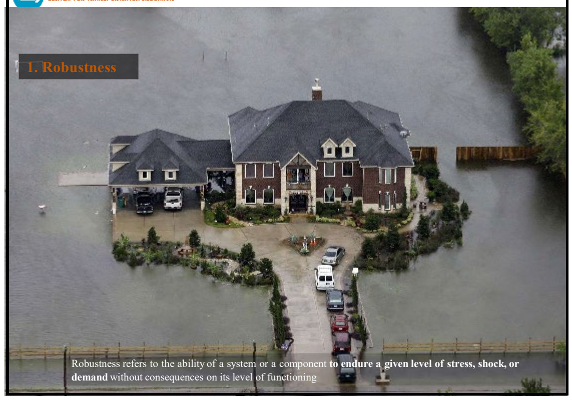
Bruneau et al. (2003) Karamouz and Zahmathkesh (2017)

- Four dimensions (characteristics) of resilience to mathematically quantify the resilience capabilities of an infrastructure system (4R's)
  - Robustness, Redundancy, Resourcefulness, Rapidity

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

1. Robustness

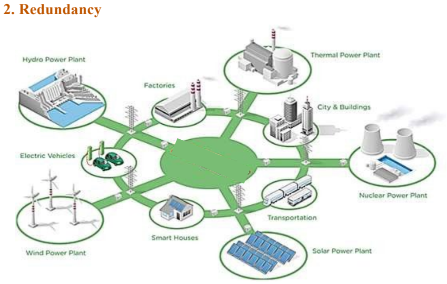


Robustness refers to the ability of a system or a component **to endure a given level of stress, shock, or demand** without consequences on its level of functioning

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

2. Redundancy

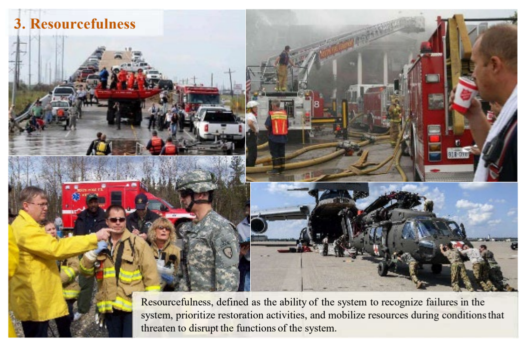


Redundancy is the ability of the system to satisfy its functional requirements and achieve stated goals by substituting its elements of the system itself in the event of disruption, degradation of loss of functionality.

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

3. Resourcefulness



Resourcefulness, defined as the ability of the system to recognize failures in the system, prioritize restoration activities, and mobilize resources during conditions that threaten to disrupt the functions of the system.

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

4. Rapidity

Rapidity is the capacity of the system to recognize problems and mobilize resources to contain and avoid further losses due to an external stress in a timely manner. Rapidity depends on a number of factors including **availability of resources**, **mobilize funds** and**timely decision making** and **coordination**

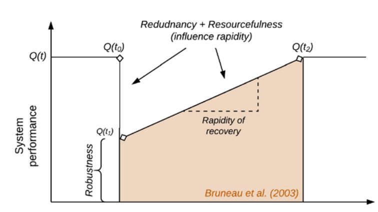
It took just six days for Japan to repair this stretch ofroad after March 2011 earthquake. Source: Daily Mail/AP

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Resilience Characteristics and Quantification

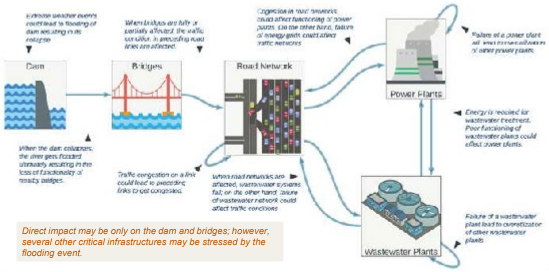
- The 4R's framework can be used for quantifying resilience of an infrastructure system



COLLABORATE. INNOVATE. EDUCATE.

Need for Considering Interdependencies

- Only a proper risk evaluation considering all infrastructure (inter)dependencies would reveal the vulnerabilities in the network.

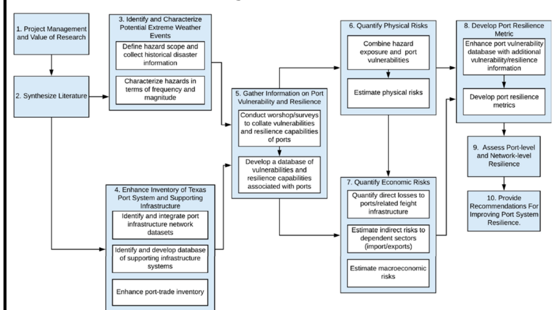


Port Resilience: Priority Areas

Ports	Supporting Infrastructure	Businesses/Shipping
How can the ports be better prepared to withstand high winds and floods?	How can the supporting infrastructure be strengthened to minimize operational disruptions due to floods and winds?	How do the businesses ensure that there are minimum damages to commodities and equipment due to floods and winds?
Do the ports have ability to substitute any of its functions or components in the event of a failure?	Do the infrastructure has adequate system redundancies to reduce the likelihood of disruption to services to ports?	Do the businesses have contingency plans such as inventory management and redundant supply chains in place?
Are there adequate access or availability of resources to ports? What are the bottlenecks?	Are there adequate access or availability of resources for response and restoration? What are the bottlenecks?	What do they do whn supply chains are broken?
How can we minimize the delays and remove bottlenecks so that restoration and recovery are faster?	How can we minimize the delays and remove bottlenecks so that restoration and recovery are faster?	What are the steps taken to improve the pace of restoring supply chains?

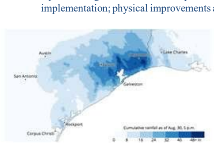
4. What we have done so far…

Overview of Project Work Plan



Findings from previous resilience studies

- Comprehensive literature review of data sets, assessment methods, and best practices:
  - Extreme weather events
    - Hurricanes, flooding, tornadoes, fires, earthquakes, fog
  - Port vulnerabilities, physical and economic risks
    - Physical, operational, economic
  - Existing resilience metrics for intermodal seaport facilities
    - Academic studies, Gulf of Mexico Alliance PRI
  - Port resilience enhancement best-practices
    - Operational/governance methods preferred due to cost-effectiveness and relative ease of implementation; physical improvements also viable in some instances



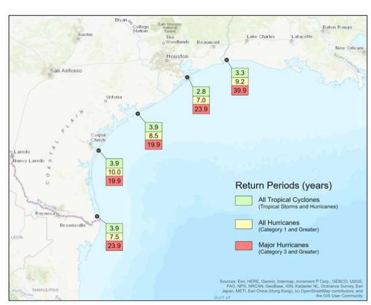
Cumulative Rainfall during Harvey (Source: Murphy, Dartmouth Flood Observatory)

		Frequency or Likelihood				
		Rare	Unlikely	Possible	Likely	Certain
Severity	Catastrophic	M	H	E	E	E
	Major	M	H	H	E	E
	Moderate	L	M	H	H	E
	Minor	L	L	M	H	H
	Low	L	L	L	M	M

Key: L = Low M = Moderate H = High E = Extreme

Risk Assessment Matrix (Source: Wambeke et Ryan al., 2012)

Extreme Weather Analysis - Cyclones

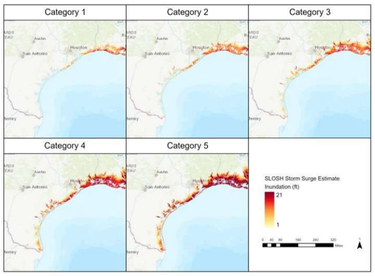


- Tropical storm and greater events occurat least every 4 years along entire TX coast
- Hurricanes show more variation, but typically occur every 10 years or less
- Major hurricanes likely occur between 20 and 40 years

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Extreme Weather Analysis – Storm Surge

- Coastal flooding is primarily caused by storm surges, mean sea level rise (SLR), extreme tides, or waves
- Data from NHC and NOAA used to create maps and identify locations with flood exposure
- Individual port facilities will be investigated for exposure in later tasks

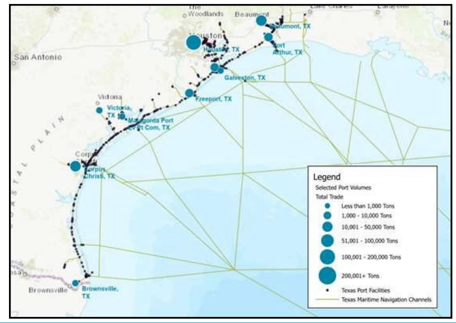


Texas coast storm surge flood exposure by hurricane intensity, inundation depth raster (data from NHC)

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Infrastructure Asset Dataset – Port Facilities



COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

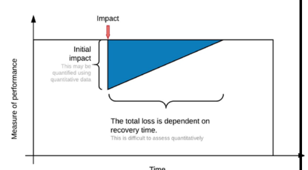
Infrastructure Asset Dataset – Supporting

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Port Vulnerability and Resilience Assessment

- Network-level and port-level vulnerabilities
- Categorize the vulnerability factors based on resilience dimensions:
  - Robustness
  - Rapidity
  - Redundancy
  - Resourcefulness
- Initial impact and long-term recovery both considered in resilience



COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Port Vulnerability and Resilience Assessment

- Identify vulnerabilities and resilience capabilities for port infrastructure, focusing on:
  - Inherent inadequacies that could amplify physical or functional damages.
  - Measures taken by ports stakeholders to speed up restoration and recovery of operations.
- Gather vulnerability data from available datasets and identifydata gaps
- Conduct **workshop/surveys** with relevant stakeholders to fill gaps in data

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

5. Discussion

COLLABORATE. INNOVATE. EDUCATE.

Workshop Goals and Structure

- This workshop serves to enhance our ability to accurately determine specificport vulnerabilities and resilience capabilities
- Filling data gaps in these areas will allow the researchers to perform the vulnerability assessment, create a resilience scoring metric, and ultimately identify physical and operational improvements that may be implemented byports and TxDOT to reduce the impacts of future extreme weather events
- This workshop is structured as a guided discussion, with questions organizedinto topics based on the four steps of the Emergency Management Cycle

COLLABORATE. INNOVATE. EDUCATE.

3. Session I: Moderated discussion

Topic A: Prevention and Preparedness

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

Do you have an established definition for resilience you use?Has COVID-19 changed this definition?

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

What processes do you use to plan for future disasters? For example have you conducted any vulnerability/risk assessment studies or any table-top exercises to discuss potential scenariosand mitigation measures?

- If so, what areas of emergency management do you discuss? Response, restoration, recovery, and adaptation? FEMA floodplainregulations?

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

How often do your employees conduct mock drills, table-top exercises, or attend training workshops to better prepare for responding to emergencies?

- Do other government agencies/stakeholders participate in these exercises?

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

When you invest in a new facility in your port, do you consider resilience as one criterion in the planning, design, and implementation phases? Do you have any planned or completedprojects specifically for reducing disaster/threat risks?

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

Are insurance rates lower for port facilities that incorporateresilience plans?

COLLABORATE. INNOVATE. EDUCATE.

Prevention and Preparedness

Are there any best-practices you have followed (e.g. content from handbooks/manuals)? Have you developed your own best- practices?

COLLABORATE. INNOVATE. EDUCATE.

4. Break (5 minutes)

COLLABORATE. INNOVATE. EDUCATE.

5. Session II: Moderated discussion

Topic B: Response Restoration Topic
C: Recovery and Adaptation

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

What are the priorities just after a natural disaster and in restoring failed components (Assuming large-scale/widespreaddamage)?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

How difficult is it to mobilize personnel and resources for immediately responding to a hurricane and restoring failed components? What are the factors that would affect the speed and scale of response/restoration? How could this be improved?

– How do evacuation routes and plans impact employee availability postdisaster?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

Does the port have any alternate arrangements in case watersupply, electricity, communications, and other utilities are disrupted?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

Do you have on-call contracts with third parties to remove debrisand mud?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

What do you do if ports are not disrupted but multimodal connections are disrupted?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

How do you deal with perishable and non-perishable goods?Have ports any role in their storage?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

How do you communicate and coordinate during response and restoration phases? Any established systems and protocols? How do agencies such as the National Guard or Coast Guard assist in the immediate response to disasters?

COLLABORATE. INNOVATE. EDUCATE.

Response and Restoration

Are there any best-practices you have followed (e.g. content from handbooks/manuals)? Have you developed your own best-practices?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

How are large recovery projects implemented after a disaster?

How does FEMA and other targeted governmental fundingsources factor into this process?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

How are resources (people, plan, money) mobilized? What arethe challenges?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

What are the design criteria for new structural projects? Are the designs based on the worst historical damage estimates or based on any risk analysis study?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

Do you consider sea level rise while implementing new projects?If so, how?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

Do you account for past disaster events and lessons learnedwhen updating emergency response plans?

COLLABORATE. INNOVATE. EDUCATE.

Recovery and Adaptation

Are there other lessons learned that have changed yourperspective on resilience adaptation?

1. How has the COVID-19 pandemic impacted your perspective?

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

6. Questions and Comments

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Follow-up Survey

- Following this workshop, a brief questionnaire will besent to attendees to further collect additional data
  - Subjective and quantitative focus, provide best estimates if possible
- Approximately 20 minutes in length
- Intended to collect more numerical information to assistwith vulnerability and resilience analysis
- Questions types:
  - Multiple choice, rating, Y/N, short reponse

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Contact Information

Name	Title	Agency	Contact information
Receiving Agency			
Joanne Steele	Research Project Manager, RTI	TxDOT	Joanne.Steele@txdot.gov
Emily Shelton	Maritime Program Coordinator, MRD	TxDOT	emily.shelton@txdot.gov
Performing Agency			
Zhanmin Zhang, Ph.D.	Professor (PI)	CTR, UT Austin	(512) 471-4534 z.zhang@mail.utexas.edu
Mike Murphy, Ph.D., P.E.	Senior Research Engineer	CTR, UT Austin	(512) 232-3134 murphymr@mail.utexas.edu
Lisa Loftus-Otway	Senior Scientist Associate	CTR, UT Austin	(512) 232-3072 ~~loftusotway@mail.utexas.edu~~
Zhe Han, Ph.D.	Research Associate	CTR, UT Austin	(512) 232-3086 hanzhe@utexas.edu
Srijith Balakrishnan	Postdoctoral Fellow	CTR, UT Austin	(737) 781-1085 srijith@utexas.edu
Kyle Bathgate	Graduate Research Assistant	CTR, UT Austin	(618) 305-0365 bathgate@utexas.edu

COLLABORATE. INNOVATE. EDUCATE.

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Thank you

COLLABORATE. INNOVATE. EDUCATE.

Appendix B. Texas Port Authorities Qualtrics Survey

Start of Block: Intro and Consent

Q26 Thank you for participating in this survey.

This study is funded by the Texas Department of Transportation and conducted by researchers at the University of Texas at Austin - Center for Transportation Research. The study seeks to assess the resilience of the port system along the Texas Gulf coast. The questions in this survey are intended to further our understanding of resilience in a port environment and the interconnections between different stakeholders involved in the emergency response procedures. Some questions are intended to expand ourknowledge of your specific port facility and ask for details such as number of tenants, trade volumes, etc.For these questions asking for specific values, please provide an estimate if values are not readily known or available.

For more information on the study, please visit:
https://utexas.box.com/s/t49xe0p5shvehcn1twdbodeu562mjnbl

Otherwise, **click the arrow button below** to move forward. If you have any further questions, pleasecontact us directly at:

Kyle Bathgate
Graduate Research Assistant
Center for Transportation Research at UT Austin
Cell: (618) 305-0365
Email: bathgate@utexas.edu
Mailing address:
The University of Texas at Austin
Department of Civil, Architectural and Environmental Engineering
(CAEE)301 E Dean Keaton St, 6.206
Austin, TX 78712

Srijith Balakrishnan
Post-Doctoral Fellow
Center for Transportation Research at UT Austin
Cell: (737) 781-1085
Email: srijith@utexas.edu
Mailing address:
The University of Texas at Austin
Department of Civil, Architectural and Environmental Engineering
(CAEE)301 E Dean Keaton St, 6.206
Austin, TX 78712

Q27 This survey contains 20 questions and will take approximately 20 minutes to complete.

Your participation in this survey is voluntary, and you will not be penalized for withdrawing from thesurvey at any moment. Your responses will be kept strictly confidential. No personal, confidential, or identifying information will be collected by the completion of this survey.
*****
By clicking the agree button below, I acknowledge that I have read and understood the above information.I consent to participate in this study.

○ Agree (1)

○ Disagree (2)

Skip To: End of Block If This survey contains 20 questions and will take approximately 20 minutes to complete. Your partic... = Agree

Q28 We are sorry that you have decided to withdraw from this survey. If you would like to reconsider,please click the "Back" button in the lower left to go back to the survey consent page. Otherwise, thankyou very much for your time.

Skip To: End of Survey If We are sorry that you have decided to withdraw from this survey. If you would like to reconsider,... Is Displayed

End of Block: Intro and Consent

Start of Block: A few questions about your role

Q3 Name of the port, and additional identifying information if needed (e.g., Port of Houston – BarboursCut Container Terminal)

____

Q4 Your designation at the port

____

Q5 Are you directly or indirectly responsible for emergency management at the port?

- ○ Yes (1)
- ○ No (2)

Page Break

End of Block: A few questions about your role

Start of Block: Port profile

Q15 From the following options, choose the operations undertaken by the port authority. Select all thatapply.

- ○ Develop and operate critical port infrastructure such as docks and piers (1)
- ○ Develop and maintain port infrastructure including roads, bridges, and drainage structures (2)
- ☐ Lease port facilities to private companies (3)
- ☐ Provide basic utility services to tenants (4)
- ☐ Provide basic amenities to vessels that visit the port (5)
- ☐ Provide basic amenities to landside transportation modes (6)
- ☐ Ensure security and coordinate emergency response during disasters (7)

Q8 Approximate annual port revenue (in US$)

____

Q9 Total number of tenants/customers (approximate)

____

Q10 Total number of jobs directly created by the port (including those working for tenants/customers;please provide your best estimate if the information is not available)

____

Q11 On an average day, how many ships/vessels visit the port?

____

Q12 Port assets: Please provide the details of the following infrastructure components (including those owned by the private sector) and the estimated component replacement cost (US$) if available. Leave theentries blank which are not applicable to the port or for which you do not have information. This information will help us quantify the losses due to the direct impact of a hurricane.

	Count (1)	Approximate replacement cost(US$) (2)
Cranes (1)		
Reachstackers and other types ofloading equipment (2)		
Docks (3)		
Piers (4)		

Q13 Please provide an estimate of the share of various landside modes (by percent) in the transportationof commodities to and from the port.

Pipeline : _______ (1)

Railroad : _______ (2)

Trucking : _______ (3)

Total : ________

End of Block: Port profile

Start of Block: Stakeholder Mapping

Q16 Which agencies or organizations do you work with during disaster preparedness (drills, table top exercises, trainings) and actual response and recovery operations for hurricane or flooding events? Selectall the entities that apply.

- ▢ Other port authorities (1)
- ▢ US Army Corps of Engineers (2)
- ▢ US Coast Guard (3)
- ▢ Texas National Guard (4)
- ▢ Federal Emergency Management Agency (FEMA) (5)
- ▢ Counties/Local government (6)
- ▢ Port tenants/customers (7)
- ▢ Texas Department of Emergency Management (TDEM) (8)
- ▢ Railroad and trucking companies (9)
- ▢ Texas Department of Transportation (TxDOT) (10)
- ▢ Local law enforcement (11)
- ▢ Utility providers (water, gas, electric) (12)
- ▢ Other (please specify) ________________________________(13)

Page Break

End of Block: Stakeholder Mapping

Start of Block: Prevention and Preparedness

Q18 How frequently does your organization perform the following actions to improve your preparednessagainst natural disasters incidents (hurricanes and floods)?

	At least once per year(1)	Every 1 to 2 years (2)	More than every 2 years (3)
Table-top exercises/workshops/ trainingswithin the organization (1)	o	o	o
Multi-juristictional table-top exercises/workshops/ trainings(2)	o	o	o
Vulnerability/risk assessmentof infrastructure components(3)	o	o	o
Review/update emergency response plans (4)	o	o	o
Mock-drills involving staffand other stakeholders (5)	o	o	o

Q20 In your opinion, what are the most *practical* methods that you would suggest to improve the overall port preparedness to handle a future natural disaster? You may consider the effectiveness of the method and the corresponding costs to define "*practical.*" Please rank the following actions in order from 1 to 5, with 1 being most effective and 5 being least effective. Please use each number one time in your response.

______Capital expenditure to implement new projects to reduce disaster risks (1)
______Retrofitting existing infrastructure to improve their strength (2)
______Workforce training to improve disaster response capabilities (3)
______Organizational adjustments to improve decision-making during disasters (4)
______Work with stakeholders and third-party vendors to improve response and recovery (5)

Q19 Approximately how often does your port perform maintenance of critical infrastructure components?

- ◯ Annually (1)
- ◯ Every two years (2)
- ◯ Every five years (3)
- ◯ Whenever a component fails (4)

Page Break

End of Block: Prevention and Preparedness

Start of Block: Response and Restoration

Q22 How do rate your port's ability to withstand a major hurricane and respond in a timely manner?

- ◯ Extremely adequate (1)
- ◯ Somewhat adequate (2)
- ◯ Neither adequate nor inadequate (3)
- ◯ Somewhat inadequate (4)
- ◯ Extremely inadequate (5)

Q21 Based on your past experience, what are the disruptions that you expect to occur at your port duringan extreme weather event such as a hurricane? Please select all that apply.

- ☐ Silting/obstruction of navigation channels (1)
- ☐ Displacement/destruction of aids to navigation (2)
- ☐ Damage to shoreline facilities/structures (3)
- ☐ Damage to port equipment (4)
- ☐ Damage to port storage facilities (5)
- ☐ Power and telecommunication outages (6)
- ☐ Flooded roads/rails (7)
- ☐ Limited employee access to the port (8)
- ☐ Debris formation on the port (9)
- ☐ Fuel shortage (gas and diesel) (10)

Q 23 Based on your own past experience, what are the top three issues that you think would impact theresponse and restoration of the operations at your port after an extreme weather event? Please note thatthe response should reflect the capabilities of your port. Please select the three items that you feel are most critical to response and restoration.

- ▢ Disruption to landside access to port (traversable roads/rails) (1)
- ▢ Lack of available labor force with necessary technical abilities (due to evacuation or other) (2)
- ▢ Delay in mobilizing emergency funds (3)
- ▢ Utility disruptions (power outage, telecommunication failures) (4)
- ▢ Waterside access to port (silted navigation channels and berths) (5)
- ▢ Conflict in communication with agencies and stakeholders (6)

End of Block: Response and Restoration

Start of Block: Recovery and Adaptation

Q25 From the aspects listed below, which do you think are important in the design and implementation ofa new project, or in the retrofitting or enhancement of existing infrastructure, to improve the overall resilience of the port? Please select all that apply.

- ▢ Exposure of various seasonal natural hazards in the region (1)
- ▢ Risks identified from recent natural disasters (2)
- ▢ Emerging threats such as sea-level rise and intensifying natural hazards (3)
- ▢ Physical and cyber vulnerabilities in the port infrastructure (4)
- ▢ Obsolete/inadequate technology (5)

Q21 What are the major challenges faced by your port for incorporating resilience criteria in disasterrecovery and adaptation projects? Please select all that apply.

- ◯ Lack of funding alternatives for financing non-revenue generating resilience- relatedprojects (eg. levees) (1)
- ◯ Lack of funding alternatives for financing revenue-generating resilience-related projects(eg. increasing height of docks) (2)
- ◯ Lack of coordination among agencies responsible for infrastructure recovery (localgovernments, private sector, etc.) (3)
- ◯ Lack of personnel with technical expertise (4)
- ◯ Lack of resilience guidelines in existing design codes (5)
- ◯ Conflicts between multiple resilience strategies (6)

Q22 Consider the following two scenarios:

(a) Current funding scenario: In this scenario, you are to allocate all the available funds for various categories of resilience interventions (listed below) according to the existing resource allocation framework. This may include multiple dedicated funding sources which are currently available to yourport.

(b) Ideal funding scenario: In this hypothetical scenario, you are allowed to spend all the available fundsfor resilience interventions with full decision-making authority. i.e., you are allowed to decide how to allocate the funds to those projects which you think can improve the overall resilience of the port the most.

Please provide the proportion of the resource allocation for the following categories under the two scenarios. You may use your past experiences and lessons learned to respond to this question. Please entervalues such that the column-wise sum is 100.

	Current funding scenario (1)	Ideal funding scenario (2)
Projects to strengthen the abilityof ports to withstand more intense natural disasters (seawalls, levees, elevated docksand related port infrastructure, etc.) (1)		
Projects to improve redundancies in the port system (backup mechanisms to handle loading equipment failure, utilitydisruptions, etc.) (2)		
Projects to enhance access to resources for response, restoration, and recovery (recruitmore staff for emergeny management, procure repair equipemnt and materials prior toextreme events, prestaging arrangements, etc.) (3)		
Projects to improve speed andefficiency of response, restoration, and recovery (identify and minimize bottlenecks and delays, education/training/mock-drillexercises for staff to respond quickly, etc.) (4)		

End of Block: Recovery and Adaptation

Appendix C. Texas Truckers Qualtrics Survey

Thank you for participating in this survey. This study is funded by the Texas Department of Transportation and conducted by researchers at the University of Texas at Austin's Center for Transportation

This survey specifically seeks to learn how hurricanes and other severe weather affects truckers, truck operations, and supply chains. We would very much your time in completing the survey if you:

1) are a trucking company representative, a trucker, or other stakeholder in truck supply chain operations, or;

2) have had your freight operations or access to customers affected by hurricanes or other emergencies at any of the ports in Texas, along the Gulf Coast from Texas to Florida, or the Eastern Seaboard from Maine to Florida. or;

3) if your freight operations occur along the western seaboard including California, Oregon and Washington State, or border states with Canada - we are interested to know your experiences regarding other types of adverse weather events at a port or intermodal facility; or,

4) if you are a freight drayage company we are particularly interested in receiving your survey since we expect you are among the more vulnerable trucking operations due to proximity to coastal ports, waterways and large metro areas.

You may move back and forth in the survey using the arrows at the bottom of each page. Thank you very much for your time. If you have any further questions, please contact us directly at:

Dr. Michael Murphy, Ph.D., P.E.
Deputy Director
Center for Transportation Research at UT Austin
Cell: (512) 300-3875
Work: (512) 232-3134
Email: murphymr@mail.utexas.edu

Mailing address:
Center for Transportation Research 3925 W. Braker Ln, Suite #4.11080
Austin, TX 78759

Kyle Bathgate
Graduate Research Assistant
Center for Transportation Research at UT Austin
Email: bathgate@utexas.edu
Mailing address:
The University of Texas at Austin
Department of Civil, Architectural and Environmental Engineering (CAEE)

301 E Dean Keaton St, 6.206
Austin, TX 78712

Page Break

This survey contains 20 questions and will take approximately 10 minutes to complete.

Your participation in this survey is voluntary, and you are free to withdraw from the survey at any moment. Your responses will be kept strictly confidential. No personal, confidential, or identifying information will be collected by the completion of this survey.
*****

End of Block: Intro and Consent

Start of Block: Default Question Block

Q1 Please enter the zip code for the home base town or city from which you operate a truck or trucking company.

____

Q2 Do you operate a portion of your truck fleet at one or more coastal ports? Please select all responses that apply.

a. Yes, this is our primary business.

b. Yes, fairly frequently, this is a percentage of our primary business.

c. Yes, though rarely, this is less than 10% of our primary business.

d. We do not operate our trucks at a Texas Port

e. We operate our trucks at one or more Ports in another US State

f. We operate our trucks at one or more Ports in another Country

g. We do not operate our trucks at any port in Texas, another US State or another country

h. I prefer not to answer

Q3 If you drive a truck or manage trucking company operations that involve a Texas coastal port, please choose from the following list each of the Texas ports at which you operate. Select all that apply.

a. Port of Houston Bayport
b. Port of Houston Barbours Cut
c. Port of Corpus Christi
d. Port of Beaumont
e. Port of Freeport
f. Port of Galveston
g. Port of Texas City
h. Port of Brownsville
i. Port of Port Arthur
j. Port of Orange
k. Port of Neches
l. Port of Harlingen
m. Port of Calhoun
n. Port of Victoria
o. We do not operate at a Texas Coastal Port
p. Other - please type your response
____
q. I prefer not to answer

Q4 What is your job with the trucking company?

a. I drive a truck
b. I am a dispatcher
c. I am in fleet maintenance
d. I am a manager
e. I am an executive
f. I am CEO for a trucking company
g. I am CFO for a trucking company
h. I am manager of supply chain logistics
i. Other - please type your response
____
j. I prefer not to answer

Q5 What is your truck fleet size?

- ○ Very small, less than 6 power units
- ○ Small, 6 - 20 power units
- ○ Medium 21 - 100 power units
- ○ Large 101 - 1000 power units
- ○ Very Large - greater than 1001 power units
- ○ I'm an Owner Operator
- ○ I prefer not to answer

Q6 We operate the following trailer types. Please check all that apply.

a. Ocean Container chassis
b. Multi-modal Chassis (53')
c. Dry Box Van
d. Refrigerated Box Van
e. Tank Trailer
f. Flat Bed
g. Step Deck
h. Low Boy
i. Vehicle Transporter
j. Dump trailer
k. Other type of trailer not listed
   ____
l. I prefer not to answer

Q7 Which of the following actions have you taken during severe weather, hurricane or other emergency? Choose all that apply.

a. Diverted normal truck operations to deliver relief supplies in the affected port city.
b. We temporarily delivered cargo to a different Texas port
c. We temporarily delivered cargo to a port in another state
d. We temporarily delivered cargo at locations other than a Texas port
e. We temporarily stopped cargo deliveries until the port was back in operation
f. The hurricane had no affect on our trucking operations since we do not operate at a Port
g. The hurricane affected our trucking operations even though we do not operate at a Port

---

Q8 We took other actions not listed in Question 7 during the hurricane or other emergency event

____

____

____

Q9 I used the following communication and information sources before, during or after a hurricane or other emergency event to make decisions about what I should do. Choose all that apply.

a. My wife, husband or partner kept me informed about what I should do

b. My trucking company dispatcher informed me about what I should do.

c. The port authorities informed me about what I should do.

d. The port tenant to which I was making the delivery informed me about what I should do.

e. I had direct communications with the ship that was going to carry the cargo I was transporting.

f. I obtained information from a Texas Department of Transportation - Travel Information Center.

g. I obtained information from the Texas Department of Public Safety (DPS).

h. I obtained information from the Texas Department of Motor Vehicles.

i. I obtained information from the city police where the port is located.

j. I obtained information from the fire department where the port is located.

k. I obtained information from city officials where the port is located.

l. I obtained information from the county where the port is located.

m. I contacted more than one information source - the information was consistent.

n. I contacted more than one information source - the information was inconsistent.

o. The information I received from these sources helped me to make good decisions about what I should do.

p. The information I received from these sources resulted in a bad decision that resulted in damage to my truck or cargo or loss of income.

Q10 I have additional comments about the information I received from authorities during the emergency event.

____

____

____

____

____

Q11 I also obtained information from the following news sources to make a decision about traveling before, during or after the hurricane. Please select all that apply.

a. Weather News from a TV station
b. Weather News from a radio station
c. Weather News from an internet news source
d. US Weather Service announcements
e. The Texas Department of Transportation (TxDOT) – DriveTexas.org website
f. Information from other truckers by cell phone
g. Information from other truckers by CB radio
h. The information I received from these sources was consistent
i. The information I received from these sources was inconsistent
j. I made a good decision using this information which kept me, my truck and cargo safe.
k. I made a bad decision that resulted in damage to my truck or cargo, or loss of income, due to inconsistent information I received from these information sources.

Q12 Please provide comments about the information received from the sources listed in question 11.

____

____

____

____

____

Q13 Based on the information received as discussed in questions 11 and 12, I took the following actions. Please select all that apply.

a. I stopped my truck at a safe distance away from the region affected by the hurricane and stayed there until it was safe to proceed.

b. I diverted my route to another port or intermodal facility to deliver or pick up cargo.

c. I was going to pick up cargo at the port, but called for a different load pickup at a location away from the region affected by the hurricane.

d. The hurricane affected truck freight operations to the point that no other loads could be found even outside the area directly affected by the hurricane.

e. I continued on to the Port thinking I had time to make a delivery or to pick up a load.

f. I continued on to the Port but was caught in the storm.

g. Other - please type your response

____

Q14 Please list the names of the hurricanes or other hazards you have experienced and how many days your normal operations affected for each.

____

____

____

____

____

Q15 I had the following experiences during one or more of the hurricane events. Choose all answers that apply.

a. I was unable to buy fuel locally and had to stay where I was until power was restored at the truck stop, and or normal fuel deliveries resumed.
b. My truck broke down and I was unable to find a mechanic until normal weather conditions resumed.
c. High winds damaged my truck due to debris impacts
d. High winds damaged my cargo due debris impacts or other reasons.
e. High winds turned my truck over.
f. Heavy rain and flooding blocked the roadway along the route to the Port causing me to turn around.
g. Heavy rain and flooding blocked bridges along the route to the Port causing me to turn around.
h. The roadway was flooded and I had to abandon my truck to seek safety.
i. The roadway was flooded and I had to be rescued from my truck.
j. The roadway was flooded, but I stayed with my truck and was able to drive to a safer location.
k. My truck and cargo were damaged by flooding.
l. My truck and cargo were destroyed by flooding.
m. High winds knocked down power lines on the route I was traveling and I could not safely leave my truck until the lines were removed by the power company.
n. I was delivering refrigerated cargo which spoiled before it could be delivered so the cargo was lost.
o. Other - please enter experiences not listed above ____

Q16 Please indicate the operating conditions you have experienced during past extreme weather events. Choose all answers that apply.

a. I was operating a truck with a permitted overweight load

b. I was operating a truck with a permitted oversize load

c. I was operating a truck with a permitted Oversize / Overweight load

d. I was operating a truck with a permitted Super Heavy Load with a transport convoy

e. I was making a pickup or a delivery at a Texas Port.

f. Other operating condition not listed - please type your response
____

Q17 I think port authorities could make the following changes to reduce impacts to truck operations during a hurricane or other hazards.

____

____

____

____

____

Q18 I think truckers could make the following changes to reduce impacts to truck operations during a hurricane or other hazards.

____

____

____

____

____

Q19 I think the Texas Department of Transportation could make the following changes to reduce impacts to truck freight operations during a hurricane or other hazards.

____

____

____

____

____

Q20 Thank you for completing this survey. If you are interested in providing additional information about your experiences or thoughts about how support to the trucking industry could be improved, please provide your email address or other contact information below.

○ Provide information if you want to be contacted

____

End of Block: Default Question Block

Appendix D. Trucking Industry Interview Questions

University of Texas at Austin
Center for Transportation Research
3925 West Braker Lane
Austin, Texas 78749

Dr. Zhanmin Zhang	**Project 0-7055 Director**
Dr. Michael R. Murphy, P.E.	**Deputy Director – CTR**
Lisa Loftus-Otway	**Research Scientist - CTR**
Dr. Zhe Han, P.E.	**Research Associate – CTR**
Kyle Bathgate	**Graduate Research Engineer – CTR**

Date: _______________ **Person Interviewed** _________________ **Location** _______________

Company position / title _________________

Operates at a Port? ______________________ **Operates at an Intermodal facility?** _________

Operates OTR? _____________________

Question 1 What steps can ports or intermodal facilities take to improve operations for truckers when severe weather is approaching?

____

Question 2 Which state agency should take the lead in providing information to truckers during severe weather?

____

____

Question 3 What steps can the Texas Department of Transportation or other DOTs take to improve operations for truckers when severe weather is approaching?

____

Question 4 Some truckers who have provided relief to cities hit by severe weather indicated FEMA directed them to arrive at the City with an empty truck. Has this been your experience? If so, do you think this is a good policy?

Question 5 What advice would you give to a new trucker about driving into an area where severe weather is expected while they are there?

____
____
____

Question 6 What good suggestions have other truck drivers given you about how they handle severe weather when on the road?

____
____

a) Who makes the final decision about whether you make a delivery or not during severe weather? ____

b) Does your fleet manager monitor your location, route conditions and other factors using an in-truck and road-view camera system for tracking GPS, weather and providing photos and videos downloaded to a website? ☐ Y ☐ N

c) If you answered Yes to b) does this system help you select the best routes or make weather related decisions?

____
____

Question 7 What is the biggest problem you face when driving a truck on the road if severe weather is approaching your destination?

____
____
____

a) What type of shelter do you search for to protect your truck and cargo when severe weather is approaching? ____________________________________

b) Do you have a rule-of-thumb for the distance in miles you must stop if driving toward a delivery location when severe weather is approaching? ☐ Y____miles ☐N

c) What wind speed causes you concerns when traveling with a fully loaded trailer? ________mile per hour

d) What wind speed causes you concerns when traveling with an empty trailer? ________mile per hour

e) How much in advance of a storm forecast do you begin changing delivery plans or making arrangements to adjust routes? _______________

f) Have you ever sought shelter at a business location when severe weather was occurring but was denied access to shelter? ______________________________________

Question 8 Have you made deliveries to ports or intermodal facilities in other states during severe weather? ☐Y ☐N

a) Did that state's port(s) or intermodal facilities have processes in place that helped make it safer for you, your truck and freight? ☐Y ☐N

If Yes, what are those processes?

- State / Facility _________________
- State / Facility _________________
- State / Facility _________________

Question 9 Do you have access to a manual or printed guidance that contains best practices for driving your truck in severe weather such as hurricanes, tornadoes, severe thunderstorms and/or winter weather?

Question 10 Does your trucking company provide training regarding best practices for driving your truck in severe weather?

Question 11 Do you have a preference whether you deliver freight to a port, intermodal facility, or a warehouse located at a private company? Please explain.

Question 12 What types of financial losses have you (or your company) incurred due to severe weather?

Question 13 One safety precaution that is often stated during severe weather events that can cause flooding is 'Turn around, don't drown'.

a) What do you do when driving your truck along a 4-lane divided roadway with a median or other barrier and encounter flooding?

____

b) Are there other safety precautions which might be hard to follow under severe weather conditions? Please discuss.

____

Appendix E. PortRESECO Resilience Scoring Questions

Preparedness

1. Does the port authority have methods to tie down or restrain equipment and items on dock, rail, and truck pads prior to the arrival of tropical force winds? Select all that apply.
2. Is it feasible to secure every critical piece of equipment that can be moved (portable, mobile)?
3. What percentage of essential equipment can be secured? (Provide an estimate (Integer using 0-100) with 0 if no plan)
4. Does this port authority have an established location for an Emergency Operations Center (EOC) that is capable of withstanding the expected impacts and remain operational?
5. Does this port conduct routine maintenance checks of the alternative operations location to ensure that batteries, generators, and other emergency items are in satisfactory supply and condition?
6. Does this port have on-site emergency power supply infrastructure such as generators, batteries, and fuel storage?
7. In addition to typical power supply means, how many of these back-up power supply infrastructures does the port have?
8. How many hours is the port able to provide its own emergency backup power?
9. Does this port have a protocol to establish emergency reactivation of utilities after an event?
10. Does the port authority have established methods for contacting port tenants and communicating port operational status and advisories to the tenants?
11. How many communication methods (radio, cell phone, social media, etc.) are available to deliver the message/instructions? If you answered No for Question 10, put a 0.
12. Does the port authority have established methods for contacting container drayage and truck freight companies that are located outside the port but operate at the port?
13. How many communication methods (radio, cell phone, social media, etc.) are available to deliver the message/instructions? If you answered No for Question 12, put a 0.
14. Does the port have established employee groups to designate individuals who are required to remain on site and "ride out" the storm, and individuals who may return to their homes or evacuate the region?
15. Does the port communicate employee expectations regarding ability to leave?
16. Does the port have established procedures regarding employee notification of when it is safe to return to the port?
17. Does the port have a plan to implement temporary housing needs of the port staff, other first responders, or other recovery assistance staff using temporary housing structures or emergency trailers?
18. Does the port have established methods for the monitoring of approaching inclement weather events (NOAA, NWS, or other similar sources for accurate information collection)?
19. Is there a USCG port coordination team, port emergency action team, or other local response initiative in which the port participates?
20. Does the port “embed” employees with other responses agencies such as the USCG or local first responders during times of disaster?

Response

1. Are containment strategies in place to minimize chemical pollution during a disaster?
2. Does the port have equipment and means for testing flooded areas for water pollution and removing the water using contracted companies knowledgeable about removing hazardous water?
3. Does the port have contracts or other means for evaluating buildings that have sustained water damage to ensure that molds and mildew, that may be dangerous to humans, are not present?
4. Are sensors and other monitoring technologies used to detect damage during disaster events?
5. Does the port maintain contracts with local contractors/companies to assist with hurricane recovery operations and repairs as needed, such as salvage companies, debris removal, etc.?
6. Do government agencies surrounding the port have framework agreements for emergency response that benefit the Port (e.g., channel dredging or highway clearing)?
7. Following the storm event, does the port prioritize preservation of life by first conducting window assessments to gauge conditions, followed by initial damage assessments of port facilities and finally formal damage assessment as per FEMA regulations?
8. Is port staff trained to document all damaged infrastructure via photographs and written reports?
9. Does your port have emergency services (e.g. fire and medical team) to respond to life threatening situations immediately after a disaster?

Recovery

1. How many days is this port able to be self-sufficient in terms of safety without external assistance after a disaster impact?
2. Has this port identified prioritization lists of the critical facilities, infrastructure and services to be restored in order for the Port to resume normal operations?
3. Does the port have procedures in place to address blocked roadway entrances into the port such as preplanned detour routes or alternative gate locations to serve as a temporary entrance point?
4. Does the port have procedures in place to address blocked or damaged rail lines into the port and within the port facility? Does the port communicate with rail operators to coordinate railroad repairs within port owned property?
5. Is there an established system to provide for coordinated response between port tenants?
6. Do port tenants have agreements to share resources and supplies with each other or the port authority during the recovery process for a disaster event?
7. Has this port identified likely post-event dredging needs for various disaster scenarios?
8. Does the port have areas to places the dredged material, accounting for increases that may arise due to shoaling caused by storms?
9. Does the port have a means to communicate with USACE to discuss dredging operations and priority for channel restoration?
10. Does the port understand the typical needs for repairs to aids to navigation (AtoNs) after disaster events and how their destruction or displacement may impact vessel traffic?

11. Does the port have a means to communicate with USCG to discuss AtoN repairs?
12. Does this port have a knowledge of disaster assistance programs (i.e., FEMA Public Assistance, FEMA Hazard Mitigation Grant Program) and how to ensure compliance with all requirements?

Adaptation

1. How often (times per year) does this Port conduct assessments of the condition of its facilities to identify maintenance requirements for corrective actions needed to increase component life and capacity?
2. During the hurricane off-season (winter months), how many actions does the port proactively prepare for storm events?
3. Does the port have an implemented hurricane preparedness plan following the USCG hurricane condition levels (or similar), with conditions assigned by time to hurricane landfall and specific action items assigned at each condition?
4. Is the document referenced in 3 readily available to port employees and other stakeholders?
5. Does this port follow existing standards for hazard zone insurance when performing capital planning for infrastructure or selecting locations for new facilities such as FEMA flood maps?
6. Does this port utilize data from past disruptive weather events to identify risks for both urgent hazards (e.g., hurricanes, fires) and long-term hazards (e.g., sea level rise, seafloor shoaling)?
7. Does this port record and implement lessons learned from past disasters? How frequently are preparedness manuals updated with new information collected from lessons learned?
8. Does this port conduct emergency response exercises for hurricane hazards with port management staff and essential personnel to prepare for future tropical weather incidents?
9. How often (times per year) do these training exercises occur?
10. Has this port identified shore regions that are exposed to hurricane storm surge inundation for various hurricane intensities?
11. Has this port identified regions that safe for employees to seek shelter from wind and water hazards?
12. Has this port identified locations for the storage of equipment that will allow for minimal damages to physical items?
13. Does this port conduct regular stakeholder meetings to review the Port's hurricane preparedness policies with customers, public agencies, and tenants?

Appendix F. Value of Research (VoR)

Introduction

The scope of TxDOT project 0-7055 includes a statement on the value of the research (VoR) that the UT/CTR team conducted. For the establishment of VoR, a total of six functional areas were identified spanning qualitative, economic (quantitative), and both categories. A summary of the selected functional areas is shown in Table F.1.

Table F.1 Functional areas of Project 0-7055

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
Level of Knowledge	X			X		
Customer Satisfaction	X			X		
System Reliability		X		X		
Infrastructure Condition		X				X
Freight Movement and Economic Vitality		X				X
Safety			X			X

Qualitative Benefits

The project identified three functional areas that contain qualitative benefits:

- Level of Knowledge,
- Customer Satisfaction, and
- Safety

The qualitative benefits related to the performance of this project are summarized as follows:

<u>Level of Knowledge</u>

Project 0-7055 increased the Level of Knowledge related to Texas port system resilience and extreme weather vulnerability. This project advanced the understanding of the current resilience and emergency response capacity of Texas ports. Additionally, the project developed frameworks for assessing the criticality, vulnerability, exposure, and risk of Texas coastal freight infrastructure, thereby furthering the knowledge of extreme weather impacts on ports in Texas. The project also conducted multiple stakeholder outreach activities with port authorities, public agencies, and private freight companies. Economic impacts of extreme weather on port infrastructure systems were also determined, and system level topological resilience was investigated. These impacts advanced the existing Level of Knowledge for TxDOT. The exact findings most applicable to the Level of Knowledge advancement are the recommendations, which provide actions that UT/CTR recommends to TxDOT and other Texas port stakeholders. The formulation of these recommendations is the direct result of knowledge gained throughout the completion of this study.

Customer Satisfaction

Customers are essential to TxDOT and Texas port operations. Considering that ports handle a massive amount of import and export trades and consumer and energy products, it is imperative that TxDOT seeks to minimize delays and disruptions to these freight systems. The PortRESECO tool and resilience assessment frameworks may be used to help TxDOT and Texas port authorities to identify system vulnerabilities and shortcomings and implement changes to reduce delays with freight systems. This is a prevalent topic considering the current issues with supply chain and port and trucking delays in the United States. Extreme weather disruptions may exacerbate already strained systems, and therefore the results of this study will help to keep freight customers and general consumers satisfied with lower risks for the delay and congestion due to extreme weather events.

Safety

Safety is critical for TxDOT, port authorities, and other relevant stakeholders. The research outcomes from this project will limit and reduce the loss due to the operation interruptions of ports caused by extreme weather events. The PortRESCO tool as well as other findings from this research will enhance the knowledge about resilience for port and related stakeholders and thus improve the operational safety. The identified vulnerability, criticality, and risk will guide the stakeholders to take proper action if natural disasters hit. In summary, the research outcomes from this research will make the ports more resilient to natural disasters and will contribute to enhancing the safe of port system operation as well as customers.

Quantitative Benefits

The economic benefits of the project are identified for four functional areas:

- System Reliability,
- Infrastructure Condition,
- Freight Movement and Economic Vitality, and
- Safety.

The economic benefits related to the performance of this project are summarized as follows:

System Reliability

System reliability is essential to port operation and all relevant stakeholders. The project will help Texas ports and port-systems to identify the weakness in the current system and provide recommendations to improve system reliability by increasing the ability of ports to withstand extreme weather events and reducing the impact to the freight transport operation during extreme weather events.

Infrastructure Condition

The project will make recommendations to protect and maintain port infrastructures. The protection and maintenance will lead to the improvement of general infrastructure assets condition. An important part of resilience assessment is the frequency of condition inspection and maintenance. The PortRESECO tool contains questions related to these factors and if ports incorporate the tool into their operations, it may result in more frequent and comprehensive infrastructure condition assessment.

Freight Movement and Economic Vitality

The research outcomes of this project will enhance the flow of freight movement by reducing the impact of extreme weather events and enhancing the resilience of the port system during and after natural disasters. The improvement in resilience may result in lower monetary loss and shorter port operation interruption duration, which contributes to a better economic vitality.

Safety

The research outcomes of this project will reduce both direct and indirect loss due to the port operation interruption during and after extreme weather events. The PortRESCO tool as well as the recommendations will give guidance for ports and stakeholders to achieve a higher resilience score. Reduction in number of related extreme weather crashes will result in savings in property damages and fatality, which renders decrease in cost due to accidents.

Quantitative Analysis of Economic Benefits

The identified economic functional areas (e.g., system reliability, infrastructure condition, freight movement and economic vitality, and safety) are mainly correlated with improvement of port resilience, including the enhanced infrastructure conditions and reduction in port operation interruption duration. Based on the availability of data for quantitative analysis of economic benefits, this preliminary VoR estimates reduction in port operation interruption duration.

The quantitative analysis of Project 0-7055's value related to the functional area of reduced port operation interruption duration is shown in Figure E-1. Other functional areas are also involved. The estimated total savings of conducting this project is approximately $4.0 million, which equates to a net present value of approximately $3.25 million. The payback period is 0.64 years and the cost-benefit ratio is 11.

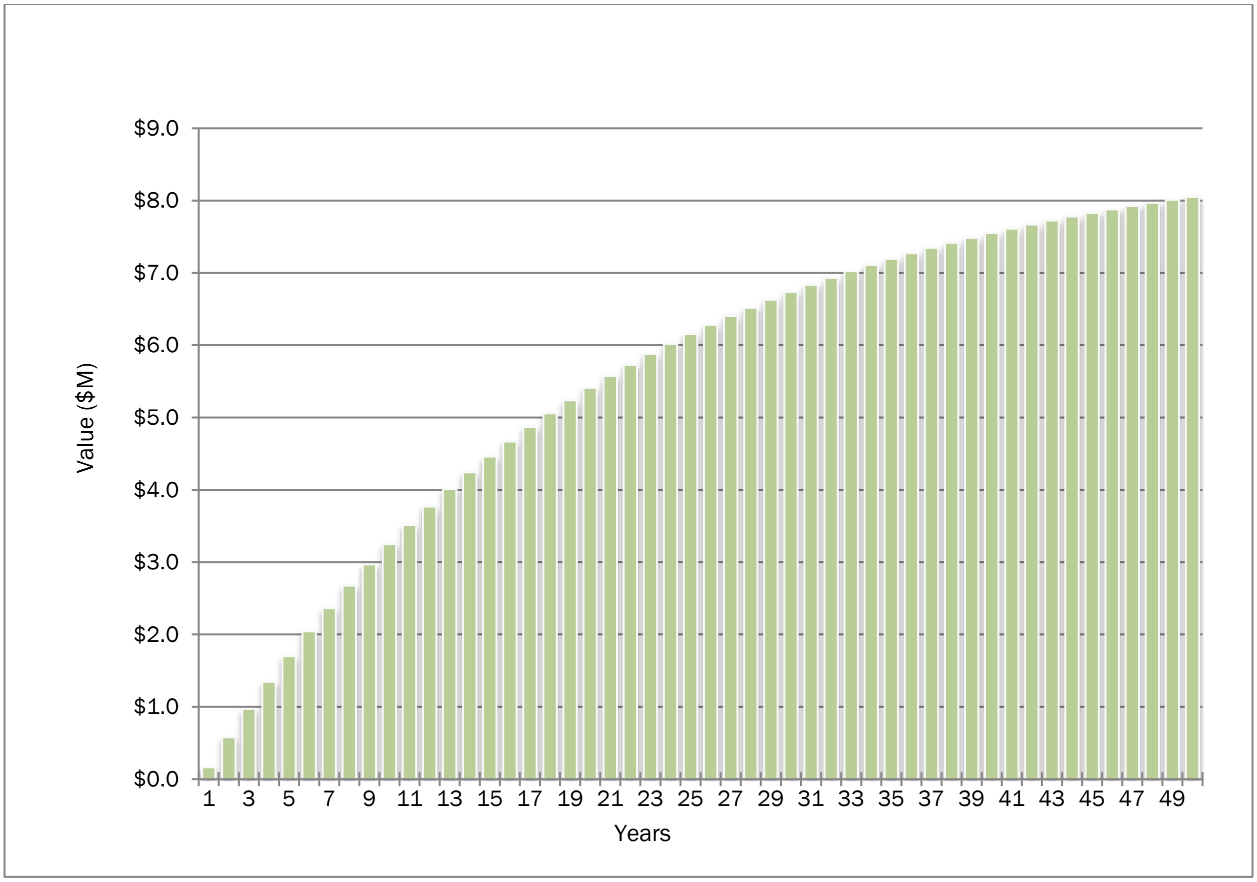


Figure F.1 Preliminary estimates of net present value of Project 0-7055

Explanation of VoR

Figure F.2 represents the input and output of the project's value analysis that develop Figure E-1. The inputs were dictated by TxDOT or other publications as well as the analyses obtained from this project. Due to the availability of Texas-specific data, some input values are assumed by the UT/CTR research team.

Texas Department of Transportation	**Project #**	0-7055			
	Project Name:	Creating a Resilient Port System in Texas: Assessing and Mitigating Extreme Weather Events			
	Agency:	UT/CTR	**Project Budget**	$	307,158
	Project Duration (Yrs)	2.0	**Exp. Value (per Yr)**	$	478,600
Expected Value Duration (Yrs)		50	**Discount Rate**		5%
Economic Value					
Total Savings:	$ 4,000,242		**Net Present Value (NPV):**	$	3,248,814
Payback Period (Yrs):	0.641784		**Cost Benefit Ratio (CBR, $1 : $___):**	$	11

Figure F.2 Input and output value of Project 0-7055

Each input term is presented in detail as follows:

Project Budget: \$307,158 is the total budget of the project. This value is determined from the project's contract.

Project Duration (Yrs): The project was initiated on January 1, 2019 and will be terminated on December 31, 2021. Therefore, the project duration is 2.0 years.

Expected Value Duration (Yrs): According to Sweeney and Assetic, the engineered design life of port infrastructure is typically 30-50 years, and even more in the case of maritime access shipping channels and under different management strategies (Sweeney 2019; Assetic 2021). Therefore, an expected duration of 50 years was assumed if new infrastructures were designed and built to increase the port resilience.

Exp. Value (per Year): Texas has 11 deep-draft ports, eight shallow-draft ports, and two recreational ports that are critical to the economic growth of the state and are key components of the state's transportation system. According to the daily operating revenue analyses in Chapter 7 (Table 7.3), the total daily operating revenue is \$1,658,097 for the eight Texas ports, averaging \$207,262 per port per day. It is further estimated that the total daily operating revenue for all 21 Texas ports is \$4,352,505. Based on the hurricane return period occurrences table at the 8 Texas ports (Chapter 7, Table 7.5), it is estimated that about 217 hurricane events (including Cat +0, Cat +1, Cat +2, Cat +3, Cat +4, and Cat +5) will occur during the expected duration of 50 years. Therefore, about 570 hurricane events are estimated to occur to all 21 Texas ports. Assuming that the average reduction in port operation interruption duration is one day per hurricane if the port resilience is improved, the overall benefit is \$1,658,097 x 570 = \$2,480.93 million over 50 years.

According to TxDOT and SCMO, approximately \$3.6 billion will be required for the state to cover the most immediate needs at its ports, and it can cost as little as \$16 million per 984 ft berth up to \$7 billion to build a port infrastructure (TxDOT Maritime Division, 2021; SCMO 2021), the average total construction and maintenance cost was assumed as \$117 million per port in case the port build new infrastructures or take other actions to increase its resilience. Therefore, the estimated implementation cost is \$2,457 million over 50 years.

The expected benefit is calculated as \$2,480.93 million - \$2,457 million = \$23.93 million, averaging \$478,600 expected value per year.

Discount Rate: The 5% discount rate recommended in the University Handbook was used (TxDOT, 2019).

Output values: The following terms were determined automatically in the spreadsheet (Figure E-1): Total Savings, Payback Period (Yrs); Net Present Value (NPV), and Cost-Benefit Ratio (CBR). These terms were determined based on the equations in the University Handbook (TxDOT, 2019).

References for VoR

Assetic. "Asset Management for Ports". Online reference. Official website of Assetic. Available at: https://www.assetic.com/industry-solutions/ports-asset-management/. Accessed on November 20, 2021.

SCMO. "How much does it cost to build a port?" Official website of SCMO. Available at: https://www.scmo.net/faq/2019/8/9/how-much-does-it-cost-to-build-a-port. Accessed on November 28, 2021.

Sweeney, Benjamin R. "Designing Port Infrastructure for Sea Level Change: A Survey of US Engineers." In Ports 2019: Port Planning and Development, pp. 477-488. Reston, VA: American Society of Civil Engineers, 2019.

TxDOT. Maritime Division. "Port Authority Advisory Committee 2022-2023 Texas Port Mission Plan Executive Summary". Available at: https://ftp.txdot.gov/pub/txdot-info/mrt/executive-summary.pdf. Accessed on November 28, 2021.

TxDOT. "University Handbook 2019". Official website of TxDOT. Available at: https://ftp.dot.state.tx.us/pub/txdot-info/rti/university-handbook.pdf. Accessed on October 25, 2021.

TxDOT. "Texas Ports". Official website of TxDOT. Available at: https://www.txdot.gov/inside-txdot/division/maritime/ports.html. Accessed on November 25, 2021.