MARINE TRANSPORTATION SYSTEM RESILIENCE ASSESSMENT

Guide

February 2023

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Cybersecurity and Infrastructure Security Agency

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ABOUT THIS GUIDE

The “Marine Transportation Systems Resilience Guide” (MTS Guide) was co-developed under a Memorandum of Agreement with the United States Army Corps of Engineers, Engineering Research and Development Center (USACE-ERDC) using a special Congressional appropriation for the agencies (members of the U.S. Committee on Marine Transportation Systems) and other resources. The MTS Guide organizes multiple methodologies and port resilience assessment tools to support resilience planning. Based on CyberSecurity and Infrastructure Security (CISA) extensive experience conducting resilience assessments through the Regional Resilience Assessment Program (RRAP) and USACE-ERDC’s significant domain subject matter expertise, the two agencies partnered to address this requirement. CISA and USACE-ERDC each drafted sections of this Guide and coordinated review and comments from internal and external team members. Parallel to Guide development, CISA has sponsored as series of case studies being conducted by Department of Homeland Security (DHS) Centers of Excellence and USACE-ERDC to demonstrate application of the MTS Guide.

The MTS Guide provides an overview of intended users and uses and discusses the importance of resilience in the maritime domain. It then provides a discussion of key objectives for assessments and a framework and methodology for conducting resilience assessments within the Marine Transportation System (MTS), beginning with issue identification and continuing through to implementation activities. The MTS Guide methodology is based on the CISA Regional Resilience Assessment Methodology (RRAP Methodology) and Infrastructure Resilience Planning Framework (IRPF) principles tailored to operators in the MTS domain. The MTS Guide is supported by an appendix linking common MTS resilience assessment methods, tools, resources, and data sources to the framework and methodology presented in the MTS Guide. Annexes include more detail on assessment objectives and a series of case studies developed by ERDC with Region 10 and the Port of Portland and through a memorandum of agreement with the DHS Coastal Resilience Center showing application of the MTS Guide.

CISA has developed three recent documents that assist in this collective defense of the nation’s critical infrastructure (1) RRAP Methodology, (2) IRPF, and (3) Marine Transportation System Resilience Assessment Guide that provide critical infrastructure security practitioners with a common framework and process for addressing complex infrastructure resilience issues. These documents focus on filling a knowledge gap by capturing practical experience gained from a decade of real-world experience conducting dozens assessments.

The MTS Guide can be implemented as either a standalone document or supplement either or both the RRAP Methodology and the IRPF.[1] First, the Methodology for Assessing Regional Infrastructure Resilience articulates core elements of a general, scalable methodology for assessing the resilience of critical infrastructure, and defining key processes and analytical techniques that can yield tangible and actionable options for enhancing resilience through voluntary, collaborative partnerships. Second, the IRPF provides an approach for localities, regions, and the private sector to work together to plan for the security and resilience of critical infrastructure services in the face of multiple threats and changes. Finally, the MTS Guide integrates these information sources, methodology and experiences into a repeatable, step-by-step framework by supplementing and improving existing processes to conduct resilience assessments and incorporate resilience enhancements into planning and investment activities.

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[1] These documents can be accessed athttps://www.cisa.gov/publication/methodology-assessing-regional-infrastructure-resilience and https://www.cisa.gov/sites/default/files/publications/Infrastructure-Resilience%20Planning-Framework-%28IRPF%29%29.pdf.

The RRAP Methodology and IRPF can further assist beyond the point of conducting a resilience assessment by helping the assessor understand and communicate how infrastructure resilience contributes to resilience of port operations; identify how threats and hazards might impact the normal functioning of port operations and critical infrastructure and delivery of services; prepare governments, owners and operators to withstand and adapt to evolving threats and hazards; integrate infrastructure security and resilience considerations, including the impacts of dependencies and cascading disruptions, into planning and investment decisions; and recover quickly from disruptions to the normal functioning of the marine transportation system.

Drafts of the MTS Guide were reviewed by assessment consultants, academic experts, system owners and operators, federal agency users and CISA regional personnel through four co-sponsored workshops including one conducted with the U.S. Committee on Maritime Transportation Security-Resilience Integrated Action Team (CMTS-RIAT). The document has been reviewed by DHS Centers of Excellence, Argonne National Laboratory, Idaho National Laboratory, and CISA. In April 2022, the MTS Guide was presented to the Port of the Futures Conference and in June 2022, the MTS Guide was presented to the PIANC USA, the U.S. section of the World Association for Waterborne Transport Infrastructure.

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1.0 INTRODUCTION

Emerging Challenges

The U.S. MTS is the waterborne component of the U.S. multimodal freight system that moves over 70 percent of U.S. international trade (by weight) and is a vital catalyst for local, regional, and national economies. The MTS supports $4.6 trillion of regional economic activity every year and generates jobs for more than 23 million workers in the United States by supporting the movement of people and commodities.[2,3] To successfully operate now and into the future, the MTS must be resilient. Resilience is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.[4] Hurricanes, coastal storms, riverine flooding, and drought can disrupt marine operations. These and other disruptions like the COVID-19 pandemic, trade policies, and labor negotiations shed light on the need to better understand functions of important infrastructure systems that support the MTS (e.g. communications and cyber infrastructure, electric power, roads, rail, wastewater, and warehousing) and the governance systems and communities that the MTS operates within. These challenges and the complicated nature of the interdependent systems that comprise the MTS are paired with an almost overwhelming number of datasets and approaches for analyzing disruptions and enhancing resilience. The variety of datasets, methods, and resources can result in a sense that resilient solutions are too complicated or costly to properly identify. However, a failure to embrace resilience as a planning paradigm can result in investments and operations that are isolated, require frequent and expensive repair, and do not consider the capability of the MTS to adapt and preserve its functions in the future.

What are the benefits of a resilience assessment?

The MTS Guide provides a process for organizing and understanding the complicated systems that comprise the MTS. The MTS Guide provides advice for assembling a diverse group of public and private stakeholders and agencies that manage these systems; a critical step in ensuring that an assessment is more than a report on a shelf. It also introduces a framework for structuring a resilience assessment and assembles a variety of resources that make an assessment possible based on the goals of the guide user.

The benefits of completing a resilience assessment include a closer relationship with stakeholders and partners who may not traditionally be involved in planning exercises, a holistic understanding of the system's most important vulnerabilities and functions, buy-in from agency or seaport leadership, an awareness of the dependencies and interdependencies within a system, and the identification of practices or investments that can reduce the risk of disruption and save time, effort, and funding in the future. Figure 1 outlines the key benefits of resilience assessments as reported by personnel involved in resilience assessments at 10 seaports across the country.

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[2] Martin Associates. "2018 National Economic Impact of the U.S. Coastal Port System," American Association of Port Authorities. March 2019. www.aapa-ports.org/advocating/PRdetail.aspx?itemnumber=22306
[3] United States Coast Guard (USCG). 2018. Maritime Commerce Strategic Outlook.
[4] The White House, Presidential Policy Directive/PPD-21. "Critical Infrastructure Security and Resilience," February 12, 2013. obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

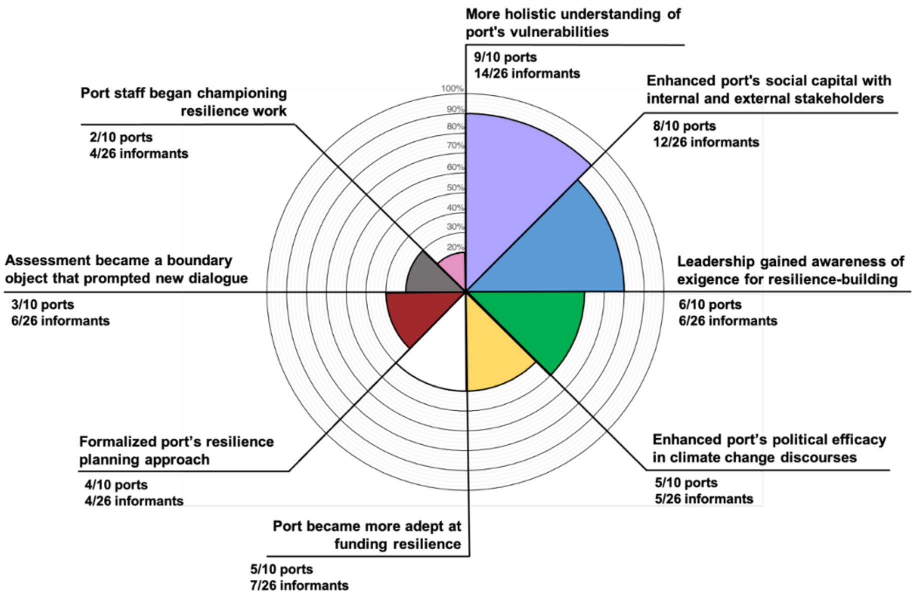

Figure 1. Eight benefits associated with resilience assessments identified in 12 interviews with 26 seaport decision makers. Each colored pie is the percentage of seaports from which at least one informant mentioned that benefit (for more information on this study, see Annex B.).

Incorporating resilience into infrastructure investment plans has become a call to action as federal funding opportunities require careful consideration of future risks like climate extremes and compounding effects of technology, community inequity, and globalization.[5] [6] In the past, many MTS owners, operators, and other stakeholders have embraced risk management paradigms (e.g. vulnerability and consequences) to provide a foundational understanding of how a system will perform in the face of potential disruptions. These paradigms are closely related to a resilience assessment (see Section 2.1 "Resilience-Related Concepts" and Section 2.2.3. "Understand the Impact of Disruptive Events").[7] [8] A resilience assessment is specifically intended understand how a system can withstand and recover from a variety of disruptions and includes an indication of how the system can better prepare and adapt to minimize the impacts of future disruptions. The methodologies to carry out resilience assessments have been in development for many years. CISA's RRAP has conducted port-related resilience assessments for over a decade. The MTS Guide builds on the RRAP methodology along with the experiences and findings of past resilience assessments.

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[5] USDOT. "U.S. Department of Transportation Announces Funding Availability for Port Infrastructure Development Program." March 29, 2021. maritime.dot.gov/newsroom/press-releases/us-department-transportation-announces-funding-availability-port-0

[6] The White House. "FACT SHEET: The American Jobs Plan". March 31, 2021.

[7] Mitchell, A. 2013. "Risk and Resilience: From Good Idea to Good Practice." Organization for Economic Co-operation and Development. oecd-ilibrary.org/docserver/5k3ttg4cxcbp-en.pdf?expires=1617998765&id=id&accname=guest&checksum=AAC084A5400756B09284DF2BFDB85E6F

[8] Kahan, J. et al. 2010. "Risk and Resilience: Exploring the Relationship". Homeland Security Studies and Analysis Institute. anser.org/docs/reports/RP10-01.03.16-01.pdf

How does the Guide fit into existing processes?

The MTS Guide is intended to supplement and improve existing processes—not to replace them—by helping guide users to conduct resilience assessments and incorporate resilience enhancements into planning and investment activities. The MTS is most easily recognized by its ports and navigation infrastructure - facilities that connect and support the movement of commodities. Ports and navigation facilities (i.e. locks, dams, channels maintained by dredging operations, channel training structures) operate on tight budgets and are driven by a variety of requirements and plans – strategic, business, capital improvements, continuity, and emergency operations, among others. Publicly owned ports and facilities also work within a broader set of economic and environmental goals for a waterfront that includes multiple stakeholders. An assessment fits into a larger planning process that must consider trends, disruptive scenarios, often divergent stakeholder interests, and concepts of a resilient future. Incorporating resilience into these existing planning processes includes defining how an assessment will help stakeholders agree on the challenges and evaluate alternative actions to successfully prepare, absorb, recover, and adapt to future hazards. Effective consideration of resilience in strategic planning will result in cost-effective investments that limit unplanned disruptions to operations, creating a competitive advantage in a close market. This benefit presents a strong case for including a resilience assessment as part of any future investment planning. The secondary benefits of increasing stakeholder engagement, greater understanding of the components and interdependencies of the system, and meeting infrastructure development or funding requirements to consider resilience, provides even more compelling reasons for completing an assessment.

1.1 PURPOSE OF THE GUIDE

The resilience of the MTS has been improved by the efforts of many federal agencies, academic institutions, and private companies. These efforts have resulted in a variety of data sources, methodologies, guidebooks, and emergency response protocols that are available to practitioners. The process provided within the MTS Guide integrates these information sources and experiences into a repeatable, step-by-step framework for conducting resilience assessments that guide users can tailor and apply to their own needs. The MTS Guide is built upon four resilience objectives that lay the foundation for how an assessment should be conducted (Figure 2). Even if these four objectives are not equally considered, they should at least be accounted for in assessment design.

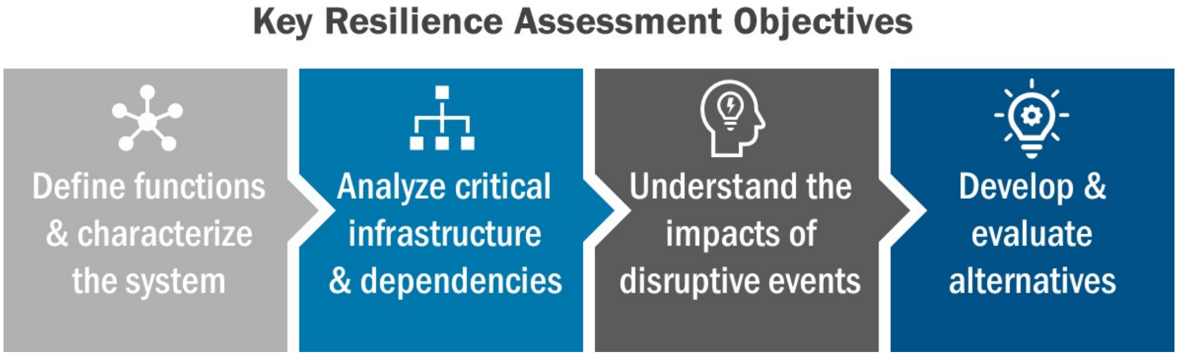

Figure 2. The four resilience assessment objectives provide a foundation for considering and designing a resilience assessment.

1.1.1 Who Uses the Guide and How Does it Help?

Sample Users and Example Applications

- CISA RRAP Program - initiating a new RRAP of an inland or maritime system
- U.S. Coast Guard office – working with Harbor Safety Committees to improve a table-top exercise
- U.S. Army Corps of Engineers District or Division - planning for future infrastructure investments based on the risks of aging infrastructure failure or channel shoaling.
- Planning or engineering department of a Port Authority – developing a strategic plan
- Private terminal operator or a corporate entity – evaluating risks and potential mitigations for a facility or supply chain.
- Contractors - hired by a port or government to conduct a resilience assessment

This MTS Guide is intended for use by those that provide technical assistance and studies to the MTS or convene the public and private agencies that support port and maritime commercial functions. Guide users can come from federal, state, local, tribal and territorial governments, and private sector owner and operators. They can be contractors who are very familiar with conducting assessments or newly assembled stakeholder groups who are interested in working together to understand their local MTS. These guide users can come from a wide variety of backgrounds and are not required to have specific expertise besides a basic understanding of the MTS. To address any differences in background, the MTS Guide provides references to existing resources, studies, and findings to help a guide user design their own assessment. The purpose of the MTS Guide is three-fold:

1. To provide guide users with a shared understanding of how to design and conduct a resilience assessment of MTS components;
2. To close the gap between available resources and needs by organizing and identifying planning tools, academic studies, datasets, and methodologies used to assess MTS resilience; and,
3. To illustrate the assessment process through examples and case studies across three scopes that have been developed to represent a wide variety of existing systems and potential applications (Figure 3).

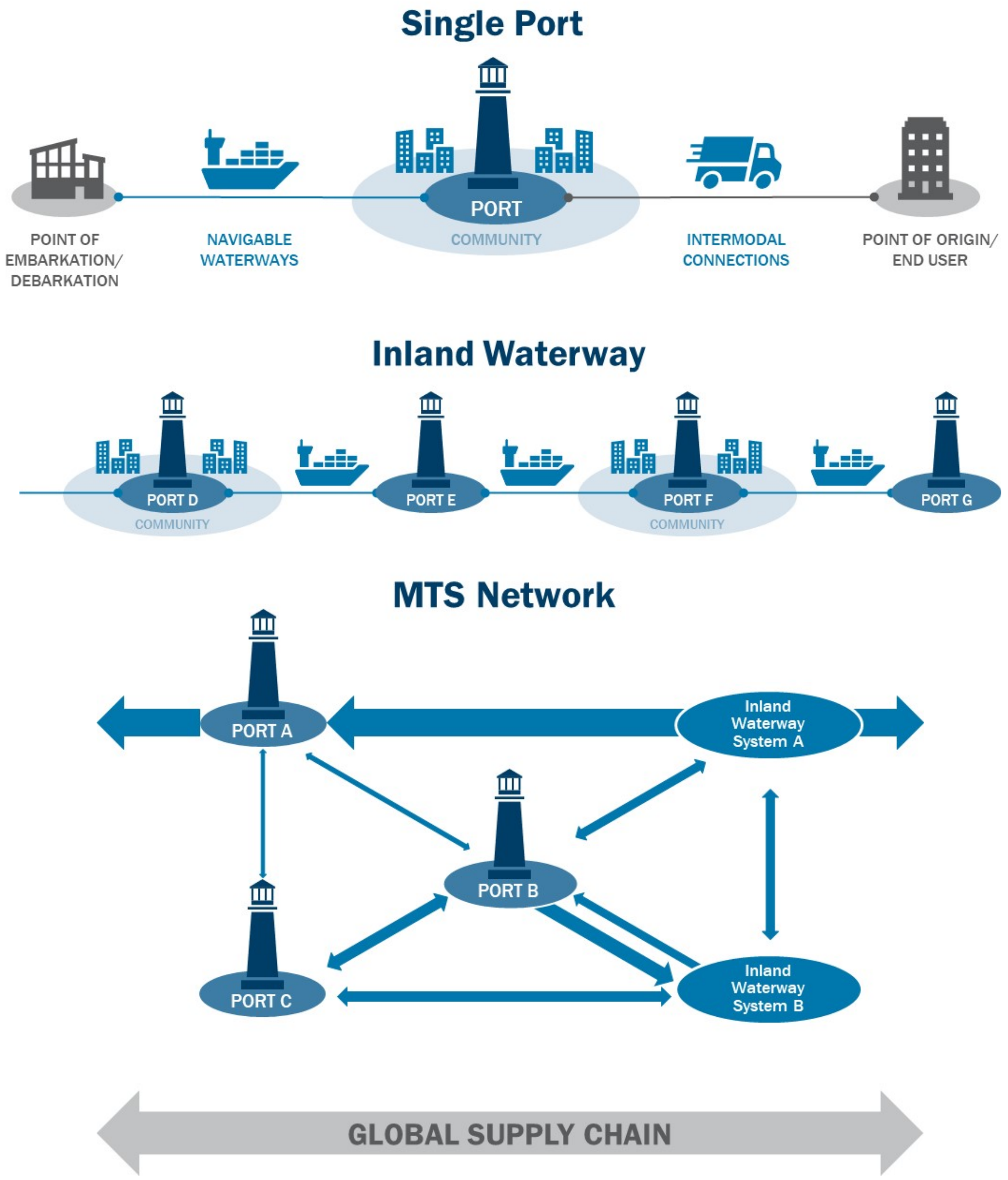

Figure 3. Three scopes have been selected to represent a wide extent of possible resilience assessments

These scopes include 1) a single port, including the navigation systems, intermodal connections, and communities that support its ability to move goods; 2) an MTS port network which embodies the connectivity of a group of ports and their ability to meet supply chain demands; and 3) an inland waterway and the physical infrastructure located along the waterway to support navigation and intermodal transportation. While there are many interests to consider within port areas (e.g. commercial fishing, recreation, environmental preservation, etc.), the MTS Guide identified these three scopes to represent the movement of people and cargo - two functions that are considered top priority for ports and the MTS.

1.1.2 How is the Guide Organized?

The MTS Guide can augment regional and port planning by guiding the user to sources of information and analysis through several phases of analysis that can help stakeholders develop a shared understanding of resilience, identify resilience gaps, and reach agreement on a path forward to address those gaps. Assessment results will link to critical functions (e.g. maintaining channel dimensions, drayage, intermodal exchanges, warehousing) and the infrastructure that supports them and provide information tailored for future decision-making needs. These linkages happen through four key Resilience Assessment Objectives that are the foundation for every resilience assessment:

Defining Participants

Champion: Champions serve as sponsors for assessments and represent a focal point for planning and scoping. They help set priorities for an assessment, support identification of and outreach to stakeholders and decisionmakers, and lead implementation activities. They are often most involved in pre-assessment, assessment design, and implementation.

Decision Makers: Decision Makers represent organizations with the ability to influence the resilience of a port and implement assessment findings. Decision Makers should be involved throughout an assessment, but especially during pre-assessment activities and the implementation phase. Since they hold the ability to effect implementation activities, their buy-in should be sought before an assessment begins in earnest.

Stakeholders: A stakeholder has a “stake” in the decisions affecting the MTS and may be positively or negatively affected by changes that may result from an assessment. Stakeholders often have data and information that can be used to support an assessment as well as a perspective on what can be done to enhance resilience. They are most often consulted during assessment execution and are often involved in implementation activities.

- Define functions and characterize the system in steady state
- Analyze critical infrastructure and dependencies
- Understand the impacts of disruptive events
- Identify and evaluate resilience enhancement alternatives

The appendices provide additional information for guide users. The Resilience Assessment Objectives are located in Appendices A – D.

1.2 HOW TO USE THE GUIDE

The MTS Guide provides an approach to conducting a resilience assessment that is customizable and scalable according to user objectives, desired level of information for decision-making, scope of interest, and available resources. The resilience assessment process shown in Figure 4 is similar to other planning and project management frameworks where the user moves through a series of phases intended to help them identify the issues and stakeholders, focus the assessment and activities, execute the assessment, and implement findings.

Figure 4. The Resilience Assessment Process includes five steps and is built upon the four resilience assessment objectives that inform the design of the assessment.

This MTS Guide introduces four major resilience assessment objectives as foundational to this process: define functions and characterize the system, analyze critical infrastructure and dependencies, understand the impacts of disruptive events, and recommend and take action to improve outcomes to disruptive events. For the pre-assessment phase, the MTS Guide provides background (and appendices) on these objectives as reference points. As a guide user moves beyond pre-assessment into design, each of these objectives should be addressed in some manner depending on the specific scope of each assessment.

Guide users may come from different backgrounds and have a variety of reasons for conducting a resilience assessment. Uses include forecasting future impacts of disruptive events to inform long term resilience planning, exploring best practices and options available for a specific project or improvement, preparation for a specific known event, or adaptation and improvement after an event. During the pre-assessment phase, guide users should reflect on the following questions:

- What decisions will this assessment inform?
- What level of detail is necessary to inform these decisions?
- What is the scope of the full system being considered?
- How much time and funding are available to complete the assessment?

The MTS Guide is organized so that the answers to these questions will provide the guide user with a suite of relevant data sources, methodologies, and guidebooks that may be useful.

2.0 RESILIENCE PRIMER

Resilience is a measure of how well a system performs its intended function over the course of either an extreme event or a gradual accumulation of stress.[9] Presidential Policy Directive 21 (PPD-21): Critical Infrastructure Security and Resilience defines resilience a set of abilities: "to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including deliberate attacks, accidents, or naturally occurring hazards."[10] Inherent to resilience is the ability to avoid disturbance in the first place; if functionality is not lost, it does not need to be recovered. However, some eventual disturbance is inevitable and therefore it is important to be prepared and able to recover rapidly from disruption and adapt as necessary following disruptions and/or anticipation of future ones.

Figure 5. The resilience cycle

Figure 5 illustrates resilience temporally and highlights that the performance of a system's critical functions is determined by different capabilities that are necessary at different times.[11]

The cycle represents:

1. How a system operates during normal times,
2. Loss of function, which depends on the ability of the system to absorb stress and withstand disruptions and damages,
3. How it then regains function over time, through response in the short-term, and recovery over a longer time horizon,
4. Potentially even improving function above pre-event or sub-optimal operations through adaptation.

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[9] Lounis, Z., & McAllister, T. P. (2016). Risk-based decision making for sustainable and resilient infrastructure systems. Journal of Structural Engineering, 142(9), F4016005. doi:10. 1061/(ASCE)ST.1943-541X.0001545

[10] The White House, Presidential Policy Directive/PPD-21. "Critical Infrastructure Security and Resilience," February 12, 2013. obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

[11] Documents and policy directives differ the terminology they use, especially in what they name the capabilities that support resilient outcomes.

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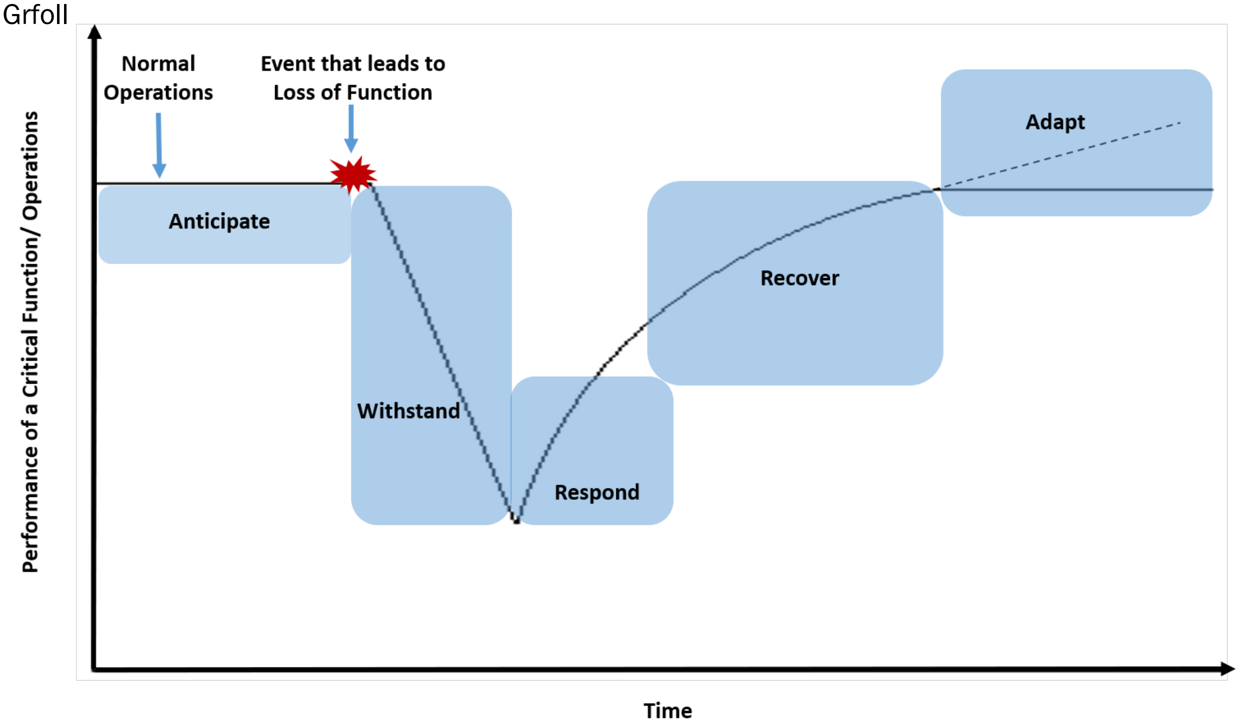

Figure 5.1 Performance of a Critical Function or Operation over Time.

Defining resilience in terms of capabilities is useful for guiding the various activities that can build these capabilities. A resilience assessment will help determine whether the necessary capabilities exist and are sufficient to maintain critical functions under stressors and shocks. This is especially done through Objective 3: by anticipating what will happen during a disruptive event, immediately after, and further out in the future.

Examples of increasing resilience of a specific function or purpose:

- International manufacturers want a resilient system-of-ports to get products to customers that avoids additional transportation costs or delays if a hazard disrupts usual origin/destination
- A port wants resilient security operations to safeguard cargo and cargo systems from physical and cyber threats
- A community wants a resilient port that recovers quickly and resumes operations so that jobs are not lost after a disruptive event
- The federal government wants a resilient MTS-based supply chain network to ensure sufficient exports and imports to meet the needs of U.S. suppliers and consumers
- Terminal operators want a resilient electric supply to power cargo handling equipment after a natural hazard event

Resilience is a property of systems and is concerned with whether they can function or operate. Note that Figure 5.1 plots function/operations over time. This view aligns with the DHS National Critical Functions construct, which acknowledges that provision of the nation's most vital functions comes from systems of entities, a perspective that evolved to more effectively address system-wide and cross-sector risks than more narrowly focused risk management.[12] Thinking about who can benefit from resilience and what functions need to be resilient is an exercise that can

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[12] National Critical Functions cisa.gov/national-critical-functions

help to identify which key functions of MTS operations should be targeted for resilience assessment and enhancement. The adjacent text box gives some examples of beneficiaries of resilient MTS functions.

The systems that deliver key functions are composed of infrastructure components, which are the backbones of MTS, along with a wide array of supporting assets, services, skillsets, governance, relationships, and communication. This is evident when infrastructure is damaged and recovery depends on other parts of the system (to sense damage, activate resources and expertise, access knowledge about contingency plans, provide redundancy, and many more activities). During normal times as well, functions rely on complex systems, which necessitates a holistic view of how functions underpin operations and how system components are interconnected. This MTS Guide emphasizes taking a broad view of the system to understand dependencies and find potential vulnerabilities and opportunities for resilience enhancement. A holistic view that looks at physical infrastructure, people, organizations, and their interactions will help to formulate a portfolio of strategies to reduce overall losses when disruptive events occur. These could include creative and "easy-win" solutions, ones that improve supporting capacities, build characteristics that activate during and after disruptive events (e.g., adaptable, agile, and flexible), and deliver diverse benefits.

2.1 RESILIENCE-RELATED CONCEPTS

Resilience is related and complementary to other system characteristics that managers aim to build, including security, sustainability, and adaptive capacity, to improve the short- and long-term success of their systems. The relationship of resilience to each is briefly discussed here to help distinguish resilience as a distinct characteristic that merits attention. Complementarity among them should not be assumed, though it is possible to achieve with deliberate effort. For example, sustainability is often sought by reducing redundancies whereas redundancies can be important for resilience.

Security, sustainability, and adaptive capacity can be treated as management objectives and can be part of a risk management approach, where risk is generally the potential for an event to occur that leads to unwanted, negative consequences (see Appendix C for more information on the role of risk assessment).[13] Risk management takes the form of various interventions to mitigate negative consequences. For example, **security** measures aim to prevent identified threats from occurring.[14] However, uncertainty and limited resources can constrain the ability to prevent all events, therefore resilience measures are necessary to enable rapid recovery and improvement between disturbances.[15] Preparatory and in-the-moment action to facilitate response and recovery are important, as is adaptive capacity. **Adaptive capacity** resides with individuals, communities or firms, and institutions, and enables systems to respond to change to be better suited to current and future realities.[16] Particularly in long-term planning or cases of repetitive damage, resilience and the course of action taken after hazards occur should be considered alongside **sustainability** to avoid maladaptive recovery and potentially wasted resources.[17] Resources can be more efficiently applied if when recovering from a disruption, a system is concurrently adapted to a future of potentially

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[13] Society of Risk Analysis Glossary, updated 2018, sra.org/wp-content/uploads/2020/04/SRA-Glossary-FINAL.pdf

[14] Department of Homeland Security (2010). Quadrennial Homeland Security Review Report: A Strategic Framework for a Secure Homeland. dhs.gov/xlibrary/assets/qhsr_report.pdf

[15] Ibid.

[16] Smit, B. and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16 (3): 282-292, https://doi.org/10.1016/j.gloenvcha.2006.03.008.

[17] World Commission on Environment and Development. (1987). Our common future. Oxford: Oxford University Press.

higher-level disturbances. At the same time, changes that seek to improve resilience can also target sustainability, such as measures that would result in lower emissions.[18] [19]

Though management objectives are often combined, they may entail complementary but distinct activities to accomplish their common goal.

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[18] PIANC. (2019) Carbon Management for Port and Navigation Infrastructure. EnviCom 188.

[19] EPA's Ports Initiative program (epa.gov/ports-initiative) accelerates adoption of cleaner technologies, planning practices such as conducting emissions inventories, and productive community engagement at ports across the country.

3.0 WHAT IS A RESILIENCE ASSESSMENT OBJECTIVE?

The overarching goal of a resilience assessment is to understand how well a system will perform its intended function(s) over time, including under scenarios that can disrupt normal functioning. This Guide describes an assessment process that is fulfilled through four key objectives that support analysis of the MTS and its diversity of system types and contexts.

These four objectives form the foundation of any resilience assessment and can provide a framework to assess project goals, determine the emphasis of an assessment, and design an assessment plan and analytic strategy that is tailored accordingly. During issue identification and early engagements with core stakeholders and collaborating partners, these objectives may reveal areas of particular interest that need to be addressed. Table 1 describes each objective and provides a series of questions that each seeks to answer.

Table 1. Assessment Objectives

Objectives	Description	Key Questions	Appendix
1. Define functions & characterize system in steady state	Concerned with identifying the functions performed by the MTS and understanding normal operations, including key stakeholders and operators, governance structures, planning activities, and characteristics of MTS activities.	What are the most important services the system provides? How does the system function during steady state? What are performance metrics that indicate how operable system functions are? During a disruption, what will the system need from the surrounding community? What will the system be relied upon for to support the community?	A
2. Analyze critical infrastructure & dependencies	Concerned with understanding the infrastructure systems that support operations as well their dependencies, including dependence on infrastructure outside of the port or region being studied.	What are the key assets of the system that lead to/support its critical functions? On what other system components/ systems are function-critical components dependent? Relevant information about system components: Condition or capabilities of assets? Location? Ownership/authority to make changes? Access to resources?	B

Objectives	Description	Key Questions	Appendix
3. Understand the impacts of disruptive events	Concerned with assessing risks from disruptive events on baseline operations, including likelihood and potential consequences from incidents as well as the capacity of a port or MTS network to prepare for, resist, recover, and adapt to adverse circumstances.	What threats and hazards could disrupt critical functions? What long-term stressors could limit or disrupt critical functions? What are the consequences of these threats and hazards occurring? How will the system perform under stress? How is the system supposed to perform during a disruption? What are the recovery time objectives? What are the existing Response and Recovery Plans? Where are the high consequence failure points and what are the cascading effects of failure?	C
4. Recommend and take actions to improve the outcome and response to disruptive events	Concerned with identifying, evaluating, and prioritizing actions that can improve resilience to disruptive events, including potential investments and planning activities that can reduce system risk.	What actions can be taken to increase preparedness for the occurrence of known and unknown threats and hazards? What strategy should be devised to build long-term resilience? How can that align with existing plans and be coordinated with other stakeholders? Which measures should be prioritized for implementation (evaluate alternatives for increasing resilience)? How should the context of adjacent communities' resilience be incorporated?	D

Ultimately, the objectives serve to ensure that the activities that are undertaken collectively comprise a resilience assessment. Moreover, this MTS Guide organizes resilience assessment methods and resources by assessment objectives to help guide users to match their assessment plan with the right tools and data.

The following subsections describe these objectives briefly and provide guidance for executing them within the context of an assessment.

3.1 DEFINE FUNCTIONS & CHARACTERIZE SYSTEM IN STEADY STATE

During project execution, a common first step is to characterize the functions and system being studied. Characterization improves the baseline understanding of functions critical to system operations, and the infrastructure assets and systems supporting them. This provides a basis for analyzing dependencies and potential system vulnerabilities and managing infrastructure risk.

Characterization begins with understanding where the guide user seeks to enhance resilience. Figure 6 depicts the geographic elements of the MTS which provides a framework for characterization:

1. **Navigable waterways:** Open-ocean, channels, and river and canal systems upon which maritime vessels operate
2. **Ports:** Nodes at the interface between maritime and land-based transportation systems where cargo is loaded and unloaded
3. **Intermodal connections:** Linkages that enable the transfer of cargo between transportation modes at the land/water boundary, located on or near terminals within the port area including truck, rail, pipeline, and air services which facilitate both inbound and outbound movement of goods
4. **Communities:** Areas and interests surrounding ports and intermodal connections that support and rely upon MTS operations and the coastal and riverine resources, including infrastructure operators providing lifeline services to the MTS, the MTS workforce; employers that rely on the MTS for operations; residents living near the MTS; and state and local government and community groups with interests in land use and transportation planning, the local economy, and environmental impacts.[20]

Figure 6. Geographic elements of the MTS

These geographic elements can help champions, guide users, and stakeholders consider where in the MTS they are seeking to enhance resilience and where the infrastructure systems of greatest concern are located.

Characterization also requires understanding the functions that the MTS both requires from and provides to surrounding communities. Ultimately, the goal of assessments should be to enhance the resilience of a function rather than any one infrastructure system or asset. A functional approach can help guide users retain a broad perspective on the causes of resilience challenges and potential solutions. The RAND Corporation and the National Academies present three “layers” that help delineate the functions that the MTS it requires:[21]

- **Physical logistics** involves the actual movement of goods through the supply chain from origin to destination
- **Transaction systems** enable procurement, tracking, and distribution of goods; of these activities which are primarily driven by information flow rather than physical movement

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[20] Greenberg, M., 2021, Ports and Environmental Justice in the United States: An Exploratory Statistical Analysis, Risk Analysis, in press.

[21] National Academies of Sciences, Engineering, and Medicine 2014. *Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains*. Washington, DC: The National Academies Press. doi.org/10.17226/23428; Willis, H. and Ortiz, D., *Assessing the Security of the Global Containerized Supply Chain,* RAND Corporation, 2005.

- **Governance** is the sum of the many ways individuals and institutions, public and private, plan and manage the common affairs and includes but is not limited to the policy and regulatory frameworks. For the MTS, this includes the systems, stakeholders, and processes that manage commerce as well as security, safety, health, environmental, and enforce rules of behavior through standards, fines, and duties.[22]

Defining Functions

"Functions" can be understood as the ultimate purpose that an infrastructure asset, system, or series of systems collectively achieves. These functions are relied upon by other systems, communities, regions, or even the Nation collectively. Functions are often provided by a diverse set of public and private sector partners and often cross geographic and jurisdictional boundaries. For example, a power plant, substations, and series of transmission and distribution lines all support the "function" of providing electric power to a port terminal, but that same function can also be provided by a generator, battery, or microgrid during a disruption. As users seek to enhance resilience, they should consider what functions are essential to port operations and seek to reduce loss of functions rather than loss of individual assets or systems.

The CISA National Risk Management Center has defined 55 "National Critical Functions" so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof. Transport of Cargo and Passengers by Vessel—a service provided by the MTS—has been identified as a National Critical Function and ports rely on this and many other functions to operate daily.

In addition, lifeline services such as power, water, fuel, communications, and emergency response are essential to MTS operations and vice versa. Navigation systems, port terminals, and intermodal nodes all rely on a complex web of power, communications, and water systems to operate, but they also provide transportation of equipment and critical products for those sectors. These four functions are linked, and disruptions to one function can have cascading consequences for others. To better understand and characterize them, each of these four functions can be broken down into more specific subfunctions that are associated with individual infrastructure systems, as illustrated in Table 2.

Table 2. MTS Functions

Functions	Sub-functions	Infrastructure Systems
Physical/Logistics	**Navigation:** Activities and systems that support safe and secure passage of vessels to and from port.	Dredging/Salvage
		Aids to Navigation
		Pilotage

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[22] "Governance can also be defined as a set of social and legal practices, institutions, knowledge, meetings, values and diverse decisions that may be best understood from the micro political as constructed by institutions in specific locations (Healey, P. 2009. City regions and place development. Regional Studies 43 (6):831-843), or operating across scales (Cash, D., W. Adger, F. Berkes, P. Garden, L. Lebel, and P. Olsson. 2006. Scale and cross-scale dynamics: Governance and information in a multilevel world. Ecology and Society 11 (2)).

Functions	Sub-functions	Infrastructure Systems
		Tug Services
		Locks and Dams
	Transfer: Activities and systems that enable the movement of cargo and passengers between the land and maritime domains.	Cargo Transfer Operations
		Intermodal Connections
		Terminal Operating Systems
		Consolidation/ Distribution
	Storage: Activities and systems that allow cargo to be stored and tracked in a safe and secure manner.	Yards
		Warehouses
		Tanks/Silos
	Ships Services: Supplementary activities that allow vessels to dock and make additional calls.	Vessel Berthing
		Fueling/Bunkering
		Ship Stores
		Shore Power
		Waste Discharge
Transactions	**Business Operations:** Activities and systems that allow cargo and commodities to be bought, sold, and moved through supply chains.	Business Operating Systems
	Tracking: Activities and systems for monitoring and tracking cargo and passengers as it moves through supply chains.	Cargo Tracking
Governance	**Security:** Activities and systems that seek to prevent criminal or adversarial use of the MTS and supply chains.	Security
		Detection/Inspections
	Regulatory/Oversight: Activities and systems for meeting regulatory and enforcement missions related to trade and the environment.	Customs
		Environmental Protection
Lifeline Services	**Lifeline Services:** Activities and systems responsible for providing fundamental services that enable all MTS functions.	Electricity
		Fuels
		Water/Wastewater
		Communications

Functions	Sub-functions	Infrastructure Systems
		Transportation
		Emergency Response

Equipped with an understanding of functions and governance structures, guide users can characterize what infrastructure systems and stakeholders support functions are of interest, establish performance goals, determine how various incidents and disruptions will impact functions, and identify and evaluate how resilience enhancements might reduce risk.

Defining functions and characterization establishes a baseline understanding of systems and steady-state operations within the MTS. Characterization activities may include collecting asset lists, reviewing planning documents, developing mapping and dependency data, and interviewing operators about their systems. The goal of characterization is not to develop an exhaustive picture of MTS operations: assessments should focus on characterizing only those functions, systems, and geographic elements critical to the purpose of the study, rather than cataloging all of the various infrastructure systems and governance structures present. Ultimately, characterization provides a point of departure for further analysis including analyzing critical dependencies, providing a benchmark for analyzing risk of disruptions, and assessing the effectiveness of mitigation options.

3.2 ANALYZE CRITICAL INFRASTRUCTURE AND DEPENDENCIES

The tasks of characterization, critical infrastructure identification, and dependency analysis are linked. To characterize a system, guide users will have to identify infrastructure assets and systems that enable MTS operations and develop an understanding of system dependencies. As discussed in the preceding section, infrastructure systems can be aligned with the functions and geographic elements that comprise the MTS to conduct characterization. When developing data collection strategies, taking a functional approach can help guide users determine which objectives of MTS operations they will focus on and which infrastructure systems will be detailed: ultimately the goal of dependency analysis is not to develop an exhaustive list of dependent relationships between infrastructure systems, but to identify high-consequence relationships that can disrupt MTS operations and functions.

A key element of assessing the resilience of MTS infrastructure systems is understanding the set of dependencies and interdependencies between these systems. As shown in Table 3, dependencies can take several forms, including physical, cyber, geographic and logical.[23]

Table 3. Categories of Dependencies

Type	Description	Example
Physical	Dependency on material output(s) of other infrastructure through a functional and structural linkage between the inputs and outputs of two assets. In other words, a commodity produced by one infrastructure is needed as an input by another infrastructure for its operation. This	Cranes reliant on electric power to move cargo

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[23] Rinaldi, Peerenboom, and Kelly (2001).

Type	Description	Example
	includes reliance on personnel needed to support infrastructure operations.	
Cyber	Dependency on information and data transmitted through the information infrastructure via electronic or informational links. Outputs from the information infrastructure serve as inputs to other infrastructure, with the relevant commodity being information.	Fuel terminal reliant on Supervisory control and data acquisition (SCADA) system and IT software to monitor and control pumps and valves that allow fuel to be transferred to and from ships
Geographic	Dependency on the local environment, where an event can trigger changes in the state of operations in multiple infrastructure assets or systems. A geographic dependency occurs when elements of infrastructure assets are in close spatial proximity (e.g., a joint utility right-of-way).	Power lines, fiber optic lines, and pipelines sharing a right of way along a bridge crossing a channel
Logical	Dependency on the state of other infrastructure via connections other than physical, cyber, or geographical. Logical dependency is attributable to human decisions and actions and is not the result of physical or cyber processes and can include policy, regulatory, and financial constraints.	Policy requirement to survey channel following a disruption before ship traffic can resume

Understanding the dependency relationships between MTS infrastructure systems and their reliance on externally provided lifeline services can be extremely valuable when seeking to understand and address resilience challenges and identify relevant stakeholders. Mitigation actions taken to harden one port system, for example, may be of little value if it has upstream dependencies on other systems that are more vulnerable to the same threat. Appendix B discusses common MTS dependencies in detail and presents a series of diagrams depicting dependency relationships in MTS.

Dependency identification and analysis can vary greatly in complexity, from open-source identification of likely dependencies, to structured interviews with MTS and infrastructure system operators, to complex modeling and analysis to assess second and third-order impacts of disruption and identify cascading failures. In all cases, the level of analysis should be structured to meet the objectives of the assessment and project constraints. The Dependency Analysis Framework developed by Argonne National Laboratory is a useful resource for understanding how to approach dependencies and determining what level of analysis is appropriate for a given assessment.[24]

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[24] Petit, Frederic, Duane Verner, and Leslie-Anne Levy, 2017, Regional Resiliency Assessment Program Dependency Analysis Framework, Argonne National Laboratory, Global Security Sciences Division, ANL/GSS-17/05, Argonne, IL. Accessed April 26, 2021 publications.anl.gov/anlpubs/2018/04/137844.pdf.

3.3 UNDERSTAND THE IMPACTS OF DISRUPTIVE EVENTS

To measure or assess the impacts of a disruptive event, one must first identify pertinent threats and hazards to consider. Then, those hazards or threats should be modeled or discussed with experts to identify potential impacts. These two steps are often the first actions undertaken in a risk assessment. Risk management is a well-developed field with a large variety of resources and methodologies that will be quickly summarized in this section. Risk assessments are closely related to resilience assessments. The nature of this relationship is debated in the literature but centers around how both concepts can be integrated as part of a management strategy to understand what losses could be suffered, the system's ability to recover degraded or lost functions, and the options that exist in the future to minimize those losses.[25] [26] [27] Preparation begins with risk awareness, leading toward proactive risk management steps that will ideally promote the flexibility of the system for a wide range of scenarios and avoid unintended consequences of future investments.

MTS stakeholders must regularly make choices and take actions to promote or increase safety, continuity, and preparedness. To do this, they must be aware of what threats could damage or disrupt the system and be able to identify and weigh options for averting losses.[28] Risk assessment methods help guide users to characterize the potential for loss or harm due to specific threats that exploit vulnerabilities in their system. The Federal Emergency Management Agency's (FEMA) Threat and Hazard Identification and Risk Assessment (THIRA) Framework[29] suggests asking the following questions:

- Which realistic threats and hazards will be the most challenging to manage?
- If they occurred, what impacts would those threats and hazards have?
- Based on those impacts, what capabilities will the system need to manage the incident?

Effective risk management reduces the parameters of risk, which are the probability of a threat materializing; the vulnerability of the system in question to the threat; and the consequences of any loss in function.

Appendix C provides a basic overview of the wide variety of threats and hazards that could impact the MTS and the different types of analysis that address these focus areas: Threat and Hazard Exposure Analysis, Vulnerability Analysis, and Consequence Analysis. These three components make up the risk assessment triplet.[30] [31] To achieve the Resilience Assessment Objective of "Understanding the Impacts of Disruptive Events", a guide user may aim to address all these focus areas or just one, depending on the objectives set during study scoping.

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[25] Van der Vegt, G., Essens, P. Wahlstrom, M., George, G. (2015). Managing Risk and Resilience: from the Editors". Academy of Management Journal. 58(4), 971 – 980.

[26] Rød, B., Lange, D., Theocharidou, M., & Pursiainen, C. (2020). From risk management to resilience management in critical infrastructure. *Journal of Management in Engineering*, *36*(4), 04020039.

[27] Parra, N. M., Nagi, A., & Kersten, W. (2018). Risk Assessment in Seaports". *Hazard Project Publication Series.*

[28] Sullivan-Wiley, K. A., & Gianotti, A. G. S. (2017). Risk perception in a multi-hazard environment. *World Development*, *97*, 138-152.

[29] FEMA. (2019). 2019 National Threat and Hazard Identification and Risk Assessment (THIRA) Overview and Methodology. fema.gov/sites/default/files/2020-06/fema_national-thira-overview-methodology_2019_0.pdf

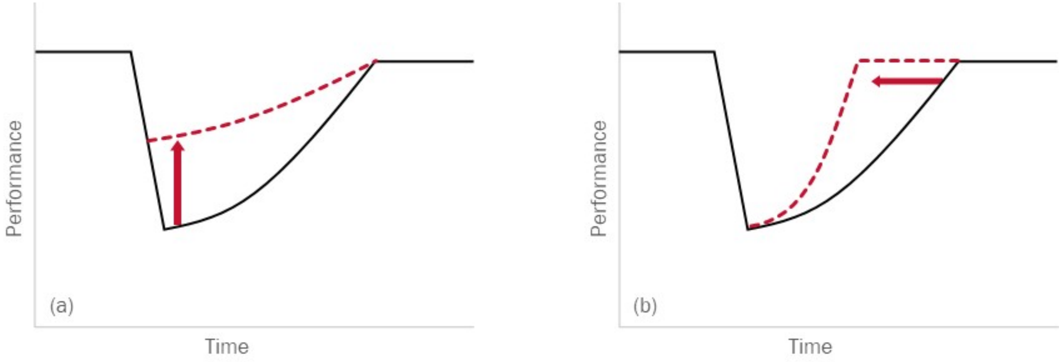
[30] Cox, Jr, L. A. (2008). Some limitations of "Risk= Threat× Vulnerability× Consequence" for risk analysis of terrorist attacks. *Risk Analysis: An International Journal*, *28*(6), 1749-1761.

[31] RAMCAP™ Framework. 2006. Available at:asme-iti.org/RAMCAP/RAMCAP_Framework_2.cfm.

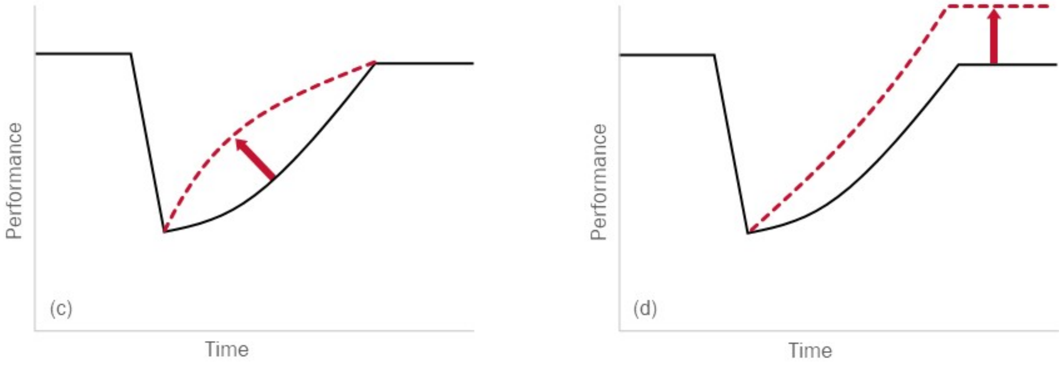
3.4 IDENTIFY AND EVALUATE RESILIENCE ENHANCEMENT ALTERNATIVES

The various activities and analyses of the resilience assessment process to achieve the objectives prescribed in this Guide (Define functions & characterize system in steady state; Analyze critical infrastructure & dependencies; and Understand the impact of disruptive events) establish a baseline picture of system resilience. Areas of relative weakness across the resilience cycle are more apparent and can be approached as opportunities for improvement. As depicted by the trajectory of the recovery curves in Figure 7, resilience enhancement can generally have an impact via:

a) Planning and mitigation measures to reduce the impact of a disruption
b) Measures to expedite recovery times
c) Measures to improve system function during recovery
d) Measures to improve system performance to better than before the disruption



IMPROVED MITIGATION **IMPROVED RECOVERY**



IMPROVED RESPONSE **IMPROVED ADAPTATION**

Figure 7. Four alternative depictions of the baseline performance of a system over time.[32]

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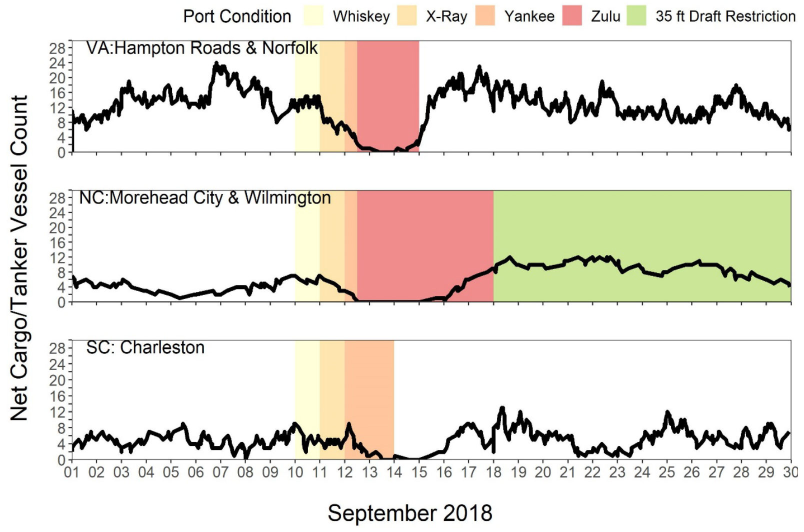
[32] Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W.,...Thiel-Clemen, T. (2014b). Changing the resilience paradigm. Nature Climate Change, 4(6), 407–409. doi:10.1038/nclimate2227

The assessment process outlined in this MTS Guide (function/operations focus, inclusive of stakeholders, and scope-tier framework) identifies avenues and ideas for enhancing resilience, where prospective projects may target different dimensions of the system; target a specific point in time before, during or after a disruptive event; target resilience over short- or long-term time horizon; and be relevant to single or multi-hazard scenarios.

Net vessel count (NVC) can serve as resilience indicator for ports. Gathered from widely available automatic identification system (AIS) data, NVC can measure the impacts of hurricanes on the recovery of port traffic at a single port or across a region (Touzinsky et al. 2018). In this figure, the impacts of hurricane Florence (2018) can be compared across three ports: Virginia, Wilmington and Morehead City, and Charleston. Net vessel counts are overlaid with USCG port conditions (CMTS 2020).



The range of options for enhancing resilience encompasses many activities, including:

- Environmental, land use, redevelopment and transportation plans that could address MTS functions in a region
- Regulatory and procedural decisions by state or federal agencies
- Private sector operational decisions to be coordinated
- Public or private investment in mitigation measures
- Collaborative information sharing and management arrangements to avoid disruptions and share resources during or after incidents
- Community education and exercise actions

The diversity of opportunities and candidate resilience measures that can be produced by the assessment process presents a challenge for evaluating, prioritizing, and selecting among them for implementation. It can be difficult to compare resilience enhancing measures; therefore, a customized method can help to systematically analyze alternatives. This will include:

1. **Performance metrics** – Aspects of the system or system performance that are indicative of how resilient it is. A resilience enhancing measure should improve the performance of the system based on the metrics a guide user has selected (e.g., cargo/time, value, water quality, response and recovery times, etc.). For example, Net Vessel Count can serve as an indicator of how well an MTS performed over time, before, during, and after a disruption. Importantly, models and methods that were used to characterize the system during steady-state and under stress will likely dictate or inform what performance metrics are feasible and they will serve as the environment for evaluating success. Simulation or less quantitative prediction of system functioning will produce outputs that are traceable over time and can be

compared to actual outcomes. Additionally, many port-related studies propose metrics that are highly related to the functionality of a port.[33]

2. **Other considerations** - Decision makers may need to balance numerous interests and management objectives when selecting a strategy to optimize their system's overall performance. These include formal costs and benefits of interventions, as well as feasibility, compatibility, buy-in, and others.
3. **Structured selection process** - Whether the evaluation process used to select resilience measures for implementation relies on an analytical framework and quantitative metrics or takes a more qualitative form, a structured process that can accommodate many considerations and reflect different priorities and preferences of stakeholders is valuable. An approach that identifies and weights criteria, and then evaluates alternatives against them should be pursued formally or conceptually.

Appendix D provides a more detailed description of how a method for evaluating resilience enhancing measures can be evaluated and selected for implementation.

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[33] Sun, W., Paolo, B., & Davidson, B. (2018). Resilience metrics and measurement methods for transportation infrastructure: The state of the art. *Sustainable and Resilient Infrastructure*, 5(3), 168-199.

4.0 THE RESILIENCE ASSESSMENT PROCESS

Assessments can take many forms, from broad studies that take a regional perspective and consider a range of threats and hazards to narrowly tailored efforts focused on a single risk scenario for an individual terminal. Regardless of scope, there is a series of activities and practices that can help ensure an assessment accomplishes its goal. While the previous section discussed the four objectives that comprise a resilience assessment, this section outlines a generalized process for planning, designing, executing an assessment and implementing its results (Figure 8). Beginning with pre-assessment, this section provides an approach for conducting resilience assessments and provides practical tips and considerations that can lay the foundation for a sound assessment and ensure it stays on track throughout execution.

Types of Decisions:

- Investments in redundancy for continuity of supply chain operations
- Investments in infrastructure to reduce vulnerabilities
- Multi-modal infrastructure investments
- Operator enhancements to cargo processing
- Collaborative governance for contingencies

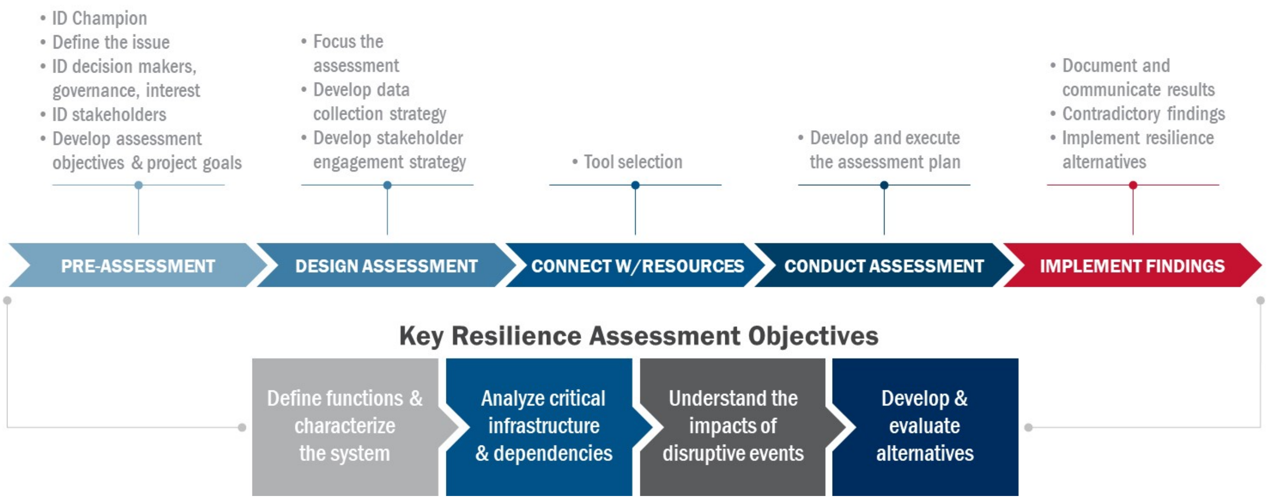

Figure 8. Generalized assessment process

4.1 CONDUCT PRE-ASSESSMENT

One of the primary challenges in enhancing resilience is that the MTS represents a nexus of over overlapping interests and authorities. An assessment process can serve to bring those interests and decision makers together to agree on a problem and the system vulnerabilities that each will have some power or resources to help address. Before beginning an assessment, guide users should consider several factors that will shape the project and help determine how it should proceed, including:

- Identify Champion: Who will sponsor the assessment, help organize stakeholders and lead implementation?
- Define the Issue: What is the resilience issue being addressed?
- Identify Decision Makers, Governance, and Interests: What governance structures, decision makers, and interests are party to the solution?
- Identify Stakeholders: How should decision makers be engaged in the assessment to increase the chance that it is used in their decisions?
- Develop Assessment Objectives and Project Goals: What are the goals and objectives of the assessment?

This section takes these factors one-by-one and introduces a set of activities that guide users should consider to increase the likelihood that resilience assessment findings and recommendations are implemented. It should be noted that these are not sequential steps. They are often conducted simultaneously and iteratively until the assessment team and key stakeholders have coalesced around a project concept that can serve as the basis for an assessment. This phase can be time-intensive and challenging, but—done well—can result in cohesion amongst decision makers and the assessment team and a unified understanding of the project's objectives and desired outcomes.

4.1.1 Identify Champion

In addition to the team that will execute an assessment, a champion is needed to sponsor the assessment and authorize time and resources. A champion should be invested in the results of an assessment, be able to shape and shepherd the process, and facilitate dialogue regarding how the assessment will contribute to a plan or decision. The team organizing an assessment may be its own champion so long as it has the authority and resources to support the study and implement results. In other cases, the assessment team may work with an external champion who is actively involved in assessment design and implementation but not project execution. Regardless of whether the champion is the organization conducting the assessment, or merely sponsoring it, a champion should assist with identifying decision makers and stakeholders, facilitating engagement to support the assessment, and managing implementation activities once the assessment is complete.

4.1.2 Define the issue

The need for a resilience assessment can come from a recent disruption, a grant opportunity, investment in MTS facilities, or an update to plans for responding to and recovering from hazards. Regardless of its origin, a successful resilience assessment requires a central issue that represents a challenge facing a port, port network, or inland waterway.

A common problem in planning and decision processes is moving from "need" to "solution" without a full understanding of the challenges contributing to a

Motivations for assessment

- Past incidents
- Exercises
- Existing plans and planning groups
- Private sector partners
- Previous assessments
- Trends and forecasts
- Intelligence/threat reports

This document is a guidance document and does not establish any legally enforceable requirements.

resilience issue. Without a comprehensive understanding of causes, solutions may not address underlying challenges. A thoughtful approach to issue identification can help guide users define their assessment in a way that mitigates this potential stumbling block. Resilience issues are perceived and experienced differently by different stakeholders and a facilitated process can be used to fully explore the dimensions of an issue before scoping an assessment.

Regardless of the source of the issue, consulting previous work and potential partners can build support for an assessment, help refine ideas, and lead to the identification of data, reports, and stakeholders that can inform the project.

4.1.3 Identify Decision Makers, Governance, and Interests

Resilience issues are perceived and experienced differently by stakeholders and a facilitated process can be used to fully explore the dimensions of an issue before scoping an assessment. Assessments benefit from an understanding of the institutional arrangements, which help shape how an assessment is scoped, executed, and implemented. This requires exploring what public and private sector entities make plans and decisions affecting MTS resilience, as well as their interests and goals for an assessment. Steady-state and response and recovery operations within the MTS depend on synchronized decisions among multiple public and private parties that operate, regulate, or utilize it. An assessment focused on reducing the risk of channel closure, for example, may involve state and local agencies, a board of elected or government-appointed port officials, terminal operators, and federal agencies such as the Coast Guard and U.S. Army Corps of Engineers, all of whom come to the table with different missions and objectives. Moreover, that same assessment will confront a range of pre-existing requirements, plans, and procedures specifying which parties are responsible for which aspects of the problem space. Table 4 outlines common key stakeholders for MTS resilience assessments, as well as key decisions and activities they may conduct related to MTS resilience.[34] Although stakeholders may share common interests such as safety, security, and continuous, efficient operations, they often have different perspectives, goals, and capability to influence or implement resilience alternatives.

Table 4. Sample stakeholders and associated decisions and activities

Stakeholder Organizations	Sample Decisions and Activities
Port Authorities	Apply for grants to assess resilience or implement resilience enhancement alternatives, develop port-wide response and recovery plans, sponsor working groups and committees to enhance resilience
Terminal Operators	Evaluate and implement resilience alternatives concerning terminal equipment, utilities and labor force that enhance terminal operations Apply for grants to assess resilience or implement resilience enhancements
Local, State and Federal Governments (USCG, USACE, State and Federal DOT)	Regulatory and governance decisions affecting port operations. Provide grants to assess resilience or implement resilience enhancement alternatives

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[34] Adapted from National Academy of Sciences, "Making U.S. Ports Resilient as Part of Extended Intermodal Supply Chains." (2014) National Academy of Sciences, Washington DC

Stakeholder Organizations	Sample Decisions and Activities
	Provide funding and contract for resilience enhancements to terminals, waterways, highways, and intermodal connections
Local Utility Companies	Ensure / upgrade utilities to terminals such as electric grid, gas, water, and communications networks are resilient and provide the required capacity to support port operations
Port and Local Fire and Police Departments and Local Hospitals	First responders to port disruption incidents. Revise response and recovery operations plans based on resilience assessments findings
Port Advisory Panels/Planning Councils/Community Groups	Pre-planning and development of incident management protocols and training exercises. Development of stakeholder interagency coordination and communications protocols
Port Labor Unions / work force (Stevedores, Crane Operators, etc.)	Collaborate with terminal operators to assess, evaluate, and implement enhancements that create a more resilient work force while ensuring appropriate working conditions
Inland Freight Carriers Trucking Firms, Railroads, Pipelines,	Provide cargo handling requirements to port authorities and terminal operators to facilitate resilient cargo operations
Maritime Vessel Operators, Shipping Lines, Barge Operators	Provide vessel cargo handling and berthing requirements to port authorities and terminal operators to facilitate resilient cargo operations

Guide users should consider in advance which public and private entities are most important to addressing the central issue of the assessment and the “decision space” they have to make a decision based on new information. Decision space refers to the range of choices an entity has and includes both its formal or mandated authority and relationships with other entities important to the outcome. The concept includes a combination of accountability, organizational capacity, roles, responsibilities, and mechanisms framing possible decisions.[35] The term here refers to the constraints and opportunities to make a decision that will affect strategies or operations. This can help guide users develop a sharper focus on what novel information an assessment can contribute to support decision makers and decision-making processes. Even when each key party has a different goal or interest, an assessment can create a shared baseline of information and support collective planning.

4.1.4 Identify Stakeholders

As guide users define what issues their resilience assessment will address, they should also consider which stakeholders will be critical to the success of the project. Decades of planning practice has shown that implementation is improved by deliberatively engaging decision makers and interests in

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[35] Tamlyn Eslie Roman,* Susan Cleary, and Diane McIntyre. *Exploring the Functioning of Decision Space: A Review of the Available Health Systems Literature.* Int J Health Policy Manag. 2017 Jul; 6(7): 365–376. Published online 2017 Feb 27. doi: 10.15171/ijhpm.2017.26 PMCID: PMC5505106 PMID: 28812832

the assessment and planning process.[36] In the previous section, the MTS Guide introduced the need to understand the range of institutional arrangements and stakeholders who will have an interest in the outcome of an assessment. As guide users define what issues their assessment will address, they should also begin outreach to the set of stakeholders who will be critical to implementation. At this stage, stakeholder engagement is designed to accomplish three outcomes:

- To share knowledge of the issue, potential challenges, and existing data and information that can support an assessment
- Build commitment to implementation of the results among multiple public and private entities responsible for aspects of port and supply chain resilience
- Build social capital among the groups that need to work together throughout the assessment, as well as during disruptions.

Sample Project Goals and Objectives

The goals guide users develop and the issues they seek to address should help determine which objectives will be a focus for their assessment. For example, an assessment that seeks to **increase awareness of roles and responsibilities for planning and mitigation activities** may involve significant focus on Defining Functions and Characterizing Systems in Steady State, as well as Identify and Evaluate Resilience Enhancement Alternatives as guide users seek to understand the range of actors responsible for MTS operations and assign responsibility for planning and mitigation activities.

An assessment focused on **identifying options for enhancing the resilience of a bridge connecting a port to its surrounding community**, by contrast implies a sharper focus on Understanding the Impacts of Disruptive Events and Identifying and Evaluation Resilience Enhancement Alternatives.

Assessments are most successful when those with practical knowledge of the system and the resources and influence to implement recommendations are involved throughout the process. A rigorous, analytically-sound assessment is worth little if the stakeholders who have the resources or authority to act on its findings have no interest in the work. Because of this, it is important to involve these decision makers to gauge their interest and seek their input on project goals and constraints. Structured and deliberate engagement is worth the time and resource commitment and is essential to both gathering assessment data and implementation of results as further detailed in Section 3.2 and 3.3.

Pre-Assessment Activities for Contracted Assessments

Working through pre-assessment considerations can help users develop an RFP for a contracted assessment to be performed by a third party by defining broad project activities, identifying key stakeholders, and establishing consensus on project goals.

4.1.5 Develop Assessment Objectives and Project Goals

Defining and refining the issue which an assessment seeks to address supports the development of project goals as well as the identification of objectives that will be central to it. Considering project

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[36] Innes, J. E., and D. E. Booher. 1999. Consensus building and complex adaptive systems - a framework for evaluating collaborative planning. *Journal of the American Planning Association* 65:412-423. https://doi.org/10.1080/01944369908976071

goals and assessment objectives should answer the question “what are we really trying to accomplish?” and articulate the desired end-state that will result from the project. Determining which objectives will be central to the assessment helps guide users determine the tier and scope of their study and ultimately informs method selection. Virtually all assessments will contain elements of the four objectives established in Section 3.0, but not all will require the same level of analytic effort to meet project goals. Moreover, this MTS Guide organizes resilience assessment methods and resources by assessment objectives; identifying which objectives are most important to the assessment can help identify the right tools and data for conducting an assessment.

Assessments can support a wide range of decisions, from informing planning activities, to identifying areas for new investment or justifying applications for grant or loan programs, to determining priorities for operational response and recovery activities. Discussing goals with core stakeholders can build consensus and focus assessment design activities.

Stakeholder Check-in: Pre-assessment

- Has an assessment champion been identified to support the assessment?
- Have key decision makers who will have roles in implementation been consulted?
- Is there concurrence amongst the assessment team, champion and key decision makers on the need for an assessment and the issue to be addressed?

4.2 DESIGN ASSESSMENT

Once a general MTS resilience issue has been identified, decision-makers and other stakeholders have been engaged, and general goals and project focus have been established, guide users can begin refining and scoping their assessment. Assessment design is concerned with elaborating on and clarifying the issue that will be studied, bounding the project, and planning data collection and stakeholder engagement activities.

4.2.1 Focus the Assessment

Identifying specific knowledge gaps supports the development of focused questions that the assessment will address. These knowledge gaps help create a set of “known unknowns” – key variables that will be targeted during data collection and analysis. At this stage, exhaustive definition of knowledge gaps is not necessary, but can help the assessment team think expansively about the issues that can be considered through the project.

Note that both the assessment team and key stakeholders may have an incomplete awareness of their knowledge gaps. For example, partners may understand their dependencies on goods and services required for day-to-day operations but may not understand the vulnerabilities of the upstream infrastructure systems they rely on or the consequences of their disruption. Identifying knowledge gaps as part of assessment design can help anticipate these challenges and improve data collection activities.

After defining knowledge gaps, discrete resilience assessment research questions should be developed. Research questions help frame an assessment and can protect against wasted time and effort in data collection and analysis.

Research Question Tips

A standard assessment will have a primary framing question, with a series of constituent key questions that drive analysis. It can be useful to further break these key questions down into more detailed sub-questions. A thorough set of sub-questions can drive a data collection strategy that helps a project team determine what information it already has, and what information it must gather to answer its research questions. Example:

As vessel traffic on the channel grows, what opportunities exist to reduce the risk of short and long-term disruption of the channel?

- How will the anticipated growth of channel traffic impact the likelihood and consequences of channel disruptions?
- What is the anticipated magnitude of growth?
- How will growth affect the likelihood of channel disruption?
- How will growth impact the consequences of disruption?
- What implications does this growth have for response and recovery operations?
- What infrastructure-related constraints might limit growth?

When developing research questions, guide users should consider several factors:

- Does the question address the identified issue and assessment objectives?
- Is it researchable and feasible for the people/place/scale of concern?
- What methods and data would be needed to answer the question?
- What would be the value of the findings?
- Is an answer feasible within the data, time, and analytic constraints?
- How will you know if the question was answered?

At their core, research questions define what must be answered by an assessment and establish a bridge between an identified issue and desired outcomes. Developing research questions are valuable because they:

- Narrow and formalize the focus of the study
- Subdivide research activities into manageable parts
- Support data collection and analysis planning
- Help organize outputs and deliverables

As research questions are developed, guide users will also work to refine the boundaries of their assessment. This process serves to establish boundaries for the project, inform planning activities, and set up the assessment for success.

Many bounding elements will be determined as an assessment issue is defined and research questions are developed. However, bounding formalizes these decisions and ensures they remain feasible within project constraints. Constraints can include financial, personnel, or other resource limitations that may impact the execution of an assessment, as well as any known data or analytic challenges stemming from stakeholder non-participation or data points that are fundamentally uncertain or unknowable. Identifying constraints at the outset can inform bounding decisions by forcing the assessment team to confront potential pitfalls or challenges to the project.

Bounding Considerations

Elements to take into consideration when bounding an assessment include:

- Geographic boundary
- Scope
- Port functions being studied
- Primary and secondary infrastructure sectors/systems
- Threats and hazards
- Constraints
- Data constraints
- Resource constraints

Ultimately, an assessment should be broad enough to provide a basis for informed decisions but narrow enough to fit within the timeline and resources allocated for an assessment. As boundaries are established, the assessment team can be planning assessment activities. Assessment planning helps the core team determine what activities are needed to answer research questions and inform decision makers. This includes establishing what data needs to be collected, how stakeholders can contribute to assessment execution, and what analytic approaches are relevant and feasible.

4.2.2 Develop Data Collection Strategy

A data collection strategy outlines how the project team will gather the data needed to complete analysis and answer research questions. This will be driven by both research questions and data constraints, and so will vary significantly from assessment to assessment. Despite this, several key considerations can help guide users think through their approach to data collection:

- What kinds of data are needed and why? How do they relate to the research questions?
- What approaches will the assessment team use to collect the data?
- Does data already exist? If not, what approaches will be used to generate data?
- How long will it take to complete the data collection process? Are there certain times of year to target or

Pre-Existing Data

For many assessments, significant information and data may have already been collected as part of previous efforts. As users develop data collection strategies, they should consider consulting:

- Prior assessments
- Port Strategic Plans
- Continuity of Operations Plans
- Marine Transportation System Recovery Unit (MTSRU) Plans
- Capital Improvement Plans
- USACE Regional Planning Studies
- Local/State Hazard Mitigation Plans
- Metropolitan Transportation Plans
- Brownfield/Urban Redevelopment Plans
- Watershed Management Plans

avoid due to potential conflicts? (e.g., seasonal hazards, budget cycles, syncing with similar efforts)

- How easy will it be to use the data once collected? What is the format of available data, and what format do analysts need to use it?
- Are there any data quality requirements or considerations? How up to date does the collected data need to be?
- If planning data or data generated from modeling is collected from several sources, are the assumptions and data used in such modeling and planning consistent across the sources? What are the impacts of discrepancies?
- Are there security or other restrictions on how information can be collected or used?

The answers to these questions can be used to develop a data collection strategy that outlines key areas for collection as well as the tools that the team plans to use. There are a number of methods guide users can pursue to meet their data requirements, including open-source research, document reviews, surveys, site assessments, interviews, and workshops; additional information on these methods can be found in the Regional Resilience Assessment Methodology [insert link when final].

4.2.3 Develop Stakeholder Engagement Strategy

A stakeholder engagement strategy can help guide users plan and organize further outreach efforts. The strategy should clarify how external partners will support each step in an assessment and identifies:

- The goals of engagement
- The stakeholders by interest and frequency of engagement
- Timeline and process for engagement
- The methods used to involve partners at each phase
- Communication strategies
- Conflict management
- Information protection practices

As depicted in Figure 9, primary stakeholders such as the assessment team, champion, and decision makers form a central core responsible for scoping, executing, and implementing the results of an assessment.

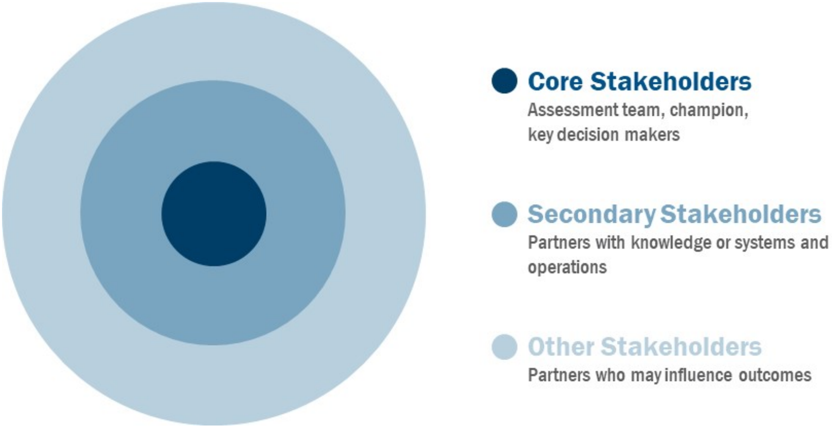

Figure 9. Stakeholder Mapping

Secondary stakeholders are collaborators; this group often includes those responsible for the infrastructure and systems of concern who will inform the assessment and use results in their own plans and activities. They represent a key source of information as well as an important audience for the assessment during implementation. The outer ring represents other stakeholders that should be consulted because they have planning, regulatory, financial, or public and private roles and power to influence, enable or impede implementation outcomes, but who are ancillary to the assessment itself.

A sound stakeholder engagement strategy will help guide users engage effectively with each of these stakeholder rings.

Stakeholder Check-in: Design Assessment

- Has a stakeholder engagement strategy been developed?
- Are there any stakeholders who may be reluctant to participate but who are critical to assessment goals?
- Has the assessment team developed an approach for sharing and protecting information collected as part of the assessment?

4.3 CONNECT WITH RESOURCES TO AID IN ANALYSIS

A resilience assessment is a mixed-methods endeavor by nature; to fulfill assessment objectives and goals, projects will leverage information generated from past efforts, available data, and analytic methods drawn from a variety of disciplines. This section provides information on selecting resources that can be used to answer research questions. The key to this section is Appendix E: The Resilience Assessment Resource Matrix, which provides a list of 100+ off-the-shelf tools, methods, data sources, guides, and useful examples from government agencies and research labs, industry, and academic institutions. This list of resources is not comprehensive, however, so guide users are encouraged to check for updates or new developments.

The following section provides background on how the Resilience Assessment Resource Matrix is organized into distinct categories selected to help guide users quickly identify the most applicable methods, tools, and resources based on their needs. The following filters are proposed to match assessment needs and existing resources (Figure 10):

- **Scope** of the system in question
- **Tier,** or level of detail of the inquiry being pursued
- **Resilience Assessment Objective**, as previously described throughout the MTS Guide.

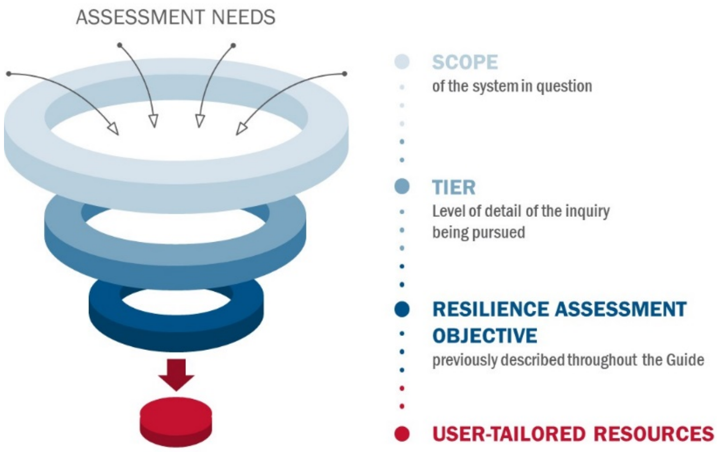

Figure 10. Identifying resources

4.3.1 TOOL SELECTION

4.3.1.1 Select Relevant Scope

The MTS Guide has divided the nationwide MTS into three scopes: a single port, network of ports, or an inland waterway. While some methods and data sources are applicable to all the MTS scopes described in this MTS Guide, others are scope-specific. Note that the scope of one critical function of the system might be different from that of another critical function. For example, a single port may be primarily concerned with continuous functioning of terminals but also interested in understanding how nearby ports can support them if terminal function is disrupted.

4.3.1.2 Select Assessment Tier

It is important to select analytic methods that will accomplish the study goals within the existing resource constraints (available staff, funding, and data) and that are matched to the level of sophistication or complexity necessary to inform decisions. The concept of assessment "tier" is adopted in this MTS Guide to categorize analytic methods by complexity, where complexity conveys both resource intensity and the level of analysis necessary to use the method. Identifying the appropriate tier for a resilience assessment study will help to filter the resources that are offered in this Guide (Figure 11).

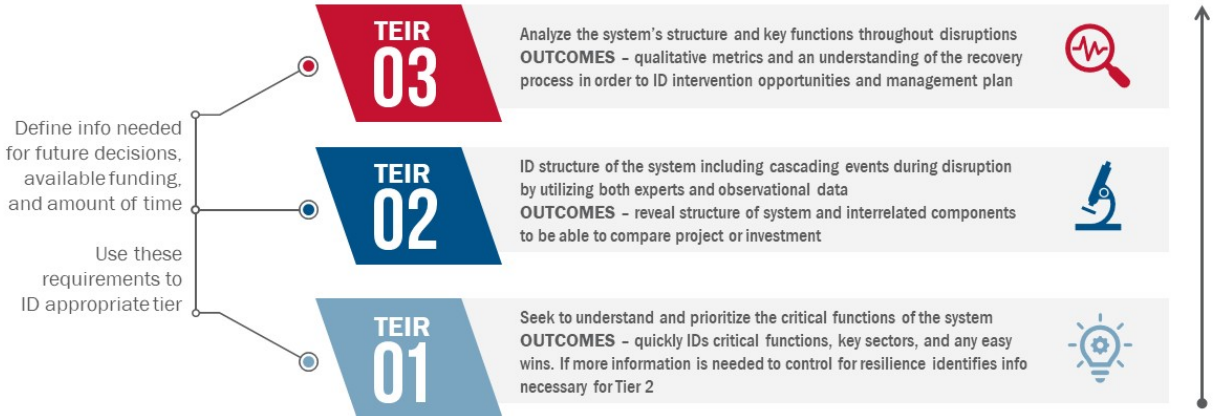

Figure 11. Using tiers to identify methods and resources

4.3.1.2.1 Tier 1 – Basic Assessments to Understand System Components (Minimal Time and Funding Requirements)

Tier 1 tools organize existing information and data to create an overview of the system. Methods for Tier 1 comprise screening-level assessments using general frameworks, indices or scorecards assembled from available metrics or surveys. Tier 1 tools can result in simple system representation, stakeholder solicitation of key functions or criteria for achieving resilience, eliciting expert judgment, and reviewing historical records, existing data, and conceptual models. These tools are often cautious in assumptions about the future.[37] Tier 1 assessments may produce inventory-type lists of resilience-relevant items. The process is valuable for forming and confirming relationships and gathering information.

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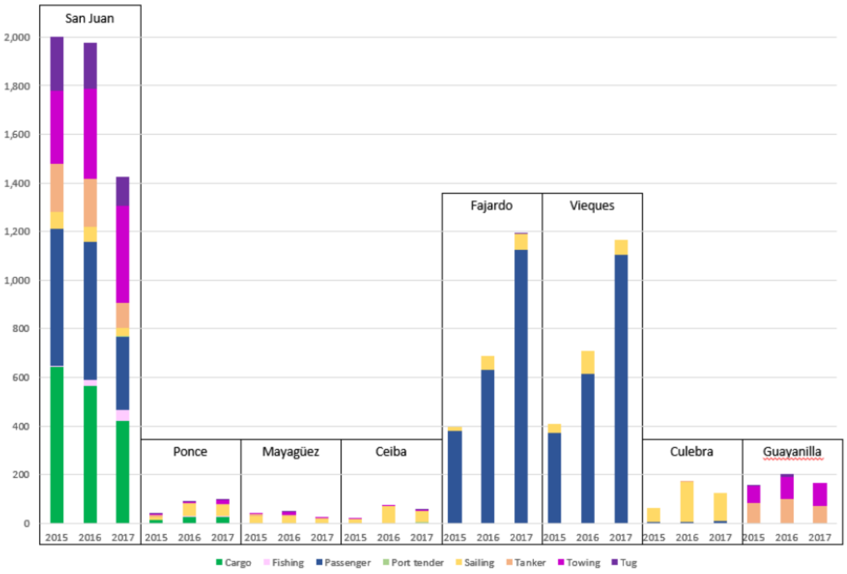
[37] Linkov, I., Fox-Lent, C., Allen, C. R., Arnott, J. C., Bellini, E., Coaffee, J., .,, Woods, D. (2018). Tiered Approach to Resilience Assessment. Risk Analysis, DOI: 10.1111/risa.12991.

Tier 1 Case Study Example: Analysis of Puerto Rico’s Marine Transportation System

The USACE ERDC contributed data to a study led by RAND on the rebuilding of Puerto Rico’s transportation systems after hurricanes Irma and Maria. This study aimed to identify the unique properties of each of Puerto Rico’s ports and harbors to see if the redundancies of the system could be improved through future investment. This information was gathered through Automatic Identification System data on vessel types and movements.



Vessel types for each arrival across Puerto Rico’s eight ports and harbors from 2015 – 2017. (Ecola et al. 2020).

Reference: Ecola, L., Davenport, A.C., Kuhn, K., Rothenberg, A.D., Cooper, E., Barrett, M., Atkin, T.F., and J. Kendall. 2020. “Rebuilding Surface, Maritime, and Air Transportation in Puerto Rico After Hurricanes Irma and Maria: Supporting Documentation for the Puerto Rico Recovery Plan”. Homeland Security Operational Analysis Center operated by the RAND Corporation, rand.org/pubs/research_reports/RR2607.html.

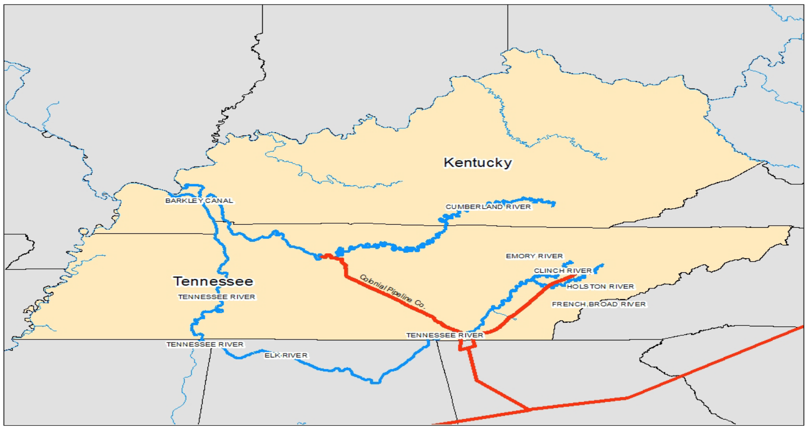
4.3.1.2.2 Tier 2 – Mid-level Assessments to Understand Systems Response to Disruption (A Range of Time and Funding Requirements)

Tier 2 methods support more detailed assessments where the main outcome is a model depicting the structure and organization of the system and its interconnected components (e.g., process or systems diagrams, interdependency analyses, vulnerability analysis). These models expand upon metrics and static indicators to describe the system’s organization, relationships, and to identify sequential and parallel events during a disruption that produce feedback processes, dependencies, and cascading system failures. These system structure representations can comprise simple process diagrams or flowcharts that encompass temporal or spatial relationships between system components or with other systems. Mapping these relationships can reveal a system’s pressure points and bottlenecks. At this tier, conservative estimates of Tier 1 results are exchanged for more faithful representations of systems.

Scenario analysis can take place at this stage, allowing stakeholders and analysts to compare interventions for strengthening resilience, according to options available and the environmental and community parameters that describe system responses.

Tier 2 Case Study Example: Resilience of the Petroleum Supply Chain on the Tennessee and Cumberland Rivers

Vanderbilt University is undertaking a study on the resilience of the Tennessee and Cumberland River Couplet System with a focus on the exposure of the petroleum supply chain to three natural hazards evaluated as independent scenarios: flood, drought, and earthquake. The resilience assessment for this system will utilize data and expert elicitation to characterize the inland system, evaluate potential disruption scenarios, and suggest resilience strategies for the region.

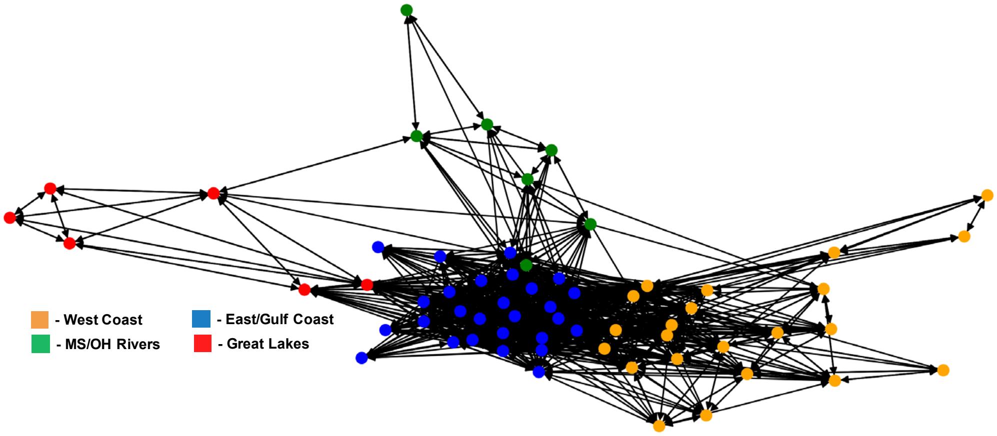


The Tennessee and Columbia River Couplet system and petroleum pipelines (red).

For more information on this study, please contact the study leads: Drs. Janey Camp (Janey.Camp@vanderbilt.edu) and Craig Philip (Craig.E.Philip@vanderbilt.edu)

Tier 2 Case Study Example: National Marine Transportation System Network

The Engineer Research and Development Center utilized ten years of Automatic Identification System (AIS) data on vessel movements to better understand the connectivity and seasonality of the top 50 tonnage ports (and several remote ports) in the United States. The structure and connectivity of the port network was determined through counts of vessel trips and is a preliminary step in learning more about the effect of disruptions on the network.



An un-directed graph model of port connectivity within and across port regions for the year of 2018.

For more information on this study, please contact the study leads: Drs. David Young (David.L.Young@usace.army.mil) and Brandan Scully (Brandan.S.Scully@usace.army.mil)

4.3.1.2.3 Tier 3 – Detailed Assessments to Provide Detailed Qualitative Information about the System (Extensive Time and Funding Requirements)

Tier 3 assessments create a detailed model of critical functions and connected subsystems that parameterize each process and each element of the system. Tier 3 methods are most applicable to assessments where systems are sufficiently complex or variable[38] and well understood and quantified (i.e., data is available) to be represented accurately.

Tier 3 methods model a real-world system in high fidelity by depicting the specific conditions in which risks occur or the performance of important functions falters (e.g., Bayesian Network Models, Agent-Based Models, probabilistic models, game theory, etc.). Accordingly, Tier 3 models are most useful for modeling "conditional" performance under unusual or emerging conditions.[39] The Tier 3 approach requires the mode of failure, not the cause, allowing a wide range of situations to test system performance in an uncertain future.

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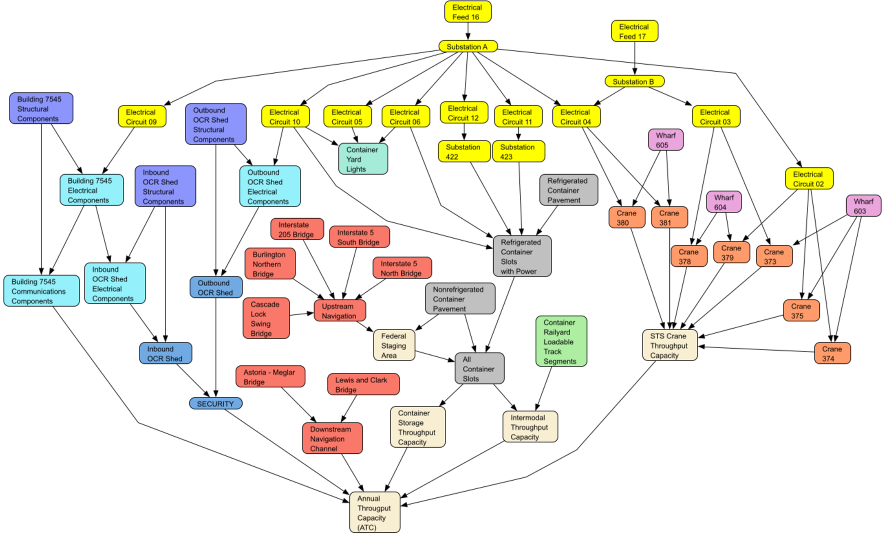
[38] Linkov, I., Fox-Lent, C., Allen, C. R., Arnott, J. C., Bellini, E., Coaffee, J., .,, Woods, D. (2018). Tiered Approach to Resilience Assessment. Risk Analysis, DOI: 10.1111/risa.12991.

[39] Linkov, I., Fox-Lent, C., Allen, C. R., Arnott, J. C., Bellini, E., Coaffee, J., Woods, D. (2018). Tiered Approach to Resilience Assessment. Risk Analysis, DOI: 10.1111/risa.12991.

Tier 3 Case Study Example: Probabilistic Network Analysis at the Port of Portland

The Engineer Research and Development Center is working with the Port of Portland to evaluate alternatives for improving the resilience of its container handling function at Terminal 6 to earthquakes. The potential for using portions of Terminal 6 as a FEMA staging area will also be evaluated. FEMA would use the staging area to receive and redistribute emergency supplies to areas affected by a disaster. To do this, researchers are constructing a probabilistic network model to simulate damage to infrastructure components from earthquakes and impacts on container throughput capacity over the recovery period. The probabilistic network model will serve as a computational tool to help stakeholders explore and evaluate alternatives for strengthening resilience.



Probabilistic networks are graphical models for reasoning about uncertainty in systems with interdependent components.

For more information on this study, please contact the study lead: Dr. Martin Schultz (Martin.T.Schultz@usace.army.mil).

4.3.1.3 Select Key Resiliency Assessment Objectives

All assessments will include some components of the four Resilience Assessment Objectives identified during pre-assessment:

- Define Functions & Characterize System in Steady State
- Identify Critical Infrastructure and Dependencies
- Understand the Impacts of Disruptive Events
- Identify and Evaluate Resilience Enhancement Alternatives

Each of these objectives should be addressed to form a picture of how to prepare the system to be resilient to shocks and stressors. However, the methods and data sources used are likely to vary for each system. Understanding the goals of an assessment for each of these Objectives can help identify the most appropriate resources in the Resilience Assessment Resource Matrix and help ensure that analytic methods will result in actionable outputs that meet project goals.

4.3.1.4 Use Filters to Identify Relevant Resources

The Resilience Assessment Resource Matrix that is available for download with this MTS Guide is organized by the filters described above to tailor and direct guide users to a list of resources that is tailored to their needs (as in Figure 12). Once scope, tier, and Resilience Assessment Objective have been determined, the guide user can "jump" directly to the most relevant available resources (tools, methodologies, data sources, guides, examples). For example, if guide users are interested in designing a resilience assessment for a single port at a cursory level (Tier 1) and want to see the resources available to help "Define functions and characterize system in steady state" they should select that combination of filters. Some resources will describe tabletop exercises with port stakeholders, others are datasets that can be used to establish how the port functions during normal times or about environmental conditions in the port vicinity, while other resources are quantitative models. Some resources are port-specific while others are hazard-specific or related to resilience and risk. The Resilience Assessment Resource Matrix documents some important caveats to further help guide users select resources that are suited for their needs (e.g., if special access is needed or resources cost money).

Each resource has a description and details for how to access its contents. Those that are applicable to multiple categories appear in multiple tables. It is also possible to view the master sheet of unfiltered entries.

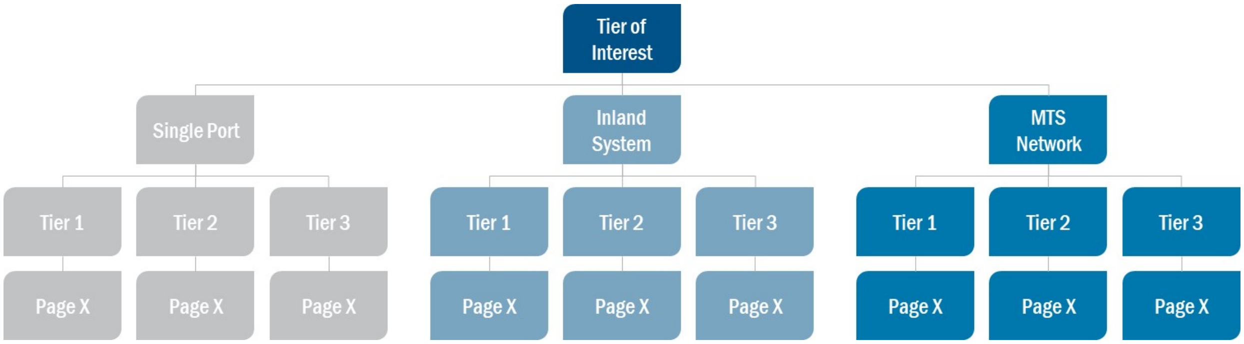


Figure 12. Demonstration of the resource database that is available for download

Stakeholder Check-in: Method Selection

- Will stakeholders be able to provide information necessary to conduct analysis?
- Will the analytic methods selected lead to results that can be clearly communicated to decision makers and stakeholders?
- What analytic products will the selected methods result in? How can they be shared or used by decision makers and stakeholders?

4.4 CONDUCT ASSESSMENT

As the data collection and analysis strategies are finalized, a project plan can be developed to serve as the blueprint for executing the assessment. A typical project plan should include all the elements developed in previous phases, including stakeholder mapping, objectives, a problem statement, knowledge gaps, research questions, the set of activities required to successfully achieve assessment objectives and answer research questions, resources allocated to each activity, and assessment timeline.

Once a project plan has been developed, the assessment team can begin formally executing the assessment. The project plan provides a roadmap for conducting an assessment and should be modified or updated to reflect changing conditions and progress. As the assessment progresses and evolves, new information, partners, and approaches may come to light, and guide users should be flexible in incorporating these developments as they occur while retaining a focus on the core project goals and decisions they seek to inform. In progress reviews with decision makers and stakeholders provide an opportunity to keep partners informed, provide initial findings, and discuss how assessment outcomes can best support implementation activities?

Stakeholder Check-in: Project Execution

- As the assessment progresses, are there additional stakeholders that need to be consulted?
- How regularly should decision makers and stakeholders be updated on assessment progress and findings?
- Are decision makers and stakeholders consulted on the development of analytic products and resources?

4.5 IMPLEMENT FINDINGS

An assessment can inform multiple types of decisions from preparedness and response planning to recovery objectives and long-term planning for system resilience and adaptation to multiple drivers and risks as noted in Figure 13 and considered in scoping the assessment objectives (Figure 8). The pre-assessment work and assessment design the guide user executed should help avoid the well-worn problem of “studies on a shelf” through strategic inclusion of a champion, decision makers, and stakeholders throughout the entire assessment process.

Resilience assessments can provide information for planning, management and investment decisions, including identifying priority areas to for long-term resilience enhancements, addressing gaps and vulnerabilities, and mitigating impacts to critical infrastructure. The implementation of an assessment recommendation requires alignment of several decision makers' interests within and outside the port area depending on the resilience-related objectives. It will also do so by identifying desired outcomes of these stakeholders, around which a guide user will build the assessment, so that the findings fit neatly into the implementation of the desired outcome of the stakeholders. Good examples of this are to perform a resilience assessment specifically with the goal of informing a long-term risk mitigation strategy, or the updating a regional emergency response plan. The findings then fit into the existing activity or process of the stakeholders.

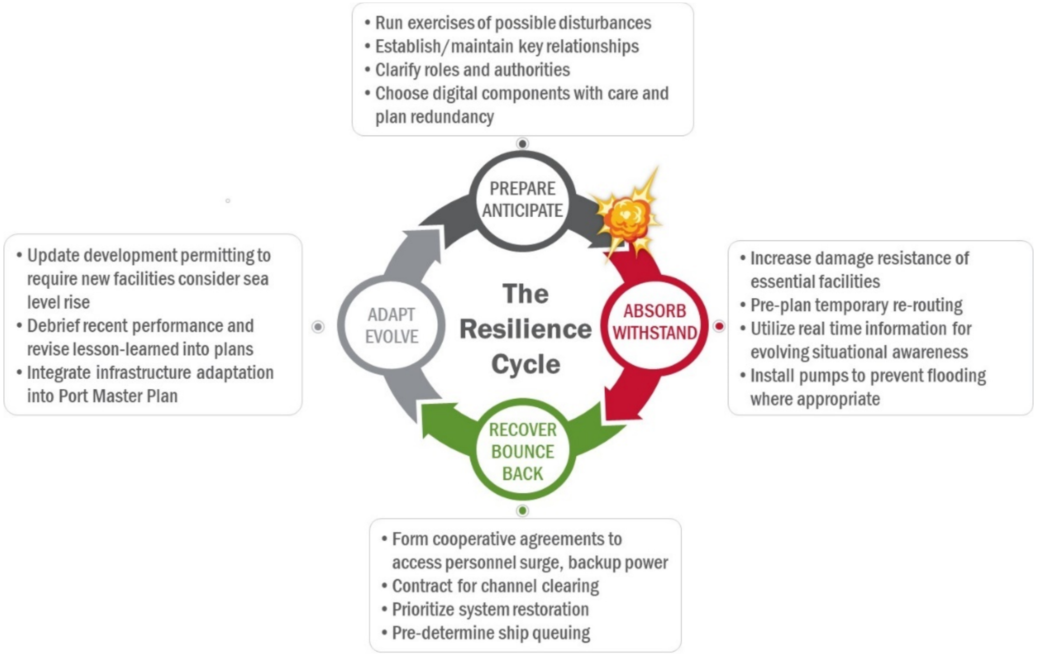


Figure 13. Assessment findings can help decision makers manage risk across the spectrum of resilience

Implementation actions and strategies for communicating results will depend on the project goal, the stakeholder responsibilities, political interests, and the authorities that enable and constrain potential actions, which will have been identified earlier when identifying the three tiers of stakeholders shown in Figure 10. The outer ring or third tier represented “stakeholders that should be consulted because they have planning, regulatory, financial, or public and private roles and power to influence, enable or impede implementation outcomes.” The communication and implementation strategy will consider the benefits and timing and framing of communications during the assessment as well as when findings are available.

For example, the National Oceanic and Atmospheric Administration (NOAA) and the USACE have responsibility for surveying channels, clearing debris, and the USCG surveys/replaces aids to navigation in order to open a port during hurricane response. However, recommendations of a resilience assessment for recovery planning would likely address the involvement of the local and state transportation planners and water, electric, and communication utility providers. In another example, the port authority may report to a city council that is responding to external economic or environmental interests. Appendix A includes a discussion of federal and state regulatory authorities that affect “the decision space” for actions during response. If the assessment recommendations address long-term system resilience or adaptive capacity, then the champion and core stakeholders will identify the types of actions needed, those responsible for those actions, their interests, and the limits of their authority or budgets “decision space” to make the “business case” for any implementation.

As guide users develop an implementation strategy, they should consider several factors, including:

- What is the short-term and long-term goal for the area of concern?
- Which findings can or should be implemented by the champion or sponsor?
- What other plans and projects could be modified or influenced by these findings?
- What are the limitations? What other public and private entities make key decisions that would need to be changed?

- What institutions exist or could be used to convene decision makers and interests to consider the assessment results?
- Who should be briefed on the findings and in what form to persuade a change in decisions?

Achieving buy-in from private sector infrastructure owners may be challenging due to concerns about potential-regulation, business sensitivities, or competing viewpoints of key partners. Identifying and effectively communicating the explicit, partner-specific benefits can help assuage concerns about perceived risks. For example, benefits for private sector partners could include enhanced awareness of how their operations may be affected by disruptions to other systems. This awareness would have implications on business continuity planning, greater visibility into government planning efforts for mitigation, response, and recovery priorities, and deeper partnerships with public sector counterparts. Benefits for government partners could include an improved understanding of the operational requirements of critical infrastructure, more realistic assumptions for disaster response and recovery, insights into possible cascading infrastructure failures, and deeper partnerships with private sector counterparts. Having these benefits identified in detail will increase the likelihood of implementation.

4.5.1 Documenting and Communicating Results

As introduced in section 4.2.3, the foundation of a communication strategy is the identification of both stakeholder interests and their role in implementing resilience enhancement alternatives suggested by the assessment: what they need to know, how they will use the information, and what is the best way to communicate the information to them. The final results of a resilience assessment might involve a wide audience with a recognizable stake in the issues explored. This audience could be from the government, private sector, and non-profit entities and may have different professional disciplines, technical expertise, roles, responsibilities and perspectives (e.g., port authority, engineers, operations and maintenance professionals, emergency managers, and security specialists).

To reach across these disciplines and interests, the bottom-line results and associated recommendations should be summarized carefully to resonate with the intended audience by synthesizing results into key findings and action items. Key findings should communicate important observations from the analysis and outline how they relate to the resilience of the MTS being assessed. The issues identified in key findings may tie back to technical specifications associated with the infrastructure, resilience gaps and failure points identified through the analysis, and stovepipes between key partners that create operational and governance challenges. Findings should not focus exclusively on gaps or problems; findings that establish effective practices or suggest that the consequences of a possible hazard are less than expected are also very valuable.

The project champion needs to ensure that assessment findings are clear and effectively communicated to primary and secondary partners who will be responsible for implementation, as well as consulting partners who have an interest in assessment results. After identifying and documenting results from a resilience assessment, an important next step is to share draft results with stakeholders to maintain their buy-in for the effort, offer opportunities for validation and refinement of findings, and generate ideas for ways to close identified resilience gaps. These draft results and associated courses of action, as well as the body of research and analysis, need to be presented to stakeholders in a compelling and useful format (or multiple formats) that meets their intended uses. Depending on the assessment goals, some results may be pertinent to a broad audience (e.g. overall summary report), while other outputs may be targeted to a specific audience (e.g. technical reports for specific agencies, site-specific findings for a specific infrastructure owner). Tabletop Exercises and workshops offer additional avenues for sharing results with interested parties; outlining outcomes from the assessment, discussing possible next steps, and providing in-depth reviews on technical analyses. As guide users prepare to communicate findings, they should consider the decision space their audience has and tailor their messaging accordingly. Identifying the most compelling results and creating digestible findings, outlining potential courses of actions that address resilience, and effectively communicating the assessment results with key stakeholders can help frame a strategy for implementation based on the final outputs.

4.5.2 Contradictory and negative findings

At times, assessment data suggest one or more resilience outcomes. Key findings can include a description of what is known and what is yet to be known, based on the assessment. “Negative” findings (or problems encountered during the assessment and/or implementation phase) can produce valuable information. Thus, negative findings should be included. Recommendations or Resilience Enhancements from an assessment can face challenges by decision-makers as their goal is to protect the resilience or capability of the MTS to perform its functions. Decision-makers tend to devote their lives to logic and facts but often can be influenced by emotions or opinions. Nonetheless, assessment bias may be an issue that often decision-makers may find themselves on the other side of the data. There could be a stigma surrounding negative, adverse, or unexpected findings as they will become a low priority for decision-makers even though the assessment findings may determine they are a high priority. Negative or unexpected findings can save guide users valuable time and resources by not repeating already performed assessments, so it is important that all results, regardless of the outcome are briefed to stakeholders.

4.5.3 Implementing Resilience Alternatives

Resilience alternatives are usually a set of actions or elements tailored to specific decision makers. Implementing these alternatives involves conveying the decision to those impacted by it and getting their buy-in. Those who participate in the process are more likely to support the outcome. As guide users document and communicate the results of assessments, they should also work to institutionalize their findings through implementation activities and develop an approach for measuring progress. These activities can range from updating plans and procedures, to conducting workshops and exercises, to investing in physical mitigation measures, or allocating budget to resilience initiatives. As guide users identify which resilience alternatives they plan to pursue, they should develop a plan for implementation. The action plan should:

- Outline how selected resilience enhancements will be incorporated into plans and operations
- Outline processes for ongoing monitoring and evaluation of the effectiveness of implemented resilience enhancements
- Support continual awareness of threats and vulnerabilities
- Articulate a clear understanding of organizational risk tolerance to assist officials with priorities and manage risk throughout the organization
- Ensure knowledge and control of changes to organizational systems and operations
- Be aligned with or integrated into ongoing risk management processes to minimize duplication of effort

Guide users should consider the sequencing of implementation activities—some resilience alternatives can be implemented right away, while others may be incorporated in planning processes and capital investment decisions years down the road. Working with decision makers and key stakeholders, guide users should determine what implementation activities are near and long-term priorities. For longer-term priorities, guide users should ensure they periodically revisit decisions when new data and information becomes available or when risk tolerance levels change to ensure that resilience alternatives are still appropriate and cost effective. Throughout implementation, guide users should seek to embed assessment findings into ongoing work and decision-making processes. If guide users have worked with key stakeholders and decision makers from the outset, this may be a straightforward process, but it should still be undertaken deliberately.

Guide users should also consider how implementation activities will be funded. Some resilience alternatives, like a holding a workshop or establishing a working group, may have minimal cost associated with them but large-scale capital improvements may have substantial upfront costs and require long-term outlays for operations and maintenance. Several approaches are available for financing resilience alternatives, including:

- Funding through operating profits
- Bond issuance
- Subsidized and unsubsidized loans
- State or local appropriations
- Federal grants

The U.S. Committee on Maritime Transportation Security, publishes a handbook of federal funding opportunities for MTS infrastructure and may be a valuable resource for guide users as they examine funding options.[40] New funding opportunities, such as the U.S. Department of Transportation Maritime Administration Port Infrastructure Development Grants, the FEMA Building Resilient Infrastructure and Communities grant program, and the FEMA Port Security Grant Program are developed and updated regularly.[41]

Finally, users should consider how they measure progress. Maintaining metrics for implementation—which can range from a simple checklist to the regular gathering of quantitative data to measure progress—can help guide users ensure the results of an assessment are being used and leading to desired outcomes. Metrics are an objective means of an assessment and they tend to have a favorable impact on productivity and could fall into categories such as infrastructure condition, employee health, emergency planning, and intermodal and community measures. Metrics provide data on expectations versus reality. With effective metrics, guide users can be more confident in the ability to influence conditions in the port community and become more actively engaged.

Stakeholder Check-in: Implementation

- Has the assessment team carefully considered how analytic findings should be communicated and who they should be communicated to?
- Have findings and analytic products been communicated to all relevant decision makers and stakeholders?
- Does each implementation activity have a party assigned for execution and progress monitoring?

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[40] U.S. Committee on the Marine Transportation System (2019). "Federal Funding Handbook for Marine Transportation System Infrastructure." CMTS Washington DC. https://www.cmts.gov/assets/uploads/documents/Federal_Funding_Handbook_2019_FINAL_Jan2020_corrected.pdf

[41] Federal Emergency Management Agency (2020). "Building Resilient Infrastructure and Communities." FEMA, Washington DC. fema.gov/grants/mitigation/building-resilient-infrastructure-communities

5.0 CONCLUSION

The MTS is composed of an array of interdependent physical parts, including coastal and inland waterways, ports and terminals, vessels, intermodal connectors like highways, railways, and pipelines, as well as the companies, organizations, and workers that use, operate, and maintain the system.

The MTS Guide offers a generalized process and tools for conceiving, designing, and implementing a resilience assessment. The process leverages four key resilience objectives to ensure that every assessment results in a broader understanding the MTS, its development drivers, interactions with stakeholders, and the critical functions and infrastructure interdependencies. The process also provides an organized set of tools and resources to complete an assessment according to guide user objectives, scope, and available resources. The objective of the MTS Guide is to draw on existing resources to provide a consistent replicable framework for conducting a resilience assessment that results in actionable resilience recommendations for federal agencies, state and local governments, academia and private industry.

APPENDIX A: DEFINE FUNCTIONS AND CHARACTERIZE THE SYSTEMS

This appendix introduces a framework for describing and characterizing port operations through the examination of the physical logistics, transaction, and oversight activities that together enable ports to perform commercial functions. This framework provides a common approach for developing and scoping assessments and describing resilience challenges and actions.

Characterization begins with understanding where within the MTS the guide user seeks to enhance resilience. Figure A-1 depicts the geographic elements of the MTS which provides a framework for characterization:

1. **Navigable waterways:** Open-ocean, channels, and river and canal systems upon which marine vessels operate.
2. **Ports:** Nodes at the interface between marine and land-based transportation systems where cargo is loaded and unloaded.
3. **Intermodal connections:** Linkages that enable the transfer of cargo between transportation modes at the land/water boundary, located on or near terminals within the port area including truck, rail, pipeline, and air services which facilitate both inbound and outbound movement of goods.
4. **Communities:** Areas and interests surrounding ports and intermodal connections that support and rely upon MTS operations and the coastal and riverine resources, including infrastructure operators providing lifeline services to the MTS, the MTS workforce; employers that rely on the MTS for operations; residents living near the MTS; and state and local government and community groups with interests in land use and transportation planning, the local economy, and environmental impacts. [42]

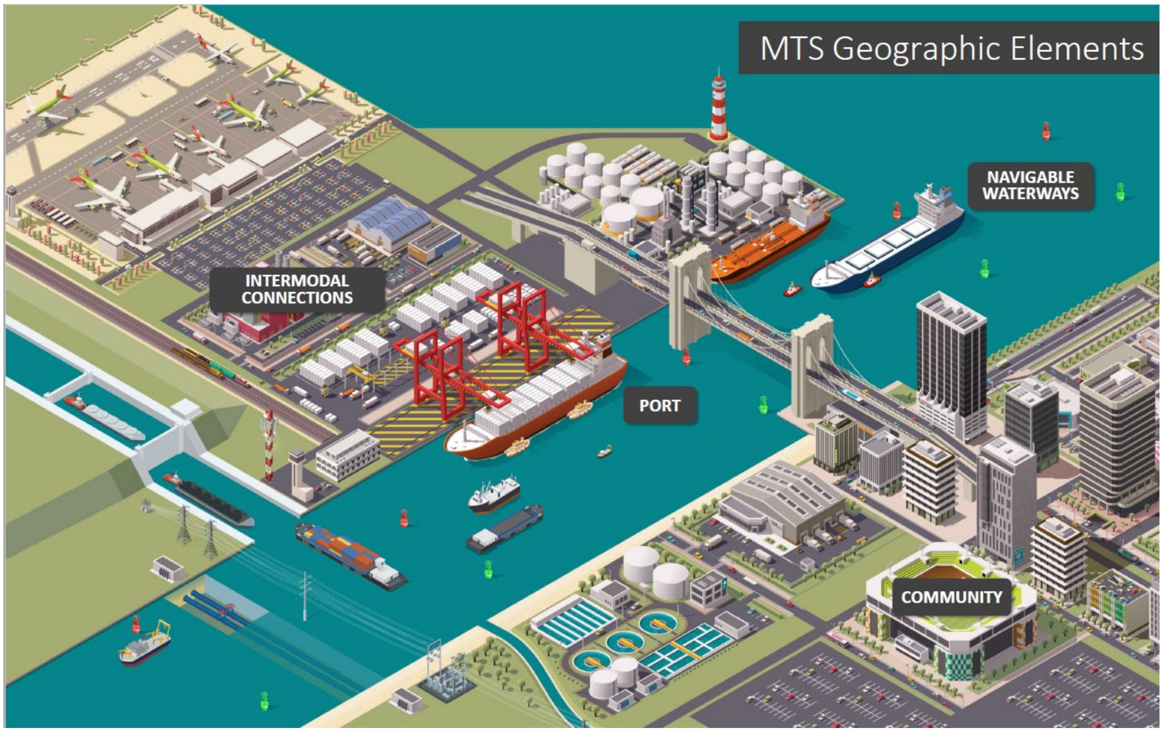

Figure A-1. Geographic elements of the MTS

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[42] Greenberg, M., 2021, Ports and Environmental Justice in the United States: An Exploratory Statistical Analysis, Risk Analysis, in press.

Within each of these geographic elements, several functions—from the movement of vessels to the transfer, storage, and tracking of cargo—are supported by infrastructure systems and assets. As illustrated in the MTS Guide, a key goal of resilience assessments is to ensure that these functions can still be performed, or rapidly recovered, even when individual infrastructure systems and assets are disrupted. Table A-1 outlines key functions performed at each of the geographic elements and identifies infrastructure systems and assets that enable those functions.

Table A-1. Functions and supporting infrastructure systems by geographic element.

Geographic Element	Functions	Infrastructure Systems
Navigable Waterways	Navigation	Aids to Navigation, Pilotage, Channel Maintenance (Dredging, Surveying and Salvage), Locks and Dams
	Transfer of Cargo	Lightering
	Vessel Tracking/Monitoring	Vessel Traffic Services
Ports	Transfer of Cargo	Cargo Handling Systems, Container Freight Stations, Terminal Operating Systems
	Trade Enforcement	Detection, Inspection, Operational Systems
	Cargo Tracking/Monitoring	Business Operations Systems, Terminal Operating Systems
	Ship Services	Berthing, Bunkering, Shore Power, Ship Services
	Storage	Container Yards, Warehouses, Silos, Tankage
	Business Operations	Business Operations Systems
Intermodal Connections	Transfer of Cargo	Cargo Handling Systems, Rail Transfer Yards, Freight Transfer Yards, Fuel Racks, Entry/Exit Gates and Scales
	Cargo Tracking/Monitoring	Business Operations Systems, Terminal Operating Systems
	Business Operations	Business Operations Systems
Communities	Lifeline Services	Electric Power, Fuels, Water, Wastewater, Communications, Transportation
	Transfer of Cargo	Consolidation and Distribution Centers

Across each of the four geographic elements, these functions and infrastructure operations governed and managed by three sets of systems that enable the MTS to perform its primary function of facilitating commerce:[43]

- **Physical logistics systems** that are responsible for the physical movement of cargo
- **Transaction systems** that manage the procurement, tracking, and distribution of cargo
- **Governance systems** that are the sum of the many ways individuals and institutions, public and private, plan and manage the common affairs and includes but is not limited to the policy and regulatory frameworks. For the MTS, this includes the systems, stakeholders, and processes that manage commerce as well as security, safety, health, environmental, and enforce rules of behavior through standards, fines, and duties.[44]

This characterization section provides an overview of the components and stakeholders that make up physical logistics, transaction, and oversight systems within navigable waterways, and at ports, intermodal connections, and communities.

NAVIGABLE WATERWAYS

Navigable waterways comprise the "marine and inland waterway" portion of the MTS and can include open ocean, shipping channels, and inland waterways depending on the scope of an assessment effort. For the purposes of this guide, "navigable waterways" includes all waterborne operations up to berth at a port. The navigable waterway also includes land-based assets and systems that support operations at sea and in channels.

Physical Logistics Systems

Within navigable waterways, physical logistics systems support two primary commercial functions: navigation and the transfer of goods. Navigation includes the infrastructure systems and assets that enable the physical movement of ships and cargo into and out of ports, including:

- Aids to navigation (ATON) that assist vessels to safely move through open ocean and channels, including physical, electronic, and virtual ATON
- Pilotage for guiding vessels to anchorages and berths
- Channel maintenance systems that ensure the navigability of the channel itself, including dredging, channel surveying, and salvage capabilities
- In the context of inland waterways, navigation also includes locks, dams, and flood control mechanisms that preserve channel navigability

Though less common, some cargo transfer does take place within navigable waterways. Lightering operations can be used to remove cargo to accommodate draft restrictions or redirect goods bound for another destination.

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[43] Modified from Making U.S. Ports Resilient, RAND Assessing Container Security, Trans Research Board Est Economic Impacts

[44] "Governance can also be defined as a set of social and legal practices, institutions, knowledge, meetings, values and diverse decisions that may be best understood from the micro political as constructed by institutions in specific locations (Healey, P. 2009. City regions and place development. Regional Studies 43 (6):831-843), or operating across scales (Cash, D., W. Adger, F. Berkes, P. Garden, L. Lebel, and P. Olsson. 2006. Scale and cross-scale dynamics: Governance and information in a multilevel world. Ecology and Society 11 (2)).

Transaction Systems

Transaction systems within navigable waterways are primarily concerned with tracking vessels and cargo at sea and on their approach to the port. This includes vessel tracking services provided by the U.S. Coast Guard, as well as other tracking services provided by port operators, pilots, or other stakeholders. These systems rely on both operations centers used to operate vessel tracking systems and remote sites located along a channel that transmit video and information about channel operations.

Governance Systems

The governance system oversees operations within navigable waterways to promote safety, commerce, national security, and environmental protection and respond to and recover from incidents. Projects to enhance the resilience of navigable waterways often involve a broad set of stakeholders who operate on a seaway or channel and manage adjacent land. This can include federal landholders, state and local agencies, private companies and individuals.

The U.S. Coast Guard plays a large role on navigable waterways and is responsible for maintaining ATON and formal Vehicle Traffic Service (VTS) services, ensuring safe and secure operations, and responding to incidents. For channels where the USCG does not operate a VTS, other stakeholders such as ports, pilots, or independent organizations may fulfill a similar role managing safe vessel traffic.

For federally maintained channels, the U.S. Army Corps of Engineers provides or contracts dredging services and both USACE and non-federal sponsors manage the acquisition and maintenance of spoil sites, often in coordination with federal, state, and local agencies to meet environmental protection missions. While USACE is responsible for maintaining federal channels, ports and private sector stakeholders are required to dredge and maintain areas outside of the federal channel. Lock and dam systems are managed, maintained, and operated by USACE through a system of navigation districts.

Ports, industrial facilities, and vessels are required to develop plans to manage spills, fires, collisions, and natural hazards. These planning documents are often a key source of information for resilience assessments and a key mechanism for implementation activities.

PORT

Ports are points where goods are circulated between the maritime domain and land domain. Ports are complex entities, with both physical and institutional components that differ by function, ownership model, cargo type, and geographic location among other factors.

Physical Logistics Systems

Within individual port terminals, the composition of the physical logistics systems is determined by the cargo type handled (see Table 2). A large port typically has multiple terminals that can collectively handle many cargo types, but individual terminals are usually designed to move a single cargo type. The requirements of loading, unloading, and storing different cargo types leads to major differences in terminal design and overall port infrastructure types which require different vessels, terminal configurations, and handling equipment.[45]

Table 2. Cargo types

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[45] DOT Port Performance Freight Stats

Containerized Cargo	Cargo is containerized when it is placed in standard shipping containers that can be handled interchangeably on vessels, in terminals, and by inland transportation modes. Containerized cargo includes most consumer goods imported, generally includes the highest value and most time-sensitive maritime commodities, and terminals are designed to handle import and export cargo. Container vessels include ships and barges, for both ocean-going and inland river transport.
Dry Bulk Cargo	Includes unpacked, homogenous commodities such as grain, iron ore, or coal. Dry bulk terminals usually handle either imports or exports, not both, and rely on trucks, rail cars, and barges to connect to domestic origins and destinations.
Liquid Bulk Cargo	Includes petroleum products, various chemicals, and Liquified Natural Gas (LNG). Tankers and terminals are designed to carry, transfer, and store specific liquid bulk product types. Barges, rail cars, trucks, and pipelines are all used in domestic transportation of crude and refined products.
Break Bulk Cargo	Includes cargos that are not containerized but carried in unitized form such as palletized, bagged, strapped, bundled, crated, or drummed. Breakbulk ships vary in size and may be geared with cranes. Barges, rail cars, and trucks are used in domestic transportation.
Ro/Ro	Includes wheeled cargo, such as cars, trucks, semi-trailer trucks, and trailers that are driven on and off the ship on their own wheels using a shipboard or shoreside ramp. Barges, rail cars, and trucks are used in domestic transportation.

Despite the differences in cargo type, the systems and assets that support the physical movement of goods at ports can be broken down into several main functions:

- Cargo transfer at ports includes systems such as cranes, conveyer belts, pipelines and other systems that physically move goods off vessels and the landside heavy equipment such as forklifts and loaders that move goods to and from storage. This also includes the terminal operating systems which manage and control the physical operation of infrastructure systems including cranes and bulk liquid and dry bulk movements, to and from vessels, storage, tanks, refineries, and processing facilities.
- Storage provides yards, warehouses, tanks, and silos where inbound and outbound cargo is staged and stored.
- Ship services includes systems such as mooring, fuel bunkering, waste reception, repair services, and provisions that enable ships to make additional calls once loaded/unloaded.

Transaction Systems

At ports, transaction systems can include both business operations Information Technology (IT) systems and terminal Operational Technology (OT) systems. The IT systems create, process, store, retrieve and send information that facilitate business services including the buying, selling, and transfer of cargo, as well as coordination between operators. The OT systems monitor and control terminal operations for the processing and transfer of cargo. Additionally, the transaction layer at ports can include office facilities and financial systems used at the port to conduct business operations. Table 3 provides a list of common maritime facility/infrastructure systems. The list although not comprehensive, represents the range of IT and OT systems that are commonly found at maritime facilities and includes systems for transaction, physical logistics and governance.[46]

IT and OT systems are increasingly being integrated to facilitate data analytics and business operations which make these systems more vulnerable to exploitation and cyber-attacks that can disrupt operations. IT systems are reliant on telecommunications suppliers for connectivity services and should be considered when characterizing transaction systems.

Table 3. Common Maritime Facility/Infrastructure IT/OT Systems

Business Systems	
Passenger Check-In Systems	Distribution
Telecommunication	Accounting
Email	Human Resource
E-Commerce	Performance Management
Enterprise Resource Planning	Custom Relationship Management
Sales	Enterprise Asset Management
Procurement	Business Intelligence
Inventory Control	
Operational Control Systems	
Distributed Control Systems	Alarm Systems
Ramp Control Systems	Fire Protection Systems
Terminal Operating Systems	Environmental Protection Systems (Spill Control)
Independent Safety Systems	Emergency Shut Down Systems
Building Management Control Systems	
Building Automation Systems	Energy Management Systems
Vertical Transport Systems (Elevators, Escalators)	Exterior Lighting Control Systems
Interior Lighting Control Systems	HVAC Systems
Digital Video Management Systems	
Building Safety Systems	
Fire Alarm Systems	Public Safety/Land Mobile Radios
Fire Sprinkler Systems	Smoke and Purge Systems
Gas Detectors	Emergency Management Systems
Security Systems	
Physical Access Control Systems	Screening Systems

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[46] Maritime Cyber Security - ABS Final Project Report, Maritime Security Center, March 9, 2018. https://www.stevens.edu/sites/stevens_edu/files/files/MSC/ABS_Maritime%20CybersecurityFinalProject%20Report.pdf

Intrusion Detection Systems

Surveillance Systems

Police Dispatch

Governance Systems

As with navigable waterways, oversight systems are complex and context-specific at ports. Ports operate under a range of ownership and leasing arrangements. “Ports” or “port authorities” are not necessarily the same entities that conduct activity in the ports. Put another way, some ports are *owned* by one entity while *operated* by one or more entirely different entities. There are some ports operated and managed by the owner of the port. However, in general, the larger the port, the more likely the port owner operates little to nothing within the port itself. These are often called “land-leasing ports”, where terminals are operated independently and typically overseen by a local, regional, or state agency or a board of elected or government appointed officials.

Regardless of ownership model, ports often contain detection, inspection, and operational systems are used by public and private operators to screen, scan, and inspect cargo and personnel, conduct tax collection, and provide security. At the federal level, Customs and Border Protection (CBP), Immigration and Customs Enforcement (ICE), and the U.S. Food and Drug Administration (FDA) Animal and Plant Health Inspection Service all have large roles in enforcing laws and regulations governing the inbound and outbound movement of goods and people. Ports may also feature CBP regulated Foreign Trade Zones where cargo can be transferred or stored without being subject to duties. At many ports, physical security systems featuring access controls and closed-circuit systems surveillance systems are used to monitor berths, storage, and office facilities and are operated by the port or terminal operators. Additionally, most ports feature facility-wide access controls requiring Transportation Worker Identification Card credentials (TWIC).

In addition to enforcement and security systems, ports also feature a range of regulations, plans, and procedures for protecting worker safety and the environment, and for managing disruptive events such as fires, spills, or natural hazards. Formal and informal groups such as Area Maritime Security Committees and Harbor Safety Committees bring together federal, state, local, and private sector stakeholders to discuss, plan for, and manage these concerns.

INTERMODAL CONNECTIONS

Intermodal connections enable the movement of cargo from the maritime domain to the land domain and vice versa, allowing cargo to be transferred between vessels, trucks, railcars, and pipelines. Because ports and intermodal facilities are often collocated or adjacent to one another there are many similarities between their physical logistics, transaction, and oversight systems, and in some instances, they will use the same infrastructure systems and assets.

Physical Logistics Systems

Physical logistics systems at intermodal connections largely mirror (and in some cases are the same as) those at ports. Cargo handling systems including cranes, conveyor belts, pipelines, forklifts, and loaders are still used to move goods between goods and storage facilities such as yards, warehouses, tanks and silos. However, where ports provide vessel services, intermodal connection points may feature railyards and freight facilities used to store and service railcars and trucks. Additionally, intermodal facilities often feature gated entry and exits points and associated security systems, inspection equipment, and scales for weighing trailer loads.

Transaction Systems

At intermodal facilities, business operations systems interface with terminal operating systems and facilitate business services including the buying, selling, and transfer of cargo, as well as coordination between operators. Additionally, the transaction layer at ports can include office facilities and financial systems used at the port to conduct business operations. Many intermodal connections are located on ports or in proximity, therefore IT systems at intermodal connections may be connected to port facilities to share information to facilitate logistic processes.

Governance Systems

As with ports, detection, inspection and operations systems may be present at intermodal facilities to conduct scanning, screening, and tax collection activities. They also commonly feature security systems and access controls (including TWIC) and a range of regulations, plans, and procedures for protecting worker safety and the environment, and for managing disruptive events similar to those found at ports.

COMMUNITIES

The communities represent the cities and regions that surround ports and provide critical support that enable port activities. This support ranges from the workforce needed to staff port operations and equipment to the lifeline systems that a port could not operate without.

Physical Logistics Systems

Within physical logistics systems, communities support the transfer of goods through consolidation and distribution centers where cargo is stored and bundled for outbound shipping or broken down for distribution. Communities also often support processing of inbound or outbound fuel and chemical shipments as well as the manufacture of raw or finished goods for bulk or containerized cargo. Perhaps most importantly, communities provide lifeline services that are critical to port operations, including electricity, fuels, water and wastewater, communications, and transportation. Understanding the infrastructure systems and assets that directly service port facilities and infrastructure systems is often a key component of characterization activities and can contribute to a better understanding of port resilience.

Transaction Systems

For communities, transaction systems are less directly relevant, as most business activities occur onsite at the port or at remote facilities via IT/OT systems. However, cargo tracking, monitoring, purchasing, and transactions still occur as goods are in transit and as they are processed at consolidation and distribution centers.

Governance Systems

Governance systems are incredibly important at the community level: state and local regulation, policy, and investment decisions impact a range of port operations from zoning, permitting, and environmental protection requirements to response and recovery planning and capabilities to port expansion. Communities are home to a wide range of stakeholders who have interest and decision authority for port operations, from trade associations that represent the interests of their local and national industries to local and regional planning organizations that develop multi-year strategies that can shape a port's operations.

The exact composition and nature of governance systems will vary by community and context, but for nearly all assessments, community governance systems will shape both project scoping and execution.

CHARACTERIZING INLAND WATERWAYS

The previous sections provided an overview of the physical logistics, transaction, and oversight systems commonly operating at each of the four spatial elements of the MTS from the perspective of a single port. While many of the components for these systems and spatial elements will be similar when conducting assessments at the inland port system scope, there are some unique attributes and challenges that differentiate them from coastal ports.

For inland port systems, many of these differences are found within the navigable waterways. The navigable waterways for inland port systems are generally shallow draft that do not accommodate deep draft vessels and may be connected to the sea through multiple rivers, canals or lock systems. Rivers are dynamic and ever-changing environments and are subject to shoaling, high and low water, and changing current conditions. These changes, combined with wear and tear on the large infrastructure that support the movement of vessels like locks, dams and channel training structures that stabilize the depth and location of the channel that can often act as single points of failure, shutting down the waterway. Because of the generally linear nature of inland port systems, upstream or downstream disruptions to the waterway can cause cascading impacts across the system.

Terminals within an inland port area may be separated by great distances along a river and to reach these terminals, vessels must often pass through a series of locks and bridges. These terminals and facilities accommodate a wide range of commodities and vessels, and a resilience assessment of an inland waterway system is likely to include multiple ports handling disparate cargos. Because of this, understanding linkages and commodity flows between ports can be an important component of characterizing and inland waterway system.

CHARACTERIZING MULTIPORT NETWORKS

Characterization of multiport networks will be similar to port assessments but at a much broader scale and can build upon the characterizations and resilience assessments of single ports within the network. Multiport network assessments often seek to understand the connections and interdependencies between ports that are geographically proximate (and therefore exposed to similar threats or likely to play supporting roles in response and recovery) or that form supply chains for specific commodities. Pending scoping decisions, analysis of multiport networks can include examination of multiple navigable waterways, ports, intermodal connections, and communities.

Within multiport network assessments, understanding the role played by transaction systems becomes more important as these systems are responsible for managing the redirection of cargo and maintenance of supply chains. Characterization of multiport networks is less likely to focus on physical characteristics and vulnerabilities of individual assets and systems within the MTS and instead focus on identifying resilience challenges within regions or supply chains. For example, a multiport network analysis may examine the movement of fuel products within a region and identify challenges associated with limited alternative storage capacity should an individual port experience disruption. This insight can be used to identify options for ensuring continuity of operations and limiting supply chain impacts that can be incorporated into response and recovery planning activities.

CHARACTERIZATION DATA

Regardless of the scope of an assessment, it is important to understand not only what infrastructure systems should be characterized, but also what information about them should be collected. For every resilience assessment, time and resources are limited, and a clear understanding of what information is needed to support analysis can help control project scope and simplify characterization. Broadly, characterization data can be categorized into several primary types:

- **Descriptive data** including the name, location, height/depth, owner/operator, and other similar data that can be used to uniquely identify and describe the infrastructure asset or system.
- **Operational data** includes information about how the infrastructure operates, what is does, how much it can do, and its relative importance to the overall system. For example, operational data for a terminal might include its number of berths, the average time at the berth, and the types of vessels the berths are configured to handle. Operational data for a crane system could include the rate at which it moves cargo from ship to landside, its average and maximum throughput, seasonal variations in use, the maximum weight it can load and unload, and requirements for maintenance and safety inspections.
- **Dependency data** includes information about inputs and outputs of an asset or system that are required for operation. This includes requirements for electricity, fuel, communications systems and software, transportation, water/wastewater, and other inputs such as chemicals or critical components. Dependency data should also include information about potential redundancies or alternatives in place for that asset or system, such as backup power, alternate communications methods, or alternate systems that can replace an asset if it is lost. Additional information about dependencies is included in the following section and diagrams of common dependencies organized by geographic element and terminal type are included in Appendix B.
- **Threat and vulnerability data** which can include information about the threat posed to an asset or system by adversarial threats, accidents, and natural hazards as well as its susceptibility to those hazards and any mitigation measures in place to reduce risk.
- **Response and recovery data** which includes information about response and continuity of operations plans, procedures, and capabilities.

Though this list is not exhaustive, it provides a basis for considering what sorts of information are most beneficial to an individual characterization effort. This data can be collected through a variety of means, from review of previous planning and assessment activities, to individual interviews and facilitated discussions, to workshops and exercises with groups of MTS operators. Once characterization data has been collected, it can be synthesized, analyzed, and used to develop mapping products and visualized using infographics and system diagrams. These products can be used to promote common understanding of port operations and port risks. Pending other objectives of a resilience assessment, characterization data can also be used to assess risk and consequences of disruptive events and provide a baseline that future changes can be evaluated against.

CONCLUSION

Defining functions and conducting characterization establishes a baseline understanding of systems and steady-state operations within the MTS. Characterization activities may include collecting asset lists, reviewing planning documents, developing mapping and dependency data, and interviewing operators about their systems. The goal of characterization is not to develop an exhaustive picture of MTS operations: assessments should focus on characterizing only those functions, systems, and geographic elements critical to the purpose of the study, rather than cataloging all the various infrastructure systems and governance structures present. Ultimately, characterization provides a point of departure for further analysis including analyzing critical dependencies, providing a benchmark for analyzing risk of disruptions, and assessing the effectiveness of mitigation options.

Equipped with an understanding of functions and governance structures, guide users can characterize what infrastructure systems and stakeholders support functions of interest, establish performance goals, determine how various incidents and disruptions will impact functions, and identify and evaluate how resilience enhancements might reduce risk.

APPENDIX B. PORT INFRASTRUCTURE DEPENDENCIES

This section expands on the MTS Guide to provide a more in-depth look at common infrastructure dependencies in the MTS. This section draws on the Dependency Analysis Framework developed by Argonne National Labs, previous RRAP findings, and on USACE and CISA subject matter expertise. Though by no means exhaustive, this appendix aims to illustrate common dependency relationships within navigable waterways, at various port terminal types, and at intermodal connections and the surrounding community.

The identification and analysis of infrastructure dependencies can support resilience assessments by providing a more complete picture of potential vulnerabilities to disruption and downstream consequences. This can lead to improved identification and selection of opportunities for enhancing resilience.

A dependency is a unidirectional relationship between two assets where the operations of one asset affect the operations of the other. For example, a refrigerated warehouse at a port depends upon electric power to provide temperature control. An interdependency is a bidirectional relationship between two assets where the operations of both assets affect each other. For example, the water treatment plant requires communications for its SCADA system, and, in turn, provides water used by the communications system to cool its equipment. Figure B-1 illustrates the definitions of dependency and interdependency.

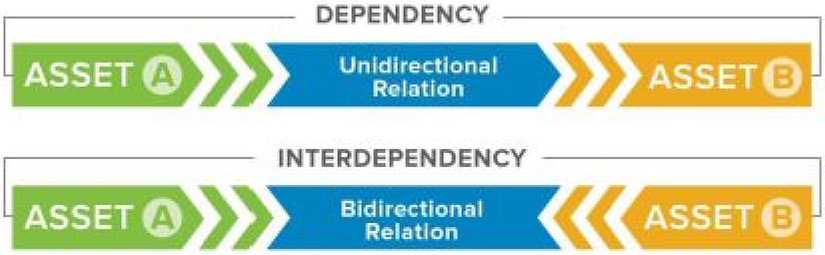

Figure B-1. Dependency and Interdependency Relationships[47]

It can also be helpful to consider different classes of dependency that represent different forms of relationships. Table B-1 describes four distinct classes of dependency relationships: physical, cyber, geographic, and logical.

Table B-3 Classes of Dependencies

Class	Description	Example
Physical	A commodity or service produced by one infrastructure asset or systems is needed as an input by another infrastructure for its operation.	Fuel tankage at a liquid bulk terminal requires electricity to operate pumps to transfer fuel.
Cyber	Operations depend on information and data transmitted through the information infrastructure via electronic or informational links. Outputs from the information infrastructure serve as inputs to other infrastructure, with the relevant commodity being information.	Container gantry cranes require communications systems to interface with terminal operating software for cargo operations.

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[47] Petit, Verner, Levy, *Regional Resilience Assessment Program Dependency Analysis Framework*, p. 1, 2017

Class	Description	Example
Geographic	Operations depend on the local environment, where an event can trigger changes in the state of operations in multiple infrastructure assets or systems. A geographic dependency occurs when elements of infrastructure assets are in close spatial proximity.	Pipelines, fiber optic cables, and surface transportation are collocated on a bridge crossing a channel and share vulnerability to vessel strikes and earthquakes.
Logical	Operations depend on the state of other infrastructure via connections other than physical, cyber, or geographical. Logical dependency is attributable to human decisions and actions and is not the result of physical or cyber processes.	Port terminals are dependent on surveying of a channel after shoaling or a disruptive event prior to reopening the waterway to traffic to prevent additional disruptive events that delay vessel movements.

The following sections will provide an overview of common dependencies relevant to the MTS within port communities, port terminals and navigable waterways.

COMMUNITY

The communities surrounding ports often provide lifeline services including electricity, fuel, communications, water, wastewater, and transportation to port terminals. They also provide secondary services to ports including manufacturing, fuel and chemical production, and logistics services for inbound and outbound cargo at consolidation and distribution centers. Table B-2 provides additional details on these relationships.

Table B-4. Community infrastructure dependencies

System	Description	Dependencies
Electric Power	Electric power systems generally feature three main components, power generation, transmission, and distribution. Ports generally receive electricity through the distribution system and are serviced by one or more substations.	Electric power systems depend on communications and information technology/operational technology (IT/OT) systems for monitoring and control of generation, transmission, and distribution processes and may depend on water systems for both cooling and to run turbines for power generation. Electric power systems often rely on transportation systems, including ports, to supply fuel (oil, coal, natural gas, among others) for power generation.
Fuel	Fuel systems extract, refine, and distribute fuels including oil and natural gas products.	Fuels systems are generally dependent on electric power for processing, pumping, and distributing product and on communications and IT/OT systems for monitoring and control of those processes. Fuel systems may require port operations for product supply and/or distribution and provide fuel for port terminal and ship operations.
Water	Water systems provide potable water to communities through reservoirs, treatment plants, pumping stations, water storage, and a network of transmission and distribution lines.	Water systems generally depend on electric power for pumping, processing, and distributing water; communications and IT/OT systems for monitoring and control of those processes. They also require chemicals for water treatment and maintenance. Water systems may depend on ports for the movement of chemicals and fuel (backup power). Port systems rely on water systems for fire suppression and potable water.

System	Description	Dependencies
Wastewater	Wastewater treatment systems manage sewage and runoff through a series of collection lines, pumping stations, and treatment plants.	Wastewater systems depend on electric power for collecting, pumping, and processing wastewater and communications and IT/OT systems for monitoring and control of those processes. They may require transportation systems for the delivery of chemicals and other treatment products. Port systems rely on wastewater systems for sanitary services to terminals and berthed vessels.
Communication	Communication systems include cellular networks, fiber optic and coaxial cable systems, telephone lines, broadcast systems, and satellite-based systems that enable information exchange.	Communication systems rely on electric power. Port systems are highly reliant on both wired and wireless communications systems that enable the use of IT/OT systems that monitor and control port operations, track cargo movement, and enable business operations.
Transportation	Transportation systems include air, maritime, and surface modes, including rail, highway, and pipeline transportation.	Transportation systems are generally reliant on fuels, electric power, and communication networks that enable the monitoring and tracking of cargo. Ports are highly reliant on transportation systems for the efficient movement of goods. Ports often play a key role in the movement of fuels used by other transportation modes.
Consolidation/ Distribution Centers	Warehouses and processing centers where cargo is stored, consolidated for shipping, and broken down for distribution.	Consolidation and distribution centers are dependent on electric power for lighting, security systems, HVAC systems, refrigeration of temperature-controlled cargo, and some cargo handling equipment. They may also require fuel for cargo handling equipment. They depend on communication networks for security systems, building and access controls, as well as performing logistic functions associated with monitoring and tracking cargo; water for fire suppression; and wastewater systems for sanitary services. Ports and consolidation and distribution centers are interdependent on one another for the efficient movement of cargo from terminals to the hinterland.

PORT TERMINALS

Port terminals contain the infrastructure necessary to facilitate the loading and uploading of cargo from vessels and the equipment to transfer cargo to storage yards and other transportation modes such as rail, truck, and barge. Port terminals are configured based upon the type(s) of cargo handled and vessels serviced:

- Break Bulk
- Dry Bulk
- Liquid Bulk
- Container
- Roll On/Roll Off (RO/RO)

A port may contain a single terminal that handles only one cargo type or multiple cargo types such as a Break Bulk /Dry Bulk or Container/RO/RO terminal, to many terminals handling different cargo types. Each terminal is configured differently depending on the cargo type but may have similar systems, functions, and dependencies. Table B-3 provides a generic list of port terminal infrastructure systems and their dependencies which apply to the terminal types. Descriptions of the terminals by cargo type and any specialized infrastructure systems dependencies specific to the type of cargo transferred are described in following sections.

Table B-5. Port Terminal Dependencies

System	Description	Dependencies
Vessel Berthing	Wharves, piers, docks that allow vessels to moor for cargo transfer operations.	Berths generally require electric power for lighting and security systems but can operate without those systems. Vessel berths may require water for potable water and fire suppression, along with wastewater systems for sanitary discharge.
Shore Power	Landside power provided to docked ships	If a vessel is required to shut down its fossil-fueled power generation system in port, the terminal must be able to supply shore power to it. If power is not available, vessels can provide their own power.
Bunkering	Systems providing fuel to vessels in port at the berth or anchorage	Bunkering services are generally provided by fuel barge and require available vessels and adequate fuel supplies.
Ship Services	Systems providing waste reception, repair services, provisions to vessels in port	Ships services may include water systems for potable water, wastewater systems for sanitary discharge, and transportation systems for the movement of personnel and provisions.
Storage Yards	Open storage areas for container, RO/RO, bulk, or break-bulk cargo pier side or adjacent to pier	Storage yards may require electric power for lighting, security, communications, IT/OT systems, refrigerated cargo, and cargo handling equipment. Fuels may be required for cargo handling equipment. Communication and IT/OT networks may be required for security systems and monitoring and tracking of cargo. Yards also require water for fire suppression.
Storage Facilities	Warehouses, Silos, Tanks for dry storage for break bulk or bulk cargo	Storage Facilities require electricity for lighting, security systems, HVAC systems, and refrigeration of temperature-controlled cargo. Communication networks may be required for security systems and building and access controls, as well as the monitoring and tracking of cargo. Storage Facilities require water for fire suppression.
RemReTank Farm	Storage tanks for liquid bulk cargo	Tank farms require electric power for cargo operations, lighting, security; communication and IT/OT systems that control and monitor liquid cargo transfer equipment. Tanks farms also require water for fire suppression.
Rail Transfer Yard	Area of a terminal with a railroad spur where cargo is loaded and unloaded from railcars	Rail transfer yards require electricity for security systems, lighting, cargo tracking and electrified cargo handling equipment, and fuel for non-electrified cargo handling equipment. Rail transfer yards also may require wired and wireless communication services for cargo tracking and monitoring. IT and communication systems enable the movement of cargo from yards to a designated location on railcars. Operational rail systems including upstream and onsite tracks, switches, and railyards are critical to rail transfer yard operations. Rail transfer yards also require water for fire suppression.

System	Description	Dependencies
Truck Loading Area	Designated area for loading and unloading cargo from trucks.	Truck loading areas require electricity for security systems, lighting, cargo tracking and electrified cargo handling equipment and fuel for container handling equipment. These areas may also require wired and wireless communication services for cargo tracking and monitoring. IT/OT and communication systems enable the movement of cargo from yards to designated vehicles. Access to highway systems and regional consolidation/distribution centers is critical to truck loading area operations. Truck loading areas also require water for fire suppression.
Terminal Operating Systems	IT systems that manage and control terminal operations, including the physical operation of infrastructure systems such as cranes, storage facilities, and intermodal connections	Terminal operating systems require a continuous power supply and fuel for generators in the case of power disruption. Terminal operating systems are heavily reliant on communication assets including sensors, Programmable Logic Controllers (PLC), and wired and wireless connections, as well as IT/OT systems responsible for managing them.
Business Operations Systems	IT systems that facilitate business services, including the buying/selling/transfer of cargo and coordination with stakeholders	Business operations systems require a continuous power supply and fuel for generators in the case of power disruption. They are also heavily reliant on wired and wireless communications connections and the IT/OT systems used to conduct business and monitor cargo.
Detection, Inspection, Operational Systems	Agency systems and assets used to accomplish port-related missions. Missions include targeting and inspection of cargo, people, port assets and equipment (e.g., CBP, ICE, USCG, EPA, USDA, PA).	Detection and inspection systems require electric power to operate screening and targeting systems, scanning and inspection equipment. These systems also rely on wired and wireless communication systems and IT/OT systems to conduct screening, scanning, and reporting functions, as well as operate equipment. Facilities housing these activities also may require water for fire suppression.
Entry/Exit Gates and Scales	Entry and exits points and associated equipment (security, inspection, tracking) for trucks, personnel, and scales for weighing cargo loads	Electric power is required for entry/exit gates, access control, scanning and screening equipment, and scales. Communication and IT/OT systems are required for scales, gate operations equipment, scanning and screening equipment and systems, and cargo, truck, and trailer tracking.

BREAK-BULK TERMINALS

Break-bulk terminals facilitate the transfer of non-containerized cargo that may be packaged on pallets, crates, boxes, or in drums. Break-bulk terminals generally handle heavy weight and oversized cargo that is too large for containers including finished and unfinished metal products (steel, copper, etc.), lumber, wind turbines, heavy machinery, construction equipment, locomotives, generators, vehicles, and boats. The function of transferring cargo consists of loading/unloading vessels using cranes on a vessel or pier. Associated heavy equipment such as forklifts and loaders move cargo between the pier, storage yard, warehouses, and intermodal connections.

Cargo transfer operations require electric power to operate lighting, security systems, and cranes (though some cranes are diesel operated). Additionally, forklifts and loaders require fuel in the form of propane, natural gas, diesel, or electric power depending on their configuration. Terminal equipment may require communications services for cargo tracking and monitoring and network connections to IT/OT systems. Figure B-2 provides an overview of infrastructure system dependencies for break-bulk terminals.

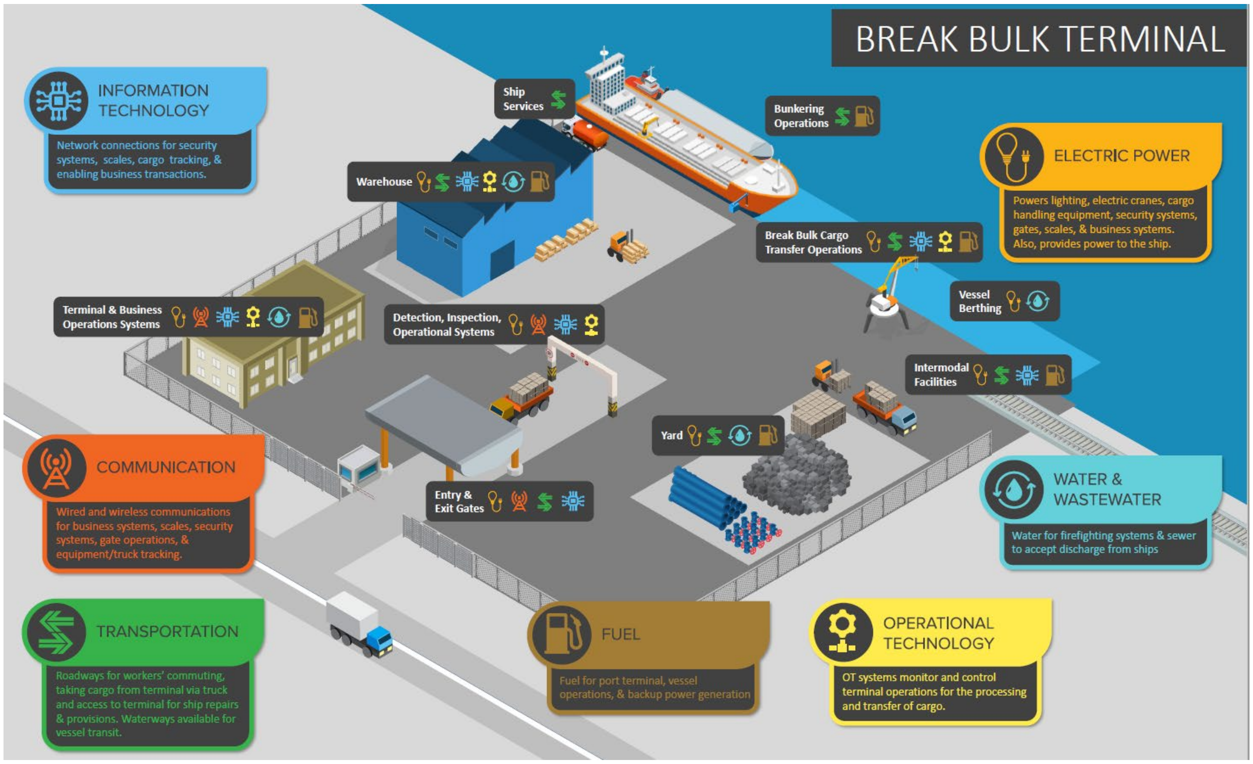

Figure B-2. Break-bulk terminal dependencies

DRY BULK TERMINALS

Dry bulk terminals facilitate the transfer of grains, ores, fertilizers, cement, coal, petroleum coke, and other unpackaged bulk cargo to/from barges and bulk carriers. The function of transferring bulk cargo consists of loading/unloading vessels using cranes, or other cargo handling equipment either installed on a vessel, pier, or barge. Shoreside bulk cargo is moved using conveyors, pipelines, loaders, and other associated heavy equipment to/from storage facilities (yards, elevators, silos, tanks, warehouses) and intermodal connections for truck and rail transportation. Some dry bulk terminals have the capability to load directly from a truck or rail car to the vessel using conveyors. Many port areas on the Lower Mississippi south of Baton Rouge transfer bulk cargo directly from barge to bulk carrier (e.g. grain, coal) and from bulk carrier to barge (e.g. fertilizers) using a crane/conveyor barge while moored in the river.

Cargo transfer systems require electric power to operate conveyors, cranes (some cranes powered by diesel fuel), lighting, security systems and scales. Additionally, fuel (primarily diesel) is required to operate some transfer equipment such as loaders/unloaders and barge mounted equipment. Silos, tanks, and warehouses may require electricity for lighting, security systems and HVAC systems. Terminal equipment may require communications services and network connections to IT/OT systems for cargo tracking and monitoring, and security systems.

Figure B-3 provides an illustration of dependencies for dry bulk terminals.

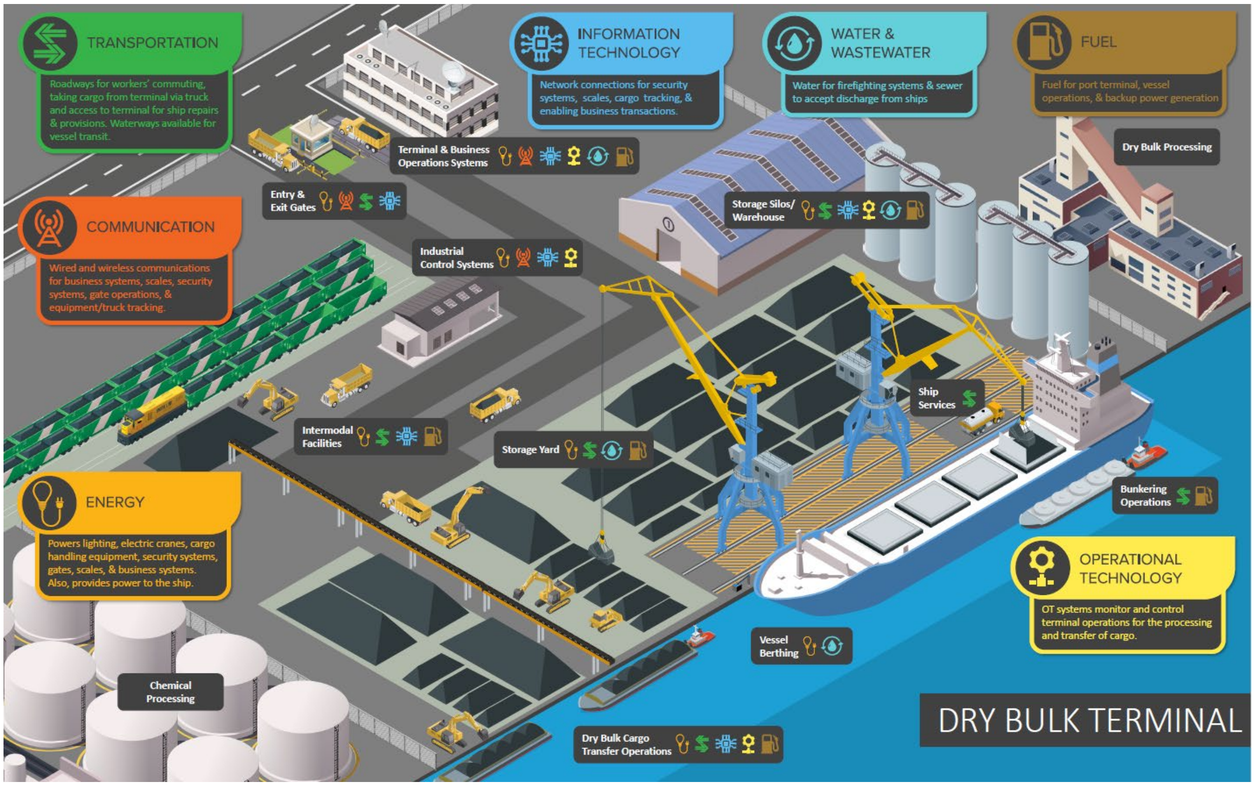

Figure B-3. Dependencies at dry bulk terminals

LIQUID BULK TERMINALS

Liquid bulk terminals facilitate the transfer of crude and refined petroleum products, liquified gases such as, Liquefied Nitrogen Gas (LNG), Liquefied Petroleum Gas (LPG), and Compressed Natural Gas (CNG) and liquid chemicals (ammonia, ethylene, propylene, etc.). These are often specialized terminals with pipeline, truck, and/or rail connections that support the movement of bulk liquids.

The function of transferring liquid bulk cargo consists of loading/unloading tank barges, tank ships and storage tanks using pipeline equipment (loading arms, manifolds, pumps, and pipelines). Intermodal facilities that connect other transportation modes include pipelines and liquid cargo loading racks used to load and unload trucks and rail cars. Liquid bulk terminals are heavily reliant on upstream intermodal transportation systems including pipelines, rail systems, and interstates for both incoming and outbound delivery of product. These systems require power and communications systems both upstream and at the terminal interface.

Electricity is required to power and monitor pipeline equipment, tanks, racks, vapor recovery units, and metering equipment, as well as lighting and security systems. Backup power generators require fuel. Terminals are reliant on communications systems and IT/OT systems for monitoring terminal operations, alignment, flow rates, metering, tank levels, and security systems.

Figure B-4 provides an illustration of dependencies for liquid bulk terminals.

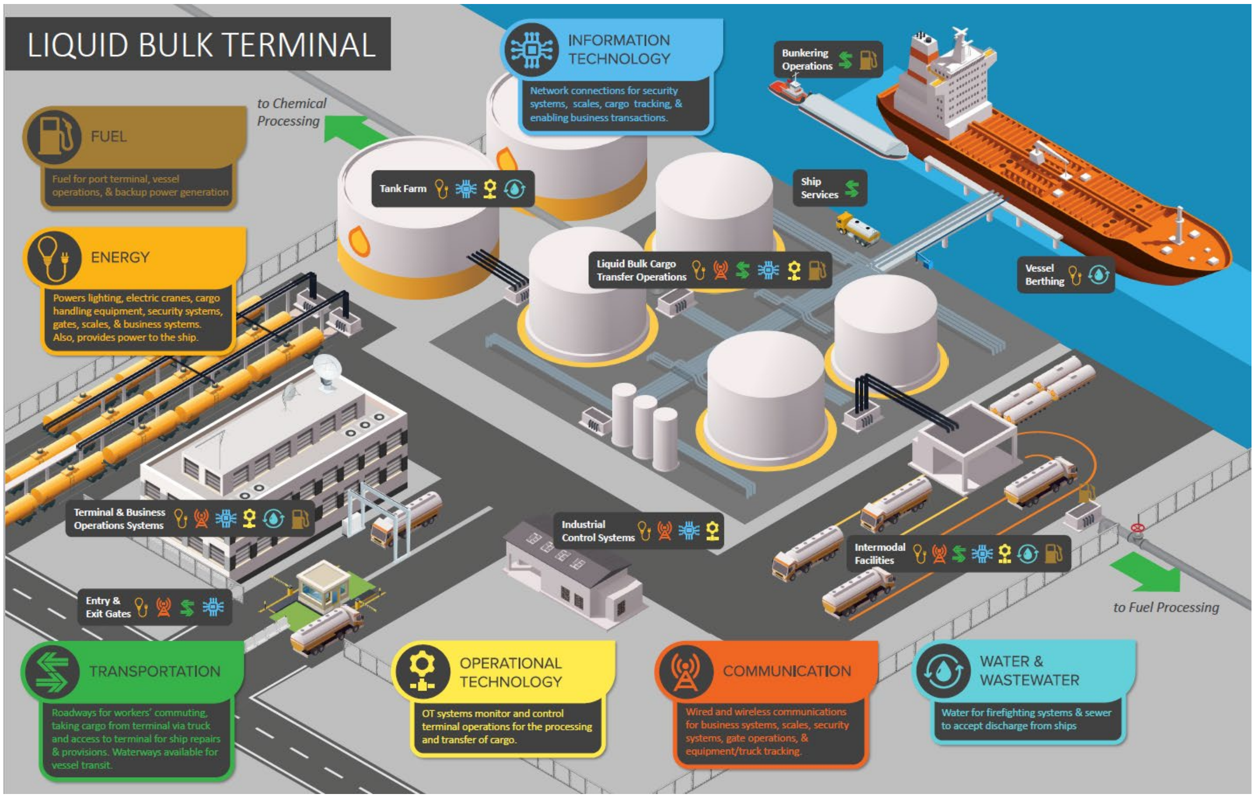

Figure B-4. Dependencies at liquid bulk terminals

CONTAINER TERMINALS

Container terminals facilitate the transfer of standardized shipping containers loaded with packaged and unpackaged cargo. The function of transferring container cargo consists of loading/unloading container vessels using specialized cranes that enable placing containers in specific locations on a vessel according to loading plans that ensure the stability and safety of the vessel. Associated heavy equipment may include trucks, trailers, cranes, straddle carriers, stackers, rail-mounted gantries, rubber-tired gantries, forklifts, and automated guided vehicles used to move containers between ships, container yards, container freight stations (CFS) and intermodal connections for truck and rail transportation. A CFS is a warehouse area within the terminal where cargo is processed, weighed, loaded into, and unloaded from containers. The area may contain temporary storage.

Container transfer systems are dependent on electric power or fuel to operate cranes and container handling equipment depending on their configuration. Container yards, CFS, and intermodal connections for truck and rail transportation require electricity for refrigerated containers, wired/wireless communications systems, container tracking, security systems and lighting. Modern transfer equipment requires wired and/or wireless communications services for safe and efficient equipment operations and cargo tracking and monitoring functions. Terminal equipment also requires network connections to enable movement of cargo to and from ships in a specific sequence and designated location based on vessel loading plans. IT/OT systems are also used to track location and movement of containers and terminal equipment. CFS facilities also require IT/OT systems for tracking contents and ownership of materials loaded/unloaded from containers and performing acceptance/delivery activities. Rail and truck transfer yards also use IT/OT and communication systems to enable the movement of containers from yards to a designated railcars and trucks. Container scanning and inspection equipment require electric power, IT/OT and wire/wireless communications systems for screening, scanning, and reporting functions. Figure B-5 provides an illustration of dependencies for container terminals.

Roadways for workers' commuting, taking cargo from terminal via truck and access to terminal for ship repairs & provisions. Waterways available for vessel transit.

Network connections for security systems, scales, cargo tracking, & enabling business transactions.

Powers lighting, electric cranes, cargo handling equipment, security systems, gates, scales, & business systems. Also, provides power to the ship.

Fuel for port terminal, vessel operations, & backup power generation

OT systems monitor and control terminal operations for the processing and transfer of cargo.

Water for firefighting systems & sewer to accept discharge from ships

Wired and wireless communications for business systems, scales, security systems, gate operations, & equipment/truck tracking.

Figure B-5. Dependencies at Container Terminals

ROLL-ON/ROLL-OFF TERMINALS

Roll-on/Roll-Off (RO/RO) terminals facilitate the transfer of vehicles including cars, trucks, farm equipment, heavy construction equipment, and heavy machinery. They generally feature large storage yards and intermodal connections to both trucking and rail modes. The function of transferring rolling cargo between vessels and storage yards consists of loading/unloading RO/RO and Con/RO (container/roll on-roll off) ships and barges using stevedores, associated equipment (e.g., tractors to move trailers) and loading ramps installed on the vessel or pier. Storage yards may contain multilevel cargo storage and intermodal connections for truck and rail transportation.

RO/RO cargo transfer systems require electric power for electric motor driven tractors or fuel for engine driven tractors that move trailers. Electric power is also required to operate cargo tracking and monitoring, refrigerated trailers, lighting and security systems. Terminal equipment may require communications services for cargo tracking and monitoring, vessel loading, security systems, and network connections to IT/OT systems. Yards may require electric power for lighting, security systems, and wired and wireless communication systems for cargo tracking and monitoring. They are also dependent on network connections to IT/OT systems for tracking and security.

Figure B-6 provides an illustration of dependencies for RO/RO terminals and table B-4 provides additional detail on the nature of these dependencies.

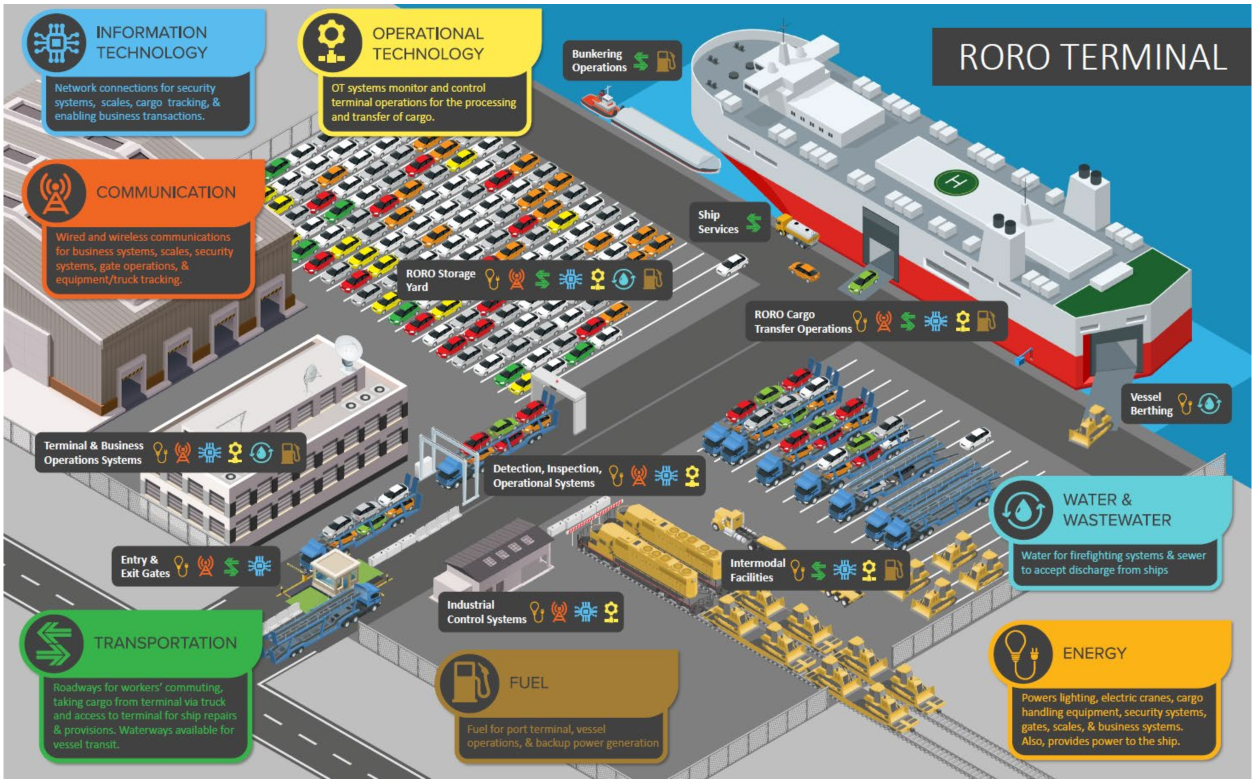

Figure B-6. Dependencies at RO/RO terminals

NAVIGABLE WATERWAYS

Navigable waterways feature infrastructure systems that support the safe and efficient movement of vessels to and from port terminals. Table B-4 provides an overview of these systems as well as a description of their dependencies. These dependency relationships are also depicted in Figure B-7.

Table B-6. Dependencies for navigable waterways

System	Description	Dependencies
Aids to navigation (ATON)	System of fixed and floating aids to mark navigable channels and hazards to safe navigation	Buoys and many fixed aids are commonly solar, and battery powered and do not require an electric source, though they can be dependent on local U.S. Coast Guard operations if they are removed from their station due to a storm or other event. Lighthouse lights, range lights, racons and fog signals require electric power and may require fuel for backup power generation.
Electronic ATON (eATON)	Automatic Information System (AIS) ATON provides electronic position data of ATON for display on electronic navigation systems. The AIS signal is transmitted for the ATON (real) or from a base station including *synthetic* (broadcasts position where a physical aid exists) and *virtual* (broadcasts position where no physical aid exists)	Transmission of the AIS ATON signal from base stations are dependent on electric power and communication systems. During a disruption, the eATON system may require fuel for backup generators, as well as transportation systems to access and repair eATON components. eATON are also reliant on the GPS communication system; degraded or altered GPS signals can result in loss of electronic AIS ATON function.
Pilotage	Pilots guide ships from/to the at-sea boundaries and the port berths and anchorage areas through maintained channels	Pilot vessels are used to transfer the pilot from shore to the ship and require fuel for operations. Pilot stations are dependent on transportation systems, electric power and communications to operate. Pilot operations are critical to the movement of vessels in shipping channels.
Tugboat Services	Tugboats provide docking, undocking to ships when mooring at terminals, ship-assist and escort services to ships transiting waterways	Tugboats generally require fuel for power, water, and wastewater services from the community. Many ships rely on tugboat services to safely transit a waterway and moor at terminals.
Vessel Traffic Services	Systems that provide monitoring and navigational advice to vessels in confined waterways, and may include VTS operations centers and remote sites	VTS operation centers and remote sites require electric power and communications to operate and transmit information. Operations centers also require water and wastewater services. Transportation systems are critical for reaching remote sites, especially following a disruptive event such as a hurricane which could damage or disable VTS equipment. VTS systems may also require fuel for backup generators in the event of power outage.
Locks and Dams	Systems used to maintain navigability of river channels, as well as associated flood control infrastructure including levees and spillways	Locks and dams require electricity to operate lock equipment, dam gates, and associated support systems. During a power disruption, facilities with backup generators require fuel. Lock and dam systems primarily rely on VHF radio communications and cellular communications as a backup. Wired and wireless communication networks and IT/OT systems are often used to monitor and control lock and dam

System	Description	Dependencies
		operations. Transportation systems are required to get to and from operations centers and remote sites.
Dredging	Systems used to maintain channel width and depth and ensure safe debris removal, including dredges, dredge spoil reception facilities and/or tug/barge	Dredge systems require fuel to operate dredges and support vessels such as tugs and barges. Dredge systems may also be reliant on transportation systems for the trucking of dredge spoils, and wastewater systems to empty sanitary tanks.
Surveying and Salvage	Systems and vessels used to identify and recover or clear obstructions from navigable waterways	Surveying and salvage vessels require access to fuel and shoreside wastewater systems to empty sanitary tanks.
Lightering	Vessels and systems used to transfer of oil, hazardous material, or other bulk cargoes at sea or at anchorage generally to reduce a vessel's draft to enable entry into a port	Lightering vessels require fuel for operations and communication systems to transmit and receive communications with port authorities.

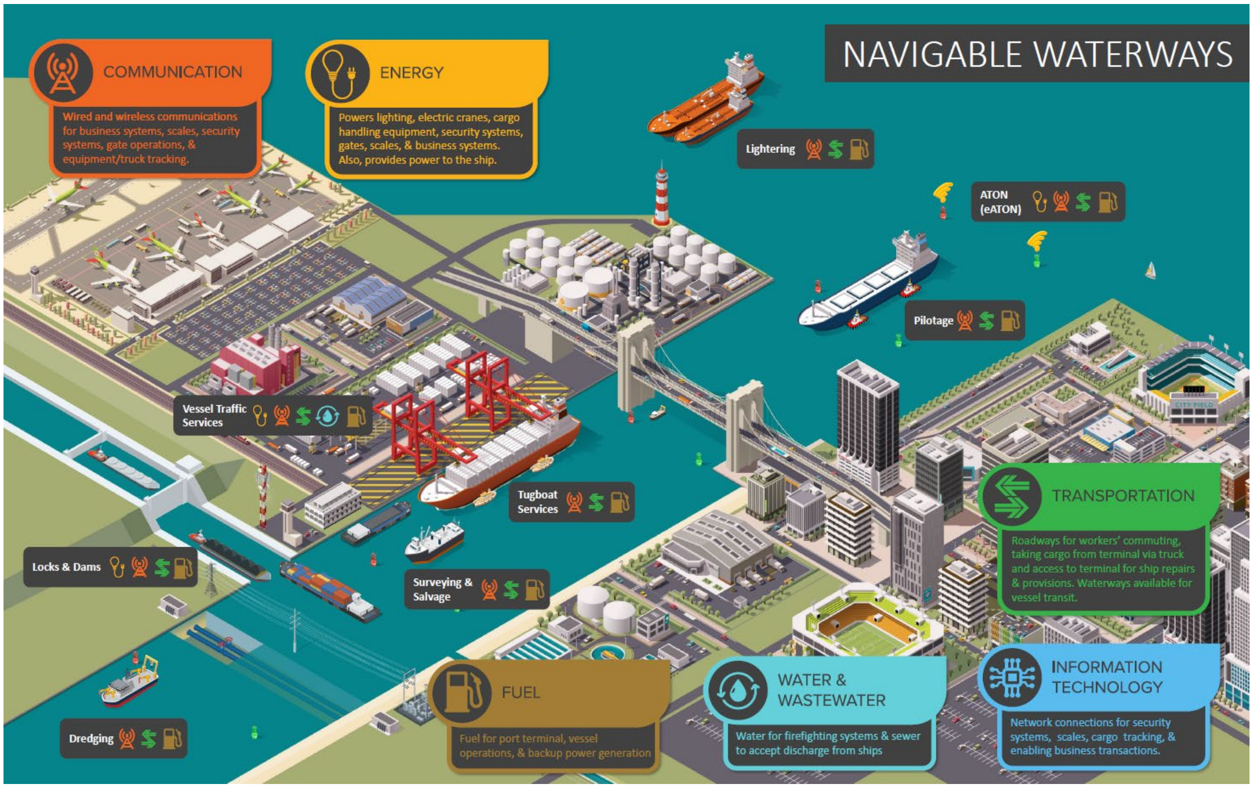

Figure B-7. Navigable Waterways Dependencies

In addition to these systems that directly support port operations, navigable waterways also routinely feature other infrastructure systems that traverse navigable waterways and share geographic dependencies with these systems including pipelines, water and wastewater lines, automobile and train tunnels, communications cables, and power lines that cross under the waterway. Similarly, bridges regularly cross waterways and can carry similar infrastructure systems. Since these infrastructure systems share a geographic dependency, a single hazard such as a hurricane, earthquake, vessel grounding or allision, or adversarial attack can compromise multiple systems simultaneously and affect both waterway operations and community infrastructure systems.

APPENDIX C: UNDERSTAND THE IMPACTS OF DISRUPTIVE EVENTS TO THE MTS

The MTS is exposed to a wide variety of threats and hazards that, if not properly understood and prepared for, can result in major setbacks in meeting operational demands. A hazard is an environmental or non-environmental disruption. A threat is different from a hazard in that is it directed towards a particular asset, system, network, or area by an adversary. Ports and inland waterways are in low-lying areas, provide extremely important economic functions to the state, region, and nation, are streamlined to meet just-in-time needs of the supply chain, and rely on the full support of a multitude of supporting infrastructure systems. These traits expose ports to a wide range of potential events – from cybersecurity attacks to earthquakes and labor strikes. This section is intended to provide readers with an overview of the types of threats and hazards that may be considered in a resilience assessment and some basic methods for conducting a risk assessment of these disruptions.

In 2016, the U.S. Committee on the Marine Transportation System Resilience Integrated Action Team (RIAT) brought together U.S. Federal agencies that actively monitor, manage, research, or operate within U.S. navigable waters (Touzinsky et al. 2018). These agencies were asked to describe the disruptions that are of most concern to their mission for the MTS. The objective was to identify a broad breadth of potential issues so that agencies can focus and identify the most key concerns across the United States. Eight agencies identified 31 potential disruptions that relate to the environment and 40 that pertain to non-environmental issues (Table C-1; Table C-2).

Table C-7. Environmental factors within the broad categories of Extreme Events, Climate Change, Operations, and Species (Touzinsky et al. 2018).

Environmental Factors*			
Extreme Events	**Climate Change**	**Operations**	**Species**
• Water level extremes • Tidal extremes • Frequency and severity of storms • Extreme precipitation • Extreme heat/thaw • Extreme cold/ice • Seismic disruptions • Tsunamis • Tornadoes • Volcanic activity • Wildfires • Waves • Coastal and riparian erosion • Worldwide pandemics	• Water level/ inundations/ surge • Arctic shipping routes opening • Frequency and severity of storms	• Navigation and channel shoaling • Corrosion • Inland waterways/ river conditions • Hazardous debris • Silting • Spill response capabilities • Visibility • General changing sea conditions • Ice • Solar weather	• Invasive species • Threatened and endangered species and protected habitats • Subsistence fishing • Changing migration patterns • Nuisance species

**Some factors are repeated between categories because of their relationship to the category heading.*

Table C-1. Non-environmental MTS resilience factors that fall under the broad categories of Logistics/ Operations, Infrastructure, Government/Policy, Technology, Security, and Energy (Touzinsky et al. 2018)

Non-Environmental Factors					
Logistics/ Operations	**Infrastructure**	**Government/ Policy**	**Technology**	**Security**	**Energy**
• Larger vessels • Hazardous materials/ oil spills • Emergency response capabilities • Industrial accidents • Maintenance and upkeep • Operational disruptions • Throughput • Personnel/Labor challenges	• Competing demands for space of multimodal systems • Aging infrastructure • Port congestion • Lock and dam features • Levee breaches • Intermodal connectors	• Community/ environmental justice • Competing uses of land/ocean/coastal areas • Regulatory/ political/ budgetary • State and federal funding • Trade relations • Distribution of management for MTS • Ship alliances • Jurisdictional conflicts • Coastal management	• Cyber disruptions • Proprietary data • Electromagnetic spectrum disruption • Navigation system failures • Greening of the fleet	• Terrorism • Criminal activity • Piracy • Law enforcement	• Electric/ power disruptions • Marketplace drivers • Energy availability • Limited alternative fuel options • Operational redundancy • Energy infrastructure redundancy • Vessel capabilities • Changing offshore resource use

This diverse group of potential disruptions were the concerns of only eight federal agencies. Including local and state governments, industry, and tribal communities in the process of identifying threats and hazards of concern would certainly include a larger list. To proceed with a resilience assessment, users of the MTS Guide must be fully aware of the significance of the threats and hazards of interest to their particular stakeholder groups and the effect on the components of the MTS (for more information on components, please see Appendix A. Define Functions and Characterize the System in a Steady State). Figure C-1 provides an overview of disruptions and the potential sector and components of the MTS that could be affected.

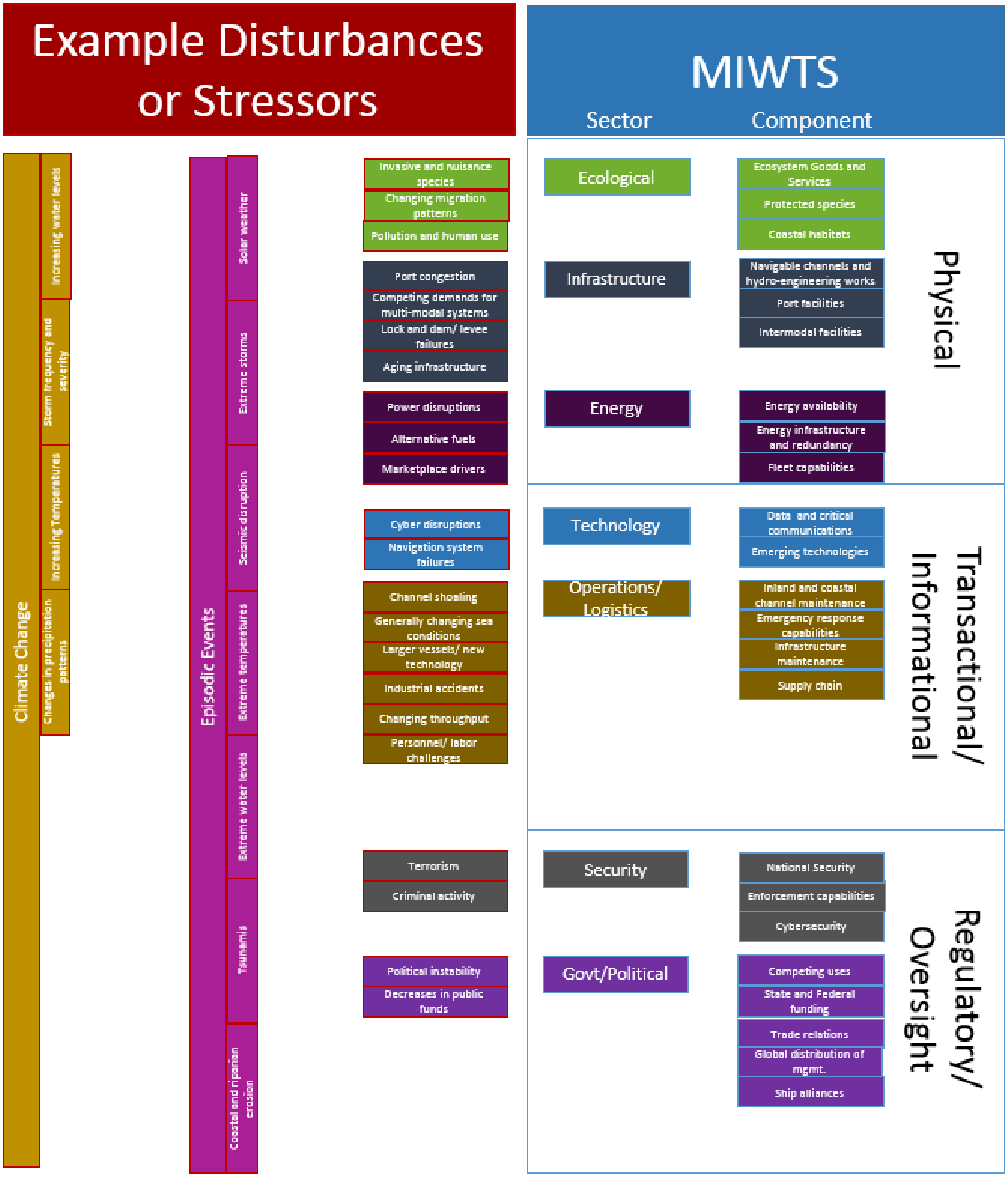

Figure C-1. Disruptions of the MTS and the components of the MTS that they affect. These disruptions are used to identify relevant sectors of the MTS where adaptive management approaches and innovative solutions can mitigate their consequences and improve the resilience of the system. Several disruptions, including climate change and episodic events can impact all sectors of the MTS (PIANC 2020).

CONDUCTING A RISK ASSESSMENT

Risk management techniques are well documented across a wide variety of disciplines and organizations. ISO 31000:2018 provides Risk Management Guidelines that provides information on risk management principles, a framework for applying risk management within an organization, and a process for undertaking risk assessment. This step – risk assessment—is the focus of this Appendix and establishes a process to identify threats and hazards, analyze their risk (including identifying areas of vulnerability, potential impacts, and consequences), and finally, to evaluate which risks should be prioritized for action and improvement (Figure C-2; ISO 2018). This process draws on the knowledge of stakeholders and best available data and information.

A risk assessment allows the user to understand their potential for loss or harm to a system due to the likelihood of a hazard or disruption. It is measured by the probability and consequence of a particular disruptive event and when it is represented numerically, is the product of those two values with corresponding uncertainty. A successful risk assessment typically involves three focus areas for analysis: 1) understanding general information about *exposure or threat of a hazard or disruption*, 2) analyzing *vulnerabilities* of the system to that disruption and 3) identifying the *consequences* of the disruption occurring. There is no risk assessment technique that will suit all needs for the MTS, selected methods will depend on the data available, degree of expertise involved, risks selected, and stakeholder knowledge. Acknowledging this, the MTS guide provides a basic overview of different types of risk analysis techniques and examples of tools that address these focus areas: Threat and Hazard Exposure Analysis, Vulnerability Analysis, and Consequence Analysis. These three components make up the risk assessment triplet (RAMCAP 2006, Cox et al. 2008). Guide users may aim to address all these focus areas or focus in-depth on only one or two, depending on the objectives set during study scoping.

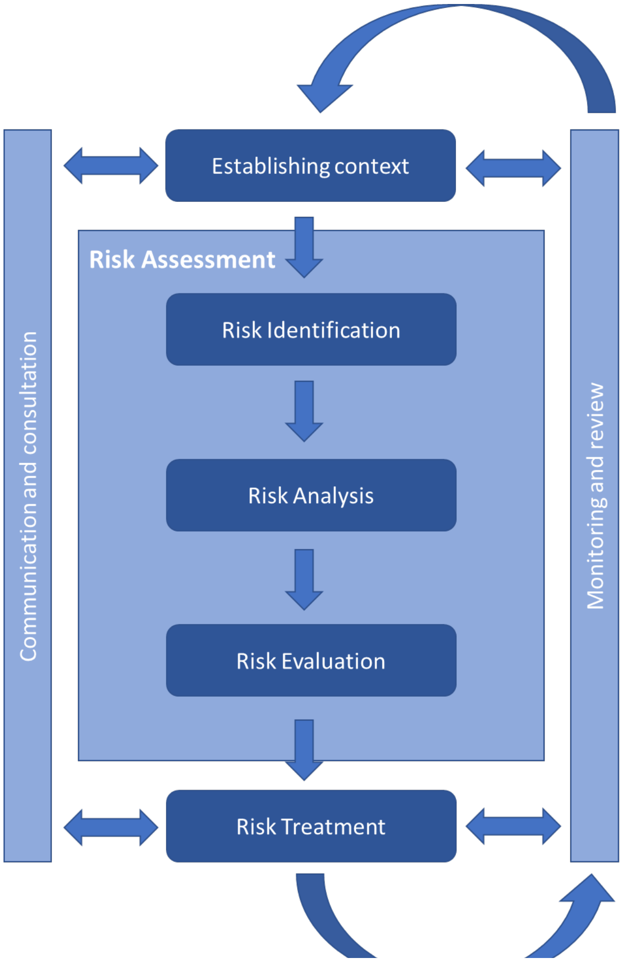

Figure C-2. Risk Assessment Process as defined by ISO 31000, adapted from ISO (2018).

Threat and Hazard Exposure Analysis

A hazard, threat or disruption is any circumstance or event that has the potential to cause damage to a system or population. The goal of the analysis is not to identify if the threat or hazard exists, but to understand how it will manifest and the exposure or impacts of the hazard on the system or region of interest. Methodologies and resources related to exposure identify how susceptible the port or marine transportation system critical infrastructure is to these hazards. The approaches identified in this guide typically have a hazard or disruption of interest pre-identified so that the type, number, and value of the critical infrastructure systems exposed to the hazard can be identified. Exposure analysis often depends on geographical location and may be map-based or interactive tools. The most straightforward of these approaches is to identify the impacts that any particular hazard will have on an area of interest using pre-existing models. The MTS Guide methodology section provides several options gathering data on model results. For example:

- **Seismic Hazards:** USGS Hazard Maps and Site-specific Data, http://earthquake.usgs.gov/hazards/hazmaps/
- **Sea Level Rise and Coastal Flooding:** Sea Level Rise and Coastal Flooding Impacts Viewer and Data Development, NOAA https://coast.noaa.gov/digitalcoast/tools/slr
- **Floods:** FEMA Flood Mapping Products, https://www.fema.gov/flood-mapping-products
- **Drought:** U.S. Drought Monitor, https://droughtmonitor.unl.edu/
- **Landslides:** Landslide Hazard Program, USGS http://landslides.usgs.gov
- **Hurricane Impacts:** Coastal Flood Exposure, NOAA https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html; Coastal Storm Modeling System, USACE ERDC, https://chs.erdc.dren.mil

Hazard analysis can also include working with a team or stakeholder group to elicit their expert judgment on the impacts of a hazard or disruption to a port or infrastructure system. These types of exercises have the benefit of increasing awareness and agreement among stakeholder groups on the impacts that can be expected and the reaction that the system will have:

- **What If Hazard Analysis** – a structured brainstorming method for developing hazard scenarios and assessing their likelihood and consequences. More information can be found at: http://web.mit.edu/course/10/10.27/www/1027CourseManual/1027CourseManual-AppVI.html
- **Threat and Hazard Identification and Risk Assessment (THIRA)** is a process for gathering communities to develop risk scenarios and execute a risk assessment. THIRA is a part of FEMA’s Comprehensive Planning Guide 201. More information can be found at: https://www.fema.gov/threat-and-hazard-identification-and-risk-assessment

Assessing Vulnerability of the MTS

Vulnerability is the weakness of a system, or its inability of a system to withstand the effects of a hazard or disruption. This moves a step beyond understanding exposure to linking the environmental or non-environmental threat or hazards to the critical functions and needs of the MTS system and community. Vulnerability assessments are designed to identify the extent to which any hazard or disruption could harm the system and limit its ability to provide critical functions either through weaknesses in design, implementation, or operations. Several tools exist to perform a vulnerability assessment.

- **Infrastructure Survey Tool (IST)** – a voluntary, web-based vulnerability survey conducted by the Cybersecurity and Infrastructure Security Agency (CISA) to identify and document the overall security and resilience of a facility. Weighted scores on a variety of factors for critical infrastructure of interest is graphically displayed on the IST dashboard so that it can be compared across similar facilities. The IST is intended to inform protective measures, planning, and resource allocation. It must by employed by a CISA Protective Security Advisor. More information about the IST can be found at: https://www.dhs.gov/sites/default/files/publications/ecip-ist-fact-sheet-508.pdf

- **Integrated Rapid Visual Screen (IRVS) -** The IRVS was developed by the DHS Science and Technology Directorate to provide a facility-level risk assessment against a range of threats and hazards. The vulnerability assessment portion of IRVS includes analysis of the site, architecture, building envelope, structural components, mechanical systems and security to assess risk. Additional information about the IRVS and a downloadable version of the tool are available at: https://www.dhs.gov/bips-04-integrated-rapid-visual-screening-series-irvs-buildings

Identifying the Consequence of a Disruption

Consequences are the undesired effects of a hazard or disruption on a system of interest. Consequences must be considered carefully; they can be both short - and long-term and have direct and indirect effects of the system. These effects can occur on physical port and MTS infrastructure, intermodal connections, the governance, the operations, personnel, and communities that compose and control a system. Consequences can be monetary, environmental, involve casualties or decreased performance, or they can be less quantifiable, like reductions in efficiency or effectiveness or breakdowns in stakeholder or political relationships. Having an awareness of potential consequences can provide study leads with a strong argument for why a risk assessment and risk mitigation measures should be undertaken.

- ***HAZUS* -** Hazus is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes. Hazus uses Geographic Information systems (GIS) technology to estimate physical, economic, and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake, hurricane, and flood. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific hazard being modeled. Additional information about Hazus can be found at: http://www.fema.gov/hazus
- **Cause-Consequence Analysis** – a diagram developed based on a threat or hazard trigger that results in a specific sequence Cause-consequence Analysis can utilize a Diagram developed based on two reliability analysis methods – Fault Tree Analysis and Event Tree Analysis. For more information on this analysis and diagram, refer to the background information provided by the HAZARD program seaport Risk Assessment Toolbox. https://hazard.logu.tuhh.de/node/75
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APPENDIX D: IDENTIFY AND EVALUATE RESILIENCE ALTERNATIVES

This appendix accompanies section 3.4 of the MTS Guide, “Identify and Evaluate Resilience Alternatives” to elaborate on how to create a system for selecting which resilience enhancements to target. While a traditional benefit cost analysis may be difficult to conduct, a similarly structured selection process can be devised, which will prioritize investments that yield the greatest gains in resilience and meet other requirements or constraints.

PERFORMANCE METRICS TO MEASURE RESILIENCE GAINS OF ALTERNATIVE INVESTMENTS

Selecting which resilience measures are “best” requires administrators to evaluate and compare the impacts of alternatives on their port system’s performance, which, in turn, necessitates some usable measure(s) of resilience. Resilience metrics are observable proxies (also referred to as indicators or measures), which allow decision makers to systematically forecast or anticipate the gains that can be achieved by implementing or investing in resilience enhancements. As an example, “down-time” of a function/ operation or function-dependent infrastructure is a widely referenced and relatively intuitive metric – resilience enhancement alternatives can be evaluated with respect to how well they reduce down-time and perhaps even more specific metrics that, in turn, influence down-time.

The ability to retain function while under stress indicates that the system possesses characteristics of resilience, which are sometimes difficult to measure or even judge, but may be important for evaluating resilience enhancements. For example, a system that can maintain or quickly restore throughput may have achieved that feat through flexibility, adaptability, redundancy, or a number of other characteristics. Whether such characteristics should be used directly as resilience metrics will depend on how the resilience assessment was conducted (assessment tier). Additionally, in general, metrics should directly reflect the operational definition and scope of resilience that informed the prior resilience assessment. Other selection criteria may include whether:

- The data associated with each metric is available or feasible to obtain, and cost to obtain is justified;
- The mathematical/computational complexity of the metric can be supported by the assessment team;
- The metric provides information to a level appropriate for policy decision-making; and
  The metric supplies relevant information with respect to the MTS component’s activities.

Table D-1 provides a list of resilience metrics proposed by researchers. Metrics vary in their use of descriptive, quantitative, or mixed methodologies, and they are often based on interviews with experts, engineering analyses, or pre-existing datasets[48].

Table D-8. Resilience Metrics

Resilience Metric	Description
Ratio of Recovery time to Degree of Damage[49]	Reductions to the vulnerability of specific network components can be compared by how recovery time improves when damage is reduced.

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[48] Sun et al., 2018

[49] Baroud & Barker, 2014

Maritime Traffic[50]	Relative changes in traffic volumes over time
Average Vessel Dwell Time[51]	A port performance metric that is calculated using U.S. Coast Guard Automatic Identification System (AIS) data for tanker, container and RO/RO vessels
Intermodal Connectivity[52]	Measured as the number of interconnected nodes within a port network
Throughput[53]	Total sum of flows of shipment between origination and destination pairs divided by their respective distance, under a specific scenario
Average Ratio of Throughput Demand and Total Demand[54]	Associated equations taken into account, for example: Nodes of the intermodal (IM) terminal; Expected throughput of IM terminal for all possible scenarios; Rate at which terminal can supply cargo; Traversal time; Recovery activities; Associated cost of disruption
Redundancy[55]	Percentage of network links damaged versus the network performance and the percentage of nodes damaged versus the network performance
Network Functionality[56]	The recovery percentage of the network functionality compared to its original functionality, with the network functionality defined as the weighted inverse distance in the network
Operational Efficiency[57]	Set of indicators of operational efficiency used are electronic data interchange (EDI) connectivity (%), turnaround time (hrs), labor productivity (tons/person), and berth occupancy rate (%)

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[50] ESPO, 2012
[51] USDOT, 2019
[52] de Langen & Sharypova, 2013
[53] Zhang & Miller-Hooks, 2015
[54] Nair, Avetisyan & Miller-Hooks, 2010
[55] Garbin & Shortle, 2007
[56] Hu et al., 2016

[57] Hsieh, Tai & Lee, 2013

Example Process for Selecting Port Resilience Metrics

Hsieh et al. developed 14 metrics of port resilience by convening a panel 11 expert stakeholders – including port officials, government officials, planners, and researchers – in a series of discussions. The metrics proposed by participants were classified into four categories: accessibility, capability, operational efficiency, and industrial cluster/energy supply.

The authors standardized the metrics based on participants' judgment about the "threshold values" for each. Threshold values indicate how the functionality of each measured component will impact the port along a 0-4 numerical scale, with 0 indicating that the port can operate normally despite the disrupted component, and 1-4 indicating that the port would experience slight, average, significant effects, and complete port failure, respectively. Using this scale, the experts identified a threshold minimum and maximum value to correspond to each level of impact. For example, if the ground access system is 90% operable, the participants anticipate that the port is not impacted. However, at 50-20% operability, they predict the port will be significantly impacted. Finally, the researchers used the Delphi method during three rounds, allowing the experts to revise their earlier answers in light of the replies of other members of their panel and achieve consensus.

The table below demonstrates the end-product of the process (modified from Hsieh et al., 2013):

Metric Category	Metric	Level of Impact to Port Caused by Corresponding Component Disturbance				
		0	1	2	3	4
Accessibility	Ground access system (%)	>90	90-80	80-50	50-20	<20
	Travel time (minute)	<90	90-120	120-150	150-180	>180
	Shipping route density (lines)	<15	15-100	100-200	200-300	>300
Capability	Gantry crane capacity (TEUs)	>90	90-70	70-50	50-35	<35
	Facility supportability (%)	>80	80-70	70-50	50-40	<40
	Wharf productivity (10^3 tons/meter)	>5	5-4	4-2	2-1.5	<1.5
Operational Efficiency	EDI connectivity (%)	>90	90-80	80-50	50-20	<20
	Turnaround time (hr)	<24	24-36	36-48	48-72	>72
	Labor productivity (tons/person)	>350	350-250	250-150	150-100	<100
	Berth occupancy rate (%)	>70	70-50	50-30	30-10	<10
Industrial Cluster / Energy Supply	Investment growth (10^9 NTD[4])	>10	10-8	8-4	4-2	<2
	FTZ business volume (10^9 NTD)	>10	10-8	8-4	4-2	<2
	Electric power supply (%)	>90	90-80	80-50	50-20	<20
	Gas supply (%)	>50	50-30	30-20	20-5	<5

nts.

Other considerations that influence selection of resilience enhancements

The procedure of selecting resilience enhancements cannot consider their “resilience worth” in isolation; rather, decision makers may need to balance a myriad of interests and management objectives when selecting a strategy to improve their system’s overall performance. Table D-2 provides a non-exhaustive list of considerations that potentially factor into decision making rationale. These are intended to stimulate dialogue and potentially be included as criteria for evaluating alternatives.

Table D-9 Considerations and Criteria for Evaluating Alternative Measures to Enhance Resilience

Financial criteria	These include the associated benefits and costs, budget constraints, and so on.
Funding	Implementation of resilience measures will depend on availability of funding and access to programs to subsidize resilience initiatives. Lists of port-specific and multi-modal funding programs are maintained by EPA[58] and CMTS[59].
Competitiveness	Overall and specific competitiveness will likely be relevant; research shows that competitiveness considerations are generally equally important to a port’s customers and investors (Hales et al., 2017). However, the conversation of how measures can further support a port’s competitive edge (e.g., by enhancing its absorptive capacity to storm perturbations and thereby allowing it to maintain functionality during storm events that other peripheral ports cannot handle) may be an important discussion topic for decision makers.
Stakeholder considerations	Identifying the stakeholders, both internal to the port and external, who are “poised to implement” different measures should factor into the selection process (Becker & Caldwell, 2015). A port’s capacity to fulfill a certain resilience building action will depend on whether or not it has the appropriate personnel to see it through.
Co-benefits of measures	Conventional estimates of return-on-investment generally consider the short-term costs and benefits of Resilience Enhancement Options (REO) given the assumption that a disturbance occurs within the specified planning horizon. Yet, even in the absence of a disruptive event, resilience investments can produce returns, or co-benefits (also articulated as positive externalities), that are valuable to a port’s

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[58] Environmental Protection Agency Funding Opportunities website: https://www.epa.gov/ports-initiative/funding-opportunities-ports-and-near-port-communities

[59] The CMTS Supply Chain and Infrastructure Integrated Action Team publishes the Federal Funding Handbook for Marine Transportation System Infrastructure which contains authorized Federal multimodal transportation infrastructure funding, financing, and technical assistance programs for infrastructure in the MTS. The handbook is available at the website: https://www.cmts.gov/downloads/Federal_Funding_Handbook_2019_FINAL_Jan2020_corrected.pdf

	external stakeholder community and should be factored into economic analyses.[60]
Political buy-in	To some extent, the political attractiveness of a REO may carry weight in the decision-making process due to the public and government interests that ports serve. This is related to the financial /funding availability considerations for REO selection.
Decision maker perceptions of urgency	Perception of the likelihood of future hazards during the planning horizon will greatly influence which measures are considered (Becker et al., 2012; Ng et al., 2018). Frequency/intensity of past disasters plays a role in perceptions; higher natural disaster intensity can increases ports' capital allocations in disaster prevention (Gong et al., 2020). Perception about the immediacy of outcomes from implementing measures (payback period) will also likely factor into decision making rationale.
Compatibility with existing planning initiatives	Measures may require a port or MTS to deviate from existing management and planning initiatives norms, which complicates the process of embedding resilience into the planning culture of a seaport. Ease of implementation may offset concerns.
Timing of intervention/ implementation	To ensure greatest efficiency in operations, resilience planning initiatives for future environmental changes should be pursued when it makes the most economic sense. Particularly in light of sea level risk (SLR), it will be important for ports to identify a timeline for infrastructure modification that is economical and less disruptive to current cargo handling efficiency[61].

STRUCTURED SELECTION PROCESS WITH DECISION ANALYSIS TOOLS

Numerous decision analysis tools exist to help decision makers balance a myriad of interests and management objectives against resilience-related initiatives, several of which have been applied in MTS and similarly complex management contexts. In particular, decision contexts that call for evaluation of alternatives with a wide array of metrics can benefits from multi-criteria methods. Many of the methods described below are combinable, for example, life-cycle cost, benefit to cost ratio, or other economic metrics can be criteria in a Multi-Criteria Decision Analysis, alongside a selection of metrics of resilience discussed above and co-benefits that could not be captured in the economic analyses.

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[60] A comprehensive review of resilience planning co-benefits and methodologies for their calculation has been provided by the National Institute of Standards and Technology: https://doi.org/10.6028/NIST.TN.1959

[61] E.g., Florida seaports are required to continually assess SLR data and evaluate when to address and plan for SLR impacts (Florida Ports Council, 2019).

Multi-Criteria Decision Analysis (MCDA)

MCDA refers to a variety of approaches for structuring the factors (monetary and non-monetary) involved in cognitively challenging analytical tasks. The numerous methodologies that fall under the MCDA umbrella share the common objective of facilitating a transparent and systematic process for organizing and ranking potential decisions to solve a problem (Huang et al., 2011). An additional key tenet of many methodologies involves convening stakeholders to rank, or weight, to decision making criteria based on their expert judgment.

Decision Tree Analysis

Decision tree analysis (DTA) provides decision makers with a graphical representation of various alternatives to solve a problem. DTA is useful in analyzing sequential decisions in which uncertainty can be treated as a discrete in time, and it provides users with an understanding of the interdependencies between initial and subsequent decisions. In port resilience contexts, DTA can be used to evaluate the expected value of cost facing disruptive events to port systems and operations with and without the implementation of an identified REO.

Real Options Analysis

Real options analysis (ROA) applies options valuation techniques towards analyzing decisions, such as whether to invest in a certain REO. ROA takes into account uncertainty about the future evolution of the parameters that determine the value of the decision, coupled with management's ability to respond to the evolution of these parameters. Inputs for ROA calculations can include spot prices, Monte Carlo simulation-derived measures of volatility, and the dividends generated by the REO.

Life-Cycle Cost Analysis (LCCA)

This analysis tool sums the initial costs and future costs over the project’s viable life under conditions in which the benefits are assumed to be equal among all projects. LCCA thus identifies most affordable means of accomplishing proposed goal.

Benefit-Cost Analysis (BCA)

Benefit-cost analysis is similar to LCCA, but accounts for both life-cycle benefits and costs for an individual strategy. It is useful for comparing alternatives when benefits are not identical, or when benefits are across projects that have different objectives.

Economic Impact Analysis

If the scope of a MTS component’s resilience analysis extends outside of the port, an economic impact analysis (EIA) can help aid evaluation of REOs, as EIAs monetize the indirect economic and climate change impacts on transportation infrastructure performance and costs. For example, an EIA may include monetary effects of a climate stressor on employment patterns, wage levels, and business activity. EIA products may also complement BCA studies, as the use of both enables consideration of direct and indirect impacts of an extreme event under a future scenario when REOs were implemented.

Input-Output Models

Input-output (I-O) models are often used in EIA studies, as they capture the regional economic effects of infrastructure disruptions, and thus can be useful for valuing resilience investments at broader scales. I-O models are flexible in that they can applied to any geographic level where Bureau of Economic Analysis (BEA) data are available.

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ANNEX A: CUMBERLAND/TENNESSEE RIVER INLAND WATERWAY RESILIENCE ANALYSIS

CONTENTS

Performed by Vanderbilt University on behalf of DHS

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INTRODUCTION

Background / Purpose

This annex provides a demonstration of the process and approaches outlined in the *MTS Guide* toward performing a resilience assessment of inland waterway systems. For this annex, the two primary navigable tributaries to the Ohio River, the Tennessee and Cumberland Rivers, and the surrounding region are used as the area of focus. As part of the case study application of the MTS MTS *Guide* concepts and approach through this case study, multiple disruption scenarios are considered including a waterway outage (such as that which may be created by flood, drought, or planned or unplanned closure due to maintenance or an incident), a major earthquake, and a disruption of the Colonial Pipeline. Given that the 2021 ransomware attack of the Colonial Pipeline occurred during the drafting of this annex, it provided a unique case study example for consideration of how the inland water system provides redundancy for energy security in the middle Tennessee region as well as several lessons learned from the experience. This case study differs from others associated with the MTS Guide in that it does not assess coastal ports, but rather exclusively considers the inland waterway system. Furthermore, this study involved a large focus on stakeholder engagement, utilized publicly available data sets for replicability of the approach to other waterway systems, and mobilized large, crowd-sourced data sets to extract previously unavailable insights regarding the extent of waterway and pipeline disruptions.

Study Objectives

Inland riverway stakeholders are as interested in resilience as their counterparts along the coasts. The inland waterways system is responsible for half of all domestic waterborne commerce, or about 6-7% of all domestic cargo and $15 billion added to U.S. GDP [21]. The complex network of modes often interface at the point of the inland waterway port, where freight is transferred from waterborne vessels and barges to rail, truck, and pipelines or vice versa [22].

Due to the complex and highly variable relationships of ports (inland and coastal) with their surrounding communities and supply chains, the MTS Guide recommends significantly tailoring resilience strategies to local considerations. This is consistent with the U.S. EPA's recently released publication, "Inland Port Community Resilience Roadmap," which strongly emphasizes conducting analysis of local trends and engagement with immediate stakeholders as part of its 5-part resilience roadmap (Table 1) [4]. The need to closely characterize a region before implementing resilience strategies is critical to understand the intricacies and potential vulnerabilities that should/could be considered. To date, most of the focus has been on coastal infrastructure and associated systems with limited research on the inland river system's intricacies, leading some to conclude that "the study of the impacts of maritime transportation and port disruptions [especially regarding inland waterways] in the literature is still in its early stages [17]", and this MTS Guide and Annex A will work to address this need.

Table 1: The U.S. EPA recommended steps for local governments and port and community stakeholders to increase their resilience to the variability of river water levels [18].

Step 1	Conduct Outreach and Identify Resilience Objectives
Step 2	Identify and Analyze Resilience Challenges
Step 3	Identify strategies to improve resilience.
Step 4	Develop institutions and performance measures to support resilience objectives.
Step 5	Implement strategies and evaluate progress.

Furthermore, for inland waterway navigation systems that interact with other modes, multiple commodities and many communities, consideration of all aspects of the system, all individual infrastructure assets and all commodities is a huge undertaking. For the purpose of this study, a system-level approach was taken (not a narrowly focused analysis of a single port or terminal) with a focus on some key commodities (including particularly petroleum movements), and a set of three scenarios of disruption. The goal was to provide a demonstration of HOW the process of a resilience analysis would be conducted, point to data and information that could be utilized, and showcase the importance and value of stakeholder engagement throughout for a robust analysis. Note, the objectives were not to arrive at specific resilience strategies for the system or any individual port or terminal, but instead to provide an example of HOW one would follow the MTS Guide's process.

As such, the project team identified the following three research questions to be considered throughout the study which are aimed at characterizing the system and approaching resilience with special consideration of petroleum product movements into the region:

- To what extent can the inland waterway system ensure supply of petroleum products to the Middle and East Tennessee regions during a disruption of the Colonial Pipeline?
- To what extent might the inland waterway system's ability to move commodities to/from the Middle Tennessee region be impacted by a New Madrid earthquake event and other natural hazards?
- Where are key ports/docks/terminals along the Tennessee and/or Cumberland River that have potential to provide loading/offloading capabilities for commodities to improve system resilience? Are these used along with other potentially redundant transportation modes?

To answer these questions, the study illustrates the process provided by the MTS Guide in both data analysis and stakeholder engagement through the following tasks:

- Task 1. Plan and Convene 2 Stakeholder Roundtable Sessions
- Task 2. Prepare summary of Priorities and Takeaways from the Stakeholder roundtables
- Task 3. Identify and secure necessary data for characterization of system – in parallel with Tasks 1 & 2
- Task 4. Apply MTS Guide method/approach and/or RRAP approaches to characterize/evaluate region
- Task 5. Create 3 disruption scenarios corresponding to the 3 Natural Hazards (navigation outage, pipeline outage, and seismic event)
- Task 6. Estimate impact for each scenario on the case study area & the petroleum supply chain

- Task 7. Identify potential operational resilience strategies including operational variability and recovery time, etc.

BACKGROUND

Defining Resilience

There are many institutional approaches to defining resilience, but they generally resemble the definition outlined by The United Nations Office of Disaster Risk: “The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” [19]. More recent approaches to resilience go a step further and emphasize that, instead of simply recovering and ‘bouncing back’ to pre-disruption levels of productivity, resilience should also include a dedicated effort to ‘bounce forward’ and improve original practices to be less susceptible to disruption in the long-term [18] [20]. The resilience of a waterway, therefore, could be understood to mean continuing an acceptable level of waterway operations with minimal disruption in service through short- and long-term environmental and human-related disturbances and stressors while also more successfully adapting to future adverse events [20].

Importance of Inland Port Resilience

The inland waterway system of the United States is an important component of the multi-modal national supply chain that moves many of the nation’s most important commodities, including petroleum, agricultural products, and production materials. The inland waterways system is responsible for half of all domestic waterborne commerce, or about 6-7% of all domestic cargo and $15 billion added to U.S. GDP [21]. The complex network of modes often interface at the point of the inland waterway port, where freight is transferred from waterborne vessels and barges to rail, truck, and pipelines or vice versa [22]. Failures of key infrastructure assets in the inland waterway system or its complimentary modal connections may cause significant disruptions to regional economies and supply chains far beyond the local community being impacted, especially as more freight shifts to waterways in response to the expansion of the Panama Canal and the increased congestion of other modes [15] [18] . Therefore, the resilience of the inland waterway system to a wide spectrum of stressors has been the subject of intense academic study [23] [17] [14] [20] [24].

The inland waterway system and its associated ports face more frequent environmental challenges than other modes. The waterway system is particularly susceptible to changes in water stage height, both in the case of extreme high water and low water events, and also freezing or seismic disruptions. Flooding events increase the difficulty of conducting safe port operations, disrupt vessel navigation, and damage lock and dam infrastructure, causing costly closures of facilities. Exacerbating the issue is the increasing frequency of extreme precipitation events due to climate change [25] and also the increasing age of river infrastructure beyond its design life. According to the U.S. Environmental Protection Agency (U.S. EPA), 78% of locks and dams were beyond their design life in 2020 [18], and delays from both scheduled and unscheduled maintenance of these assets caused in 2010 caused $33 billion in costs on U.S. products [26]. In 2013, there were 142,000 hours of unplanned lock closures to make repairs [27]. As a result of these discrepancies and a lack of sufficient appropriations to remedy the situation, the American Society of Civil Engineers (ASCE) 2021 Report Card on Infrastructure gives the country’s dams a ‘D’ score [28] . In addition, many ports are located in low income and/or minority communities with limited resources to combat flooding challenges to supporting infrastructure in port communities [18]. Like flooding periods, low level water events also restrict the ability of barges to operate at capacity. The American Waterways Operators Association estimates that with every 1-inch loss of water, a barge is able to move 17 less tons of cargo, resulting in a loss of 756 tons per inch of reduced water for a typical

Mississippi configuration of 30-45 barges [29] . When water height falls below the 9 foot inland navigation channel standard maintained by the USACE and the river system is closed, a towing company may lose as much as $10,000 a day per idle towboat [29] . Increasing extreme weather events will continue to cause adverse impacts on the efficiency and maintenance of the inland waterway system.

Human-related disturbances also present uniquely difficult situations for the inland waterway system. Vessel collisions and groundings, intersecting infrastructure failures, and activist or terrorist interventions can leave entire segments of rivers closed for days without redundant or alternative routes to deliver freight. For example, in 2005 a towboat, the *Elizabeth M*, and its barge flotilla inadvertently shut down the Ohio River after a fatal collision with Montgomery Lock and Dam during an extremely high-water event. The Coast Guard Captain of the Port declared a 4-mile safety zone for the duration of 4 days of search and rescue operations, effectively halting freight operations [30] [13]. In 2019, 22 Greenpeace climate activists intentionally dangled themselves from a bridge over the Houston Shipping Lane, the largest oil export channel in the US, in order to protest the production of petroleum products. Due to the navigational hazard, the U.S. Coast Guard closed portions of the channel for most of the day, causing “untold millions of dollars” of losses in the river which normally sees 700,000 barrels of oil moved per day [31] [32]. In all of the above cases, freight sat idle due to the nature of single point of failure of infrastructure, typical along riverways, negatively impacting port and supply chain economics. Single point of failure infrastructure in other non-waterborne modes of transportation, such as pipelines and rail, create shocks in demand for barges that also test port and inland waterway resilience.

Overview of the Case Study Region

Two primary navigable tributaries to the Ohio River, the Tennessee (TN) and Cumberland Rivers, present an excellent case study to demonstrate the value of the MTS Guide in an Inland Port setting, by characterizing this regional system’s resilience to anticipated regional hazards. Both rivers moved 30.8 million tons of freight valued at $5.2 billion of goods in 2018, the majority of which was inbound to Tennessee [1]. By weight, the top commodities transported on TN rivers included gravel/salt, coal, and petroleum products, respectively. These rivers service the middle and east regions of Tennessee, and include the major metropolitan and industry city centers of Nashville, TN; Huntsville, AL; Chattanooga, TN; and Knoxville, TN.

Of these cities, Nashville and Chattanooga’s critical petroleum fuel needs are primarily served by a single non-waterborne source, the Colonial Pipeline, which supersede secondary barge shipments (Knoxville is served by both Colonial and the separate Plantation Pipeline) [2]. The Colonial Pipeline spans 5,500 miles and carries up to three million barrels of fuel per day to its customers (Figure 1 and Figure 2). The Colonial pipeline, which also serves 45% of the East Coast’s petroleum needs, has a recent history of single point of failure closures, due to explosions, as occurred in 2016 [3], from Hurricanes, as occurred in 2017 with Harvey [4], and most recently from a ransomware cyber-attack, which occurred in 2021 [5] [6].

The river couplet is vulnerable to environmental hazards as well, such as extreme river stage height events as occurred in the Cumberland River Flood of May 2010 [7]. The river couplet may also be exposed to, and unprepared for, a large seismic event from the New Madrid fault in West Tennessee [8] [9]. Geological evidence from the years 900, 1450, and 1811 suggests that the New Madrid region experiences large, sudden earthquakes that liquefy bedrock approximately every 500 years, with a minimum recurrence rate of 200 years [10]. The overlap of competing commodity transportation between the inherently multimodal waterways, pipelines, and other modes in this region could yield promising resilience strategies and add redundancy to all involved systems.

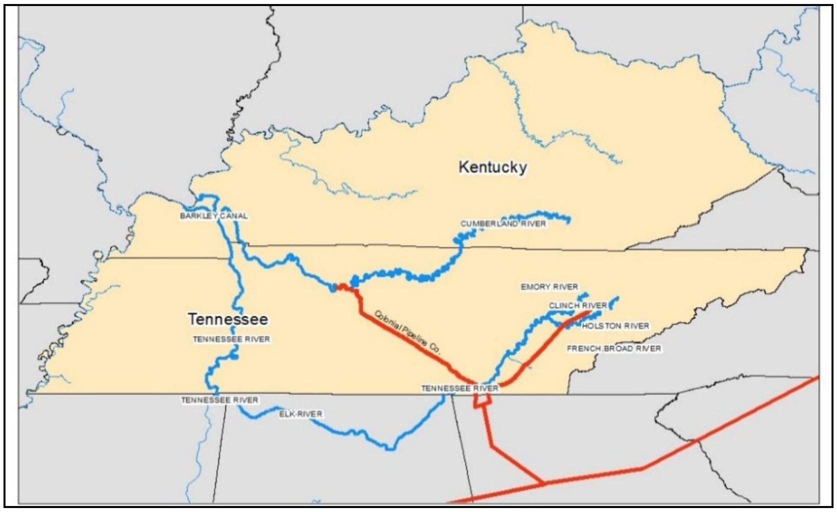


Figure 1: The case study area including the Cumberland and Tennessee Rivers in blue and the Colonial Pipeline in red.

Figure 2: Colonial Pipeline service route. Colonial is the primary source of petroleum products for Nashville and Chattanooga, while Knoxville is also served by the Plantation Pipeline. Image Courtesy of New York Times [11].

Interplay between Refined Petroleum Product Movements and Inland Waterway Transport

To understand the intermodal dynamic relevant to this case study, an historical perspective is helpful that will apply across the entire inland network and to numerous other commodities. Commercial use of the nation's inland waterways originated with the country's founding—beginning with rivers along the eastern seaboard and the construction of elaborate canal systems that extended these waterways inland. Construction included the Erie Canal in New York, and quickly extended the westward frontier down the Ohio River and beyond to the Mississippi River. Flat-bottom boats allowed one-way travel all the way to New Orleans, and round-trip travel emerged with the arrival of steamboats in the 19th century.[1]

The Federal Government, through the USACE, became responsible for establishing the infrastructure to allow commercial navigation on designated waterways such as the Ohio and Mississippi Rivers. The first projects achieved a channel depth of 6 feet, but Congress legislated a 9 foot channel in the Rivers and Harbors Act of 1910, which became the minimum channel depth adopted on the Ohio River and applied to new projects on the inland river network. This 9 foot depth design standard survives to this day.

The construction of a modern system of navigational dams along the Mississippi River began during the Great Depression, followed on the Illinois River, allowing connection to the Great Lakes at Chicago and on the Tennessee and Cumberland Rivers, which coincided with the creation of the Tennessee Valley Authority in the 1930s.

In the post-WWII era, a comprehensive modernization program commenced on the Ohio River. This upriver system extended north from New Orleans and reached Pittsburgh, Chicago, and Minneapolis. This system connected to a shallow draft navigable channel established along the Gulf Coast from Brownsville, Texas, to the Florida Panhandle, called the Gulf Intracoastal Waterway.

This extensive, fully integrated and connected system was a foundation for the nation's industrial development in the 20th century, and supported the robust growth of the nation's energy, agriculture, industrial and construction markets. Looking specifically at the petroleum market, refineries and product terminals were located along this navigable waterway network so that refined products could be delivered into consuming markets inexpensively, from many different refineries as Figure 3 below illustrates.

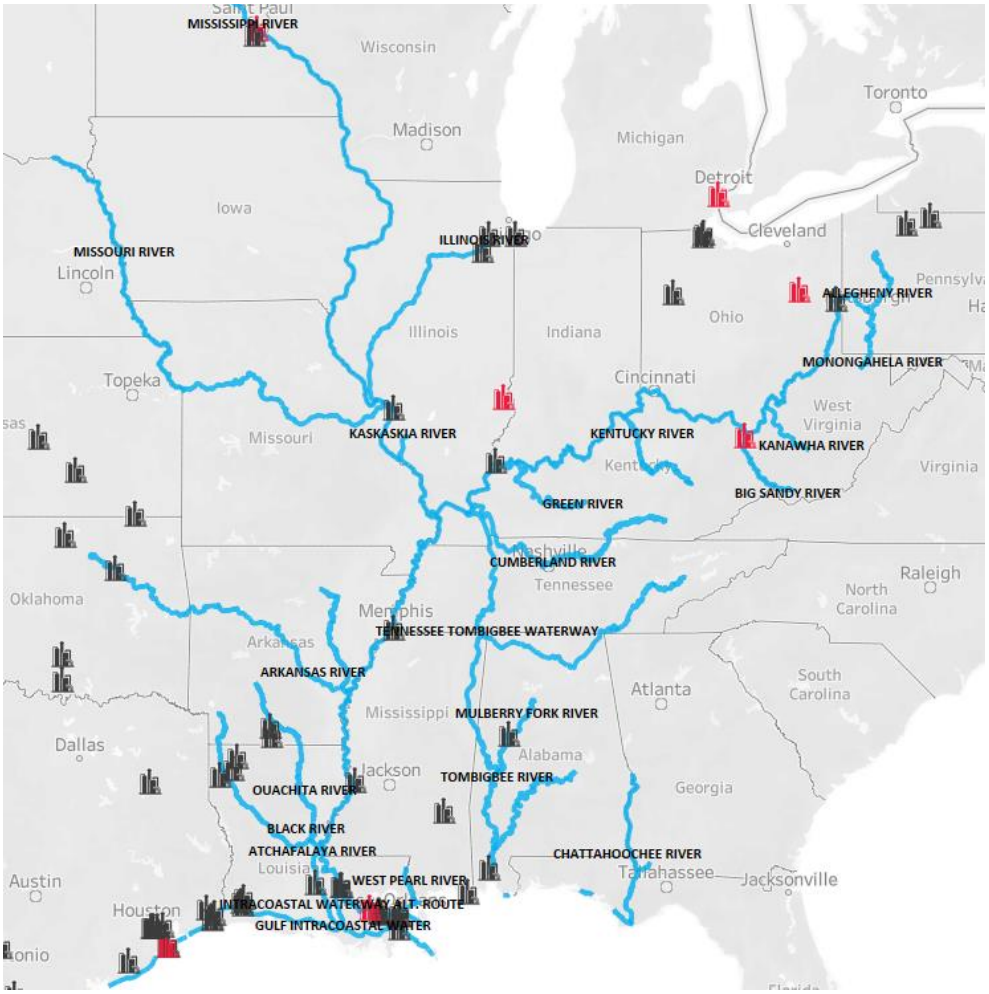


Figure 3: The nation's refineries/major dock facilities and the inland waterways are truly an integrated system. Marathon Refineries are in red (Source: Operations Group, Marathon Petroleum).

Refined product terminals were established along the Tennessee and Cumberland Rivers in the major metropolitan areas so that these products could be delivered by barge, and this continued into the latter third of the 20th century when the introduction of large interstate petroleum product pipelines disrupted this system. In Tennessee, the disruption came in the form of the Colonial Pipeline which was constructed in phases beginning in the 1960's to bring refined products from refineries along the gulf coast to multiple states from Louisiana all the way to New York/New Jersey. A spur off the main stem provided competing access to Tennessee markets in Nashville, Chattanooga, and Knoxville, and a second pipeline serving similar markets was also constructed. Since pipeline economics are generally more favorable, eventually deliveries by barge disappeared altogether.

Perhaps related to the periodic disruptions on these pipelines and also the limits to their capacity, in the last decade, two of the major petroleum companies elected to reinstate barge service to their terminals in Nashville where it was economic to reactivate the barge terminal delivery infrastructure.

Review of Historic Disruptions and Impacts to Region/Supply Chains

Over the last decade, there have been a variety of disruptions with noteworthy impacts on the supply chain of the river basins of Tennessee. These disruptions have been caused both by natural disasters and weather events as well as lock outages and adjacent modal events. In the sections that follow, there is a summary of disruptive events that have occurred exclusively on or adjacent to the Tennessee and Cumberland River couplet.

Natural weather events are responsible for numerous disruptions to the Tennessee and Cumberland River waterways and will likely continue to cause disruptions going forward. In May 2003, a heavy rain event near Chattanooga exceeded the dam capacity of navigation projects on the Tennessee river and caused flooding and navigation challenges near Hamilton County, Tennessee [33]. In the summer of 2007, a major drought threatened the navigability of the inland waterway system in Tennessee. The Tennessee Valley Authority was forced to drastically reduce lake reservoirs to preserve the minimum 9 foot draft required for barges [33]. The Chickamauga Dam recorded a record-breaking, 105-year low average system inflow during the drought. [34] In May of 2010, a 36-hour historic rainfall event caused massive flooding across the Cumberland River basin, infamously inundating much of downtown Nashville. The inland waterway supply chain was disrupted for the duration of the event as the USCG Captain of the Port suspended navigation on the river and the USACE fought to prevent dams from overtopping [7]. Cheatham Lock and Dam was completely submerged at the event's peak, and the USACE made the difficult decision to implement spillway gate operations, or intentional controlled flooding of the basin, to prevent the overtopping of the Cordell Hull and Old Hickory navigation projects. The USACE After Action Report found that these actions successfully reduced flood crest in Nashville by 5 feet, however also acknowledged that the basin was not "immune" to flooding at that some damage was inevitable [7]. The event ultimately resulted in 26 fatalities, $2 billion in damages, and hundreds of businesses shuttered [35]. Interestingly, the USACE identified that both scheduled and unscheduled maintenance of dam turbines and spillway gates during the event contributed additional challenges to water control operations [7]. In addition to floods and droughts, tornadoes have also notably generated substantial debris that halts river traffic, as the March 2020 Nashville tornadoes demonstrated by plunging several transmission towers into the Cumberland River [36]. Looking forward, a U.S. EPA's report regarding climate change impacts in Tennessee finds that heavy precipitation events have increased by 57% in the Southeast and heavy rainstorms and increasingly frequent droughts are likely to continue [33].

Maintenance and adjacent infrastructure issues also caused negative impacts on the inland waterway system. In 2021, a crack in the I-40 Hernando DeSoto Bridge paralyzed Mississippi River traffic (which feeds the Cumberland and Tennessee) for 4 days, causing the delay of 1,058 barges while U.S. Coast Guard and other safety officials evaluated the integrity of the structure before reopening the channel to traffic [37]. According to a report developed by the University of Tennessee investigating the impacts of Chickamauga Lock closure, these increasing outages may cause irreversible loss of business. A greater than 90 day outage would cause the permanent loss of business to rail for local asphalt shippers and the state DOT would further lose $2.8 million. As inland waterway infrastructure continues to age, operators and other stakeholders should be mindful of how historic maintenance disruptions may occur again and at greater scales.

APPROACH

Characterizing the Region with Publicly Accessible Data

As part of the effort to identify the location of key ports/docks/terminals along the Tennessee and Cumberland Rivers that have potential to provide loading/offloading capabilities for commodities to other primary modes when portions of the waterways may become unnavigable, 31 public ports were identified, mapped into Environmental Systems Research Institute (ESRI), ArcGIS Pro, and finally characterized based on information from the 2020 Inland River Port Guide [39]. In some cases, follow up correspondence was conducted with listed contact information to confirm data presented in the MTS Guide. Key attributes of the port were identified, including primary types of commodity handled (especially if liquid bulk products were serviceable), connectivity to rail, and river mile/address. Using the provided location information, addresses were converted to latitude and longitude coordinates using the Google Maps API [40] and mapped along the Tennessee and Cumberland Rivers. Then, using the ArcGIS Pro suite, ports were identified as being within 5 miles of a primary road/highway or within 1 mile of Class 1 rail per shapefiles provided by the U.S. Census [41]. Listed rail connectivity was checked against the proximity to rail metric performed using GIS software. Finally, to determine if the ports, dams, or associated inland waterway infrastructure were potentially vulnerable to a New Madrid seismic event, shapefiles of the liquefication zones from the 3 previous large New Madrid Earthquake events, provided by Tuttle et al., were overlayed onto the system [10]. Overlapping, primary infrastructure was identified and assessed for single point of failure potential considering documented seismic risk.

This study also utilized USACE Lock Monitoring Performance System (LPMS) Data [44] to investigate the commodity flows in the region and understand historical shifts in commodity movements. This data was also used to investigate the dynamics of petroleum product movements and other commodities within the region (i.e., where might commodities be coming into or leaving the system). LPMS data captures the total monthly tonnage of commodity that travels through each of the USACE's locks. There are nine locks on the Tennessee River (Figure 4) and four locks on the Cumberland River. The commodity can be classified as one of eight types: Coal, Petroleum, Chemical, Crude Materials, Manufactured Goods, Food, Machinery, and a Miscellaneous group. LPMS data records whether or not a commodity was headed upriver or down river.

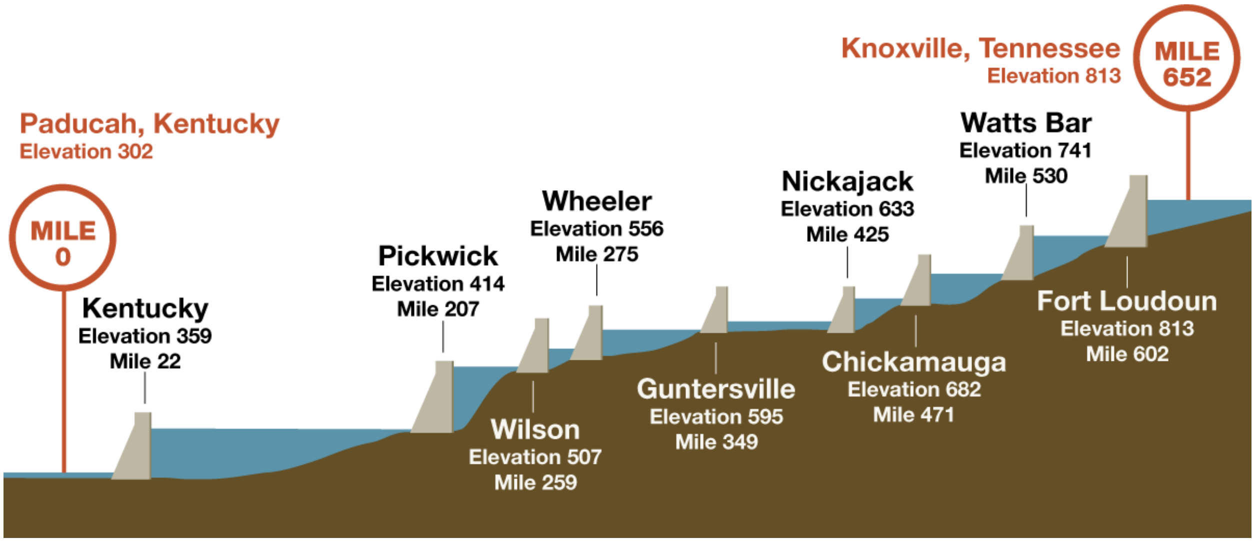


Figure 4: A diagram of the Tennessee River and its nine locks and dams owned by the Tennessee Valley Authority (TVA). The space between each dam usually spans several counties and represents a "lock-pair river segment." Photo courtesy of TVA [12].

For this study, a historical 'snapshot' is generated by evaluating changing commodity trends for a single lock on each river. LPMS data was collected for the time period between January 2012 and November 2020 at Cheatham Lock on the Cumberland River and Pickwick Lock on the Tennessee River to evaluate what commodities experienced changes in demand (these locks were selected for their downstream orientation relative to major Tennessee cities in the study area). Then, monthly 2019 LPMS data for lock-pair river segments containing the major inland port cities of Nashville, TN;

Huntsville, AL; Chattanooga, TN; and Knoxville, TN were analyzed to approximate total freight volume change in these urban communities. As a note, there are no locks upstream of Knoxville, so for the purpose of this study, all traffic traveling upstream of Fort Loudoun dam are assumed to be en route to the Knoxville region, and all traffic traveling downstream of Fort Loudoun dam is assumed to be shipped from Fort Loudoun. The differences in total commodity flux between the cities was used to assess the different existing capabilities in regards to the respective city's capabilities to accept certain commodities at its ports and terminals. The navigable waterways and location of these locks were mapped on ArcGIS to provide geospatial context for the lock-pair river segments relative to other important system attributes [47].

Stakeholder Engagement as a Means to Validate Process and Information

A key aspect of this project was to engage a diverse group of stakeholders from across the region to provide input and feedback throughout the project. Stakeholders were identified through existing and prior relationships of the project team, recommendations from DHS and USACE project leads, and additional recommendations from identified stakeholders. Ultimately, over 40 individuals representing all levels of government, private sector and Non-Governmental Organizaiton (NGO), planning organizations, academics, comprised the stakeholder group. The stakeholders were asked to participate in two virtual meetings using the Zoom platform where the research team and others presented information and gathered input/feedback through discussion, Zoom chats, Google Jamboards, etc. Notes were taken by the project team members and assembled. The Jamboards were saved for further review and usage.

Additionally, some stakeholders were engaged by the project team for separate conversations throughout the project to provide input, help guide the decisions on the selection of scenarios, and some were asked to present information at the second stakeholder meeting about their knowledge related to the disruption scenarios.

A general, high-level summary of each of the primary stakeholder meetings is provided below. The Jamboards are shared in the following sections. The agendas and a list of participants from each meeting is provided in appendices A.2 and A.3.

Stakeholder Meeting 1:

On September 29, 2020, Vanderbilt University's VECTOR Research Team conducted a meeting to gather feedback from key stakeholders in the Tennessee Inland Waterway System to establish 'boots on the ground' perspectives on how the waterway system would be impacted by flood, drought, or earthquake. Twenty-nine participants from federal government, state government, terminals and barge operators, and other industry groups discussed a range of resilience topics, including an overview of the MTS Guide, a discussion on the Tennessee and Cumberland Rivers inland waterway system's major assets, and individual organization resilience plans to natural hazards. One of the first items of information discussed was what the term "resilience" means to members of the group. The responses were captured using a Jamboard, an online application that allowed participants to interactively contribute and arrange their input on a series of shared slides
(Figure 5 below).


What does resilience mean to you?

Multiple choices

Bouncing back

love the bend but not break! adverse events are acute and chronic!

Ability to adapt

ability to sustain operations in the face of adversity

Ability to respond to changes in the norm.

I like the one provided earlier: Prepare, Resist, Recover, and Adapt

a critical means for ensuring a better future.(Katherine Chambers, ERDC)

Two major rivers is a big assets for the region if we maintain them

Severing the Ohio River by earthquake or flood or drought

Responding to disruptions in a system

Returning to pre-event activity levels

The ability to withstand impacts from natural and man-made shocks to a system

Ability to recover

Ability to Keep Going

Cross-sector collaboration between public & private stakeholders

Recovering AND 'bouncing forward'

Maintaining function during and after disruption

the ability to recover quickly from a disruption

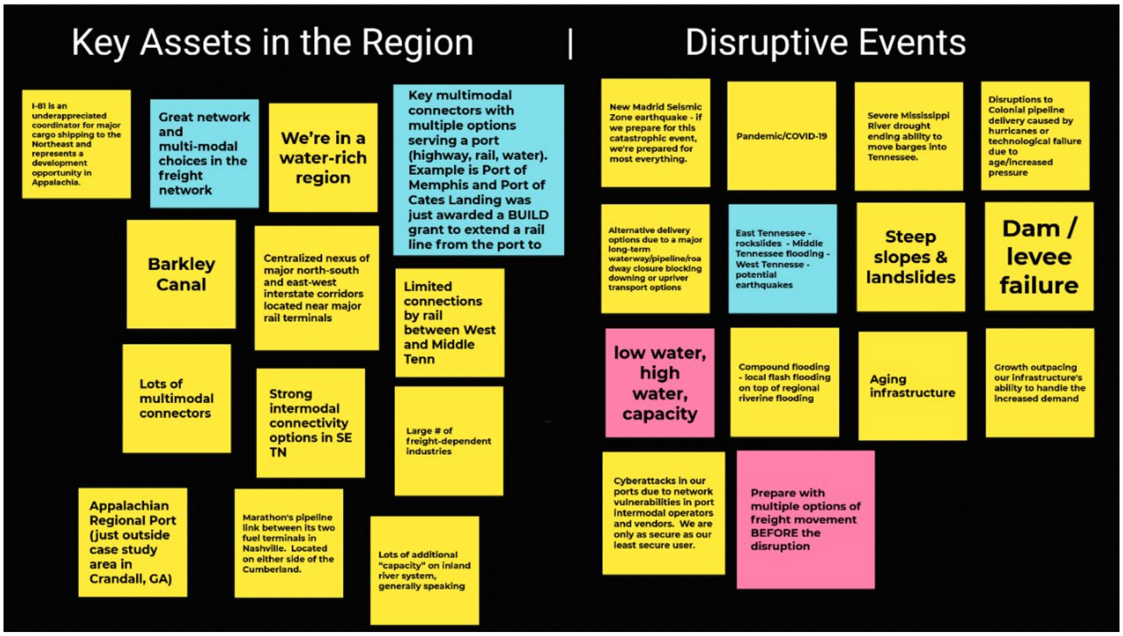
Ability to react and overcome a challenge

Ability to absorb impacts of disruption/change and keep moving forward

planned response, quick recovery,

Figure 5: Jamboard capturing the stakeholder perspectives on the term "resilience".

Additionally, key infrastructure assets as well as potential and historic disruptive events were identified for the region (Figure 6). The event concluded with a discussion and questions. The feedback from this meeting was used to inform the interpretation of the analytical results and subsequent conclusions.


Key Assets in the Region | Disruptive Events

I-81 is an underappreciated coordinator for major cargo shipping to the Northeast and represents a development opportunity in Appalachia.

Great network and multi-modal choices in the freight network

We're in a water-rich region

Key multimodal connectors with multiple options serving a port (highway, rail, water). Example is Port of Memphis and Port of Cates Landing was just awarded a BUILD grant to extend a rail line from the port to

Barkley Canal

Centralized nexus of major north-south and east-west interstate corridors located near major rail terminals

Limited connections by rail between West and Middle Tenn

Lots of multimodal connectors

Strong intermodal connectivity options in SE TN

Large # of freight-dependent industries

Appalachian Regional Port (just outside case study area in Crandall, GA)

Marathon's pipeline link between its two fuel terminals in Nashville. Located on either side of the Cumberland.

Lots of additional "capacity" on inland river system, generally speaking

New Madrid Seismic Zone earthquake - if we prepare for this catastrophic event, we're prepared for most everything.

Pandemic/COVID-19

Severe Mississippi River drought ending ability to move barges into Tennessee.

Disruptions to Colonial pipeline delivery caused by hurricanes or technological failure due to age/increased pressure

Alternative delivery options due to a major long-term waterway/pipeline/roadway closure blocking downing or upriver transport options

East Tennessee - rockslides - Middle Tennessee flooding - West Tennesse - potential earthquakes

Steep slopes & landslides

Dam / levee failure

low water, high water, capacity

Compound flooding - local flash flooding on top of regional riverine flooding

Aging infrastructure

Growth outpacing our infrastructure's ability to handle the increased demand

Cyberattacks in our ports due to network vulnerabilities in port intermodal operators and vendors. We are only as secure as our least secure user.

Prepare with multiple options of freight movement BEFORE the disruption

Figure 6: Jamboard from first stakeholder meeting where participants were asked to help identify key assets in the region and also potentially disruptive events for consideration.

Stakeholder Meeting 2:

On June 11, 2021, Vanderbilt University's VECTOR Research Team conducted a second meeting with key stakeholders in the Tennessee Inland Waterway System to estimate the specific impacts of the identified disruption scenarios on the waterway system and further to evaluate the proposed resilience enhancement options that are the final product of this annex. Stakeholders introduced case examples for the identified disruptions, and an expert panel facilitated discussion regarding what REO's would be best suited to the case example. The three case examples considered where as follows:

1. Alternative Mode Impacted: Colonial Pipeline Spur to Tennessee Service Interruption
2. Lock Outage: Cheatham Lock and Dam Maintenance
3. Navigability of Waterway Junction Impacted by Earthquake: New Madrid Fault Event

Identifying Disruption Scenarios

The selection of disruption scenarios for consideration as part of the study was an iterative process. Initially, the project team identified three scenarios for consideration based upon individual knowledge and expertise of disruptions and the dynamics associated with the shift in petroleum movements by barge into the region. The initial scenarios planned for disruption were flood, drought, and earthquake.

As the project team began investigating historical disruptions and having preliminary conversations with stakeholders about their involvement in the project and interests, it became apparent that consideration of a Colonial Pipeline disruptive event should be considered as opposed to drought. Given that both the Cumberland and Tennessee rivers are "managed" rivers with water levels maintained in pools between the locks/dams by TVA and USACE, the likelihood of a severe drought being a consideration that would significantly affect waterway navigation became a lower interest scenario for consideration. However, there is still potential for severe drought to impact the region, but given the timeline and interest in exploring more pressing and near-term feasible potential disruptions meant that it was tabled for this study.

Similarly, the conversations with stakeholders and awareness of activities happening on the waterways of focus shifted another disruption scenario from flooding to river closure in general. For this consideration, the project team decided to use the scheduled maintenance outages of Cheatham lock as a real-life, ongoing disruption that provided a timely and useful disruption even which would allow stakeholders to have conversations about the actual impacts of the waterway disruptions and how they were managing them to be resilient as well as lessons learned that may inform future disruption response and recovery activities.

A key takeaway from the efforts to define the disruption scenarios is that identification of disruption scenarios can and probably should be driven by stakeholders input and can be an iterative process as information and situations in the region change. The project team decided to focus one stakeholder meeting solely on presentations and discussions about the three disruption scenarios with stakeholders presenting both impacts, concerns, and how agencies responded and was prepared to respond to each of the scenarios. The team and stakeholders leveraged the information and activities that developed with the ransomware attack and disruption of the Colonial Pipeline to help highlight an understanding of the impacts to the region across modes/sectors/communities, lessons learned, and opportunities for resilience such as petroleum coming into the region by barge.

Generalizable Resilience Options Considered

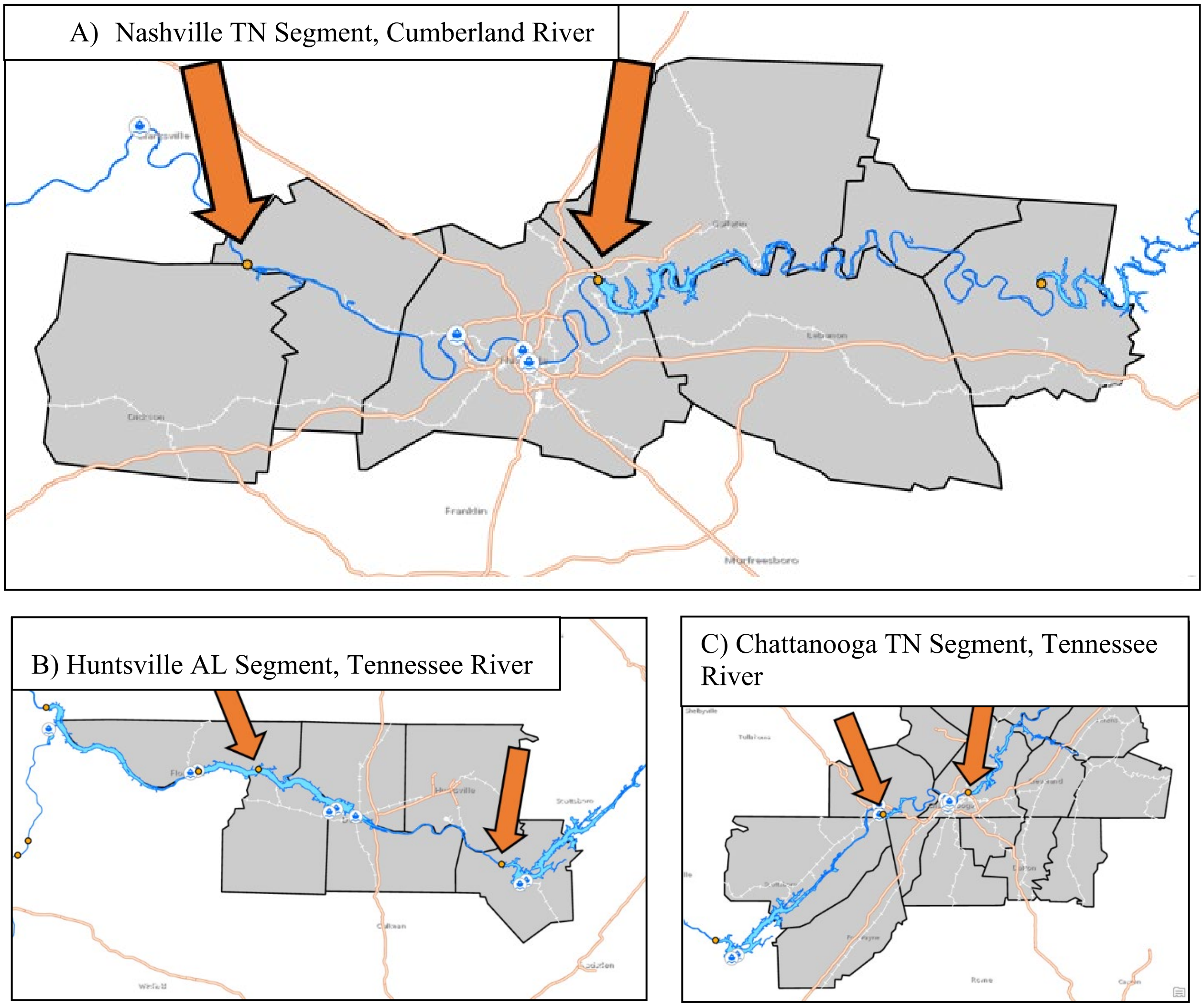
The U.S. Department of Homeland Security has over time developed multiple Regional Resiliency Assessment Programs (RRAPs). RRAPs are voluntary, cooperative assessment of specific critical infrastructure that identifies a range of security and resilience issues that could have regionally or nationally significant consequences [52]. Through partnership with DHS Guide project leads, the project team obtained summaries of RRAPs that were considered relevant to the study domain. For security purposes, the RRAP reports were scrubbed of their original city information and any specifics about the critical infrastructure. The project team summarized the findings from the RRAP information provided into four relevant general categories of resilience enhancement options which are presented below. These general resilience categories were shared with stakeholders as foundational examples to guide discussions on what REO's might be applicable to the study region. Others trying to implement similar resilience assessments may benefit from considering these general categories.

- **Resiliency Enhancement Option # 1: More Robust Resilience Response Organization** - Establish a state incident command system. Hire full time emergency planners and establish protocols for relevant hazards. Identify, maintain list, and include private stakeholders in planning and workshops. Expand training opportunities and outreach to isolated areas and neighboring states. Leverage federal funding, resources, and partnerships using existing grant opportunities.
- **Resiliency Enhancement Option # 2: Responses to Flood Events** - Identify and rank critical infrastructure in the flood plain, using modeling techniques and federal resources. Elevate and harden back up power for key infrastructure, including ports, fuel terminals, hospitals, radio, etc. Consider adding back-up or uninterruptible power supplies (UPS). Identify, upgrade, and test secondary ports to serve as alternates in disruptions. Develop cargo prioritization tools, and establish state protocols for key outages, including releasing and inspecting cargo in a streamlined fashion. Develop mapping and business continuity plans for port complex.
- **Resiliency Enhancement Option # 3: Fuel Shortage Responses** - Formalize prioritization of limited fuel supplies to critical infrastructure, partnering with nearby states and stakeholders. Use web-based tool sets that understand interdependencies between critical infrastructure, considering security implications as well, for duration of disruption. Engage directly with fuel facilities, establish emergency fuel contracts in advance. Consider fuel contingency plans, relationships with refineries, airports, critical facilities, and fire fighting for alternative fuel delivery methods/plans. Consider using locomotives as a backup power source.
- **Resiliency Enhancement Option # 4: Earthquake Responses** - Port and state authorities should design seismic/liquefaction standards for ports, highways, and other critical infrastructure with USGS and other federal partners, including inspections and retrofits. Add UPS at terminals. Model hazard impacts on infrastructure and update port, state, and stakeholder plans. Identify state hazardous materials and other risk-prone assets. Workshop seismic event disruptions with stakeholders. Consider how earthquake simultaneously impacts multiple modes of transportation.

RESULTS

Region Characterization and Key Assets

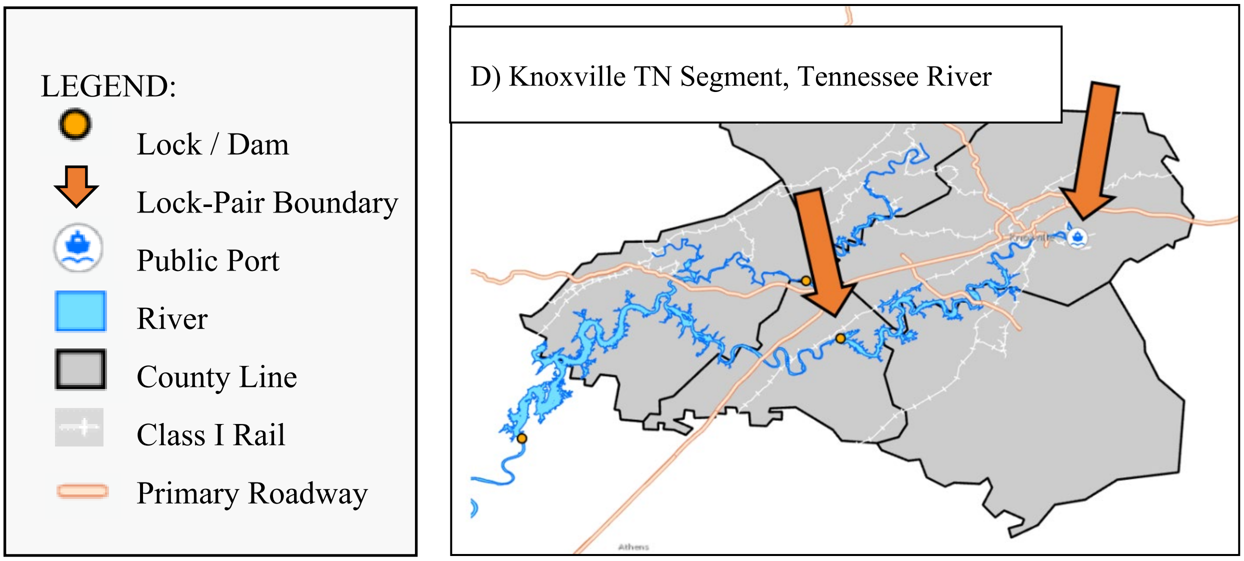
Initial analysis of historical commodity flow data suggest that the inland waterway system has developed significant capacity to deliver petroleum products to Middle Tennessee via barge since 2012, while East Tennessee has not yet developed this multimodal redundancy and may not be as resilient to a disruption of the Colonial Pipeline (Figure 7). The Cumberland's petroleum shipments grew from 3% to 22% of the river's total annual tonnage volume over the 8-year study period, while petroleum volume on the Tennessee River only grew from 6% to 8% (Figure 8).



A) Nashville TN Segment, Cumberland River

B) Huntsville AL Segment, Tennessee River

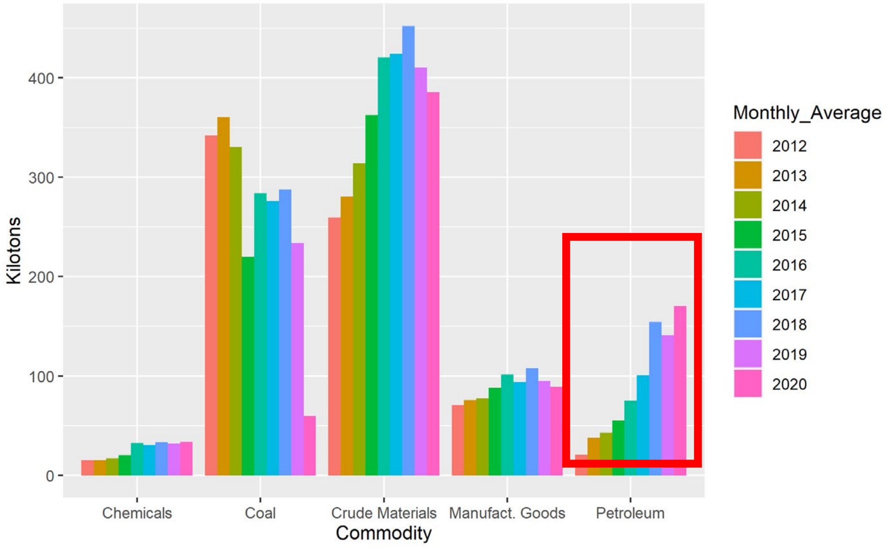
C) Chattanooga TN Segment, Tennessee River



D) Knoxville TN Segment, Tennessee River

Figure 7: Characterized metropolitan regions include the location of all public ports, Class I rail, and primary roadways. The lock-pair river segments, represented by the space between orange arrows, indicate the region in which commodity flux is calculated to approximate waterborne commerce in A) Nashville, B) Huntsville, C) Chattanooga, and D) Knoxville, respectively.

a) Cheatham Lock, Cumberland River



b) Pickwick Lock, Tennessee River

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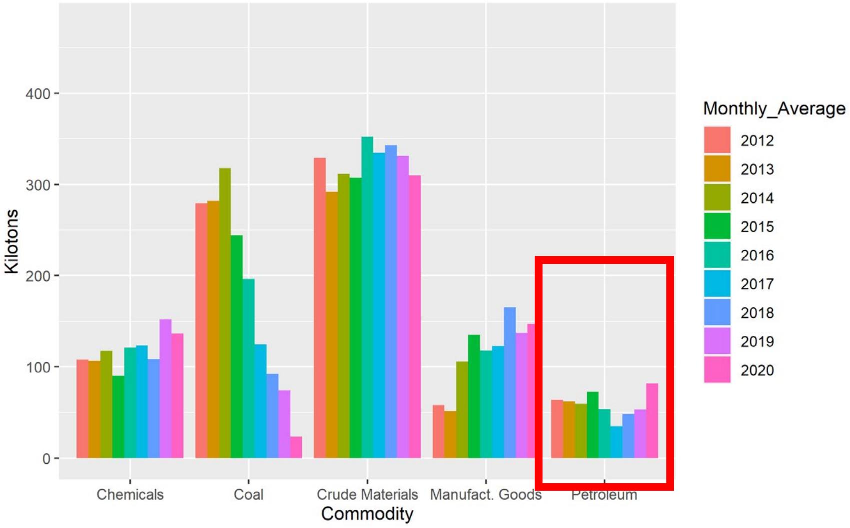

Figure 8: Historical Monthly Average Commodity Flows, 2012 – 2020, through the a) Cheatham Lock on the Cumberland River and b) Pickwick Lock on the Tennessee River. Each lock serves as a snapshot of changing waterborne freight trends to Nashville on the Cumberland and to Huntsville, Chattanooga, and Knoxville on the Tennessee. Of note is the increase in the monthly average shipments of petroleum products on the Cumberland, highlight by the red box (a) compared to the relatively static average monthly petroleum shipments on the Tennessee (b).

Of the 31 public ports in the study region, 27 of the ports featured significant multimodal access, meaning they were either within 1 mile of Class I rail or within 5 miles of a primary U.S. roadway. Of these multimodal ports, 3 ports were within 1 mile of rail but did not officially list connectivity to rail in the Inland River Guide publication, suggesting potential for the development of such a connection. All 3 terminals with liquid bulk capabilities listed connectivity to Class I rail. In addition, all ports within a lock-pair city segment featured significant multimodal access. A full characterization of each of the 31 ports is available in Appendix A.1 with examples of how port interconnectivity was calculated in Figure 9.

Figure 9: An example of the intermodal connectivity calculation for the Port of Hailey's Harbor Intermodal River Terminal. The Port is within 1 mile of Class I Rail (inner circle) and also within 5 miles of a primary road (outer circle), suggesting it has full multimodal connectivity. In addition, Hailey's Harbor is listed in the Inland River Guide has having a direct connection to the NWR rail line.

None of the 31 ports or the 13 dams in the study area fell in the liquification zone of the three historical New Madrid fault earthquakes. However, at least one piece of primary infrastructure, the I-155 bridge on the Mississippi River, was directly on top of an area that geologists found liquified in all three of the previous major seismic events, as depicted in Figure 8. According to a follow up search for information about the bridge's structural resistance to earthquakes, a publication in the Transportation Review Board finds that the bridge has only 30-45% of the displacement capacity needed to handle the 40-65 feet of soil liquification expected in a new 500 year event, meaning that the bridge would be among the first infrastructure causalities to experience damages and be rendered unusable if the fault ruptures [42]. An additional case study of a large New Madrid event identifies the I-555 bridge as a likely casualty [43]. A damaged or severely damaged I-155 bridge would likely close the Mississippi to navigation for sometime, as occurred with the I-40 bridge in Memphis earlier in 2021, impeding freight flow to the Tennessee and Cumberland Rivers as illustrated in Figure 10.

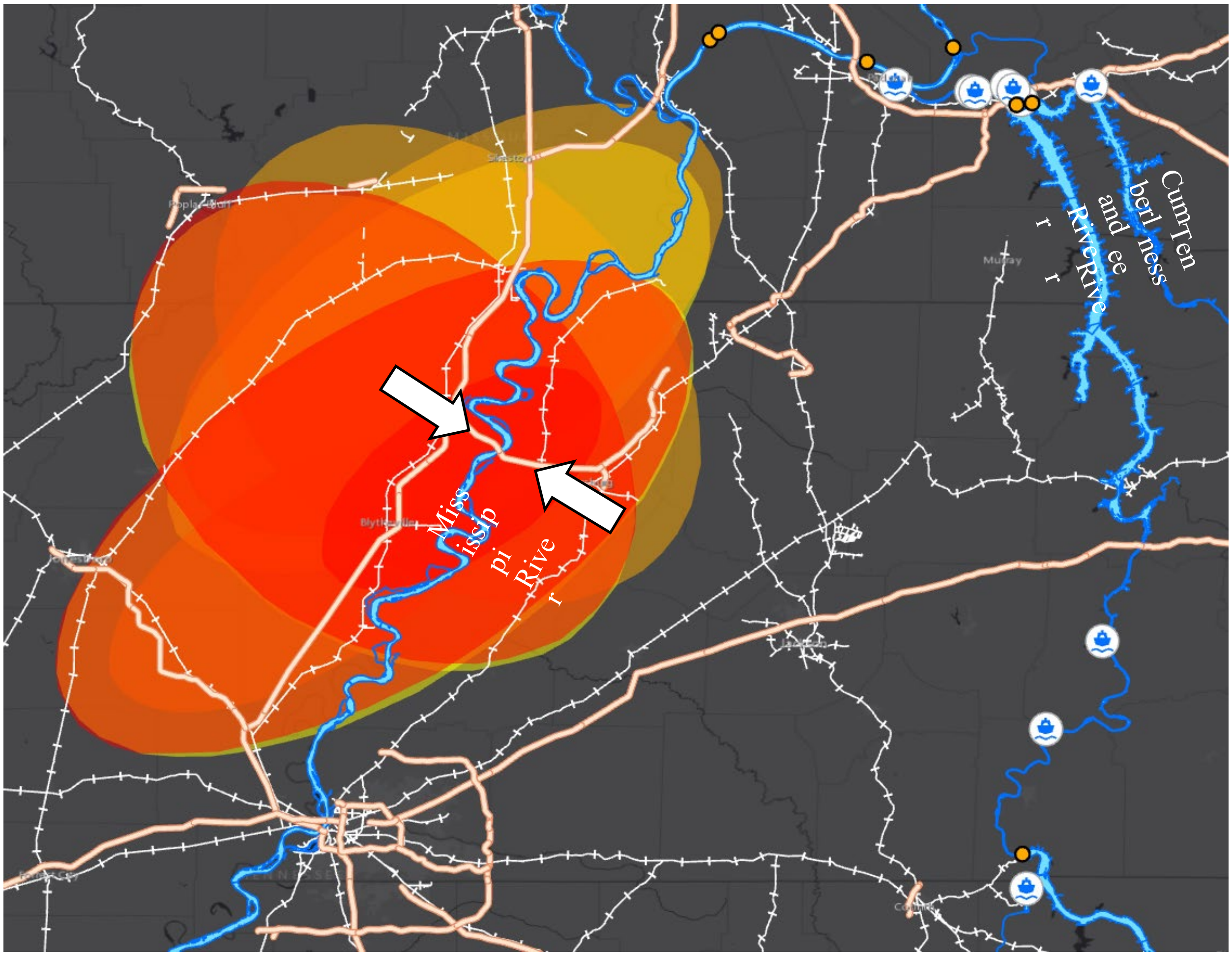

Figure 10: New Madrid Liquification zones for year 900 (shown in orange), 1450 (red), and 1811 (yellow) Earthquake events. The I-155 Bridge, seen here crossing the Mississippi River between a pair of white arrows, intersects with all three liquification zones and its failure may disrupt upstream freight movements from the Gulf of Mexico to the study area.

In stakeholder meeting #1, the participants identified additional key infrastructure assets, resilience measures, and hazards to consider for resilience planning (see the Jamboard in Figure 6 from that meeting). In regard to assets, the Port and City of Memphis was mentioned frequently as beneficial due to the nexus of freight corridors it brought to the state over nearly all modes of transportation. The Barkley Canal was also highlighted for the redundancy it added to the waterway system by connecting the Tennessee and Cumberland rivers at a second location beyond the Kentucky and Barkley dams. The canal may serve as an effective “detour” in the likely event of an outage of either dam. The Tennessee Tombigbee Waterway, which connects the Tennessee River to the Black Warrior-Tombigbee River system, was also identified as a potential freight “detour” in the event of an outage of the Mississippi River. Operators confirmed the importance of the Colonial Pipeline, estimating that 70% of fuel in Nashville was derived from Colonial Pipeline alone, while an even higher share of Chattanooga was exclusively served by Colonial Pipeline products. The group agreed that the Tennessee Valley overall had access to an extensive network of multi-modal assets.

In the first stakeholder meeting, the group also identified additional hazards or disruptive events to the inland waterway system for consideration (Figure 6). These included dam/levee structural failure, rockslides, pandemics, and cyber-attacks. However, community members overall expressed that the greatest concerns were related to future flood and seismic events. These events cause lasting damage that take longer to repair as compared to experienced “down time” for other disruptive events. Representatives from the USACE shared that the Agency was implementing measures to harden dams against flooding, including by raising and waterproofing emergency power sources.

Quantifying/Characterizing the Impacts of the Disruption Scenarios

The 2021 Colonial Pipeline disruption case study may corroborate the notion that cities with increased access to waterborne petroleum were more resilient to fuel shortage challenges caused by pipelines. A forthcoming study of six southeastern, pipeline dependent cities by Moravec et. al. found a statistically significant relationship between a city’s annual waterborne petroleum volumes (adjusted per capita) and the proportion of gas station outages during the summer disruption of the pipeline, especially as the closure continued into its second week. The fuel volumes were calculated using USACE Lock Performing Monitoring System (LPMS) data, while the outages data were collected from crowdsourced GasBuddy data (Figure 11). The Cumberland River Nashville region, which had the largest waterborne fuel volumes per capita of the cities studied, reported the fewest stations out of fuel by the 2nd week of the disruption (18.9%), while Knoxville, which receives less waterborne fuel as a port on the Tennessee River, reported a more significant outage (31.6%) on the same day in the 2nd week of the pipeline failure. Cities in North Carolina with no waterborne access reported outages as high as 40 to 60 percent the same day. While this may partially be attributed to differences in state emergency management policy, as North Carolina declared a state of emergency that may have instigated panic buying while Tennessee refrained from such a declaration, USACE and energy industry officials openly accredited the passage of 12 fuel barges through Cheatham Lock on the Cumberland, for example, for directly moving 1.5 million gallons of fuel into the Nashville market during the disruption that objectively contributed to helping prevent fuel shortages. This analysis demonstrated that inland terminals with liquid bulk capabilities measurably reduced the impact of a pipeline disruption and further played a critical role in securing the region’s supply of energy products, and is just one example of applying the MTS Guide methodology to identify Resilience Enhancement Options for the area.

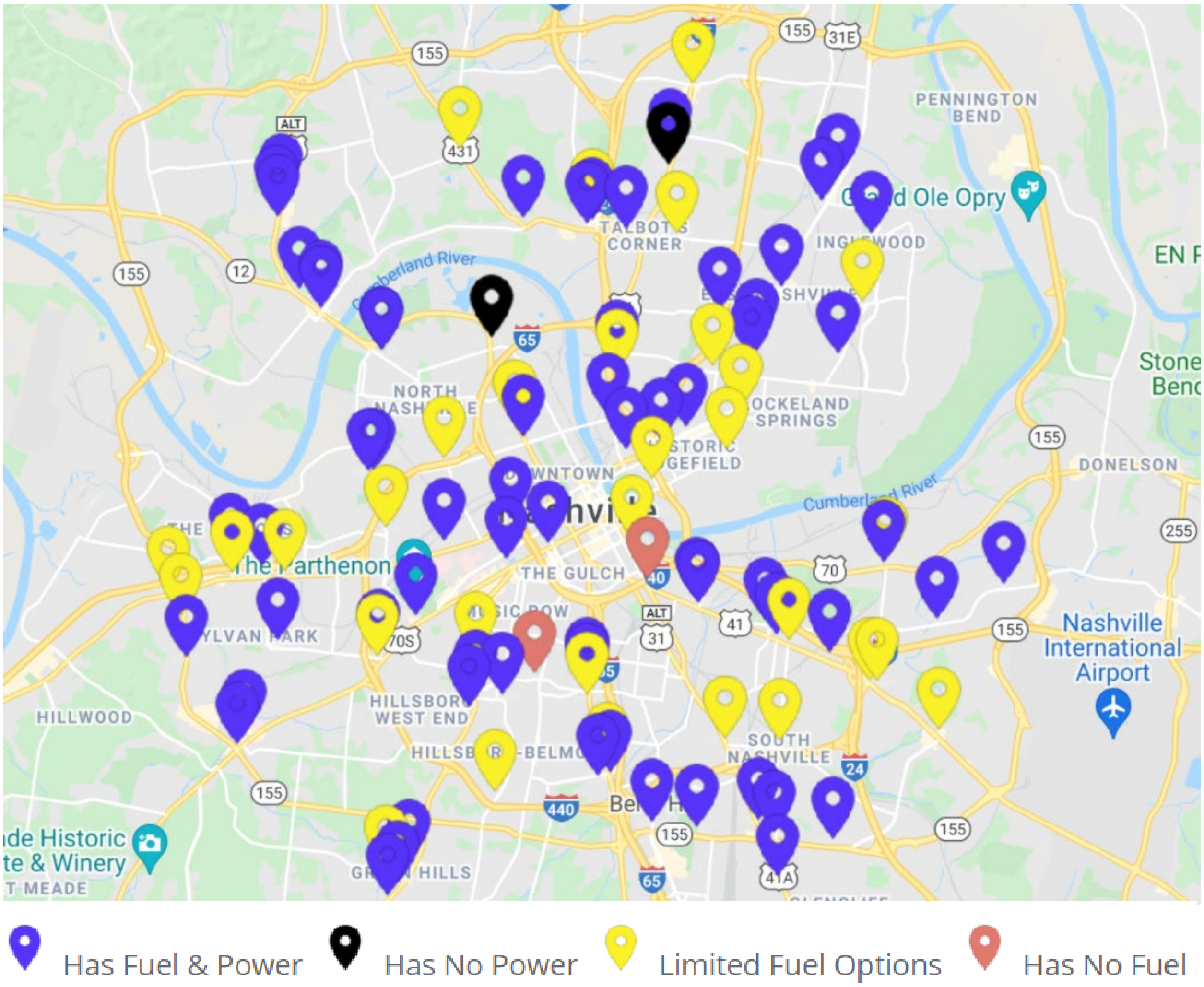

Figure 11: An example of gas station outage tracking for Nashville, TN, using GasBuddy.

Identified REOs for Region

In the second stakeholder meeting, presentations were made by various agencies with first-hand knowledge and accounts of planning activities and specific knowledge about each of the three disruption scenarios under consideration, the goal was to help all stakeholders gain awareness and understanding of the scenarios and potential impacts to serve as a foundation for resilience discussions. Many commented both during the session and offline that this was one of the most beneficial and interesting meetings that they have been engaged with of late. For each disruption scenario, 2-3 speakers gave presentations about their agency approaches, the impacts, and efforts to "manage" the given scenario. The discussion was moderated by project team members.

In the discussion that followed the presentations, stakeholders were asked to help identify specific resilience opportunities for the region. There was no requirement that these fall into the REO Categories mentioned earlier because those were presented to help set the stage for participants to think about the types of activities that may serve as viable options. The region-specific REOs that emerged from the stakeholder session are provided below with a general title, a "theme" which may align with a general REO category, the applicable disruption scenarios to help in identifying REOs that may have mutually beneficial application to different types of disruptions, and additional notes to provide context for the REO.

REO 1: Expand Chattanooga and Knoxville terminals to accept fuel barges and add terminal at Clarksville

- Theme: New Infrastructure
- Applicable disruption scenarios: New Madrid Earthquake, Disruption of Colonial Pipeline
- Note: Colonial pipeline purchased one of the fuel terminals in Chattanooga, so when their services went offline it impacted that terminal as well

REO 2: Explore the Feasibility of Increasing Traffic on Tombigbee River as an Alternate Route

- Theme: Coordination (with other waterway managers and port/terminal operators)
- Applicable Disruption Scenarios: New Madrid Earthquake, Disruption of Colonial Pipeline, Closure of Tennessee or Cumberland Rivers
- Notes: Instead of traffic coming up through Kentucky and Barkley it would come through Tenn Tom through Pickwick and up through Cheatham Lock as an alternative route. One thing to consider is that the Tenn Tom is much more narrow than the Tennessee River. Traffic on the Tenn Tom could serve different areas of the region in different disruption events: (1) tows may navigate up the Tenn Tom to Paducah and onto the Cumberland Waterway using the Barkley Canal to serve the Cumberland area, (2) tows may use the Tenn Tom to reach the upper Tennessee areas of Chattanooga and Knoxville if portions of the main branch of the Tennessee River in West TN are impacted, (3) the Tenn Tom can provide a connection to the upper Mississippi River and/or Ohio if the western portion of the Tennessee River is operational to circumvent a disruption on the Mississippi River providing much needed connectivity with the upper midwest portions of the nation.

REO 3: Update building codes for waterway (ports, terminals, locks and dams) and other infrastructure

- Theme: Policy/Guidelines
- Applicable Disruption Scenarios: New Madrid Earthquake
- Notes: The more resilient building codes are, the less likely to have significant impacts to key infrastructure assets. Typically, some assets are “grandfathered” allowing them to use historic, less robust building codes and standards. When considering resilience and potential future disruptions, the approach to considering the hardiness of key assets should be proactive as opposed to reactive. Another consideration that was discussed is the fact that the Tenn Tom and associated infrastructure components may not have been evaluated for potential impacts of a New Madrid event nor has its use as an alternative pathway been truly explored.

REO 4: Industry specific messaging during fuel-related events

- Theme: Policy/Guidelines
- Applicable Disruption Scenarios: Disruption of Colonial Pipeline
- Notes: As learned from the Colonial Pipeline event, some messaging created additional supply shortages by public panic which could have been prevented if appropriate stakeholders had been engaged. Allowing industry leaders to guide messaging related to fuel events can help minimize public panic and ensure fuel reserves are maintained as much as possible for uses such as emergency response and other activities. This REO could be

beneficial when considering other potential supply chain shortages caused by disruptive events.

CONCLUSIONS

The primary objective of this study was to demonstrate use of the *Port Resilience Guide*'s approach and processes for an inland waterway system. Analysis of LPMS commodity and GasBuddy outage data, the mapping and characterization of public ports and assets in the region, and the convening of community stakeholders in interactive meetings provided an example of assessing inland port and waterway resilience for Middle and East Tennessee.

Key takeaways from the study are framed in the context of addressing the three main research questions below for simplicity:

1) To what extent can the inland waterway system ensure supply of petroleum products to the Middle and East Tennessee regions during a disruption of the Colonial Pipeline?

There is a statistically significant relationship between access to waterborne petroleum and decreased gas station outages during a prolonged disruption of the Colonial Pipeline. As a disruption of the Pipeline continues, the relationship becomes increasingly significant. This may explain why Nashville experienced less gas station outages than Chattanooga, Knoxville, and peer cities in North Carolina during the 2021 Pipeline Outage, which may further suggest that the Cumberland waterway's market decision to embrace more petroleum shipments since 2012 was wise from a resilience standpoint. Chattanooga and East Tennessee officials should consider developing additional liquid bulk terminal capacity and incentivizing the sale of waterborne petroleum to create a more resilient energy market in the area. Future work could expand on and validate this assessment by considering outage rates during other, historical disruptions of the Colonial Pipeline or by analyzing a wider survey of cities affected by the 2021 disruption.

2) To what extent might the inland waterway system's ability to move commodities to/from the Middle Tennessee region be impacted by a New Madrid Earthquake event and other natural hazards?

While a New Madrid Earthquake event may not directly damage middle and east Tennessee waterway infrastructure, a seismic event in this area may significantly disrupt the upstream supply chain by damaging and closing the shipping lane under the I-155 bridge as well as other important infrastructure along the Mississippi. According to stakeholders, alternative routes such as the Tennessee Tombigbee Waterway could create a redundant shipping lane to access the Gulf of Mexico in the event of a Mississippi closure. In addition, flood, droughts, and other earthquakes may threaten the inland waterway's system ability to remain open to the point of reducing the system's overall reliability. Shippers should consider opportunities to develop more redundant river detours, such as the Barkley Canal, or more multimodal capable ports, to navigate past outages in the event of disruptions. Port and terminal operators should consider following USACE's example hardening their equipment and power supplies from extreme river stage heights, while state DOT's should harden bridges and other single point of failure infrastructure that may jeopardize the supply chain. Future work could identify which ports should be prioritized for resiliency upgrades by leveraging flood and seismic mapping tools such as U.S. EPA's EnviroAtlas [18].

3) Where are key ports/docks/terminals along the Tennessee and/or Cumberland River that have potential to provide loading/offloading capabilities for commodities? Are these used along with other potentially redundant transportation modes?

Thirty-one key ports were characterized and geolocated within the broader Tennessee waterway system. Key attributes of these ports are available in Appendix A.1 to allow decision makers to rapidly identify modal alternatives for their commodities in the event of a disruption. Nearly all public ports feature at least one multimodal connection to a primary competing transportation mode, ensuring local distribution of commodity once it arrives. Three ports were identified as being within one mile of Class 1 rail yet listed no connectivity to the rail system. A potential resilience enhancing measure for the state of Tennessee could be to invest in connecting track at these locations to interface freight across both rail and water-based modes. The actual use of these ports as redundant transportation modes was identified only anecdotally during the stakeholder meeting. Future work could assign bounding spatial areas to the geolocated ports and use AIS traffic data to better determine the shift of freight to these facilities during times of non-waterborne logistical disruptions.

Finally, this study was intended to demonstrate how one might apply the processes and approach outlined in the MTS Guide to undertake a resilience assessment for an inland waterway system and assets within that system. Furthermore, while several potential REOs for the region were identified as part of this study, additional exploration and consideration is needed to explore the actual feasibility of each REO's potential implementation and develop associated resilience plans. The REO's presented are by no means all encompassing, but what was arrived at for the region with the stakeholders that were involved in the process. Additional scenarios and REOs could and should be considered in partnership with stakeholders as was demonstrated in this Case Study.

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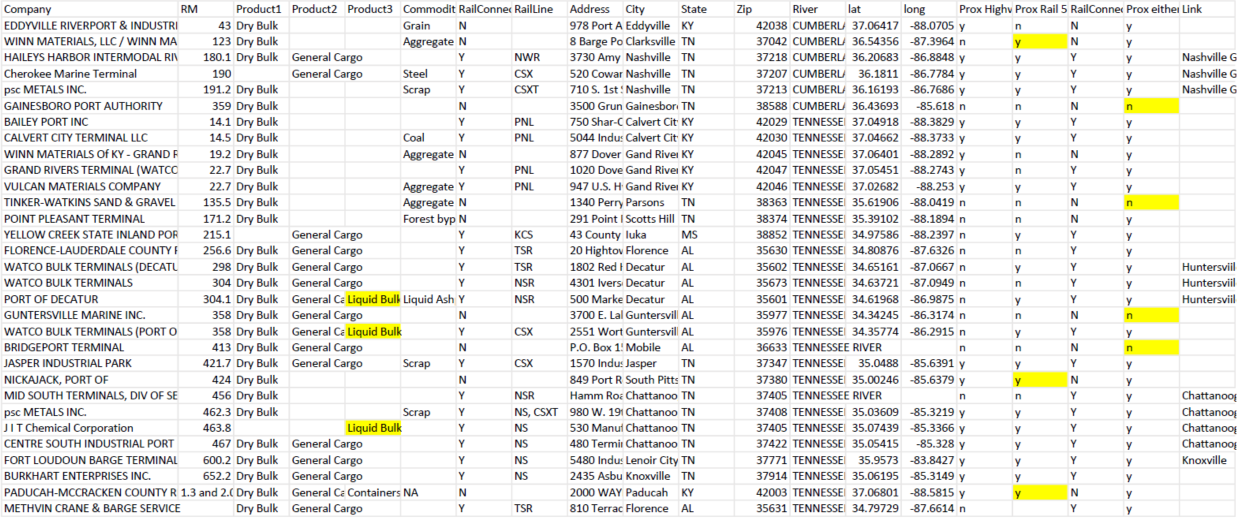
APPENDICES

APPENDIX A.1: PUBLIC PORT CHARACTERIZATION - TENNESSEE AND CUMBERLAND RIVERS



Company	RM	Product1	Product2	Product3	Commodit	RailConne	RailLine	Address	City	State	Zip	River	lat	long	Prox High	Prox Rail 5	RailConne	Prox eithe	Link
EDDYVILLE RIVERPORT & INDUSTRI	43	Dry Bulk			Grain	N		978 Port A	Eddyville	KY	42038	CUMBERL	37.06417	-88.0705	y	n	N	y	
WINN MATERIALS, LLC / WINN MA	123	Dry Bulk			Aggregate	N		8 Barge Po	Clarksville	TN	37042	CUMBERL	36.54356	-87.3964	n	y	N	y	
HAILEYS HARBOR INTERMODAL RI	180.1	Dry Bulk	General Cargo			Y	NWR	3730 Amy	Nashville	TN	37218	CUMBERL	36.20683	-86.8848	y	y	Y	y	Nashville G
Cherokee Marine Terminal	190		General Cargo		Steel	Y	CSX	520 Cowar	Nashville	TN	37207	CUMBERL	36.1811	-86.7784	y	y	Y	y	Nashville G
psc METALS INC.	191.2	Dry Bulk			Scrap	Y	CSXT	710 S. 1st	Nashville	TN	37213	CUMBERL	36.16193	-86.7686	y	y	Y	y	Nashville G
GAINESBORO PORT AUTHORITY	359	Dry Bulk				N		3500 Grun	Gainesbor	TN	38588	CUMBERL	36.43693	-85.618	n	n	N	n	
BAILEY PORT INC	14.1	Dry Bulk				Y	PNL	750 Shar-C	Calvert Cit	KY	42029	TENNESSE	37.04918	-88.3829	y	y	Y	y	
CALVERT CITY TERMINAL LLC	14.5	Dry Bulk			Coal	Y	PNL	5044 Indus	Calvert Cit	KY	42030	TENNESSE	37.04662	-88.3733	y	y	Y	y	
WINN MATERIALS Of KY - GRAND	19.2	Dry Bulk			Aggregate	N		877 Dover	Gand Rive	KY	42045	TENNESSE	37.06401	-88.2892	y	n	N	y	
GRAND RIVERS TERMINAL (WATCO	22.7	Dry Bulk				Y	PNL	1020 Dove	Gand Rive	KY	42047	TENNESSE	37.05451	-88.2743	y	n	Y	y	
VULCAN MATERIALS COMPANY	22.7	Dry Bulk			Aggregate	Y	PNL	947 U.S. H	Gand Rive	KY	42046	TENNESSE	37.02682	-88.253	y	y	Y	y	
TINKER-WATKINS SAND & GRAVEL	135.5	Dry Bulk			Aggregate	N		1340 Perry	Parsons	TN	38363	TENNESSE	35.61906	-88.0419	n	n	N	n	
POINT PLEASANT TERMINAL	171.2	Dry Bulk			Forest byp	N		291 Point	Scotts Hill	TN	38374	TENNESSE	35.39102	-88.1894	n	n	N	y	
YELLOW CREEK STATE INLAND POR	215.1		General Cargo			Y	KCS	43 County	Iuka	MS	38852	TENNESSE	34.97586	-88.2397	n	y	Y	y	
FLORENCE-LAUDERDALE COUNTY	256.6	Dry Bulk	General Cargo			Y	TSR	20 Highto	Florence	AL	35630	TENNESSE	34.80876	-87.6326	n	n	Y	y	
WATCO BULK TERMINALS (DECATU	298	Dry Bulk	General Cargo			Y	TSR	1802 Red	Decatur	AL	35602	TENNESSE	34.65161	-87.0667	n	y	Y	y	Huntersvil
WATCO BULK TERMINALS	304	Dry Bulk	General Cargo			Y	NSR	4301 Ivers	Decatur	AL	35673	TENNESSE	34.63721	-87.0949	n	n	Y	y	Huntersvil
PORT OF DECATUR	304.1	Dry Bulk	General Ca	Liquid Bul	Liquid Ash	Y	NSR	500 Marke	Decatur	AL	35601	TENNESSE	34.61968	-86.9875	n	y	Y	y	Huntersvil
GUNTERSVILLE MARINE INC.	358	Dry Bulk	General Cargo			N		3700 E. La	Guntersvil	AL	35977	TENNESSE	34.34245	-86.3174	n	n	N	n	
WATCO BULK TERMINALS (PORT O	358	Dry Bulk	General Ca	Liquid Bulk		Y	CSX	2551 Wort	Guntersvil	AL	35976	TENNESSE	34.35774	-86.2915	n	y	Y	y	
BRIDGEPORT TERMINAL	413	Dry Bulk	General Cargo			N		P.O. Box 1	Mobile	AL	36633	TENNESSEE RIVER			n	n	N	n	
JASPER INDUSTRIAL PARK	421.7	Dry Bulk	General Cargo		Scrap	Y	CSX	1570 Indus	Jasper	TN	37347	TENNESSE	35.0488	-85.6391	y	y	Y	y	
NICKAJACK, PORT OF	424	Dry Bulk				N		849 Port R	South Pitts	TN	37380	TENNESSE	35.00246	-85.6379	y	y	N	y	
MID SOUTH TERMINALS, DIV OF SE	456	Dry Bulk				Y	NSR	Hamm Roa	Chattanoo	TN	37405	TENNESSEE RIVER			n	n	Y	y	Chattanoo
psc METALS INC.	462.3	Dry Bulk			Scrap	Y	NS, CSXT	980 W. 19	Chattanoo	TN	37408	TENNESSE	35.03609	-85.3219	y	y	Y	y	Chattanoo
J I T Chemical Corporation	463.8			Liquid Bulk		Y	NS	530 Manu	Chattanoo	TN	37405	TENNESSE	35.07439	-85.3366	y	y	Y	y	Chattanoo
CENTRE SOUTH INDUSTRIAL PORT	467	Dry Bulk	General Cargo			Y	NS	480 Termi	Chattanoo	TN	37422	TENNESSE	35.05415	-85.328	y	y	Y	y	Chattanoo
FORT LOUDOUN BARGE TERMINAL	600.2	Dry Bulk	General Cargo			Y	NS	5480 Indus	Lenoir City	TN	37771	TENNESSE	35.9573	-83.8427	y	y	Y	y	Knoxville
BURKHART ENTERPRISES INC.	652.2	Dry Bulk	General Cargo			Y	NS	2435 Asbu	Knoxville	TN	37914	TENNESSE	35.06195	-85.3149	y	y	Y	y	
PADUCAH-MCCRACKEN COUNTY R	1.3 and 2.	Dry Bulk	General Ca	Containers	NA	N		2000 WAY	Paducah	KY	42003	TENNESSE	37.06801	-88.5815	y	y	N	y	
METHVIN CRANE & BARGE SERVICE		Dry Bulk	General Cargo			Y	TSR	810 Terrac	Florence	AL	35631	TENNESSE	34.79729	-87.6614	n		Y	y	

This document is a guidance document and does not establish any legally enforceable requirements.

APPENDIX A.2: MEETING ATTENDEE LISTS

Stakeholder Meeting 1:

- Aaron Huffaker, Mapco Express
- Ben Bolton, TDEC Office of Energy Programs
- Brent Eubanks Mapco Express
- Chad Dorsey, MARAD
- Cline Jones, Energy Fairness, TRVA
- Craig Philip, Vanderbilt
- Craig Carrington, USACE
- Dan Pallme, TDOT
- Debra Stone, McKee Foods
- Don Getty, USACE Nashville District
- Janey Camp, Vanderbilt
- Jeremy Edgeworth, Kentucky Transportation Cabinet
- Jevon Daniel, DHS CISA
- Justin Lampert, The American Waterways Operators
- Katherine Chambers, USACE
- Katherine Turner, Vanderbilt
- Mekayle Houghton, Cumberland River Compact
- Miguel Moravec, Vanderbilt
- Mike Golias, University of Memphis
- Ned Mitchell, USACE-ERDC
- Nikki Berger, Tennessee Valley Authority
- Sandra Knight, WaterWonks, LLC
- Sarena Bonora, Vanderbilt VECTOR Staff
- Shannon Millsaps, Thrive Regional Partnership
- Tim Cahill, Paducah-McCracken County Riverport Authority
- Tom Richardson, Coastal Resilience Center at UNC-Chapel Hill
- Others – unidentified participating via phone

Stakeholder Meeting 2:

- Aimee Andres, IRPT
- Barry Gibson, James Companies
- Ben Bolton, TDEC Office of Energy Programs
- Braxtol Myers, Pine Bluff Materials
- Carson Cooper, Research Analyst at Greater Nashville Regional Council
- Chris Atkins, U.S. Army Corps of Engineers, Nashville District
- Craig Philip, Vanderbilt
- Dan Pallme, TDOT
- David Earl, Marathon Petroleum Corp.
- Deb Calhoun, Waterways Council, Inc.
- Debra Stone, McKee Foods
- Gray Perry, Cumberland River Compact
- Harley Hall, Tennessee Valley Towing
- Janey Camp, Vanderbilt
- Jason Johnson, USACE Nashville District
- Jeremy Edgeworth, Kentucky Transportation Cabinet
- Joe Crabtree, Kentucky Transportation Center
- Justin Lampert, The American Waterways Operators
- Katherine Chambers, USACE
- Katherine Turner, Vanderbilt
- Marissa Shapiro, Vanderbilt Communications
- Max Baker, Director of Research & Analytics, GNRC
- Megan Simpson, USACE Nashville District
- Miguel Moravec, Vanderbilt
- Mike Golias, University of Memphis
- Ned Mitchell, USACE ERDC
- Pamela Coyle, Vanderbilt Communications
- Dr. Sandra Pinel, CISA
- Shannon Millsaps, Thrive Regional Partnership

- Tim Cahill, Paducah-McCracken County Riverport Authority
- Zach Langel, USACE Nashville District

APPENDIX A.3: AGENDAS FROM STAKEHOLDER MEETINGS

Cumberland and Tennessee Rivers Port Resilience Case Study
Stakeholder Meeting #1 – September 29, 2020
Agenda

8:30 – 8:45 am Welcome and Introductions
- Welcome and Introduce Project Team
- Housekeeping Items

8:45 – 9:00 am Resilience 101
- Definitions and Port/Waterway Considerations

9:00 – 9:30 am Overview of DHS Port Resilience Guide Effort
- Guide Objectives and Timeline
- Overview of Other Case Studies
- TN/Cumberland Case Study Overview

9:30 – 9:40 am Discussion/Q&A – Quick Reactions

9:40 – 10:30 am Introducing the Multiple Lens' of the Case Study – A Panel of
Perspectives

- Introduction of Panel and Disruption Scenarios Under Consideration
    - System Profile Overviews
    - Definition/Perspectives of Disruption
- Q&A/Discussion

10:30 – 11:00 am Discussion
- Summary of Key Takeaways
- Feedback/Input from Stakeholders
- Discuss Next Steps

Cumberland and Tennessee Rivers Port Resilience Case Study
Stakeholder Meeting #2 – June 11, 2021 (12:00 pm – 3:30 pm Central)
Agenda

12:00 – 12:15 pm Welcome and Overview

- Housekeeping Items
- Review Objectives and Quick Progress Update
    - System Characterization
    - Disruption Scenarios

12:15 – 1:15 pm Disruption Scenario 1 – Multimodal Impacts

- Case Example: Colonial Pipeline Spur to Tennessee, Service Interruption *(Contingency Plans, Impacts, Lessons Learned, Recovery and Resilience)*
- Speakers:
    - Ben Bolton - TDEC
    - Megan Simpson – USACE Nashville District
    - Barry Gipson - James Companies, former Pipeline Company Executive
    - Moderator: Miguel Moravec – Vanderbilt University

1:15 – 2:15 pm Disruption Scenario 2 – Lock Outage

- Case Example: Cheatham Lock and Dam Maintenance
- Speakers:
    - Megan Simpson – USACE Nashville District
    - Gene Whelan - Pine Bluff Materials, Operator of Largest Multicommodity Marine Terminal on the Cumberland River
    - Steve Southern - Ingram Barge Company, Activation of Waterway Action Plans to Improve Stakeholder Coordination
    - Moderator: Craig Philip – Vanderbilt University

2:15 – 3:00 pm Disruption 3: Waterway Navigability Impacted by Earthquake

- Case Example: New Madrid Fault Event Impacting Tennessee/Cumberland/Ohio River Confluence and Bridge Crossings
- Speakers:
    - James M. Wilkinson, Jr. – Executive Director, CUSEC (Central U.S. Earthquake Consortium)
    - Ben Bolton - TDEC
    - Moderator: Janey Camp - Vanderbilt University

3:00 – 3:30 pm Group Discussion - Disruptions to Solutions: The Role of Resilience Enhancement Options (REOs)

ANNEX B. INSIGHTS FROM SEAPORT RESILIENCE ASSESSMENT INTERVENTIONS

TABLE OF CONTENTS

AUTHORS AND ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Homeland Security through the Coastal Resilience Center at the University of Rhode Island. It was executed by the Marine Affairs Coastal Resilience Lab (MACRL). The lead prinicple investigators were Dr. Austin Becker, and Mr. Ellis Kalaidjian. The survey and other data collection instruments used in the project were developed in collaboration with personnel from the U.S. Army Engineer Research and Development Center (ERDC) and the Cybersecurity and Infrastructure Security Agency (CISA), including Katherine Chambers (ERDC), Margaret Kurth (ERDC), Dr. Sandra Pinel (CISA), and Jevon Daniel (CISA). Special thanks go to the many diverse stakeholders who provided valuable feedback and input throughout this project.

OVERVIEW

Summary

Resilience assessments have been proposed to aid the management of complex critical infrastructure systems in the face of the evolving risks and uncertainties associated with climate change and other threats and hazards. We synthesized the experiences of 10 U.S. seaports that have undertaken resilience assessments using a qualitative research approach. Through survey and interview responses from 26 seaport decision-makers, the following results were obtained:

Finding 1: Resilience assessments offer more than just a nuanced understanding of vulnerabilities

We found that resilience assessments provide a suite of co-benefits beyond identifying vulnerabilities in infrastructure and management systems. Among these co-benefits were enhanced social capital between the port organization and its internal and external stakeholders as a result of the collaborative processes that resilience assessments require.

"The workshop and the internal stakeholder engagement in the development of the [resilience assessment], really brought us together as a port team."

Finding 2: The most widespread challenge of resilience assessments was engaging stakeholders in the process

Unlike the benefits, challenges associated with resilience assessments were often case specific, though several overarching challenges should be expected by organizers of future resilience assessments. For example, engaging stakeholders in various phases of the assessment stymied processes such as selecting sea level rise projections to plan for or getting consensus on what resilience means for their seaport. Communicating vulnerabilities that were discovered through the resilience assessment was also a challenge for decision-makers who were concerned about how such information would impact the seaport's marketability to potential tenants and investors.

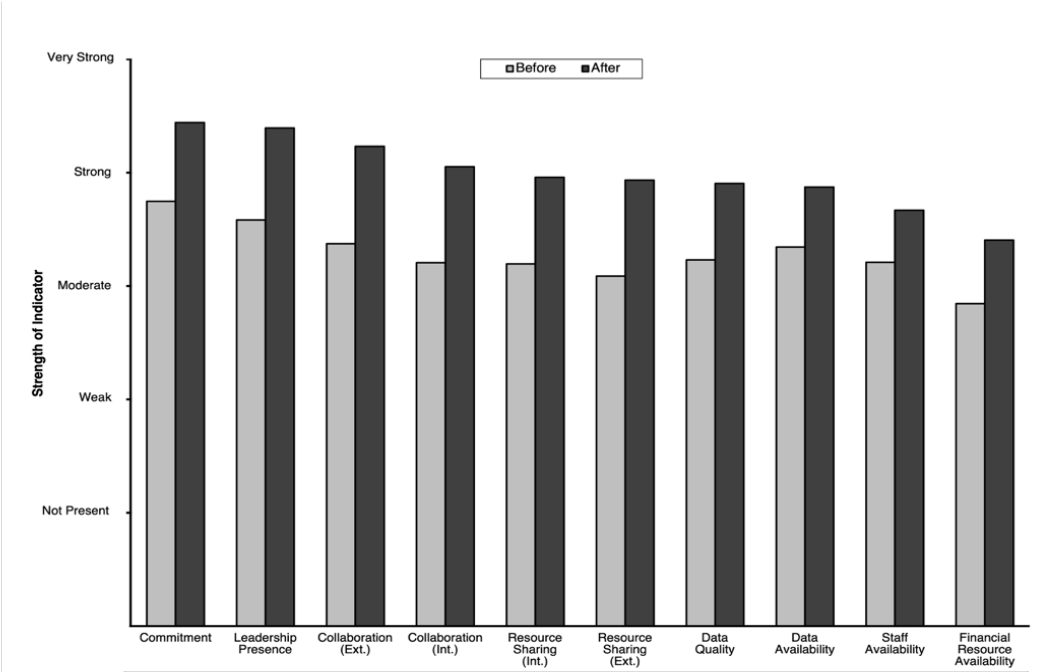
"The major challenge was just getting everybody on the same page and getting them to participate, because everybody has different priorities for their jobs."

Finding 3: Seaports often prioritized infrastructure-related investments as a result of their resilience assessment findings

The study team identified 155 resilience enhancement strategies that were prescribed to seaports, which were categorized into six different strategy typologies. Of these 155, infrastructure enhancements were most frequently implemented following resilience assessments. In particular, stormwater management infrastructure improvements and/or installations were prioritized most often. By contrast, strategies falling under building codes and land use regulations (e.g., basing design flood elevations on sea level rise projections) were both prescribed to and implemented by seaports the least.

Finding 4: According to study participants, resilience assessments improved their organizations' capacities to manage their seaports' resilience and adapt to climate change

Nonetheless, many interviewed decision-makers found that their organizations' capacities to manage their seaports' resilience improved as a result of undertaking a resilience assessment. Additional takeaways captured in this research provide valuable insights that can inform users of this guidebook on how to undertake their resilience endeavors in a calculated manner and how to plan for obstacles along the way.



	Commitment	Leadership Presence	Collaboration (Ext.)	Collaboration (Int.)	Resource Sharing (Int.)	Resource Sharing (Ext.)	Data Quality	Data Availability	Staff Availability	Financial Resource Availability
N	**19**	**18**	**19**	**19**	**19**	**14**	**17**	**18**	**19**	**18**
N (Δ noted)	12	12	12	12	11	9	10	10	10	7
N (no Δ noted)	7	6	7	7	8	5	7	8	9	11

Figure 1. Average strengths of key institutional capacities prior to (light grey) and after (dark grey) completion of resilience assessments.

b) Statement of Task

The purpose of this study was to elucidate the key benefits and challenges associated with undertaking resilience assessment interventions; (2) to identify the resilience enhancement options that seaports pursue after completing resilience assessments; and (3) to determine the extent to which resilience assessments enhance seaports' capacities to manage and adapt to climate hazards.

BACKGROUND

The seaport: A complex socio-technological system

The need for a resilient maritime transportation system is well supported in earlier sections of this Guide. Resilience refers to capabilities of a system that allow it to maintain desired functions through time, including during disruptive events[62,63]. A resilient seaport system is conceived here as being equipped with the human and technological resources that enable it to process freight in an efficient, cost-effective manner under scenarios of serious threats[64]. This requires the seaport to thoroughly plan for a range of disruptive scenarios; sustain the impacts of disturbances while maintaining a desired baseline functionality; quickly recover back to pre-disturbance functionality; and/or self-organize and learn from past experiences to adapt to emerging circumstances[65].

Despite a recognized need for seaport resilience, the process of resilience-building within seaport organizations is challenged by their inherent complexities. For example, the day-to-day operations of one seaport are supported by numerous assets and critical infrastructure networks, which are, in turn, supported by infrastructure extending outside the bounds of the seaport[66]. As a result, decision-makers often lack nuanced knowledge about the cascading repercussions of disruptions at their seaports, which often induces administrative paralysis around long-term resilience planning[67]. Seaport ownership and governance arrangements further complicate their capacities for resilience-building, as factors such the distributed ownership of infrastructure obscure understanding of responsibilities for risk management or implementation of resilience enhancement strategies[68].

Seaports require resilience assessments to successfully manage system resilience

The complexities of seaports warrant resilience assessment approaches to successfully manage the known and unknown risks posed to them. Seaports may undertake a resilience assessment intervention for many reasons, including long-term planning for future impacts of disruptive events, exploring best practices and options available for a specific project or improvement, or satisfying a government mandate. Seaports conduct resilience assessments through different approaches depending on the scope of their planning objectives, the granularity of vulnerability data they desire, the level of stakeholder (internal versus external) engagement they seek, the seaport's financial means, time and staff resource availability, and other criteria. For example, seaports with larger budgets may hire a consulting firm to lead the data collection, stakeholder outreach, and reporting associated with the resilience assessment. Resilience assessments can also be coordinated through

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agency-led programs such as the RRAP[69] or Hazard Mitigation Grant Program[70]. Another less-involved and less costly approach available to seaports is to consult self-assessment tools, such as the Ports Resilience Index, which convenes seaport stakeholders in a day-long workshop to answer questions regarding the seaport's capacity to maintain operations during and after disruptions[71].

While resilience assessments may be conducted at various scales and tailored to specific needs and contexts, the process is typically underpinned by four key stages that are interconnected within an iterative framework, as follows[72, 73, 74, 75]:

1) *Defining functions and characterizing the system in steady state*
2) *Identifying critical infrastructure and dependencies*
3) *Understanding the impacts of disruptive* events
4) *Developing and evaluating resilience enhancement strategies*

The resilience assessment concept is relatively new and thus scarce research has investigated seaport resilience assessment initiatives and best practices. In particular, the connection between resilience assessments and the realization of capacities proposed to enhance system resilience is not well understood, especially for seaports. This study was thus guided by the following three research questions:

> *RQ1) What are the key benefits and challenges (or limitations) associated with undertaking resilience assessments?*
>
> *RQ2) What resilience-building actions do seaports pursue after completing a resilience assessment?*
>
> *RQ3) How do such assessments enhance seaports' capacities to manage resilience to climate hazards?*

GOALS, METHODOLOGY, AND DELIVERABLES

Overall Goals of the Study

The objectives of this study were threefold: (1) to elucidate the key benefits and challenges associated with undertaking resilience assessment interventions; (2) to identify the resilience enhancement options that seaports pursue after completing resilience assessments; and (3) to determine the extent to which resilience assessments enhance seaports' capacities to manage and adapt to climate hazards.

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Project Methodology

Case study & informant selection

In consultation with a steering committee composed of personnel from the U.S. Army Engineering Research and Design Center and the Cybersecurity and Infrastructure Security Agency, the study team searched for seaports that had completed resilience assessment interventions based on several criteria, such as the geographic scope of their planning and the hazards they addressed. We then contacted (via email and/or phone correspondence) all 115 U.S. ports within 10 miles of the coastline (**Figure 2**). Of those ports that responded to emails and/or were available to participate, the study team chose 10 (**Table 1**) that had completed a resilience assessment approach in the following three categories:

(1) Vulnerability assessments led by a private consultant, hereon referred to as "**contractor assessments**;"
(2) Seaport-focused **Hazard Mitigation Plans**, which are developed under the auspices of FEMA;
(3) Seaports that used the **Ports Resilience Index** (PRI) self-assessment tool, a qualitative resilience index which was developed by colleagues at Louisiana Sea Grant.

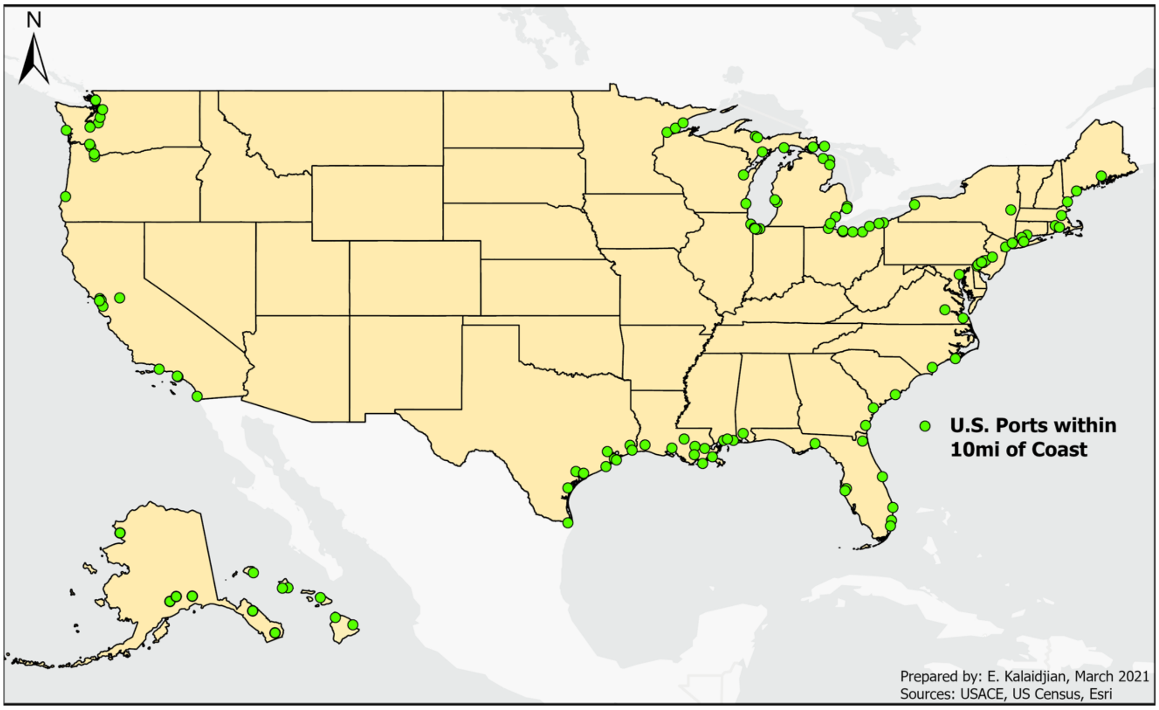

Figure 2 – Map of all U.S. ports within 10 miles of the coastline (data from NOAA Principal Ports Database)

Table 10 – List of participating seaports and their respective resilience assessment initiatives. Note: Asterisks (*) indicate that seaports have undertaken (or are in the process of undertaking) additional planning initiatives since (and/or before) the one listed.

Assessment Approach	Port of	Year Completed	Type(s) of Hazard(s) Assessed	# of Pages
Contractor Assessment (6)	San Diego (CA)*	2019	SLR, storm surge	298
	Los Angeles (CA)*	2018	SLR, storm surge	108
	Virginia (VA)*	2017	SLR, subsidence, storm surge, lightning strike frequency, karst geology	47
	Long Beach (CA)*	2016	SLR, storm surge, extreme heat, precipitation and riverine flooding, extreme wind, ocean acidification	172
	Seattle (WA)	2015	SLR, storm surge	26
	Baltimore (MD)*	2010	SLR, storm surge, extreme wind, precipitation and riverine flooding	120
Hazard Mitigation Plan (2)	Grays Harbor (WA)	2016	Tsunami, earthquake, severe weather, flooding, extreme heat, hurricanes, hazmat release, erosion, wildfire, levee failure	10
	Freeport (TX)*	2012	Erosion, drought, earthquake, expansive soils, severe weather, hurricanes, levee failure, land subsidence, winter storm, wildfire, hazmat release, pipeline failure	104
Port Resilience Index (2)	Morgan City (LA)	2018	Coastal hazards	24
	Tampa Bay (FL)*	2017	Coastal hazards	24

From each seaport, the study team identified and invited two to four informants that were internal to the seaport management structure and typically make decisions related to their seaports' climate resilience endeavors—directors/managers, safety planners, engineers, and environmental specialists (**Table 2**). In most cases, at least one informant was considerably involved with their seaports' resilience assessment process.

Table 11 – Description of select informants' titles and responsibilities (N = 27)

Position	Number Interviewed	Responsibilities
Directors or managers	7	Run port operations and systems
Common titles:		Perform maintenance of vessels and facilities
(Deputy) Executive director		Supervise employees
Director of operations		Manage specific functions of port facilities

Chief information officer Economic development manager		Plan efficient use of port resources, with attention to security, safety, and health of personnel
Environmental specialists *Common titles:* Director of environmental affairs Manager of strategic planning Environmental management specialist Environmental manager Project manager - sustainability Climate mitigation and resilience manager	11	Monitor related environmental regulations Oversee environmental protection and other social responsibility functions
Engineers *Common titles:* Director of engineering Director of construction & maintenance Civil engineer	5	Manage/engage in engineering projects Ensure compliance with safety regulations Prepare & manage department budgets Coordinate with external stakeholders for new integrations and tools
Safety planners *Common titles:* Vice president of sustainability Director of protective services General manager - operations & safety	4	Monitor and assess hazardous and unsafe situations Develop guidelines for personnel safety

Data collection

We undertook a three-part data collection process (Figure 3), which started with a systematic review of the final reports resulting from each seaport's resilience assessment process. The specific information collected from each document included the start and end dates of the assessment, the methodology used, the key findings, and the resilience enhancement strategies recommended to the seaport. This information was then built into a survey and interview instrument to account for the contextual discrepancies between each seaport's approach.

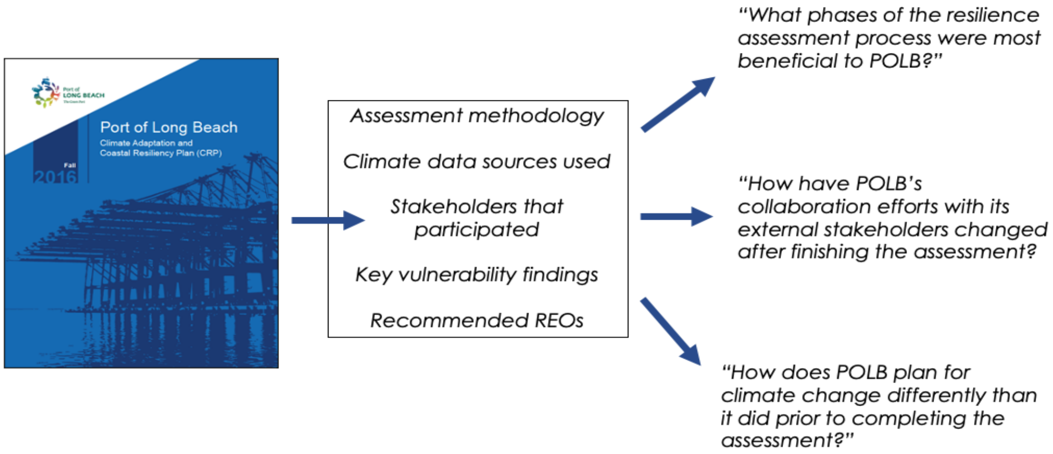

Figure 3 – Example of the data collection workflow

Online survey

A survey was administered electronically to informants prior to interviewing. The survey was divided into two sections, the first of which asked informants to identify whether the resilience enhancement strategies that seaports identified in their planning, were subsequently implemented. The second section gauged the institutional impacts of resilience assessments by presenting informants with the following 10 institutional capacities that have been proposed as critical to organizational adaptive capacity in the academic literature. We asked informants to rate the strength of each capacity prior to and after the completion of their seaports' resilience assessment initiatives:

(1) The seaport's **commitment** to resilience-building
(2) **Presence of leadership** to champion the seaport's resilience-building endeavors
(3) **Staff availability** to work on resilience-building endeavors;
(4) **Data availability**
(5) **Data quality** for resilience-building
(6) **Financial resource availability** for resilience-building
(7) **Resource sharing** (staff, information, data, etc.) across the seaport's departments
(8) **Resource sharing** (staff, information, data, etc.) with external stakeholder groups
(9) **Collaboration with internal stakeholders** on resilience-building endeavors
(10) **Collaboration with external stakeholders** on resilience-building endeavors

Interviews

We then held 12 Zoom interviews of about 45 minutes each, nine of which were in focus groups of two to four individuals, and three interviews were held individually with informants of the same seaport that could not participate together due to scheduling conflicts. The interview instrument was divided into four sections. The first section consisted of introductory questions designed to better acquaint the researcher with the case study's resilience planning process, such as "what drove your organization to undertake the resilience assessment?". The second section focused on informants' perceptions of the key benefits or utilities of their seaport's resilience planning effort, either those associated with the process itself or the findings documented in the final report. The third section addressed challenges that the organization experienced along the course of the process and any aspects of the effort that were of limited utility. The final section focused on institutional impacts, such as whether it changed the organization's climate change planning culture.

Limitations of this research

Overall, the results should be generalizable to port authorities given the mutual objectives they strive to meet and audiences they serve. However, there are several limitations of the research approach that should be considered in the interpretation of the results. For example, the variability in positions and responsibilities of interviewees undoubtedly impacts their perceptions of the resilience assessment process and introduces bias into the data. Informants also had varying degrees of participation in their seaports' resilience assessments, which limited the ability to collect their insights on them. Our research design also limits the reliability of the conclusions regarding the impacts of resilience assessments. Decisions to collaborate with external organizations or implement resilience-related capital improvements, are not made in a vacuum; hence, a direct causality cannot be inferred between the implementation of a given strategy and the resilience assessment, for example.

Tasks

Activities and Milestones Table

Activity	Completion Date
Lessons learned from port vulnerability assessments New research was conducted through semi-structured interviews and surveys with port representatives. It identified 10 ports that have conducted a comprehensive resilience/vulnerability assessment within the last 10 years in order to ascertain how ports have implemented recommendations and/or made resilience investments based on findings from the assessment. Results will inform the Hazard Resilience Guide and identify areas to strengthen of develop in order to make the MTS Guide useful for its intended audience. It should be noted that the research intended to include ports that had completed RRAPs in the study sample. Though 5 candidate RRAP ports were identified, points of contact at some ports could be not included for interviews for various reasons, while other ports could not be reached entirely.	**Interim Deliverable: Draft outline and research plan: 06/2020** **Final Deliverables: Chapter report for guidebook: 08/2021;** **Peer-reviewed publication: 06/2022**
Steering Committee Engagement The research was supported by a steering committee composed of members from ERDC (Margaret Kurth and Katherine Chambers) and CISA (Jevon Daniel and Sandra Pinel). In addition to biweekly meetings held with the Hazard Resilience Guide team, the study team held 11 meetings with the steering committee members. Meetings served multiple purposes, such as to provide updates, to seek feedback on the research design and methodology, or to discuss potential seaports to include in the study sample and identify POCs.	**ongoing**

Deliverables

The deliverable for this work is an annex to the *MTS Resilience Assessment Guide* that focuses on lessons learned on implementing resilience assessment recommendations, as well as one or more peer-reviewed publications in relevant journals.

ANALYSIS

Findings

This section presents the results from the data collection process described above. Results are organized in the following subsections by the research question to which the data pertain. Each subsection starts with an overview of the results, followed by analyses and interpretations. When quoting participants, the following abbreviations are used if the quote came from a director/manager, DIR; environmental specialist, ES; engineer, ENG; or safety planner, SP, to ensure participant anonymity.

Key benefits/utilities of resilience assessment interventions

The first broad question this research intended to answer was: **What are the key benefits and challenges of undertaking resilience assessment interventions?** Through analyses of the 12 interviews with 26 key informants, the study team identified eight discrete benefit/utility categories (**Figure 4; Table 3**).

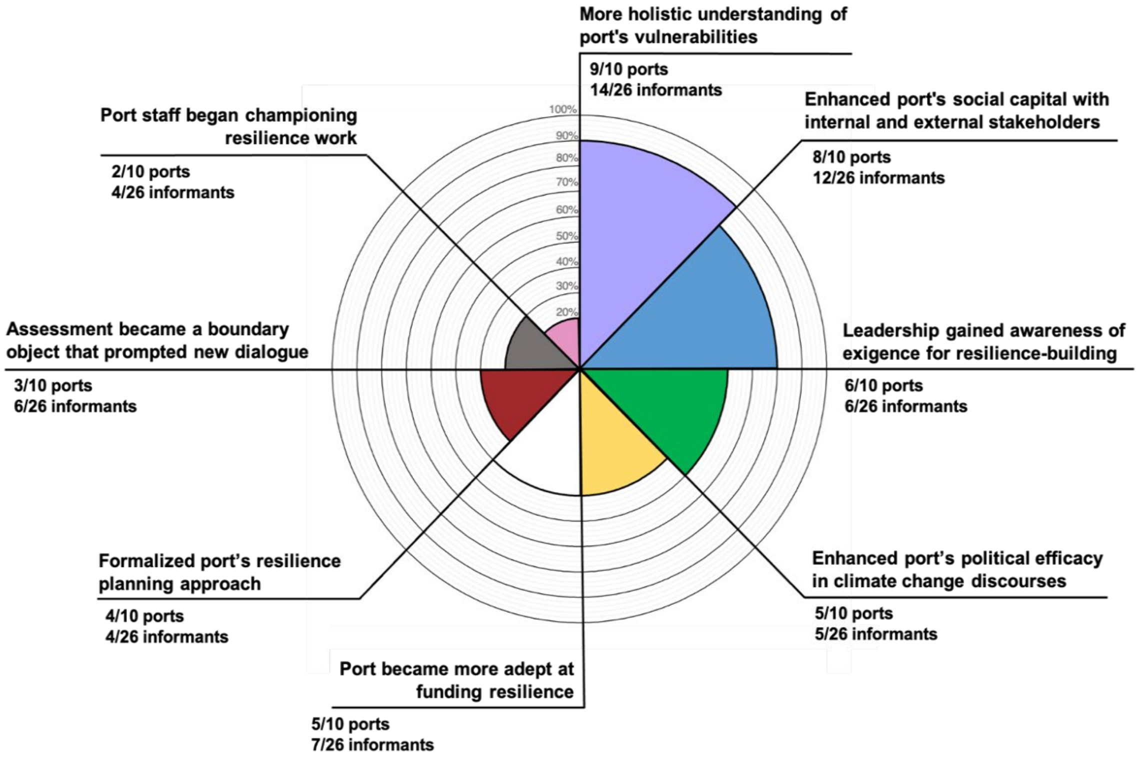

Figure 4 – Eight benefits associated with resilience assessments identified in 12 interviews with 26 seaport decision makers. Each colored pie is the percentage of seaports from which at least one informant mentioned that benefit.

Table 12 – Example quotations that were coded as one of eight resilience assessment benefit

Benefit of RPI	Example(s)
B1. More comprehensive and nuanced understanding the seaports' vulnerabilities (Mentioned by at least one informant from 9/10 seaports)	*"...we had never undertaken a study of that granularity, that got down to individual assets. We might have known anecdotally, 'that intersection floods' or 'that building needs to be built a little higher,' or something like that, but I would not say we had a comprehensive look at all those things together." (SP, September 2020).* *[The sea level rise map] is some of the most valuable information, for me, because we do the maintenance on everything...If we start to see effects of inundation on something, we might bring it forward to engineering for a different design or some sort of capital project, moving forward to help address that." (ENG, November 2020).* *The whole operation for unloading the cranes is to send a boom out over the ship...The concern was that the vertical clearance for that boom over that ship, was going to disappear because of sea level rise. Well, it didn't take us too long to show that, no, [that's not going to happen]...I couldn't put their mind at ease until I turned it into a formal study..." (ES, December 2020).*
B2. Enhanced social capital with internal and external stakeholders (Mentioned by at least one informant from 8/10 seaports)	*"The biggest takeaway for me in the whole process was involving all the players...If you keep it in-house, you sometimes get tunnel vision and you don't see the overall effects." (SP, November 2020).* *"[The assessment process] made us more of an information network . . . [our economic development manager] is constantly sending emails out, or updates, from the weather service or whoever it is—constantly sending it out to all of our stakeholders." (DIR, January 2021)* *"Most of us were not really on the same page on how a port would approach [climate change issues]. I think the workshop and the internal stakeholder engagement in the development of the [assessment], really brought us together as a port team." (ES, October 2020).* *"[The assessment process] made us more of an information network . . . [our economic development manager] is constantly sending emails out, or updates, from the weather service or whoever it is—constantly sending it out to all of our stakeholders." (DIR, January 2021).*
B3. The intervention became a boundary object (Mentioned by at least one informant from 3/10 seaports)	*"I think our port's collaboration became better because the issue of climate change in general was highlighted, emphasized, and probably talked about within groups that otherwise maybe would not have talked about it." (ES, October 2020).*

Table 13 (cont.) – Example quotations that were coded as one of eight resilience assessment benefit

B4. Leadership gained awareness of importance of resilience (Mentioned by at least one informant from 6/10 seaports)	*"… in the past, there were a lot of people at the port that weren't aware or were dismissive of climate change and the hazards that it poses to us…after seeing the results of the study, I think it raises a couple eyebrows to see [our main piers] underwater." (DIR, October 2020).* *"I think going through this process and bringing it to the attention of the leadership of the port, brought us further into our master planning process, including resilience planning and sustainability into our long-term planning aspect." (ES, September 2020).*
B5. Improved political efficacy in climate change conversations (Mentioned by at least one informant from 5/10 seaports)	*"We deal with a number of federal and state agencies…These issues, topics, and risk assessments and stuff are things that other people are doing, so [the resilience assessment] really gives us an ability to communicate with them… [and it also] helps us in understanding what they're talking about, or what they're looking at." (ES, November 2020).*
B6. Seaports became more adept at funding resilience projects (Mentioned by at least one informant from 5/10 seaports)	*"We've got four competing pillars—operations, IT, maintenance, and the civil side of the house—who are competing for a capital dollars. [The resilience assessment] allows us to illustrate why this feature, why this project is important, and that helps sell the project. And when [our director of engineering] brings it up, or I bring it up, or whomever brings it up, they know that it is a valid part of a conversation." (SP, September, 2020).*
B7. Formalized resilience planning approaches (Mentioned by at least one informant from 4/10 seaports)	*"[The assessment] standardized how we approach projects from a resiliency standpoint—not just now, but also in the future…You can't get to that point without starting somewhere, right? The assessment was kind of that "kindling for the fire," if you will." (ENG, September 2020).*
B8. Motivated staff to champion resilience projects (Mentioned by at least one informant from 2/10 seaports)	*"Three specific staffers [in our program management division] have really taken this role to help me out, to be my voice in the engineering team. Most of the engineers don't want to listen to [an environmental specialist]. So, I have three reps within our Program Management Division, who really sort of carry that torch on [our port's] climate programs." (ES, October 2020).*

Benefit 1: More comprehensive and nuanced understanding of the seaports' vulnerabilities

Key informants from nine of the 10 case studies described a more comprehensive and nuanced understanding of their seaports' vulnerabilities as a benefit of their assessments (24 mentions voiced by 14 informants). In many instances, informants described their resilience assessment as their seaports' first detailed investigation of their vulnerabilities. The impetuses to undertake these efforts were either a state mandate (as was the case for four case studies, though some started adaptation planning voluntarily prior); to obtain federal mitigation funding (two case studies); growing recognition of the threats posed by climate change as evidenced by recent natural hazard events (one case study); or for some other reason (three case studies). Interestingly, some informants felt that, along with identifying risks to proactively mitigate, their resilience assessment revealed what *not* to worry about.

Several informants also valued the byproducts of their planning, such as inventories of their seaport's vulnerable assets or GIS-based inundation maps, as this information allowed them to better understand the geographic extent of climate risk and aided their roles in their respective departments.

Benefits 2 & 3: Enhanced social capital with internal and external stakeholders; The intervention became a boundary object that prompted new dialogue

Twelve informants, representing eight of the 10 participating seaports, found the resilience assessment process to enhance their seaports' social capital with internal and external stakeholders (24 mentions; 12 informants). Social capital refers to the quality of relationships of trust, reciprocity, and exchange between stakeholders[76,77,78]. Informants explained that their seaports' enhanced social capital was a byproduct of another interrelated benefit: the assessment served as a boundary object—something that bridges communities, stakeholders, and disciplines[79]—that stimulated dialogue. Hence, these two benefits are considered together, as mention of one usually coincided with mention of the other.

Informants remarked how the resilience assessment process enhanced social capital both during and after planning was complete. Many of the informants felt that engaging key stakeholders—especially during the preliminary planning phases of scoping and defining objectives—built social cohesion and facilitated mutual understandings amongst different departments and, in some instances, with the external community. For example, one informant remarked how his seaport's inclusion of external stakeholders (city officials, NGOs, state government officials, etc.) provided a systems perspective of vulnerability otherwise unattainable through conventional planning approaches. In the opinion of another informant, his seaport became a centralized hazard information network for the surrounding community (DIR, January 2021).

Our data also revealed the potential of resilience assessment interventions to facilitate common understandings and coordinated approaches to seaports' resilience-building efforts—ergo, their role as a boundary object. As one informant explained, *"I would argue that most of us were not really on the same page on how a port would approach [climate change issues]. I think the workshop and the internal stakeholder engagement in the development of the [assessment], really brought us together as a port team."* (ES, October 2020). Lastly, the ability of the resilience assessment to convene new actors in conversations to which they otherwise would not be privy (or reluctant to participate in) was also captured in interviews. One group emphasized the importance of including oil industry stakeholders in a workshop to identify the seaport's strengths and weaknesses in operations.

Benefit 4: Leadership gained awareness of importance of resilience

Another benefit that was voiced in six of the 10 focus groups was the impact that resilience assessments had on their seaports' leadership (12 mentions; six informants). Decision makers explained how, prior to their seaports' resilience assessments, their leadership did not view resilience as a pressing matter that warranted capital expenditure, stymying long-term resilience-building efforts.

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[79] Star, S. L. (2010). This is not a boundary object: Reflections on the origin of a concept. *Science, Technology, & Human Values, 35*(5), 601-617.

When reports from the assessments were presented to lead decision makers, however, informants felt that leaders gained a heightened awareness of the exigence for resilience-building. We speculate that the information products that come out of resilience assessments, such as SLR inundation maps, may add tangibility to impending threats posed by climate change[80,81] for leaders who are otherwise preoccupied with the short-term concerns of running a public enterprise.

Benefits 5 & 6: Enhanced political efficacy in climate change conversations; Seaports become more adept at funding resilience projects

Five of the 10 case studies described their seaports' enhanced political efficacy in climate change conversations as a benefit of their resilience assessments (seven mentions; five respondents). In the opinion of several informants, resilience assessments enhanced their organizations' abilities to engage in political arenas that previously challenged staff that were not accustomed to climate change jargon or concepts. Mentions of Benefit 5 coincided with mentions of another benefit: divisions of the seaport became more adept at funding resilience projects (11 mentions; five informants). Informants explained that the ability to sway decision-making in favor of resilience was enabled, at least in part, by the resilience assessment findings, resulting in resilience projects receiving funding. In some cases, the ability to mobilize funds for resilience projects also improved. In the opinion of a director,

> "*Prior to [our resilience assessment], we would have the tendency to Op-EX lots of stuff that would otherwise need to be able to be capitalized. As we've gone through these last few years, we've freed up a lot of additional funds by capitalizing things where otherwise we previously weren't doing it. That has brought in more funds that give us more ability to do some resilience-building projects.*" (DIR, October 2020).

Critical infrastructure sectors are increasingly engaged in political conversations at local, state, and federal levels, and thus the ability to understand and influence climate-change related political affairs becomes paramount to resilience-building. By working with different departments and incorporating climate change expertise (e.g., from consultants), seaport decision makers may learn how to "talk the talk" of climate change. The improved abilities to mobilize and advocate financial resources after the resilience assessment also have direct implications for seaport adaptive capacity[82, 83] and support the utility value of resilience assessment interventions.

Benefits 7 & 8: Resilience planning became formalized; Staff became motivated to champion resilience projects

Two additional benefits were mentioned in conjunction with one another. Four seaports valued how resilience assessments formalized the seaport's strategic planning for climate change (eight mentions; four informants) and two felt that this motivated personnel from different divisions to champion resilience initiatives (four mentions; four informants). Informants explained that their seaports' climate change planning was largely an internal discussion with senior leadership or addressed by different departments in isolation, prior to their assessments. Following an intervention,

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[80] Retchless, D. (2018). Understanding Local Sea Level Rise Risk Perceptions and the Power of Maps to Change Them: The Effects of Distance and Doubt. *Environment and Behavior, 50*(5), 483-511.

[81] van Valkengoed, A. M., & Steg, L. (2019). Meta-analyses of factors motivating climate change adaptation behaviour. Nature Climate Change, 9(2), 158-163. https://doi.org/10.1038/s41558-018-0371-y

[82] Moser, S. C., Ekstrom, J. A., Kim, J., & Heitsch, S. (2019). Adaptation finance archetypes: local governments’ persistent challenges of funding adaptation to climate change and ways to overcome them. Ecology and Society, 24(2). https://doi.org/10.5751/es-10980-240228

[83] Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. Global Environmental Change, 16(3), 282-292. https://doi.org/10.1016/j.gloenvcha.2006.03.008

however, an engineer noted, *"[The assessment] standardized how we approach projects from a resiliency standpoint—not just now, but also in the future…"* (ENG, September 2020). In some cases, the formalization of climate change planning inspired staff to carry out resilience projects in their respective departments. *"At first, our engineering director was like, 'We can't afford to go above and beyond building code. We're not going to add resilience.' But now, they are adding resilience into their projects and even applying for federal grants,"* an environmental specialist explained (ES, November 2020).

RQ1 – Key challenges/limitations of resilience assessment interventions

Along with benefits, this study also highlights challenges of climate change resilience assessments. In total, the study team coded 56 statements that fell into one of 21 discrete categories of challenges. Because of the comparatively large number of challenges, the study team included only those that were mentioned by at least two case studies in the analysis. The breadth of challenges reflects the highly contextual nature of resilience planning. Four challenges (**Table 4**) are considered in the subsequent discussion.

Table 14 – Four main challenges mentioned in 12 interviews with 26 seaport decision makers

Challenge	Example
1. Engaging stakeholders (different priorities, scheduling conflicts, etc.)	*"It was difficult to talk to people, to get them to speak back to you, and give you information. Many of the commercial stakeholders think that everything they do is proprietary information…"*
2. Addressing hazards that lacked scientifically robust data	*"What was really challenging is the areas that don't have a lot of good data…you start talking about sea level rise–I'm either going to be at 19 feet elevation or I'm going to be four feet under. So, which do you start to try to plan for?".*
3. The lack of an archetype resilience assessment model challenged the organization of the assessment	*"[The assessment] was a challenge because we were kind of starting fresh, with a new thing…I needed something to go on, some sort of adaptation plan template…and it just simply didn't exist…"*
4. Communicating vulnerability findings to stakeholders could negatively impact seaports' marketability	*"…some port leaders have felt like, 'If we start showing these maps of sea level rise, is that going to deter investment into our waterfront?'…are these investment groups going to say, 'Oh my gosh, [that port] is going to be flooded!'?".*

Challenge 1: Engaging stakeholders complicated the execution of various phases of the resilience assessment

The most frequently mentioned challenge of RPIs involved engaging stakeholders (20 mentions; 10 informants). Our data reveal that stakeholder engagement was a challenge in all phases of the resilience assessment process. For example, during the preliminary organization of the assessment, convening stakeholders was complicated by schedule conflicts or their views that the assessment was not worthy of their time. One safety planner remarked about the difficulty of conveying to stakeholders the value of participating in an exercise with no immediate or tangible benefits, as processes like disaster mitigation and prevention are “difficult to measure” (SP, November 2020). Additionally, assessments necessitate discussion of vulnerabilities, often requiring participants to disclose sensitive information, which they may be reluctant to do. Scoping the assessment and defining objectives were also noted as bureaucratically cumbersome. For example, one informant mentioned the challenge of reaching consensus among his seaport’s myriad stakeholder groups regarding the appropriate climate scenarios to plan for (ES, September 2020). Following the completion of their seaports’ resilience assessments, several informants emphasized the challenge of communicating the vulnerability assessment findings to stakeholders and educating them about how to use the assessment (ES, September 2020). Two other focus groups’ participants were challenged in their efforts to continue dialogue about the assessment after it was complete or raise awareness of the assessment to other departments that had not participated. In the opinion of informant,

> *“…even when talking to some of our capital project managers about how to incorporate some of the recommendations in this plan into their project planning, there's kind of a disconnect there. They weren't even necessarily aware that there were strategies that could specifically relate to their projects in this plan…It's hard to get this on their radar.”* (ES, December 2020).

Challenge 2: Addressing vulnerabilities that lacked scientifically robust data

While the most commonly mentioned benefit was the enhanced vulnerability information, some informants acknowledged the limitations of the information their resilience assessments provided. Some seaports completed their interventions over five years ago, when, as several informants mentioned, the science for certain climate hazards was less accurate and available as more recently. Informants from three focus groups felt that the lack of accurate, locally relevant climate hazard data (e.g., sea level rise projections) limited their seaports’ abilities to identify and plan for those respective hazards (four mentions; four informants).

The finding that only three case studies mentioned this limitation is noteworthy. Though many case studies had completed their assessments more recently, and thus had access to more accurate scientific information, this does not mean that uncertainties did not exist in their information products. For this reason, it was anticipated that this challenge would be more frequently mentioned.

Challenge 3: The lack of an archetype resilience assessment model to follow

Several informants noted how the resilience assessments that their seaports undertook were different than conventional planning procedures, for example, because of the larger time horizons considered or the integration of numerous stakeholder groups. Informants from two case studies expressed the difficulty of organizing a planning process with which they had little experience and that had no model to reference, as a challenge (three mentions; three informants). In the opinion of one informant,

> *“Most challenging to start was that [the assessment] was something brand new. I contacted other representatives up and down the West Coast and East Coast…I needed something to go on, some sort of adaptation plan…and it just simply didn't exist…So, it was really a challenge because we were kind of starting fresh, with a new thing.”* (ES, October 2020).

Another informant from the same seaport explained that, unlike conventional risk assessment approaches, his seaport’s assessment was necessarily improvised as it progressed. Unsurprisingly, when asked how they would execute their assessments differently knowing what they do now, informants explained that they would seek advice from colleagues at other seaports that had already undertaken a similar effort.

Challenge 4: Communicating vulnerability findings to private stakeholders

An unanticipated challenge mentioned in two focus group interviews was communicating the vulnerability assessment results in a manner that would not harm the seaports' marketability to future lessees and investors (two mentions; two informants). Informants that mentioned this challenge felt that disclosing information about their seaports' vulnerabilities to external stakeholder groups may deter investment into their lands. For one informant's seaport,

> *"The larger challenge was figuring out how to do a plan without scaring the tenants…We actually stopped our planning process at one point and realized, 'That's going to be really scary to a tenant or even our own staff.' And so, we kind of stepped back and then we revamped our process and our approach a little bit, to look at the [vulnerabilities of] systems."* (ES, September 2020).

As discussed earlier, U.S. port authorities and agencies act as "public enterprises" that have civic responsibilities while also competing to secure market share, market their services, and facilitate economic development via private enterprise (Fawcett, 2007). Therefore, decision makers that wish to undertake a resilience assessment or similar initiative may want to include a communication strategy for navigating the potential publicity issues of disclosing vulnerabilities.

RQ2 – Resilience enhancement strategies that seaports implement after undertaking resilience assessments

The second objective of this research was to identify the types of resilience enhancement strategies that seaports implemented as a result of their resilience assessment interventions. We counted 155 discrete strategies from eight of the 10 case studies' resilience assessment documents[84] (and several

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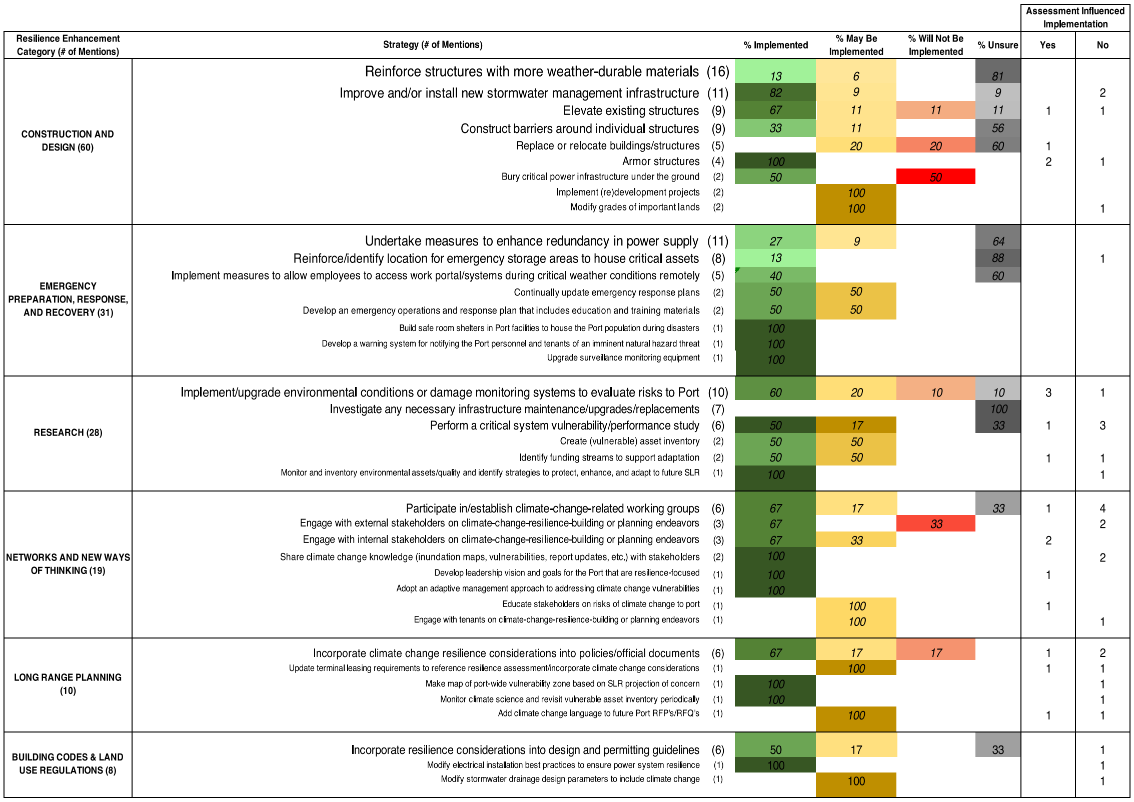
[84] Resilience assessment document from two of the case studies mentioned no resilience enhancement strategies, as this was beyond the scope of their specific approaches. Therefore, these were left out of the count.



Resilience Enhancement Category (# of Mentions)	Strategy (# of Mentions)		% Implemented	% May Be Implemented	% Will Not Be Implemented	% Unsure	Assessment Influenced Implementation	
							Yes	No
CONSTRUCTION AND DESIGN (60)	Reinforce structures with more weather-durable materials	(16)	13	6		81		
	Improve and/or install new stormwater management infrastructure	(11)	82	9		9		2
	Elevate existing structures	(9)	67	11	11	11	1	1
	Construct barriers around individual structures	(9)	33	11		56		
	Replace or relocate buildings/structures	(5)		20	20	60	1	
	Armor structures	(4)	100				2	1
	Bury critical power infrastructure under the ground	(2)	50		50			
	Implement (re)development projects	(2)		100				
	Modify grades of important lands	(2)		100				1
EMERGENCY PREPARATION, RESPONSE, AND RECOVERY (31)	Undertake measures to enhance redundancy in power supply	(11)	27	9		64		
	Reinforce/identify location for emergency storage areas to house critical assets	(8)	13			88		1
	Implement measures to allow employees to access work portal/systems during critical weather conditions remotely	(5)	40			60		
	Continually update emergency response plans	(2)	50	50				
	Develop an emergency operations and response plan that includes education and training materials	(2)	50	50				
	Build safe room shelters in Port facilities to house the Port population during disasters	(1)	100					
	Develop a warning system for notifying the Port personnel and tenants of an imminent natural hazard threat	(1)	100					
	Upgrade surveillance monitoring equipment	(1)	100					
RESEARCH (28)	Implement/upgrade environmental conditions or damage monitoring systems to evaluate risks to Port	(10)	60	20	10	10	3	1
	Investigate any necessary infrastructure maintenance/upgrades/replacements	(7)				100		
	Perform a critical system vulnerability/performance study	(6)	50	17		33	1	3
	Create (vulnerable) asset inventory	(2)	50	50				
	Identify funding streams to support adaptation	(2)	50	50			1	1
	Monitor and inventory environmental assets/quality and identify strategies to protect, enhance, and adapt to future SLR	(1)	100					1
NETWORKS AND NEW WAYS OF THINKING (19)	Participate in/establish climate-change-related working groups	(6)	67	17		33	1	4
	Engage with external stakeholders on climate-change-resilience-building or planning endeavors	(3)	67		33			2
	Engage with internal stakeholders on climate-change-resilience-building or planning endeavors	(3)	67	33			2	
	Share climate change knowledge (inundation maps, vulnerabilities, report updates, etc.) with stakeholders	(2)	100					2
	Develop leadership vision and goals for the Port that are resilience-focused	(1)	100				1	
	Adopt an adaptive management approach to addressing climate change vulnerabilities	(1)	100					
	Educate stakeholders on risks of climate change to port	(1)		100			1	
	Engage with tenants on climate-change-resilience-building or planning endeavors	(1)		100				1
LONG RANGE PLANNING (10)	Incorporate climate change resilience considerations into policies/official documents	(6)	67	17	17		1	2
	Update terminal leasing requirements to reference resilience assessment/incorporate climate change considerations	(1)		100			1	1
	Make map of port-wide vulnerability zone based on SLR projection of concern	(1)	100					1
	Monitor climate science and revisit vulnerable asset inventory periodically	(1)	100					1
	Add climate change language to future Port RFP's/RFQ's	(1)		100			1	1
BUILDING CODES & LAND USE REGULATIONS (8)	Incorporate resilience considerations into design and permitting guidelines	(6)	50	17		33		1
	Modify electrical installation best practices to ensure power system resilience	(1)	100					1
	Modify stormwater drainage design parameters to include climate change	(1)		100				1

Figure 5 – Heat map of mentioned resilience enhancement strategies that respondents indicated had been/will be implemented, may be implemented, and will not be implemented after completing a resilience assessment. Strategy font size correlates with total number

others during interviews) (Figure 5). Of these 155, the study team found that construction and design strategies were most frequently mentioned (N_m=60) and implemented (N_i=25); however, no statistically significant difference in terms of implementation, existed between the six typologies (p = 0.689, Fisher's exact test, two-sided). Construction and design strategies comprised developing and implementing physical changes either on or off the seaport. The most frequently mentioned strategy of this type was reinforcing structures, such as terminal assets, with more durable materials (N_m=16). The most frequently implemented strategy of the construction and design typology was stormwater management infrastructure improvements (N_i=9). Following construction and design strategies, the identified 31 total emergency preparation, response, and recovery strategies; 28 research strategies; 18 networks and new ways of thinking strategies; 10 long range planning strategies; and eight building codes and land use regulations strategies. In terms of total quantities implemented, research strategies were the next most implemented (N_i=12) after construction and design, followed by networks and new ways of thinking strategies (N_i=11), emergency preparation, response, and recovery (N_i=11), long range planning (N_i=6), and, finally, building codes and land use regulation (N_i=4).

Influence of the resilience assessment on strategy identification and/or implementation

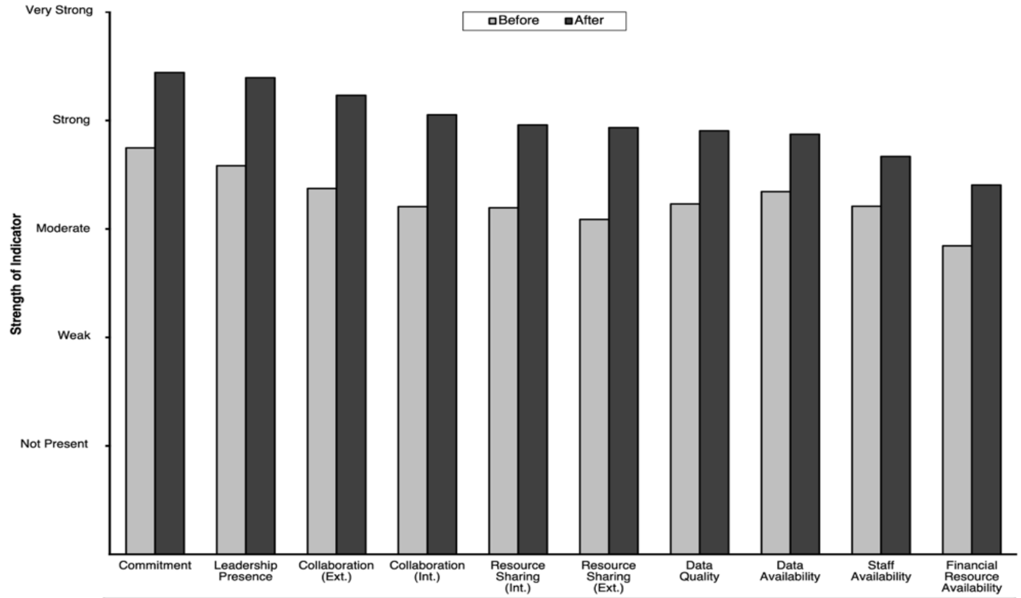
Few informants indicated the likelihood of their seaports' identifying or implementing specific strategies in the absence of their resilience assessments. Most respondents either left this section blank or answered "unsure." We counted only the responses indicating that implementation of a given strategy was likely—suggesting that the resilience assessment did not influence that area of the seaport's resilience portfolio—and not likely—suggesting that the resilience assessment introduced the seaport to areas of resilience improvement. Overall, the informants found their resilience assessments to have the greatest influence on the implementation of monitoring systems that continually track environmental conditions (such as sea level height) or infrastructure damage, which fell under the research typology. By contrast, most respondents felt that participating in or establishing a climate change-related working group or ad-hoc committee was likely to be an implemented strategy in the absence of the assessment.

Interpretation of resilience enhancement strategy results

It is difficult to glean insights from the survey results. The insignificant difference between implemented resilience enhancement typologies may suggest that resilience enhancement strategies are too case-specific for cross-seaport comparisons. The inability of most informants to indicate whether implementation was likely in the absence of the resilience assessment, may indicate a weakness in the survey instrument to address the sought inquiry—the question may have been too speculative for informants. One potential explanation of why construction and design strategies were most frequently mentioned and implemented, is that infrastructure improvements and modifications are going to be pursued regardless of climate change. Without functional infrastructure, the seaport's capacity to facilitate the transfer of cargo is compromised; thus, having resilient infrastructure is merely complementary to the seaport's mission.

RQ3 – Perceived changes in seaports' capacities to manage system resilience

In the online pre-survey that informants completed before the focus group interview, the study team measured informants' perceptions of changes in their seaports' capacities to plan for and manage climate change, to further evaluate resilience assessment interventions. Figure 6 presents the aggregated pre- and post-resilience-assessment strengths of the 10 institutional capacities. The primary takeaway from these survey results was that each capacity's strength increased after the assessment (however, the study team found that not all informants indicated a change after their assessment). On average, seaports' commitment to resilience-building endeavors was strongest before (3.7, moderate-to-strong) and after (4.4, strong-to-very-strong) the intervention. The other



	Commitment	Leadership Presence	Collaboration (Ext.)	Collaboration (Int.)	Resource Sharing (Int.)	Resource Sharing (Ext.)	Data Quality	Data Availability	Staff Availability	Financial Resource Availability
N	19	18	19	19	19	14	17	18	19	18
N (Δ noted)	12	12	12	12	11	9	10	10	10	7
N (no Δ noted)	7	6	7	7	8	5	7	8	9	11

Figure 6 – Average strengths of key institutional capacities prior to (light grey) and after (dark grey) completion of resilience assessments.

indicators' pre- and post-assessment strengths were generally similar; most increased from moderate to strong after the assessment. In terms of percent change in strength, the greatest increase (27.4%) was in resources sharing with external stakeholder groups, followed by internal collaboration (26.4%), external collaboration (25.4%), internal resources sharing (23.9%), leadership presence (22.6%), data quality (20.8%), financial resource availability (19.7%), commitment (18.5%), data availability (15.8%), and staff availability (14.3%).

The coincidence that informants mentioned nearly all 10 adaptive capacity indicators as benefits further validates interview findings. For example, the increased strength in data quality and availability corresponds with Benefit 1–more holistic understanding of seaport vulnerabilities; or, the increased strength in financial resource availability reiterates Benefit 6—seaports became more adept at funding resilience. Together, the survey and interview data have important implications for the role of resilience assessments in building adaptive capacity. In particular, the study team finds Benefit 2—enhanced social capital—and the increased strength of internal and external collaboration and resource sharing, to be significant. The role of social capital in enhancing coping capacity and reducing vulnerability is well-recognized in resilience literature, as vertical and horizontal exchanges amongst agencies can build networks and help institutions avoid maladaptation[85, 86, 87].

Recommendations

Our results demonstrate that resilience assessments provide many "low-hanging fruit" opportunities for resilience-building that are not costly and ultimately lead to a more functional seaport. Not only do resilience assessments serve as an effective planning framework for managing known and unknown risks, but they also come with a suite co-benefits. In addition, practitioners that are unfamiliar with seaport resilience may access this research to gain a more tangible notion of what resilience actually entails through the documentation of enhancement strategies. Lastly, the study team documents important challenges that seaport audiences should consider when planning their assessments. Given the stakeholder engagement challenges described above, audiences of this guide should make significant effort on the front half of their resilience assessments—i.e., Steps 1 & 2 described in the main text of the MTS Guide—to ensure that strategies are in place to transcend obstacles that come up along the way. For example, to overcome the issues of communicating vulnerability findings to external stakeholders, the preliminary stages of the assessment should include the development of a results communications plan.

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[85] Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., & Rockstrom, J. (2005, Aug 12). Social-ecological resilience to coastal disasters. Science, 309(5737), 1036-1039. https://doi.org/10.1126/science.1112122

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CONCLUSION

This research constitutes a valuable contribution to practitioner audiences on resilience planning and adaptive management of climate change risks by exploring how seaports and stakeholders operationalize resilience planning and assessment practice. Seaports, with their importance to regional and national transportation services, their complex ownership and governance context, and climate change challenges, present an important setting for evaluating largely normative resilience planning and adaptive management theories for managing complex social and ecological systems. Although most of the selected cases were undertaken by the port authorities and not the larger set of stakeholders, and were initially focused on protecting business operations, the perceived benefits supported adaptive management and resilience assessment premises—that planning builds social capital that is essential to adapting to climate change and other threats across a complex system. Resilience assessment practices enhanced social capital developed between the seaport and its stakeholders and seemed to result in shared information and political will needed for implementation of resilience enhancement alternatives. Seaport leaders reported improved awareness of the exigence of resilience-building, which has important implications for seaport adaptive capacity, as supported by existing research. Survey results capturing decision makers' perceptions of their resilience assessments' institutional impacts, further complemented the findings regarding the adaptive capacity impacts of resilience assessments. Findings suggest that organizers of future assessments should strategize how to transcend anticipated stakeholder-related obstacles early in the process.

APPENDIX B.1 PUBLIC INFORMATION ABOUT THE PROJECT

Publications

The research that supported the Hazard Resilience Guide is featured in the following publications:

1. Kalaidjian, E., Becker A., & Pinel, S. (In Revew). An evaluation of resilience planning at 10 U.S. seaports: Insights for theory and practice. *Journal of Climatic Change*
2. Kalaidjian, E. (2021). Institutionalizing resilience: Insights from assessment initiatives at 10 U.S. seaports. Open Access Master's Theses.

Presentations

The research that supported the Hazard Resilience Guide was featured in the following presentations:

1. Becker, A. (2021), Port Adaptation and Resiliency: Key Issues for Business and Investment. World Ocean Council Port Coastal Adaptation Working Group Meeting, Aug. 4.
2. Kalaidjian, E. (2021). “Institutionalizing Resilience: Insights from Initiatives at 10 U.S. Seaports”. Department of Homeland Security Center of Excellence Summit, May 17th, 2021.
3. Becker, A. (2021), Resilience and the Maritime Transportation Sector, TS Resilience Under Climate Change and a Dynamic Global Supply Chain Hosted by the U.S. Committee on the Marine Transportation System and the American Association of Port Authorities, May 11.
4. Becker, A. (2021). Research Overview. Sea Education Association Class Talk (Virtual), April 1
5. Becker, A. (2021). A Resilient Port of the Future. 2021 Port of the Future Conference, (Virtual), March 16.
6. Becker, A. (2021). Advancing climate resilience for coastal infrastructure: Insights from a decade of applied research. Center for Coastal Physical Oceanography (CCPO)and Institute for Coastal Adaptation & Resilience (ICAR) Spring 2021 Virtual Seminar Series. March 15
7. Becker, A. (2021). Advancing climate resilience for coastal infrastructure: Insights from a decade of applied research. Lecture of Opportunity, U.S. Naval War College, Newport, RI, Feb.2
8. Becker, A. (2020). Advancing climate resilience for coastal infrastructure: Insights from a decade of applied research. Brown University Policy Lab Speaker Series. Nov. 17.
9. Becker, A. (2020). Advancing climate resilience for U.S. seaports: Insights from a decade of applied research. American Association of Port Authorities Energy and Environment Seminar and Expo. Oct. 29th, 2020.
10. Kalaidjian, E. (2020). “Institutionalizing Resilience: Insights from Initiatives at 10 U.S. Seaports”. Maritime Risk Symposium, Oct. 28th, 2020.
11. Becker, A. (2020). “Advancing Climate Resilience for Seaports: Insights from a Decade of Applied Research”. UNCTAD Multiyear Expert Meeting on Transport, Trade logistics and Trade facilitation (8th session) Climate Change Adaptation

for Seaports in Support of the 2030 Sustainable Development, Oct. 27th, 2020.

12. Becker, A., & Kalaidjian, E. (2020). Institutionalizing Resilience: Insights from Assessment Initiatives at U.S. Seaports. Florida Seaport Environmental Management Committee, Sept. 1st, 2020.
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ANNEX C. PROBABILISTIC SEISMIC RESILIENCE ASSESSMENT AT A NAVIGATION TERMINAL

TABLE OF CONTENTS

AUTHORS AND ACKNOWLEDGEMENTS

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INTRODUCTION

Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions, which are any forces that could disrupt the ability of a system to maintain its function. A large body of research has focused on finding quantitative metrics and methods to characterize this ability (Bruneau *et al.* 2003, Chang and Shinozuka 2004, Schultz and Smith 2016, Cimellaro *et al.*, 2016, Poulin and Kane 2021). Efforts to quantify resilience are aimed at providing system managers with an objective assessment under the system's baseline configuration and provide guidance on what modifications to the system would yield the greatest improvement. Approaches vary widely, depending upon the nature and scale of the systems of interest. No single approach is applicable to all systems. This study investigates how the seismic resilience of the commercial cargo handling function can be assessed at a navigation terminal.

In this study, a network is used to capture the dependencies among infrastructure components at the navigation terminal and the contribution of those components to the flow of commercial cargo. Networks offer an intuitive way to represent systems and model the consequences of cascading failures in those systems (Ouyang 2014). The networks used in this study are probabilistic. Probabilistic methods offer a rigorous way to address the large number of uncertainties that exist when considering the consequences of events that may or may not happen in the future and with which there may be limited past experience. As demonstrated here, probabilistic resilience assessment quantifies the probability, severity, and duration of potential losses in system function so that alternatives for strengthening resilience can be evaluated and compared. Where losses in functional performance can be monetized, this sets up a cost benefit analysis that supports decisions about investments in resilience strengthening measures.

The approach to resilience assessment developed in this study can be readily adapted for other navigation terminals, other hazards, and other types of systems supported by networked infrastructure. The initial step is to conduct a hazards analysis to estimate the probability and severity of disturbance events. The throughput capacity of the system is then modeled as a function of the availability of critical infrastructure components (CIC). CIC are any infrastructure components that, if damaged by a disturbance and rendered non-functional, would reduce the capacity or performance of the system. Dependencies among CIC are modeled using a probabilistic network in which CIC damage states are uncertain and directly dependent upon seismic loads. These uncertainties are propagated through the network to characterize uncertainty in CIC functionality, throughput capacity, and CIC restoration times. The outputs of the analysis are many realizations of the resilience curve that describe recovery of the system's throughput capacity over the restoration period.

This demonstration of the resilience assessment method focuses on the commercial cargo handling function at a container terminal located on the Columbia River, in the Port of Portland's Terminal 6. Portland, Oregon is located in the vicinity of the Cascadia Subduction Zone (CSZ) and numerous other tectonic sources. Thus, the hazards addressed in this study are ground motion and ground deformation caused by seismic activity. A probabilistic seismic hazards analysis (PSHA) was completed to understand the frequency and intensity of seismic loads that might affect Terminal 6. PSHA is a process for estimating the frequency and severity of seismic loads at a site of interest considering the distance to and contribution of potential sources of seismic activity, which are the geologic faults located within the region (McGuire 2004). This analysis considered seismic loads from all tectonic sources in the region, including both CSZ and non-CSZ sources.

Annual throughput capacity (ATC) describes how many twenty-foot containers could be handled over a one-year period given the combination of CIC that are available at a point in time. ATC is at a maximum when all CIC are functional, it decreases when CIC are damaged and become non-functional, and it increases as CIC functionality is restored following a seismic event. The extent of a decrease in ATC depends upon the combination of CIC that are non-functional. The length of time required to restore ATC to its pre-disturbance level depends on the severity of damage to CIC. Damage to and restoration of CIC are stochastic processes. In other words, the consequences of a seismic event are uncertain. Identical CIC subject to the same seismic load may exhibit more or less severe damage than the others. This uncertainty is modeled by sampling damage states and restoration times from probability distributions using Monte Carlo simulation. The uncertainty is propagated to estimates of ATC at points in time during the one-year restoration period. This creates a set of simulated recovery trajectories, or resilience curves, with statistical properties that are consistent with the range of potential outcomes following a seismic event.

A resilience curve, or recovery trajectory, describes how much ATC is reduced by damage to CIC and how long it takes to restore the pre-disturbance level of throughput capacity. Measures of resilience are computed from the recovery trajectories. The measure of resilience used in this study is the expected value of the ratio of residual ATC over the one-year restoration period to maximum ATC given the seismic load. The metric ranges from 0-1 and the higher the conditional expected value, the greater the resilience of the system. This measure resembles one used by Ouyang *et al.* (2012). This measure of resilience is normalized to a static capacity, ATC, so it describes restoration to full function (Poulin and Kane 2021).

The benefit of a resilience strengthening alternative is calculated from two recovery trajectories, one generated with the proposed improvements to the infrastructure in place and the other with the status quo configuration of infrastructure, absent the improvements proposed under the alternative. This measure of the benefit describes the increase in ATC achieved by an alternative over a one-year restoration period. This metric can be calculated for any alternative, provided that there is a nexus to the infrastructure network used to model ATC. Measuring the overall effect of an alternative on ATC over a one-year restoration period enables very different types of alternatives to be compared. For example, retrofits to infrastructure that improve the reliability of electrical components can be compared to contracting for the removal of debris from the navigation channel.

This study demonstrates that alternatives differ in terms of whether or not they mitigate damage to infrastructure components caused by events that are more or less severe and in terms of whether or not those damages are restored more or less quickly. For example, retrofits to electrical components reduce the frequency of electrical outages caused by more moderate seismic events, but are less effective against more severe events. In contrast, contracting in advance for removal of debris from the navigation channel would only mitigate damages caused by more severe seismic events because only the more severe events would cause bridges to collapse in the navigation channel. Whereas electrical components can be restored relatively quickly, the removal of debris from the navigation channel can take months because of the contracting process. Therefore, each alternative is more or less effective at reducing restoration times. Alternatives that address infrastructure failures associated with lengthy restoration times have the potential to yield much greater benefits than those that reduce shorter restoration times. However, those benefits may be offset if the frequency of events that cause those damages is lower.

The benefits of investments in infrastructure systems are realized over many years and investment decisions are typically based on a benefit-cost analysis in which those benefits and costs are estimated over planning horizons that span 30 to 50 years. It is equally important to estimate the benefits of resilience strengthening measures over similar planning horizons. The expected benefit of an investment will be a function of how many times the investment mitigates damages from seismic events during the planning horizon. Therefore, expected benefits are calculated from a joint probability distribution on the number and severity of seismic events realized during the planning horizon.

Study Site

The Port of Portland’s Terminal 6 is a 419 acre multi-use navigation terminal located just upstream of the confluence of the Columbia and Willamette Rivers, approximately 100 river miles from the Pacific Ocean. The layout of Terminal 6 is illustrated in Figure 1. The terminal is capable of handling containers, breakbulk cargo, autos, and has container-on-barge capability. The terminal provides a point of intermodal connection to both road and rail networks. Terminal 6 also hosts two auto import export facilities with a combined auto storage area of 242 acres. These operate independently of the container terminal and are not the subject of this analysis. Access to Terminal 6 is via the Columbia River navigation channel. The channel provides 43 feet of draft between the Pacific Ocean and the Interstate 5 Bridge at Portland. Upstream of the Interstate 5 Bridge, the authorized depth is 27 feet, but the channel is maintained at 17 feet. While the focus of this study is on resilience of the container yard, it should be noted that operations at the Terminal 6 container yard were suspended in 2014 because of a dispute between the operator and the labor union (OregonLive, November 04, 2019). Container operations resumed at Terminal 6 in 2021.

The primary purpose of the terminal is to transfer cargo between waterways and road and rail networks (Bassan 2007). Accordingly, the primary objective of this study is to quantify the resilience of cargo handling capacity to seismic hazards. However, the Port of Portland has also determined that, in the immediate wake of a natural disaster, the role of its marine facilities would be to support emergency operations and response and regional long-term recovery efforts (Port of Portland 2019). Thus, a second but equally important question addressed in this study is how to quantify the readiness and ability to support a Federal Staging Area (FSA) at Terminal 6 and assess its impact on container operations at the terminal. An FSA is a site that is operated by the Federal Emergency Management Agency (FEMA) to provide logistical support to a population affected by a disaster. An FSA receives and redistributes emergency supplies to state-operated distribution centers. Supplies include meals, water, cots, blankets, infant and toddler kits, durable medical equipment, surgical kits, and generators.

Since no FSA has ever been operated at Terminal 6, it was first necessary to develop a scenario describing where in the terminal an FSA would be located and how it would function. The following scenario was developed in consultation with the Logistics Branch in the Response Division of FEMA Region X and the Port of Portland. Supplies would be shipped from a site in Eastern Washington to the FSA via the Columbia River Navigation Channel. Tractor trailers containing supplies would be shipped piggyback on barges through the Columbia River navigation locks. Supplies would be offloaded at Berth 606, an ad-hoc barge berth located between Berth 605 and Berth 607. Berth 607 is a floating dock equipped for loading and off-loading roll-on roll-off auto carriers (Figure 1). The minimum requirements for operating an FSA are ingress, egress, security, and ten acres of hardstand, which is a paved area for loading and storage of tractor trailers. Security would be provided by the existing fence around the container terminal and FEMA would build its own temporary access to Marine Drive. The area of hardstand designated for the proposed FSA is adjacent to the ad-hoc barge berth and is presently used for container storage.

Figure 1: Terminal 6 Container Yard Layout.

Objectives of Resilience Assessment

The tactical objectives of this resilience assessment are to: 1) quantify the seismic resilience of container terminal operations at Terminal 6 under the status quo; 2) evaluate alternatives for strengthening resilience; 3) assess the readiness and ability to support an FSA; and 4) assess the impact of an FSA on container terminal operations.

Critical Infrastructure

The critical components of an infrastructure network at a navigation terminal are those that, if damaged, would reduce throughput capacity at the terminal. This section of the report identifies and describes the dependence relationships of CIC in the container terminal and the CRNC. While there are many other buildings and infrastructure components located at Terminal 6, and these also support the handling of commercial cargo, they have not been included in the short list of CIC because there is insufficient information to describe how damage to these components would affect throughput capacity.

Critical Infrastructure Components (CIC)

The infrastructure network that supports ATC is illustrated in Figure 2. Each node represents a CIC or a capacity metric. Directed edges between nodes represent dependence of the downstream node on the upstream node. The network has a single terminal node, which represents the ATC metric. The container terminal ATC is a function of the individual throughput capacities of those systems that support the transfer of containers between waterways and road and rail networks. These include the nodes labelled "Ship to Shore (STS) Crane Throughput Capacity," "Container Storage Throughput Capacity," and "Intermodal Throughput Capacity."

STS throughput capacity is provided by four post-Panamax container cranes. These gantry cranes are mounted on rails with a 100-foot gage and located on the wharves at Berths 604 and 605. Both wharves were recently retrofitted to increase their ability to withstand seismic loads. There are also three smaller Panamax cranes. These are mounted on rails with a 50-foot gage and located on the wharf at Berth 603, which is downstream of Berth 604. The wharf at Berth 603 has not been seismically retrofit. The three wharves are adjacent to one another and form a single contiguous dock that is 2,850-feet in length. The post-Panamax cranes can be positioned anywhere along the length of Berths 604 and 605. Although they are presently not operational, the Panamax cranes can be positioned anywhere along the contiguous dock, but must remain downstream of the post-Panamax cranes. All cranes require a connection to the electrical grid, which is supplied by a variety of electrical circuits and substations as shown in Figure 2. Drafts at each berth range from 40-43 feet.

Container storage takes place in a 125 acre container yard. The container yard is divided into three parts, CY604, CY605, or CY606 correspond to the areas located behind container Berths 604, 605, and 606, respectively. The container yard includes both refrigerated and non-refrigerated container slots. Level pavement is required to stack containers and damage to pavement caused by ground deformation could reduce storage throughput capacity by preventing the stacking of containers. Refrigerated container slots also require connections to the electrical grid. In the 604 container storage yard (CY604), located behind the wharf at Berth 604, these connections are supplied by electrical substations 422 and 423. In the 605 container storage yard (CY605), these are supplied by electrical circuit 06. All power to refrigerated container slots is routed through electrical substation A.

Intermodal throughput capacity depends on the ability to transfer containers to and from road and rail networks. Transfers to rail networks require access to undamaged rail segments within the rail yard, and these segments must be accessible from the connection to the Burlington Northern rail network at the boundary of the terminal. Transfers of containers to road networks take place in the container yard. Road trucks drive into the container storage yard where they meet container handling equipment that loads the container onto the chassis. Road trucks and container handling equipment require pavement exhibiting less than several inches of ground deformation. Excessive damage to pavement would impede road truck access to container storage areas.

Three other systems are essential for maintaining container terminal ATC. These are communications, security, and downstream navigation. The communications system is represented by the "Building 7545 Communications Components" node. This node represents a system for wireless communications with container handling equipment operating in the container storage yard and a connection to Tideworks, the container tracking system. The communications system is housed in Building 7545. This Container Yard Gate Building is a light wood frame structure located at the entrance to the container yard. For the communications capability to remain functional, Building 7545 must remain structurally sound (Building 7545 Structural Components) and the electrical and communications components within that structure (Building 7545 Electrical Components) must also remain functional. Electricity is supplied to Building 7545 by electrical circuit circuit 09, which is fed from substation A.

Security at the terminal requires the maintenance of a boundary fence, lights and surveillance cameras, roving security personnel, and the ability to scan vehicles and containers entering and leaving the terminal. While there are several aspects to maintaining security, it was ultimately determined that only the inability to scan vehicles and containers entering and leaving the terminal would disrupt throughput capacity. Terminal operators use optical character readers (OCR) to document the vehicles and containers entering and leaving the terminal and scan each container to detect radioactive material. The inbound OCR (IBOCR) and the outbound OCR (OBOCR) are low-rise steel moment frame structures. To provide security, the structural and electrical components of each structure and the connection must remain intact and there must be a connection to the electrical grid. Electricity is supplied to the IBOCR via Building 7545 and to the OBOCR via electrical circuit 10, which is supplied by substation A.

All processes at the terminal depend on a connection to the electrical grid. Electrical CIC are represented by yellow nodes in the upper portion of Figure 2, which include eleven electrical circuits and four substations. Substations A and B are located underground and are independently fed from the external grid. With the exception of circuit 04, each circuit depends on a single substation. Circuits 02-04 support the ship to shore cranes. Circuits 06, 10, 11, and 12 supply electricity to the refrigerated container yards, with those in CY604 additionally supported by substations 423 and 422. Circuits 05, 06, and 12 support lighting in the container yard. Circuits 09 and 10 supply power to Building 7545, the IBOCR, and the OBOCR.

Cargo is delivered to and from Terminal 6 via the Columbia River Navigation Channel (CRNC). The ability to navigate downstream of the terminal is represented by the node labelled “Downstream Navigation Channel.” There are two bridges which, if collapsed into the navigation channel could disrupt navigation. These are the Astoria-Megler Bridge near Astoria, Oregon, and the Lewis and Clark Bridge, which crosses the navigation channel at Longview, Washington. Navigation infrastructure is discussed in more detail below.

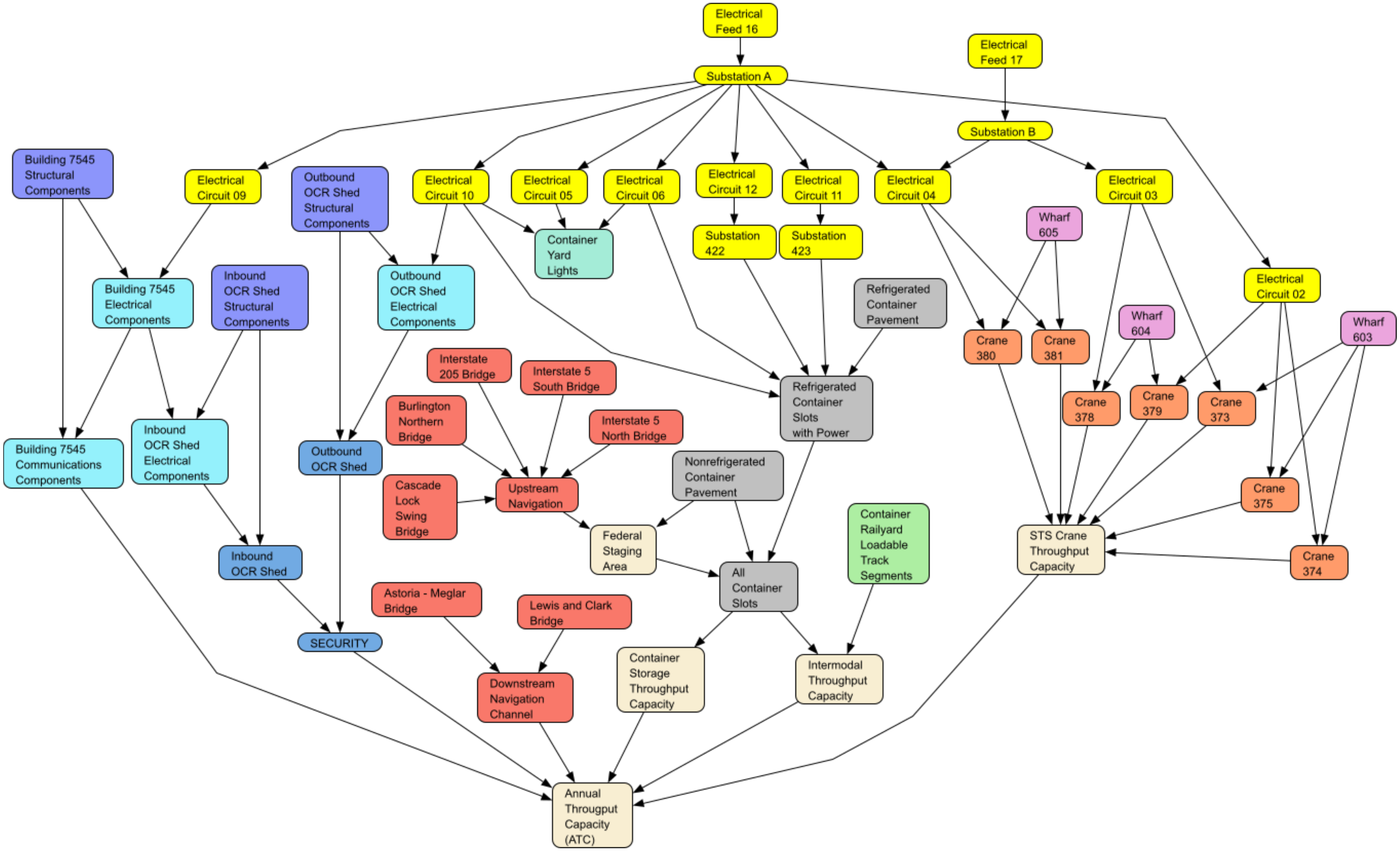

Figure 2. Container Yard Critical Infrastructure Components (CIC).

Federal Staging Area (FSA)

For the purpose of this study, it is assumed that an FSA would be located in a ten acre paved container storage area adjacent to Berth 606 (Figure 1). Ingress and egress on the land side would be provided by entrances and exits constructed, controlled, and monitored by FEMA. A minimum level of security is provided by the existing fence surrounding the terminal. Additional fencing could be constructed to separate the FSA from container terminal operations. Emergency supplies would be shipped from Eastern Washington in tractor trailers mounted on barges. Access between the navigation channel and the FSA would be provided via Berth 606, where a spud barge anchored to the bank would serve as a temporary floating dock. Trailers would be rolled off of the barges and up an existing gravel ramp to the paved container storage area.

The ability to support an FSA depends on the ability to navigate between Terminal 6 and Eastern Washington. Navigation could be blocked by bridges collapsed in the water, by failure of the mechanical swing bridge at Bonneville Lock, or by damage to navigation miter gates. CRNC infrastructure components are discussed in more detail below. Dependence of upstream navigation on five bridges is represented in the graph in Figure 2. The figure also shows dependence of the FSA on container yard pavement, which is potentially damaged in a seismic event, and dependence of container storage throughput capacity on the FSA. The operation of an FSA in the 606 container yard would reduce container storage throughput capacity by reducing the area available for non-refrigerated container storage. The area designated for the FSA encompasses 1,120 container ground slots, or almost 26% of the 4,344 non-refrigerated ground slots that are available at the terminal.

1.3.3 Columbia River Navigation Channel (CRNC)

The CRNC extends from the mouth of the Columbia River to the Ports of Lewiston, Idaho and Clarkston, Washington. It provides deep draft navigation for cargo ships between the Pacific Ocean and the Interstate 5 (I-5) Bridge at Portland, Oregon. Downstream of Terminal 6, the channel is 600 feet wide and 43 feet deep over much of its length. Upstream of the I-5 Bridge, the CRNC serves as an inland waterway for commercial barge traffic and the channel is maintained at 17 feet. Bonneville Dam is located approximately 40 miles upstream of Terminal 6 and represents the upstream extent of the CRNC considered in this study. The CRNC includes several infrastructure components that are also discussed in this section. These include the new lock at Bonneville Dam, seven bridges that provide air clearance for navigation, and the rubble mound jetty at the river mouth.

To access Terminal 6 from downstream, cargo vessels must traverse the navigation channel from the river mouth to the I-5 Bridge. Similarly, to deliver emergency supplies to an FSA at Terminal 6, barges would need to navigate downstream through the Bonneville Lock. Therefore, the navigation channel is a critical component that must remain functional in order to maintain both throughput capacity and the readiness and ability to support an FSA at Terminal 6. Seismic events could obstruct the navigation channel in several ways. Geologic material adjacent to the channel could fall into the dredged void. Bridges that provide air clearance for navigation could collapse into the channel. The rubble mound jetty at the river mouth could be damaged, reducing navigability of the channel entrance. These damages could be caused by ground shaking, ground deformation, or a tsunami.

Partial obstruction of the channel would certainly make navigation in the channel more difficult. However, only total obstruction of the channel would prevent the passage of deep draft vessels or barges. The possibility that a seismic event would fully obstruct the channel by causing geologic material from adjacent portions of the riverbed to slide into the channel was judged to be negligible because the ratio of the height of the channel embankments to the width of the channel is very low. Channel reaches between Astoria, Oregon and the river mouth are located within the tsunami affected zone and could accumulate debris, but presently there is no way to predict how much debris would accumulate or whether the passage of deep draft vessels would be blocked. Other authors have explored more extreme scenarios, such as a large scale collapse of the canyon walls into the river (Wang and Scofield 2003). These risks do exist, but their probability is very low. Neglecting such extreme scenarios will not interfere with the demonstration of the resilience assessment methodology.

The Columbia River Bar along with several other locations in the Pacific Northwest, are known collectively as the Graveyard of the Pacific. A large number of vessels have sunk while attempting to cross the Columbia River Bar. The U.S. Army Corps of Engineers constructed the jetty to improve navigability over the bar by arresting cross currents and to reduce the need for dredging by improving sediment transport. The south jetty was originally built in 1884 and the north jetty was added in 1914. Seismic activity, including a tsunami, could damage the jetty and reduce its effectiveness. In a study of vessel transits at several river entrances including the Columbia River, Young and Scully (2018) demonstrated that it is possible to quantify the contribution of jetties to the maneuverability of vessels. The authors conclude that improvements in navigability are statistically significant. However, damaged jetties can continue to improve navigability as long as the channel remains stable (Oliver 1997, Goda 2010 in Young and Scully 2018). For example, while a damaged jetty may allow greater transmission of wave energy during wave conditions exceeding the 6-month return period, it may be that vessels avoid crossing the bar in such bad weather (Young and Scully 2018). While the jetty improves navigability at the river entrance, damage to the jetty would not prevent access to the terminal or reduce throughput capacity at Terminal 6. Therefore, the jetty has not been included here as a critical infrastructure component.

Bridges that provide air clearance for vessels navigating the CRNC have been included as CIC. The Astoria-Megler and Lewis and Clark bridges cross the navigation channel at Astoria, OR and Longview, WA, respectively. Upstream of the terminal, five bridges cross the channel. A Burlington Northern railroad bridge crosses the channel about three miles upstream of Terminal 6. About one mile upstream of the railroad bridge are two bridges that carry I-5 South and I-5 North. The I-205 bridge crosses the channel at Government Island and the New Lock Swing Bridge crosses the navigation channel at Bonneville Lock and Dam. The swing bridge provides access to Bonneville Dam from the south side of the river. The bridge swings open to allow towboats with flying bridges to pass through the lock chamber. Failure of the bridges mechanical features while the bridge is in the closed position could prevent towboats from passing through the lock.

The pool above Bonneville Dam is maintained by the dam and the miter gates of two navigation locks. The older of the two is abandoned in place. Presently, its upstream and downstream miter gates help to maintain the pool. A permanent concrete stop log structure is planned to replace these miter gates. The new lock is functional. The lock walls have been built to withstand regional seismic activity, but the miter gates and electrical components of the navigation lock are potential points of failure. The power plant at Bonneville Dam has “black start” capability, meaning that it does not require and external source of power to restore operation. However, it is estimated that repair of the lock’s electrical components could take two days to two weeks (Ross Hiner, p.c.). Other authors have considered the possibility of catastrophic dam failure (Wang and Scofield 2003), but a site-specific PSHA (Unruh 2018) indicates that the seismic loads associated with a 9,750 year event at Lower Columbia River Dams (Bonneville, The Dalles, and John Day) would not exceed the loads that these dams were built to withstand. Thus, the probability of catastrophic dam failure is regarded as extremely low.

1.4 Alternatives for Strengthening Resilience

The alternatives for strengthening resilience addressed in this report have been developed for demonstration purposes, to illustrate how alternatives could be evaluated using this methodology.

Five alternatives are considered and are summarized in Table 1. These were chosen because the information needed to estimate the impact of each alternative ATC was readily available. Other alternatives for strengthening resilience could be considered, but each would require establishing a nexus to the CIC network used in estimating ATC.

Table 1. Alternatives for Strengthening Resilience.

#	Title	Description
1	SEC	Secure ability to conduct OCR and radiation scans.
2	COMM	Secure ability to track containers and communicate with equipment.
3	ELEC	Seismically retrofit electrical substations and circuits.
4	B603	Seismically retrofit Berth 603 and refurbish the Panamax cranes.
5	NAV	Advance contract for removal of debris from the CRNC.

Security and communications are critical subsystems that are essential to operation of the terminal. The SEC and COMM alternatives would secure the ability to maintain these functions so that they would not fail given the occurrence of a seismic load with a 4750-year return period. While it is not clear exactly how that would be done, it could include having hand-held scanners and communication equipment on hand in addition to backup power sources. These alternatives were implemented by ensuring the ability to perfom these functions despite damage to the CIC supporting them.

All of the activities at Terminal 6 are supported by a connection to the electrical grid. ELEC would retrofit electrical substations and circuits to make them more resistant to seismic loads by anchoring the components of those substations and circuits. FEMA's HAZUS MH-2.1 Earthquake Manual contains fragility curves for standard substations and circuits with unanchored components and seismically retrofit substations and circuits with anchored components. This alternative was implemented by substituting standard fragility curves with seismically retrofit fragility curves.

Container yard wharfs at Berths 604 and 605 have been seismically retrofit to increase their robustness to ground deformation. The B603 alternative would increase the robustness of the wharf at Berth 603 to the same level as that at Berths 604 and 605 and would restore the functionality of the Panamax cranes. Seismic retrofits to container wharfs are represented by adjusting the parameters of HAZUS fragility curves for waterfront structures so that they were more robust to more severe seismic loads and had a higher probability of remaining functional given a 2475-year load.

Navigation in the Columbia River could be disrupted by the collapse of one or more bridges into the CRNC. Removing the bridges from the channel would require a contract with an industrial salvage company. Contracting is a lengthy process and establishing a contract from scratch would require considerable lead time. For example, the Diane, a 45-foot recreational tug caught fire, sank, and was abandoned in the channel below Bonneville Dam in 2017. Although it was declared a hazard to navigation, it required approximately eighteen months to contract with a salvage company to remove the vessel. The navigation alternative, NAV, is implemented by eliminating the contracting lead time that has been built into the navigation recovery function.

METHODOLOGY

The several steps for assessing the seismic resilience of a navigation terminal are described here. A probabilistic seismic hazard analysis (PSHA) was used to estimate the probability and severity of seismic loads, including ground shaking and ground deformation. CIC are identified and functions are developed to estimate ATC given information about the functional state of CIC. ATC decreases as more CIC become non-functional. Uncertainty in ATC was simulated using Monte Carlo simulation. The simulation accounted for uncertainty in the seismic loads, the uncertain response of CIC to the seismic loads, and uncertainty in the length of time to restore the functional performance of CIC given its damage state. The probabilities of CIC damage states are calculated using seismic fragility curves from FEMA's multi-hazard loss estimation methodology as described in the HAZUS MH-2.1 Technical Manual: Earthquake Model (FEMA n.d.). The functionality of each infrastructure component was inferred from the description of the damage state and probabilistic restoration functions are used to estimate the length of time required to restore each CIC given its damage state. ATC increases over time as CIC are restored following a seismic event and ATC is calculated at points in time over a one-year restoration period following each event.

Probabilistic Seismic Hazards Analysis

A probabilistic seismic hazard analysis (PSHA) was undertaken to characterize the probability and severity of seismic loads potentially affecting Terminal 6 and the Astoria-Megler Bridge. This analysis considers all of the potential sources of seismic activity in the region and accounts for the distance to those sources and uncertainty in the magnitude of energy potentially released from those sources. Details of the methods used in this analysis are summarized in Appendix C.1, as are estimates of the seismic loads at Terminal 6 and the Astoria-Megler Bridge. Seismic loads were estimated for six nominal return periods: 72, 225, 475, 975, 2475, and 4750 years. A return period is the average length of time between years with seismic loads of a given severity. For example, years in which the worst seismic load to be observed are associated with the 475-year return period occur, on average, once every 475 years. Seismic loads associated with higher return periods are more severe and occur less often.

Return periods were discretized into six intervals (Table 2) so that a probability distribution could be constructed for severity. The midpoint of each interval is the nominal return period, r, and the lower and upper bounds of each interval midway between the next lower or higher return period, respectively. For discrete return period intervals, r is the midpoint and $r_L \leq r < r_U$, where the subscripts L and U represent the lower and upper bounds, respectively. The probability of each discrete return period interval is $p(r_L \leq r < r_U) = r_U^{-1} - r_L^{-1}$. The 72-year return period is the minimum return period and is associated with seismic loads that are sufficiently low that they would not be expected to cause damage to infrastructure or interfere with operations at Terminal 6.

Table 2. Discrete Return Period Intervals and their Probabilities.

Return Period Interval			Probability, $\boldsymbol{p(R = r)}$
Lower Bound (*L*)	Nominal Return Period	Upper Bound (UB)	
1	72	148.5	0.993266
148.5	225	350	3.876×10^{-3}
350	475	725	1.477×10^{-3}
725	975	1725	7.99×10^{-4}
1725	2475	3612.5	3.02×10^{-4}
3612.5	4750	∞	2.75×10^{-4}

Annual Throughput Capacity (ATC)

A wide variety of metrics are available for describing the capacity, relative efficiency, and performance of seaports (Bassan 2007, Bureau of Transportation Statistics 2018, Montfort 2011, Lagoudis and Rice n.d., Soberon 2012). The cargo handling capacity of a terminal can be expressed in terms of static capacity or throughput. Static capacity is the volume of cargo a port can handle at a given point in time and is a function of the amount of space and resources available. Throughput capacity is the volume of cargo a port can process over a period of time. It depends on operational parameters that reflect labor skill and technology as well as the space and resources available (Lagoudis and Rice, n.d.). Maximum ATC is the maximum amount of cargo that can be processed over the period of one year assuming all CIC are functional and given certain operating parameters. Seismic loads have the potential to reduce throughput capacity by damaging CIC, causing them to become non-functional. When CIC are damaged by seismic loads, ATC is reduced until these components can be restored.

The effect of seismic loads on cargo handling capability at Terminal 6 is described through a model that relates ATC to the functionality of CIC through a set of operating parameters. Operating parameters include factors such as mean container stacking height, crane availability, the average number of days required to load a train, or the average number of cars loaded on a rail car. These factors reflect labor skill and technology of the operator as well as technological or operating constraints that may be beyond the control of the operator. Ideally, the operating parameters used in this study would be based on observations at the terminal. However, it was not possible to observe container operations at Terminal 6 because they were suspended in 2014 and at the time of this study. Therefore, the operating parameters used in this study reflect industry averages and critically reasoned estimates.

The operating parameters used in the model are constants. They do not change in response to changes in the combination of CIC that are functional. Therefore, a limitation of the model is that it does not describe how a terminal operator might modify its operations or adapt to changes in the combination of CIC available to process cargo. For example, container storage requires level pavement on which to stack containers. If a seismic event caused ground deformation severe enough to reduce container storage area, one would expect an increase in mean stack height, an increase in the number of container moves required to process each container, and an increase in container dwell time. However, there is insufficient information about operations at Terminal 6 to describe how much container dwell time might change given a change in mean stack height, or how the operator might adapt to changes in container storage area. Therefore, treating operating parameters as constants may lead to underestimates of throughput capacity given resource constraints.

The estimates of throughput capacity developed in this study appear reasonable and compare well with historical throughput statistics at the terminal. Nevertheless, these throughput capacity estimates might best be interpreted in relative terms, to compare one outcome to another, rather than in absolute terms. In addition, throughput capacity should not be interpreted as a measure of performance. A measure of performance would describe how efficiently the terminal processed a given volume of containers relative to how efficiently it could have processed that volume of containers. This model does not describe how a terminal operator might adjust its operating parameters to compensate for a change in the availability of infrastructure components. Therefore, it does not describe performance.

Container throughput capacity is the maximum number of twenty-equivalent units (TEUs) that can be processed through the facility in the period of one year. An annualized measure of throughput capacity is needed for comparison to historical records of throughput, which are expressed in TEUs/year. While this metric is annualized, it is not limited to year over year comparisons. It can also be used to make relative comparisons of the throughput capacity under different scenarios that describe the functionality of CIC at different points in time.

2.2.1 Estimation of Maximum Annual Throughput Capacity (ATC)

The container yard ATC is estimated by finding the minimum throughput capacity of three potential bottlenecks in the container handling process: 1) the transfer of containers to and from vessels by STS gantry cranes, 2) the storage and tracking of containers in the container yard, and 3) the transfer of containers to road and rail. As the process of transferring containers to and from the container storage yard is generally not a factor limiting throughput capacity (Soberon 2012), this process is not considered. The terminal's container throughput capacity, C_{MAX}, is the minimum of the three potentially limiting throughput capacities:

$$C_{MAX} = MIN(C_{STS}, C_{CY}, C_I).$$

Where C_{STS} is throughput capacity of the STS gantry crane system, C_{CY} is the throughput capacity of the container storage yard, and C_I is the intermodal throughput capacity, which is the sum of intermodal road and rail throughput capacities, $C_I = C_{I_{Road}} + C_{I_{Rail}}$.

Throughput capacity of the STS gantry crane system can be estimated as follows:

$$C_{STS} = \sum_{\omega \in \Omega} h\alpha(1-\beta)\tau_{1_\omega} c_\omega.$$

h is annual operating hours and crane availability, α, is the fraction of time the crane is available to allow for maintenance and repair. A study of working terminals in Busan, South Korea, found that gantry cranes were available 95% of the time (Jo and Kim 2020). β is the container transshipment rate, which is the proportion of containers that are offloaded from one cargo vessel, stored at the terminal, and loaded onto another cargo vessel. A nominal transshipment rate of β = 0.10 was chosen for this study. τ_1 is the twin-pick rate, c_ω is the number of cycles per hour for crane ω, and Ω is the set of operational cranes. Modern cranes are equipped with spreaders that enable them to lift two containers at a time, and the twin pick rate is the average number of containers in each lift. The term $\tau_{1_k} c_k$ is the productivity of crane ω in TEUs/hour. Crane productivity was estimated from data on the travelling speed of each crane and the distance travelled during each cycle, from the vessel to the wharf and back to the vessel. Estimated cycle times range from 2.39 minutes for the post-Panamax cranes to 3.28 minutes for the Panamax cranes. Post-Panamax cranes have twin pick capability and a twin pick rate of τ_{1_ω} = 1.7 containers per cycle, this yields estimates of crane productivity as summarized in Table 3. The Panamax cranes do not have twin-pick capability, so their productivities are much lower than the post-Panamax cranes.

Table 3: Crane productivity (TEUs/hour).

	Panamax Cranes			**Post-Panamax Cranes**			
	373	374	375	378	379	380	381
Productivity (TEU's/hour)	18.3	18.3	18.3	36.2	34.4	42.6	42.6

ATC of the container yard depends on the number ground slots that are available, the mean height of container stacks, and dwell time. It can be calculated as follows (Soberon 2012, Lagoudis and Rice, n.d.):

$$C_Y = \frac{365}{T_{Dwell}} \eta N_{Slots}.$$

The ratio 365/T_{Dwell} is the average number of container turnovers per year, where 365 is the number days per calendar year and T_{Dwell} is the container dwell time in days. η is the mean operational stack height and N_{Slots} is the number of container ground slots available in the container yard. A nominal value of $T_{Dwell} = 7$ is used for container dwell time. This is based on industry statistics, which suggest that container dwell times at large ports range from five to seven days for imported containers and three to five days for exported containers (Merk 2013). However, the average dwell time of a container at Los-Angeles and Long Beach, California is two to three days and shippers incur demurrage costs when containers remain for more than four days (JOC 2016). A nominal mean stack height of two is assumed for non-refrigerated containers. There are a total of 4,354 non-refrigerated container ground slots in CY604, CY605, and CY606 (Table 4). For refrigerated containers, a mean operational stack height of 1.58 is based on the ratio of electrical outlets to refrigerated container slots. There are 395 refrigerated container ground slots in CY604 and CY605, with 40 of those in CY604 designated for cleaning. Refrigerated container slots are served by 626 electrical outlets.

Table 4: Container Ground Slots by Container Yard.

Container Yard	**Non-refrigerated Ground Slots** (Number)	**Refrigerated Ground Slots** (Number)
CY603	-	-
CY604	909	291
CY605	1,692	104
CY606	1,753	-
Total	4,354	395

Container transfers to road and rail networks are also potentially limiting. The intermodal ATC is the sum of ATC for road and rail, which are derived separately. The ATC of the intermodal railyard is:

$$C_{I_{Rail}} = \rho d C_S.$$

Where, C_S is the static capacity of loadable rail, ρ is the number rotations per day, or the number of trains that can be loaded in a single day, and d is the number of operating days. The static capacity of the railyard is estimated from the length of loadable track, 18,586 feet. If the average overall length of a double stack rail car is 75 feet, then about 248 rail cars can occupy the container railyard at any given time. Each railcar holds 4 TEUs. Therefore, the maximum static capacity of the container intermodal railyard is 992 TEUs. It is assumed that two days would be required to stage and load/offload containers in the railyard ($\rho = 0.5$). Residual ATC is proportional to the fraction of loadable rail segments in the container railyard that remain functional and are accessible from the railroad entrance at the boundary of the terminal.

Estimates of the maximum ATC for container transfers to the road network are based on the understanding that the OCR sheds at Terminal 6 form two bottlenecks. All road trucks must pass through an OCR shed and complete a radiation check upon entering and exiting the terminal. Therefore, the maximum throughput capacity can be estimated from the average time it takes for a truck to cycle through the OCR shed and radiation scan. The maximum throughput capacity of the intermodal function can be estimated as follows:

$$C_{I_{Road}} = h\tau_2 C_{OCR}.$$

Where C_{OCR} is the capacity of the OCR shed and radiation scan in trailers per hour, h is annual working hours, and τ_2 is the number of TEUs per trailer. Industry materials suggest the latest radiation scanners can scan 70-80 trailers/hour. A conservative capacity of 60 trailers/hour is assumed for the OCRs at Terminal 6. If the number of TEUs/trailer, τ_2, is 1.75 TEUs/trailer, then each OCR shed has a throughput capacity of 105 TEUs/hour. The residual ATC for road truck transfers is proportional to the fraction of container storage yard pavement that remains functional provided that both of the OCR sheds remain functional.

Operating Parameters for Annual Throughput Capacity Estimation

The estimate of ATC at Terminal 6 requires the specification of operating parameters. Operating parameters used in this study are summarized in Table 5. Since the terminal is not currently in operation, the parameters used in this study reflect industry averages or critically reasoned estimates. It is assumed that the container yard would operate on two eight hour shifts five days a week for 52 weeks each year. Therefore, all estimates are predicated on the assumption that the annual number of working hours, *h*, is 4,160 and the annual number of working days in 270.

Table 5. Summary of Operating Parameters for the Container Yard.

Symbol	Description	Value
h	Annual working hours (hours/year).	4,160
d	Number of operating days per year (days/year).	270
α	Crane availability rate.	0.95
β	Transshipment rate.	0.10
τ_1	Twin pick rate for Post-Panamax cranes.	1.7
c	Lifts per hour (moves/hour)	*Varies*
p	Container productivity (TEUs/hour).	See Table 2
η	Mean operational stack height (containers).	2
T_{Dwell}	Container dwell time (days).	7
ρ	Number of trains that can be loaded or offloaded in a single day.	0.5
τ_2	Number of TEUs per road truck trailer.	1.75

Monte Carlo Simulation of Relative Residual Annual Throughput Capacity (ATC)

Damage to infrastructure components can be caused by ground shaking or ground deformation. The severity of ground shaking is expressed in terms of peak ground acceleration (PGA) and the severity of ground deformation is expressed in terms of peak ground deformation (PGD). Seismic events with higher return periods have lower probabilities of occurrence and are associated with higher PGAs and PGDs. PSHA was used to estimate PGA and PGD at Terminal 6 (Appendix 1). For every return period, PSHA yields one estimate of PGA for every return period and twenty-four potential estimates of PGD. Which estimate of PGD is valid for a given location and structure within the terminal depends upon additional information about the source of the seismic event and whether or not it causes liquefaction to occur at that location. Liquefaction occurs when ground shaking causes soils to behave more like a liquid than a solid. Liquefaction is less likely to occur in stiffer soils. The stiffness of soils is described by a random variable called site class.

PGD is the maximum amount of ground deformation that can be expected to occur at a location within Terminal 6 given the source of the seismic load and the site class of the structure or location in question. Over larger areas such as Terminal 6, the amount of ground deformation that actually occurs at any one location will vary, and in most cases, this will be much less than PGD. This resilience assessment accounts for this variability in ground deformation within the terminal. Variability in local ground deformation (LGD) was represented by overlaying a one-acre grid across the terminal and, for each realization of the Monte Carlo simulation, a value for ground deformation was sampled from a lognormal distribution in each grid cell. This distribution was assigned the parameters $m_{LGD} = 0.1 \cdot PGD$ and $\sigma_{LGD} = \exp(1.175)$. In general, this produced distributions with 95th percentiles that approximated the estimate of PGD. A distribution for site class was proposed based on information from boring logs described in HNTB (2015). Each grid cell has a 60% probability of being in site class D and a 40% probability of being in site class D/E. However, those infrastructure components that are founded on piles were assigned a site class of B because they are less susceptible to damage from liquefaction.

Component Damage States

Uncertainty in CIC damage states was simulated using fragility curves from FEMA's HAZUS MH-2.1 Earthquake Manual (FEMA n.d.). Fragility functions describe the probability that an infrastructure component will be in a particular damage state given that it is subjected to a seismic load. The condition of each component is described either by the absence of damage or by one of four damage states: "Slight," "Moderate," "Extensive," or "Complete."

HAZUS fragility curves are lognormal probability distributions defined for each type of infrastructure component, each potential damage state, and each type of seismic load, depending upon the sensitivity of the component to those loads. The lognormal probability distribution estimates the probability that a CIC is in a damage state greater than or equal to the damage state s_{ij}, given the seismic load, x_j:

$$p[S \geq s_{ij}|x_j] = \Phi\left[\frac{1}{\beta_{s_{ij}}} \cdot ln\left(\frac{x_j}{m_{x_j,s_{ij}}}\right)\right].$$

Where Φ is the cumulative standard normal distribution function. $m_{x,s_{ij}}$ is the median of the distribution for damage state *i* and seismic load *j*. $\beta_{s_{ij}}$ is the standard deviation of the natural logarithm of x_j: $\beta_{s_{ij}} = \sigma_{ln(x)}$. Component damage states and the parameters of each fragility curve are summarized in Appendix C.2. Table A2.1 describes damage states. Table A2.2 lists parameters of fragility curves for infrastructure components sensitive to acceleration, or ground shaking. Table A2.3 lists parameters of fragility curves for infrastructure components sensitive to drift, or ground deformation.

The probability that a particular component is in damage state *i* is the difference between the probability of being in a state greater than or equal to *i* and the probability of being in the next highest damage state:

$$p[S = s_{ij}|x] = p[S \geq s_{ij}|x] - p[S \geq s_{i+1,j}|x].$$

STS gantry cranes and bridges are sensitive to both ground shaking and ground deformation. For these components, the probabilities of damage states are calculated separately and a probability for the combined damage state is calculated assuming the two seismic loads are acting independently to damage the structure:

$$p[S = s_i] = \sum_j p[S = s_{ij}|x_j] - \prod_j p[S = s_{ij}|x_j].$$

Some components may remain undamaged given the seismic load. The probability that a component remains undamaged is calculated from the sum of the probabilities over all potential damage states greater than “None:”

$$p[S = None] = 1 - \sum_{i>None} p[S = s_i].$$

For each realization of the Monte Carlo simulation, the state of each CIC is sampled from a discrete distribution with a domain over all potential damage states, including “None.” The parameters of this discrete distribution correspond to the calculated probabilities of damage states given the seismic loads for that realization of the Monte Carlo simulation in the grid cell where each component is located.

For those components that span multiple grid cells and are sensitive to ground deformation, a single value of LGD was needed to estimate damage state probabilities. For structures founded on piles, such as wharves, the maximum LGD in each of the grid cells encompassed by the structure was used. For cranes, the mean LGD in those grid cells encompassing the wharf on which each crane is principally located was used. For those structures that are built on foundations, the mean LGD was calculated over grid cells encompassed by that structure. Railroad tracks were decomposed into a network of 59 rail segments, with nodes representing intersections and links between nodes representing the segment. Each segment spanned one or more grid cells and the maximum LGD in those grid cells intersected by each segment was used to calculate damage state probabilities for that segment. For each bridge, a single value of LGD was sampled to represent ground deformation at the location where each bridge crosses the navigation channel.

Component Function States

For each realization of the Monte Carlo simulation, the function state of each CIC is determined from its damage state as described in Appendix C.2 (Table A2.1). The function state is ‘F’ if the CIC remains functional given the damage and ‘NF’ otherwise. Electrical circuits present an exception to this rule. The damage states for electrical circuits in HAZUS MH-2.1 describe the fraction of circuits that have failed for the system as a whole rather than the damage state of an individual circuit. Therefore, a damage state for the system was first sampled given the seismic load, and then, for each damage state from Slight to Complete, a fraction of failed circuits was sampled from a uniform distribution corresponding to that damage state (Table A2.1). The bounds of the uniform distribution corresponded to HAZUS lower bound of failed circuits for that damage state and the lower bound of HAZUS interval for the next highest damage state. This fraction of circuits failed was then used as the parameter of a Bernoulli distribution, which was sampled to determine the functional state (F or NF) of each circuit.

This analysis accounts for the dependencies among networked infrastructure components. Therefore, the functionality of CIC may also depend on the functionality of other CIC. For example, downstream electrical circuits that distribute power at the terminal remain functional if and only if an uninterrupted pathway to the electrical grid at the boundary of Terminal 6 remains functional. These functional dependencies are described in Figure 2. A similar type of dependence analysis was used to estimate functionality of loadable rail segments. Each segment remains functional if and only if all of the rail segments that provide an uninterrupted pathway between that segment and the railway entrance on the southeastern boundary of the terminal remain functional.

Component Restoration Times

Restoration functions describe the time required to restore CIC to pre-earthquake usability. The restoration functions used in this study are from FEMAs HAZUS MH-2.1 Earthquake Manual, which adopted estimates from ATC-13 (ATC 1985), a report prepared by the Applied Technology Council (ATC) entitled Earthquake Damage Evaluation Data for California. Restoration functions are normal distribution functions defined by the parameters summarized in Appendix C.2, Table A2.4. The table also shows the probability that each type of component would be restored at select times between 1 and 365 days after a seismic event.

Applied to individual CIC, restoration functions describe the probability that CIC is restored within t days following the seismic event given its damage state. A restoration time is sampled from the restoration function for each realization of the Monte Carlo simulation. Applied to sub-systems with distributed components, such as pavement and rail networks, restoration functions describe the fraction of the sub-system that remains functional as a function of the restoration time. For each iteration of the Monte Carlo simulation, a damage state was calculated for each acre of paved area and each rail segment. The damage state of the sub-system was obtained by calculating the fraction of paved area or rail segments remaining functional. The restoration time for the sub-system was then calculated as the difference between the time at which 99 percent of the system would be restored and the time that fraction would be restored. It should be noted that the HAZUS MH-2.1 Earthquake Manual describes only three damage states for railroad tracks (Slight, Moderate, and Extensive/Complete), but provides railroad track restoration functions for four damage states (Slight, Moderate, Extensive, and Complete). If the damage to the rail system was classified as "Extensive/Complete," a restoration time was sampled from the restoration function for the "Complete" damage state.

Recovery Trajectories

Recovery trajectories were simulated by estimating relative residual ATC at points in time during a one year restoration period following the seismic event, determining which CIC were functional, and calculating ATC at that point in time. Relative residual ATC is the fraction of maximum ATC remaining at a point in time during the restoration period given the function state or availability of each CIC:

$$M(t)_{kr} = \frac{C(t)_{kr}}{C_{MAX}}$$

The numerator $C(t)_{kr}$ is the residual ATC at time t following an event with return period r for the k^{th} Monte Carlo realization, and C_{MAX} is the maximum ATC given no damage to CIC. $M(t)_{kr}$ is the dimensionless capacity metric, which is the residual fraction of throughput capacity under damage scenario k. Relative residual ATC increases following the seismic event as damaged CIC are restored during the restoration period. Many realizations of the recovery trajectories were obtained by sampling damage states and restoration times from probability distributions using a median Latin hypercube sampling algorithm and a sample size of 2500 realizations. This sample size produced convergence of the mean and variance of the expected benefits of resilience strengthening alternatives, which suggests an adequate sample size (Ballio and Guadagnini 2004).

Status Quo Resilience

The resilience metric describes the residual fraction of ATC over a one-year restoration period following the disturbance. It is calculated for each realization of the Monte Carlo simulation by aggregating residual ATC over the restoration period and then dividing by the length of the restoration period. Under status quo conditions, A_0, the resilience of the container yard function to seismic loads of a given return period r can be calculated for the k^{th} realization of the recovery trajectory as follows:

$$E\left[M_{A_0} \middle| R = r\right]_k = \frac{1}{T} \cdot \sum_{t=0}^{T} M_{A_0}(t)_{kr}.$$

$M_{A_0}(t)_{kr}$ is the recovery trajectory for return period r and the k^{th} realization of the Monte Carlo simulation under the status quo. The conditional resilience metric describes the expected fraction of maximum ATC retained over the restoration period given the occurrence of a seismic load with return period r.

Another resilience metric can be calculated to describe overall resilience to seismic hazards that are potentially damaging. For each realization of the simulation, k, an expected resilience given the occurrence of a seismic load with a return period greater than the minimal return period is calculated as the weighted sum of conditional resilience metrics:

$$E\left[M_{A_0}|R > r_{min}\right]_k = \sum_{r>r_{min}}^{R} \frac{p(R=r)}{p(r>r_{min})} \cdot E\left[M_{A_0}|R = r\right]_k.$$

The weights are the ratio of return period probabilities divided by the probability of a seismic load greater than the minimal return period. The summation is over all return periods greater than r_{min}, $R > r_{min}$. This metric can be interpreted as an overall measure of the expected resilience to potentially damaging seismic events under the status quo.

Benefits of Resilience Strengthening Alternatives

The benefit of implementing an alternative is the potential increase in residual ATC relative to the status quo. Given a seismic load of return period r, the conditional benefit of an alternative, A, is the average difference in the recovery trajectory given that alternative and the recovery trajectory given the status quo over the restoration period, T:

$$E[B_A|R = r]_k = \frac{1}{T} \cdot \sum_{t=1}^{T} \left(M_A(t)_r - M_{A_0}(t)_r\right)_{kt}.$$

The differences are aggregated over the restoration period and averaged over T (Figure 3). t is an index of days during the restoration period and $T = 365$. Dividing by T yields the fraction of maximum ATC recovered over the one-year restoration period. This conditional expected benefit estimate can be converted to TEUs by multiplying it by the maximum ATC in the container yard. It describes the number of TEUs recovered by implementing the alternative over a one year period compared to the status quo for the k^{th} realization of the Monte Carlo simulation.

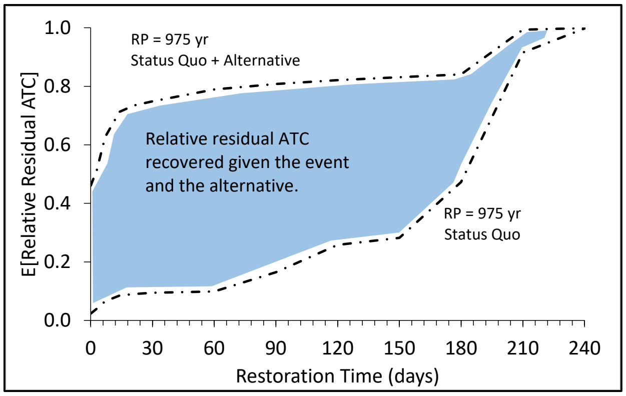

Figure 3: Resilience Benefit of an Alternative Given a 975-year Seismic Load.

Costs and benefits of infrastructure investments are typically evaluated over a planning horizon that spans many years and reflects the life of that investment. Similarly, it is important to consider the length of the planning horizon when evaluating the benefits of investments in resilience strengthening alternatives. The reason is that the benefits of implementing an alternative are a function of the number of times that the events of severity r occur during the investment horizon.

Given y occurrences of seismic loads with return period r, y_r, over an n-year planning horizon, the total resilience benefit realized by implementing alternative A with respect to events of severity r are proportional to y_r:

$$b_{Akry} = y_r \cdot E[B_A|R = r]_k.$$

For example, if two 975-year loads were to occur over a 30-year period, the benefits of the investment in alternative A given a 975-year load would be realized twice. Similarly, if four 975-year events were to occur over the same 30-year period, that benefit would be realized four times. In the latter case, the benefit realized from the investment is twice as high as if there had been only two occurrences of the 975-year load.

It is important to account for the number of events that could occur over the planning horizon because some alternatives are more effective at mitigating damages caused by seismic loads with low or moderate return periods and others are more effective at mitigating damages caused by seismic loads with longer return periods. Over an n-year planning horizon, seismic loads with shorter return periods are more likely to occur multiple times than seismic loads with longer return periods. Over an n-year planning horizon, the probability of y occurrences of an event with severity r is a function of the probability of the event, r. Assuming independence of seismic loads from year to year, the probability that y events of return period r occur during the n-year planning horizon can be calculated using the binomial probability distribution function:

$$p(Y = y|R = r) = \binom{n}{y} p(R = r)^y \big(1 - p(R = r)\big)^{n-y}.$$

The probabilities of realizing some number of occurrences of the seismic loads associated with each return period over 30 years are shown in Figure 4. Over a 30-year investment horizon, the probability of realizing multiple 72-year events increases from zero to 30 occurrences while the probability of realizing 0 to 30 occurrences of seismic loads with longer return periods decreases. The higher the return period, the faster that probability decreases. There is an 81.1% chance that, over a 30-year period, no seismic loads greater than those associated with the minimal return period would affect Terminal 6. If that occurred, no benefits would be realized from the investment.

The implication is that the expected benefit of an alternative must be calculated from a joint probability distribution over the return period and the number of occurrences of seismic loads for each return period over the planning horizon. The joint probability of realizing y events of return period r over the n-year planning horizon is:

$$p_{YR}(y, r) = p(Y = y|R = r) \cdot p(R = r).$$

The expected benefit of an alternative can be calculated for the k^{th} realization of the Monte Carlo simulation:

$$E[B_A]_k = \textstyle\sum_Y \sum_R p_{YR}(y, r) \cdot b_{Akry}.$$

$E[B_A]_k$ is a dimensionless value representing the fraction of maximum ATC recovered by the alternative over a one year period. As above, an overall expected benefit, $E[B_A]$, for the simulation can be calculated by averaging over all Monte Carlo realizations. These benefit estimates can be expressed in terms of TEUs/year by multiplying them by maximum ATC.

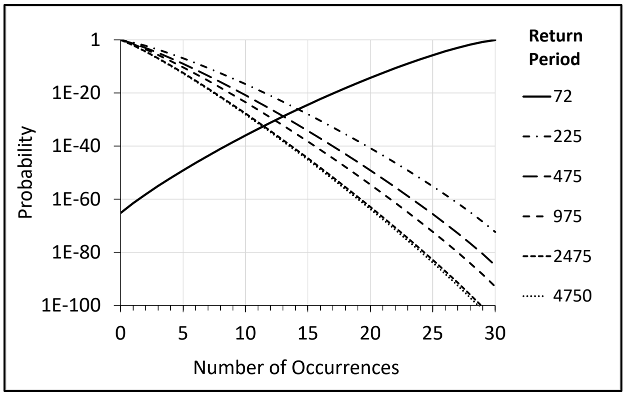

Figure 4: Probability of Realizing 0-30 Events of Return Period r over 30 Years.

2.3.7 Bayesian Network for Resilience Assessment

A Bayesian network is a directed acyclic graph designed for probabilistic reasoning about a system (Pearl 1988; Kjaerulfff and Madsen 2008). The nodes of a Bayesian network represent random variables and the edges between nodes signify direct dependence between two variables. Bayesian networks offer a natural way to model the dependence among the components of an infrastructure system and there are several advantages to using them for resilience assessment (Schultz and Smith 2016, Kameshwar et al. 2019). The dependence relationships among random variables are transparent and probabilistic inferences about the system are easy to make. Extensive post-processing of numerical simulation results would be required to make the same kinds of probabilistic inferences that are readily available from the Bayesian network. The disadvantage of a Bayesian network over a numerical simulation is that all of the variables must be discretized and the results can be sensitive to this discretization (Barton et al. 2008). Therefore, continuous metrics of resilience and the benefits of resilience strengthening alternatives are estimated from the numerical simulation.

A Bayesian network has been developed to validate the results of numerical simulation. It would not be practical to display the actual Bayesian network in this report. However, the structure of the Bayesian network for a system consisting of two CIC is shown in Figure 5 to illustrate the dependence relationships among random variables. The random variables characterizing the hazard are return period, site class, and liquefaction. The seismic loads are PGA and LGD. CIC damage states depend on seismic loads, and CIC function states and restoration times depend on CIC damage states. With exception of the return period node, the conditional probability tables have not been parameterized, so the probabilities of random variable states are all uniform. The terminal node, RRATC describes the relative residual ATC at a point in time during the restoration period and depends on function state nodes. CIC are either functional (F) or non-functional (NF) depending upon their own damage state and the function state of other CIC upon which they depend. For example, the function state of CIC B is directly dependent on the function state of CIC A. There are many other details specific to this application to Terminal 6. However, this figure represents the transferable structure of the Bayesian network for resilience assessment. It is broadly applicable to many different types of systems.

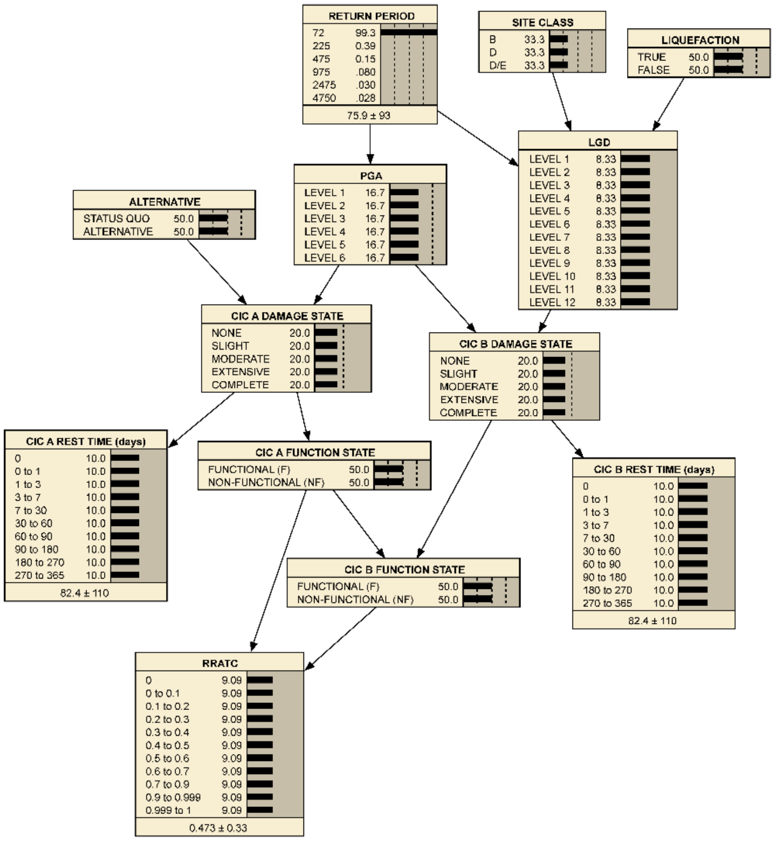

Figure 5: Dependence Relationships in the Bayesian Network.

The Bayesian network was created in Netica® (Norsys Software Corporation, Vancouver, British Columbia). The conditional probability tables for each node were learned from a case file that reported the state of each random variable in the network for each of 10,000 realizations of the Monte Carlo simulation at each return period. The counting algorithm contained in Netica® was used to learn the conditional probability tables from the case file. Learning from the case file produced a uniform conditional probability table for the return period node. The return period node was subsequently parameterized manually with the probabilities of return period intervals (Table 2) to finalize parameterization of the network.

RESULTS

Annual Throughput Capacity

The maximum ATC of the container yard was estimated to be 474,656 TEUs/year and the process limiting ATC was container storage. The ATC for intermodal container transfers was 565,630 TEUs/year and the ATC for ship to shore container transfers was 554,149 TEUs/year. These estimates of maximum ATC are reasonable when compared to statistics of annual throughput at Terminal 6. Historical records of annual throughput were obtained from the Port of Portland. Between 1994 and 2004, container throughput ranged from 250,000 to 350,000 TEUs per year (Figure 6). Throughput dropped off in 2005 and, from 2005 to 2014, container volumes ranged from 150,000 to 250,000 TEUs/year. There was very little container throughput at the terminal between 2014 and 2020. Container terminal operations resumed under a new operator in 2021.

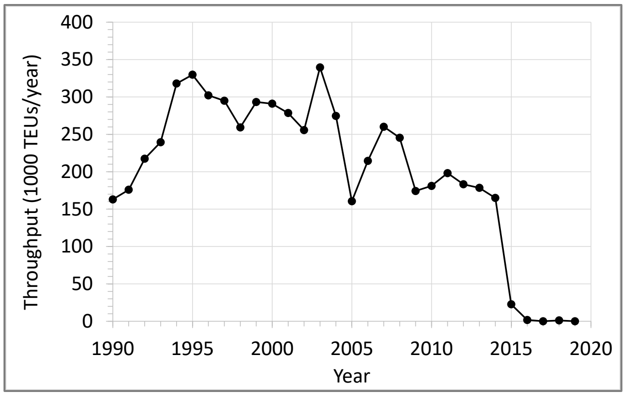

Figure 6. Actual Container Throughput (TEUs/year) at Terminal 6, 1990-2019.

Status Quo Resilience

The outputs of the simulation are a set of recovery trajectories for each return period and Monte Carlo realization. These results are summarized in Figure 7, which shows the average or expected value of each recovery trajectory given seismic loads of each return period over the first 240 days of the restoration period. Results are not shown for the 72-year return period because it has no effect on operations. Immediately following the seismic event, expected relative residual ATC ranges from 0.72 for the 225-year event to 1×10^{-4} for the 4,750-year event. For all return periods, the expected relative residual ATC increases to 0.99 by day 240 of the restoration period. While the expected relative residual ATC increases to nearly 1, individual realizations of the Monte Carlo simulation may require longer to achieve that level of restoration. However, HAZUS restoration functions indicate that all of the CIC included in this infrastructure network are restored within one year (Table A2.4).

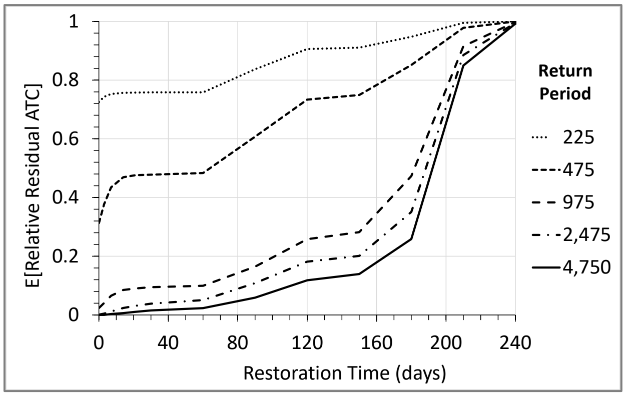

Figure 7. Expected Recovery Trajectories under the Status Quo through Day 240.

Conditional metrics of resilience describe how well the system would perform given the occurrence of a seismic load with return period r. Conditional metrics of resilience for the container terminal are summarized in Table 6. For example, given the occurrence of a seismic load with a 225-year return period, the expected relative residual ATC in the container yard is $E\left[M_{A_0} | R = r\right] = 0.918$, which means that it is expected the terminal could process 91.8% of maximum ATC over the subsequent one-year restoration period. Given a more severe load with a 4,750-year return period, the expected residual ATC is 50.5% over the subsequent one-year restoration period. Overall, the status quo resilience of the container yard to seismic events that might disrupt the transfer of containers between road and rail networks is $E\left[M_{A_0}\right] = 0.817$. Interpreted, this means that, given the occurrence of a seismic load severe enough to disrupt the transfer of containers between waterways and road or rail networks, the expected residual ATC over the subsequent one-year restoration period is 81.7% of maximum ATC.

Table 6: Expected Resilience to Seismic Loads of Return Period r under the Status Quo.

Return Period, r	**Expected Conditional Resilience,** $E[M_{A_0}\|R=r]$
72	1.000
225	0.918
475	0.803
975	0.571
2475	0.529
4750	0.505

Outcomes of the simulation vary widely from one realization of the Monte Carlo simulation to another. The expected value of the conditional resilience metric provides no window into that uncertainty. The conditional resilience metric is an uncertainty quantity that can be described by an empirical cumulative distribution. Figure 8 plots the cumulative distribution of conditional resilience metrics to describe the variability of those estimates from the Monte Carlo simulation. For example, given a seismic load with a 225-year return period, 25% of the Monte Carlo simulations exhibited resilience metrics between 0.384 and 0.8. Similarly, given a seismic load with a 475-year return period, nearly half of the simulation results indicate that relative residual ATC is less than 0.8 over the one-year restoration period.

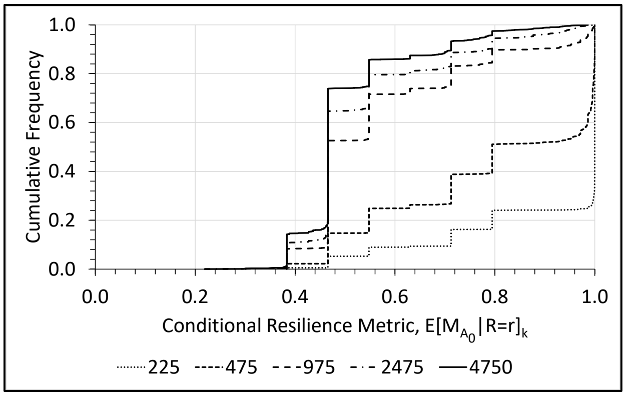

Figure 8: Uncertainty in the Conditional Resilience Metric.

Benefits of Alternatives

The benefit of an alternative is the expected increase in relative residual ATC achieved by implementing that alternative. The first six rows of Table 7 list the expected conditional benefit, $E[M_A|R=r]$, for the SEC and COMM alternatives. The SEC alternative would increase the number of TEUs that can be processed in the year following a seismic load with a 225-year return period an expected 19,549 TEUs. The expected conditional benefit reaches a maximum of 48,529 TEUs given a return period of 975 years. The expected conditional benefit of this alternative decreases given seismic loads that have longer return periods and are more severe. Compared to the SEC alternative, the COMM alternative yields very little benefit. The expected benefit over 30 years, $E[B_A]$, is calculated from the joint probability of realizing between 0 and 30 events of each return period over the 30-year planning horizon. The expected benefits are much lower than the conditional expected values because the probability of realizing multiple seismic events that cause damage to CIC are very low.

Table 7: Benefit of Implementing SEC and COMM (TEUs).

Benefit	**Return Period**	**Alternative**		
		SEC	**COMM**	**SEC & COMM**
Expected conditional benefit, $E\left[M_{A_1 k} \middle\| R=r\right]$	72	0	0	0
	225	19,549	3	38,696
	475	39,230	8	84,979
	975	48,529	45	148,834
	2475	35,487	17	97,752
	4750	24,474	18	71,542
Expected benefit over 30-years, $E[B_A]$		373.8	0.080	788.5

The expected conditional benefits of implementing the SEC and COMM alternatives together (SEC & COMM) are super-additive (Table 7). In other words, the benefit of implementing these alternatives together is greater than the sum of implementing each by itself. Both the security and communications sub-functions are critical for operation of the terminal. Without one or the other, there is no throughput of containers at the terminal. In addition, damages to CIC that support these sub-functions are correlated. When seismic loads damage CIC that support security, they also tend to damage CIC that support communications. Implementing one of the alternatives by itself does relatively little to improve residual ATC because the inability to carry out the other sub-function is still limiting ATC. This can also be seen in Figure 9, which plots relative residual ATC on the *y*-axis and return period on the *x*-axis.

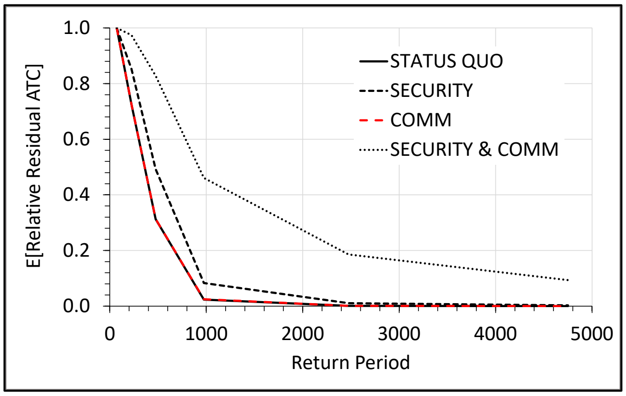

Figure 9: Expected Relative Residual ATC for the SEC and COMM Alternatives.

The expected benefits in Table 7 are themselves uncertain quantities calculated from benefits estimated for each realization of the Monte Carlo simulation, and there is a great deal of variability in these estimates. Uncertainty in the SEC and COMM alternatives is illustrated in Figure 10, which shows the cumulative distribution function for $E[B_A]_k$. There is a 75% chance that expected benefits are less than 1,000 TEUs over the 30-year planning horizon and a 25% chance that expected benefits will be between 1,000 and 5,000 TEUs.

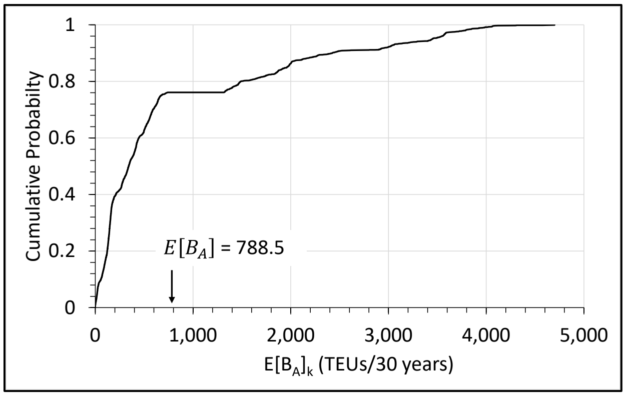

Figure 10: Uncertainty in $E[B_A]$ for SEC & COMM.

The benefits of the remaining alternatives (NAV, ELEC, and B603) are evaluated assuming that SEC & COMM has already been implemented. The estimated benefits in Table 8 are in addition to those that would be expected from implementation of SEC and COMM. Of the three alternatives, NAV yields the greatest benefit, with the greatest benefit being realized for seismic loads with a 4750-year return period. In contrast, ELEC has the lowest benefit and B603 has the second lowest benefit. The benefit of ELEC and B603 are each at a maximum given a seismic load with a 2475-year return period. The last column lists the benefit of implementing all three of these alternatives simultaneously in addition to SEC & COMM. The benefits of these three alternatives are super additive, although this is not as pronounced as for SEC & COMM in Table 7. This lower level of super additivity is attributed to a lower correlation between the damages that are mitigated by each alternative.

Table 8: Benefit of Implementing NAV, ELEC, and B603 (TEUs).

Benefit	**Return Period**	**Alternative in Addition to SEC and COMM**			
		NAV	**ELEC**	**B603**	**ALL**
Expected conditional benefit, $E[M_{A_1k} \mid R = r]$	72	0	0	0	0
	225	465	3	319	787
	475	4,790	24	3,257	8,098
	975	33,644	38	7,982	43,144
	2475	65,803	69	12,010	86,036
	4750	87,459	35	11,007	109,530
Expected benefit over 30 years, $E[B_A]$		46.4	0.112	17.0	65.9

Readiness and Ability to Support a Federal Staging Area (FSA)

The requirements for an FSA are approximately ten acres of hardstand, security, ingress, and egress. Security would be provided by the existing fence around the terminal and ingress and egress would be provided by the ad-hoc barge berth and an access point at Marine Drive. Emergency supplies would be delivered from Eastern Washington by barge. There are at least two scenarios that could interfere with operation of the FSA. Excessive damage to the pavement in the portion of the 606 container yard designated for the FSA could prevent efficient use of the hardstand and one or more bridges collapsed between Bonneville Dam and Terminal 6 could impede the delivery of emergency supplies. It is assumed that the site could be used for an FSA if at least 80% of the hardstand remained functional, defined as less than several inches of ground deformation, and the navigation channel upstream of Terminal 6 remains open. The readiness and ability to support an FSA at Terminal 6 is represented by the probability that these conditions are met. These results are illustrated in Figure 11(a), which shows the probability that the FSA would be functional is 1.0 given a seismic load with a 72-year return period and this decreases to 0.417 given a seismic load with a 2475-year period. Figure 11(b) shows the probability the FSA would be functional after 30 days. This allows time for restoration of much of the pavement. Under the status quo, readiness and ability improve slightly, but the inability to navigate between Bonneville Dam and Terminal 6 is limiting. Figure 11(b) shows that advance contracting for removal of collapsed bridges from the navigation channel significantly improves the probability that an FSA could be established at Terminal 6 following a seismic event.

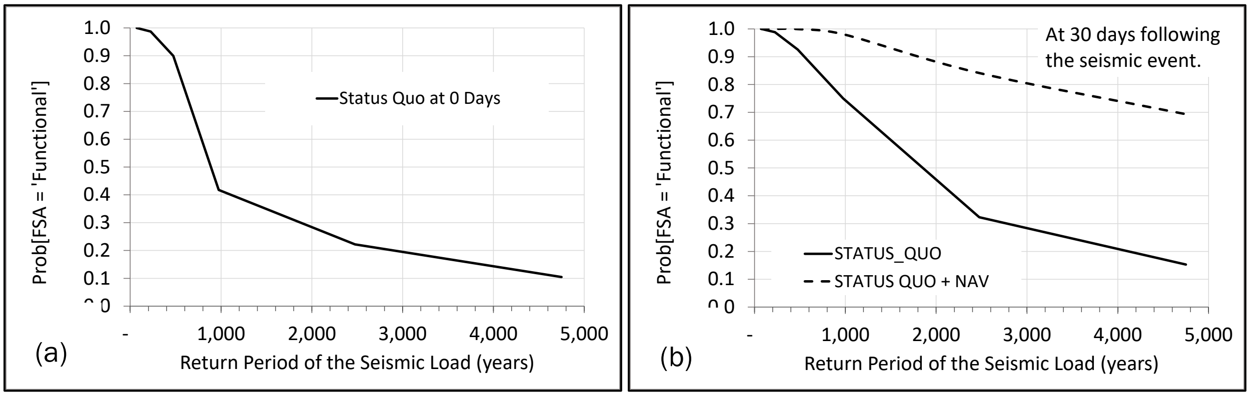

Figure 11: Readiness and ability to support an FSA.

Impact of the FSA on Container Terminal Operations

The presence of an FSA at Terminal 6 would reduce ATC by decreasing the number of container slots available in the 606 container yard. Under the status quo, container storage is the factor limiting ATC. The area that has been designated for the FSA removes 1,120 container ground slots from the inventory, further limiting ATC. Under normal operating conditions, an FSA would reduce ATC by 24.6%. This result is shown in Figure 10, which shows that, under the status quo, without the FSA, the expected relative residual ATC is equal to 1 given a seismic load with a 72-year return period. Under the status quo with the FSA in place, expected residual ATC is 0.754. The 72-year event is the minimal return period and is associated with seismic loads that would not be expected to damage CIC or otherwise interfere with container terminal operations. Therefore, this also describes the impact that an FSA might have if it were established in response to some type of natural disaster other than a seismic event. At higher return periods, expected relative residual ATC decreases, but the FSA has less impact on operations of the terminal because ATC is already being limited by damage to CIC. One alternative for mitigating the impact of the FSA on container terminal operations would be to extend container storage to the 603 container yard (CY603), which is presently used for storage of break bulk cargo. This could add approximately 1,170 ground slots to the inventory and offset any impacts of the FSA on the existing ATC.

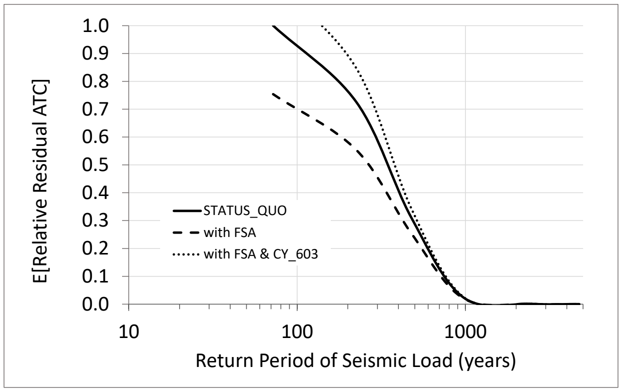

Figure 12: Impact of the FSA on Container Terminal Operations.

DISCUSSION

The seismic resilience of the container yard at the Port of Portland's Terminal 6 has been assessed using a probabilistic network model that describes the dependence relationships among CIC. The terminal is located in a seismically active region and seismic loads may originate from a variety of sources. The model provides a tool for understanding the extent of damage to CIC caused by seismic loads and the effect of those damages in terms of ATC over the restoration period. Monte Carlo simulation is used to propagate uncertainty in CIC damage states and restoration times to estimates of ATC during the restoration period to create many realizations of the recovery trajectory. Metrics of resilience and the potential benefits of measures to strengthen resilience are calculated from the recovery trajectories. The resilience metric is the ratio of residual ATC to maximum ATC aggregated over a one-year restoration period following a seismic event.

Expected conditional resilience is the average value of the resilience metric for seismic loads of a given level of severity, averaged over all realizations of the Monte Carlo simulation (Table 6). Expected conditional resilience is 91.8 for seismic loads with a 225-year return period. This indicates that, given a seismic load with a 225-year return period, the residual capacity over a one-year restoration period is expected to be 91.8% of maximum ATC. Expected resilience decreases to 0.571 for a seismic load with a 975-year return period and decreases further to 0.505 for a seismic load with a 4750-year return period. Steep declines in the resilience metric given loads with shorter return periods indicates that there is a critical dependence on CIC that are highly vulnerable to seismic loads with low severity.

This vulnerability to seismic loads of low to moderate severity can also be seen in the expected recovery trajectories under the status quo (Figure 7). For example, expected relative residual ATC decreases to 0.7 given a seismic load with a 225-year return period and 0.3 given a seismic load of 475-year return period. It is expected that six months would be needed to restore ATC to its pre-disturbance levels. This result reflects the critical dependence of container operations on security and communications, which are relatively fragile sub-systems that have multiple points of failure, including connections to the electrical grid. Simulation results indicate that securing these two functions is essential to improving seismic resilience. The model does not specify how these two functions would be secured. Although these improvements are essential to enhancing the seismic resilience of the container terminal, the measures needed to achieve them do not necessarily need to be expensive or difficult. For example, it may be that these critical dependencies could easily be resolved simply by having mobile OCR and radiation scanners or hand-held communication equipment available along with a backup power source.

Several alternatives for strengthening resilience have been evaluated in terms of their ability to increase relative residual ATC over a one-year restoration period relative to the status quo (Table 1). The expected value of the conditional benefit metric is the average of that metric over all realizations of the Monte Carlo simulation. Given the occurrence of seismic loads, the benefits of the several alternatives appear to be substantial (Tables 7 and 8). For example, given the occurrence of a seismic load with a 975-year return period, implementation of the SEC and COMM alternatives together (SEC & COMM) would increase the number of TEUs that could be processed during the restoration period by an expected 148,834 TEUs (Table 7). This is 30% of maximum ATC, suggesting that these two alternatives are highly effective.

SEC & COMM should be implemented before the other alternatives because these subsystems are critical to operation of the terminal and vulnerable to seismic loads of lower severity. Without these two alternatives in place, the benefits of NAV, ELEC, and B603 are minimal. Therefore, the benefits of NAV, ELEC, and B603 were estimated with SEC & COMM (Table 8). The expected conditional benefit of NAV is comparable to that which is realized by SEC & COMM. However, in contrast to SEC & COMM, the greatest expected benefit is realized given seismic loads with a 4750-year return period. The alternative mitigates damage caused by the more severe loads because it reduces time required to remove collapsed bridges from the navigation channel and, the greater the severity of the load, the more likely it is that bridges will be collapsed in the navigation channel. SEC & COMM are effective at mitigating damages caused by low to moderate loads, but are less effective at mitigating damages at higher seismic loads. NAV is more effective at mitigating damages caused by more severe seismic loads.

Strengthening the electrical subsystem would seem to be a fairly obvious step towards improving resilience given the importance of the electrical system to container operations and the relatively high vulnerability of substations and electrical circuits to low and moderate seismic loads (Figure 2). ELEC would seismically retrofit electrical substations and circuits. Contrary to intuition, the benefits of this alternative are much lower than the benefits of either NAV or B603 (Table 8). This can be explained as follows. Although electrical components are more vulnerable to seismic loads, they are associated with more rapid restoration times than other CIC (Table A2.4). Another factor that contributes to this result is that the benefits of seismic retrofits are limited to a marginal decrease in the probability that substations and circuits will be in a non-functional damage state given the seismic load. In contrast, SEC and COMM prevent the security and communications subsystems from becoming non-functional.

The final alternative being considered here is B603, a seismic retrofit of the wharf at Berth 603 and restoration of the Panamax cranes. This alternative is aimed at increasing the throughput capacity and reliability of ship to shore container transfers. The wharf is less likely to be damaged and there are a larger number of cranes, which reduces the probability that ship to shore throughput capacity would limit residual ATC. Similar to NAV, the conditional expected benefits of this alternative are highest given seismic loads of greater severity because only the most severe loads would be expected to damage the wharf. However, the conditional expected benefits are only 10-20% percent of those for NAV.

Accurately assessing the benefit of implementing two or more alternatives requires simulating the alternatives together rather than one at a time because conditional expected benefits are not necessarily additive. The benefits may be super-additive if they are aimed at mitigating damages to CIC that are correlated, such as SEC and COMM (Table 7). The super-additivity of benefits estimated in Table 8 was more limited than those in Table 7 because these alternatives are aimed at mitigating damages that have lower correlation, or co-occur less frequently. Although it was not observed in this study, the benefit of two or more alternatives may also be sub-additive. For example, this would occur if two or more alternatives are aimed at mitigating damages to a single CIC or critical subsystem.

Resilience strengthening alternatives are multi-year investments that should be evaluated over planning horizons that reflect their life spans. In this study, expected benefits are calculated over a 30-year planning horizon using a joint probability distribution on the number and severity of seismic loads. The reason for this is that the benefits of an alternative are proportional to the number of times that seismic loads occur and, during a 30-year planning horizon, seismic loads of a given return period may occur multiple times, or not at all. The expected benefits of each alternative over a 30-year planning horizon are summarized in Tables 7 and 8. These estimates describe the expected increase in ATC achieved over 30-years by implementing each alternative.

Expected benefits over 30 years are two or three orders of magnitude less than conditional expected benefit estimates. This is a product of the low probability of realizing seismic loads during the planning horizon. For example, over a 30-year planning horizon, there is an 81.1% chance that no benefits from the investments would be realized because no seismic loads greater than those with a 72-year return period would be realized. Another factor contributing to the low estimates of expected benefit is that the planning horizon is much shorter than the return periods of seismic loads that might cause damage to the terminal. For example, increasing the planning horizon from 30 to 100 years would increase the expected benefit of the SEC & COMM alternative from 788.5 TEUs to 8760 TEUs. Increasing the length of the planning horizon by a factor of 3.3 increases the benefit estimate by a factor of 11. However, in general, the length of a planning horizon should reflect the life span of the investment that is being evaluated.

This study has compared and evaluated a wide variety of alternatives. These alternatives differ from one another in several ways. Each is more or less effective at mitigating damage from seismic loads with different severities and restoration times. When benefits are calculated over a planning horizon, this creates a complicated dynamic and it is difficult to anticipate which alternatives will yield the greatest benefit. For example, the benefit of those alternatives that mitigate damage from seismic loads with shorter return periods may be greater because these loads are more likely to occur. In contrast, the benefits of alternatives that mitigate damages associated with longer restoration times may be greater because these alternatives have the potential to achieve greater increases in residual ATC during the restoration period. However, this effect could be offset if the damages associated with longer restoration periods tend to be more severe and less likely to occur.

The decision to invest in any one resilience strengthening alternative requires an economic benefit-cost analysis. While a benefit-cost analysis of alternatives is beyond the scope of this study, the economic benefits of resilience strengthening alternatives can be estimated from the recovery trajectories that have been simulated in this study. The economic benefits of an alternative should reflect the costs avoided by implementing that alternative over the restoration period. It seems likely that these costs are not proportional to residual ATC. Large increases in ATC may have disproportionately greater value than smaller increases in residual ATC. Therefore, economic benefits should be calculated from increases in residual ATC at points in time over the one-year restoration period and aggregated over the restoration period for each realization of the Monte Carlo simulation. It should be noted that increases in cargo-handling capacity at a point in time will only have an economic value if there is sufficient demand for that service at points in time during the restoration period.

This study has also explored the readiness and ability to support an FSA at Terminal 6 and the impact of the FSA on container operations. The ability to support an FSA could be disrupted either by the inability to navigate between Bonneville Dam and Terminal 6 or excessive damage to pavement. Implementation of the NAV alternative, advance contracting for removal of debris from the navigation channel, greatly improved the readiness and ability to support an FSA by reducing the contracting lead time. The proposed location of the FSA at Terminal 6 is adjacent to Berth 606, the ad-hoc barge berth. However, this location contains a large number of container ground slots. If the container terminal were fully operational, an FSA at this location would reduce container terminal

ATC by 25%. For example, this could represent the impact of the FSA on container terminal operations if the FSA were established in response to a disaster other than a seismic event. However, if the FSA were established in response to a seismic event the effect of the FSA on operation of the container terminal might be more limited because the residual ATC is already limited during the restoration period.

The resilience metric used in this study focuses on throughput capacity, which is a static measure that describes the ability to move containers. Some authors would argue that resilience metrics should reflect impacts to productivity or performance over time (Poulin and Kane 2021). A focus on performance would describe how many containers were moved relative to how many containers could have been moved. In the absence of demand for the service, then there is no impact on productivity or performance. The productivity or performance of a container terminal is not easily estimated because it requires an understanding the demand for services at the terminal and the variability in that demand over time. That was not feasible for this study because the terminal was not in operation for several years preceding this study. Nevertheless, this study has been able to provide useful insights into managing for seismic resilience at Terminal 6.

This study demonstrates that quantitative and probabilistic methods are needed to evaluate resilience and compare resilience strengthening alternatives. The approach to resilience assessment described in this report could be readily adapted for other types of systems and hazards. A probabilistic approach to resilience assessment requires a model to estimate ATC using information about the functionality of CIC, fragility curves to estimate CIC damage states and function states, and restoration functions to estimate CIC restoration times. For this study, estimates of ATC are based on functions adapted from the port capacity literature. Fragility curves and restoration functions are from the HAZUS MH-2.1 Earthquake Model. Fragility curves and restoration functions are relatively well developed for evaluating seismic risks to CIC at Terminal 6. However, if fragility curves and restoration functions are less well developed for other types of systems and hazards, this could be an impediment to probabilistic resilience assessments. There is a need to build up libraries of these functions to support resilience assessment.

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APPENDIX C.1: PROBABILISTIC SEISMIC HAZARD ANALYSIS AND SEISMIC LOADS

Infrastructure in regions of historically significant seismicity is designed to meet certain seismic hazards criteria; thus, there must be a realistic understanding of source potential in the context of past seismicity and current seismic trends for those locations. The current standard of practice to determine the associative risk is through the means of a Probabilistic Seismic Hazard Analysis (PSHA) using a model of a memory-less stationary homogeneous Poisson process with a constant, time-independent frequency of occurrence (McGuire 2004):

$$\gamma(a) = \sum_{i=1}^{S} \nu_i \iiint f_{M,i}(m)\, f_{R,i}(r|m) f_{\varepsilon,i}(\varepsilon) P[A > a|m, r, \varepsilon] dr dm d\varepsilon \qquad \text{(A1.1)}$$

where $\gamma(a)$ is the annual probability of exceedance of a ground motion amplitude, a; $f_{M,i}(m)$ is the probability density function of magnitude; $f_{R,i}(r|m)$ is the probability density function for the site-to-source distance; $f_{\varepsilon,i}(\varepsilon)$ is the ground motion probability density function; ε is the ground motion uncertainty; P [A > a] is the probability that the ground motion, A, will exceed a threshold value, a, for a given m, r, and ε; S is the number of seismic sources affecting the structure of interest; and ν is the frequency of occurrence for a seismic source.

Equation 1 quantifies the seismic hazard, or probability of exceedance of a specified ground motion intensity, for tectonic events (e.g., the PGA, PGV, spectral content, etc.) can readily be determined from the United States Geological Survey (USGS) seismic hazard mapping website using multiple ground motion prediction equations (GMPE) to determine P[A > a] for any given *m, r*, and ε combination. The use of an internal logic tree regression assigns a GPME weighting system to account for uncertainties within the root GMPE derivation and data. The resulting USGS seismic hazard mapping website is a tremendous resource to the engineering community and the ground motion information that is provided is widely used in practice. This ground motion data has become the basis for the National Earthquake Hazards Reduction Program (NEHRP) provisions for seismic design of new buildings (ICC 2006, AASHTO 2013) and these hazard maps can be accessed by third-party graphical user interfaces, e.g., ASCE 41-17. Within this study, the USGS uniform hazard spectrum (UHS) is used with the spectral outputs, i.e., spectral acceleration (SA) and spectral displacement (SD), validated against the ASCE 41-17 hazard mapping results and site-specific analyses (HTMB et al. 2015; Unruh et al. 2018). However, seismic hazard analyses must also incorporate ground motion time histories or duration-dependent scaling factors for the magnitudes of the earthquakes that contribute to the UHS. This information cannot be obtained from the maps directly, e.g., ASCE 41-17, it must be determined from the seismic source data and ground motion estimates for each of the sources independently.

It is computationally intensive to incorporate all potential faults independently in this study and assign recurrence rates (seismological *b*-values) for this region where recorded events are statistically sparse (Unruh et al. 2018). To overcome this limitation, the source locations are defined by gridding the region around the site by azimuth and distance, and the magnitude distributions of all sources are lumped in groups of nearly equivalent magnitude, i.e., bins of *m, r*, and ε combinations, for four main source types: (1) localized shallow western U.S. faults (WUS Shallow Gridded), (2) localized deeper Washington-Oregon faults (Wash-Oreg faults), (3) regional slab faults (Slab), and (4) the Cascadia Subduction Zone (CSZ). The UHS is then used to evaluate the relative contribution of each seismic source to the cumulative ground motion hazard and then de-aggregated to quantify the event magnitudes and the source-to-site distances, i.e., the contributing *m-r* pairs that dominate the Terminal 6 seismic hazard. This allows for the quantification of the relative impact of multi-modal seismic sources and the probabilities of the *m-r* pairs that would generate the PGA ground motion in exceedance of the threshold value relating to the earthquake return period. The contribution, or probability, of a specific *m-r* pairing associated with a source type can then be directly used as an input into this study without being computationally intensive. This allows for source variability and duration effects to be specifically accounted for in the quantification of the seismic risk at Terminal 6.

The seismic risk is the product of the *seismic hazard* and the *vulnerability* of the region or structure of interest and is defined as:

$$Seismic\ Risk = Seismic\ Hazard \ \Theta \ Vulnerability \qquad \text{(A1.2)}$$

The vulnerability of any structure is a function of exposure (within proximity of the seismic event such that it may potentially be affected), fragility (susceptibility of the structure to the ground intensities) and consequence (socio-economic impact should failure occur) (Wang 2010).

In order to understand the vulnerability associated with the Port of Portland Terminal 6 subsurface to seismic hazards, the Federal Emergency Management Agency (FEMA) Multi-hazard Loss Estimation Manual (HAZUS) is used in this study in lieu of expensive, site-specific deterministic analyses. A 2015 site-specific seismic hazard analysis was conducted (HNTB et al. 2015) for the entire Port of Portland region, extending beyond Terminal 6, but lacked sufficient detail as a direct input into this study. Moreover, the PSHA models have been updated since the report's release. Therefore, the HNTB report was used as a validation of the reasonableness of the HAZUS loss estimations to ensure that vulnerability calculations are not generating unrealistic values. The HAZUS loss estimation manual is used to estimate the site resilience (liquefaction potential, lateral spreading, and landslide deformation) with respect to each *m-r-return period* combination for each potential site classification. Based on the HNTB et al. (2015) report, three site classifications are considered at Terminal 6: B/C, D, and D/E.

The HAZUS is a regional to sub-regional map-based analysis wherein the initial input is the mapped relative susceptibility of the area-of-interest (AOI) to which a "probability factor", P_{ml}, is assigned as a portion of the AOI that will undergo liquefaction. Based on the Oregon Department of Geology and Mineral Industry (DOGAMI) geological Interpretive Map Series (IMS), the Terminal 6 is defined as "Very High" for liquefaction susceptibility with a maximum ground settlement of 12 inches. This was verified against the HNTB et al. (2015) site-specific analysis. Therefore, the $P_{ml} = 0.25$ for use within the HAZUS framework. The probability of liquefaction for a given susceptibility category is quantified as (HAZUS):

$$P[Liq_{SC}] = \frac{P[Liq_{SC}|PGA=a]}{K_M \cdot K_w} \cdot P_{ml} \qquad \text{(A1.3)}$$

where $P[Liq_{SC}|PGA = a]$ is the conditional probability of liquefaction for a given peak ground acceleration; K_M is the moment magnitude correction factor for a given *m-r* pair; and K_w is the groundwater correction factor. For a "Very High" liquefaction susceptibility, the conditional probability of liquefaction for a given peak ground acceleration can be calculated as (HAZUS):

$$P[Liq_{SC}|PGA = a]\text{:}\ 0 \leq 9.09a - 0.82 \leq 1.0 \qquad \text{(A1.4)}$$

The moment magnitude (*M*) correction factor is calculated as (HAZUS)

$$K_M = 0.0027M^3 - 0.0267M^2 - 0.2055M + 2.9188 \qquad \text{(A1.5)}$$

The groundwater correction factor, based on the depth-to-groundwater (d_w), is calculated as (HAZUS):

$$K_w = 0.022d_w + 0.93 \qquad \text{(A1.6)}$$

To determine the maximum permanent ground displacements from lateral spreading, $E[PGD_{SC}]$, the HAZUS uses the following empirical relationship based on the ratio of the peak ground acceleration, PGA, to a threshold zero-liquefaction probability acceleration, $PGA(t)$, where any acceleration below this threshold will not yield liquefaction.

$$E[PGD_{SC}] = E\left[PGD|\left(\frac{PGA}{PL_{SC}}\right) = a\right] \cdot K_\Delta \qquad \text{(A1.7)}$$

where:

$$E\left[PGD|\left(\frac{PGA}{PL_{SC}}\right) = a\right] = \begin{cases} 12\frac{PGA}{PGA(t)} - 12\, for\ 1 < \frac{PGA}{PGA(t)} < 2 \\ 18\frac{PGA}{PGA(t)} - 24\, for\ 2 < \frac{PGA}{PGA(t)} < 3 \\ 70\frac{PGA}{PGA(t)} - 180\, for\ 3 < \frac{PGA}{PGA(t)} < 4 \end{cases} \qquad \text{(A1.8)}$$

and the moment magnitude correction factor, K_Δ, is (HAZUS):

$$K_\Delta = 0.0086M^3 - 0.0914M^2 + 0.4698M + 0.9835 \qquad \text{(A1.9)}$$

The HNBT et al. (2015) report only provides the maximum lateral spreading potential and therefore is of limited use in this study, but is used to validate the maximum HAZUS lateral spreading results and was found in good agreement. Therefore, a high degree of confidence exists for the reasonableness of the quantification of lateral spreading potential for the other *m-r* pairs considered in this study.

During strong earthquake ground motions, a Newmark (1965) analysis is typically performed wherein slip along a slope during the compression phase (i.e., the acceleration resultant in the direction of gravitational forces of the earthquake exceeds a critical threshold acceleration for each cycle of loading). The accumulation of each phase over the duration of motion results in the maximum landslide slip potential at Terminal 6. However, there is not a generally accepted empirical relationship to determine the landslide potential based on a map-based generalization of the critical acceleration, a_c, necessary to induce movement during strong earthquake ground motions. The HAZUS, therefore, uses a conservative approach proposed by Wilson and Keefer (1985) that calculates the maximum permanent ground deformation resulting from the landslide slip potential, $E[PGD]$, as:

$$E[PGD] = E\left[\frac{d}{a_{is}}\right] \cdot a_{is} \cdot n \qquad \text{(A1.10)}$$

where a_{is} is the induced seismic acceleration (in units of g), n is the number of loading cycles as a function of the moment magnitude, equation 11, and $E\left[\frac{d}{a_{is}}\right]$ is the slip displacement factor (calculated from the upper bound of the HAZUS Figure 4.13 as a function of $\frac{a_c}{a_{si}}$). Terminal 6 is susceptible to small shallow slides, constrained by geography to the Columbia River-Port of Portland interface, the constrained displacement potential, a_{is} can is assumed to equal the peak ground acceleration, *PGA*, from the PSHA ground motion calculations.

$$n = 0.3419M^3 - 5.5214M^2 + 33.6154M - 70.7692 \qquad \text{(A1.11)}$$

Based on the HNTB et al. (2015) report, DOGAMI IMS, and topography of the Columbia River-Port of Portland interfaces the HAZUS landslide susceptibility geological group was determined as Group B and that any landslides would originate below the Columbia River waterline, thus, conservatively, $a_c = 0.10$.

The PSHA provided estimates of ground motion and ground deformation associated with selected return periods. These are summarized for Terminal 6 in Tables A1.1 – A1.3 and for the Astoria-Megler Bridge in Tables A1.4 – A1.6. As the Astoria-Megler Bridge was the only structure of interest in the vicinity of Astoria, Oregon, only those results for site-class B/C are reported.

Table A1.1: Estimates of Ground Shaking and Spectral Acceleration at Terminal 6.

Return Period	Site Class	PGA (g)	Spectral Acceleration (g)	
			SA 0.3 sec	SA 1.0 sec
72	B/C	0.038	0.068	0.023
	D	0.058	0.145	0.063
	D/E	0.065	0.179	0.086
225	B/C	0.103	0.185	0.066
	D	0.148	0.356	0.166
	D/E	0.160	0.413	0.215
475	B/C	0.176	0.317	0.125
	D	0.240	0.574	0.295
	D/E	0.253	0.635	0.371
975	B/C	0.270	0.487	0.205
	D	0.351	0.839	0.464
	D/E	0.362	0.888	0.579
2475	B/C	0.426	0.777	0.338
	D	0.527	1.265	0.746
	D/E	0.534	1.218	0.926
4750	B/C	0.555	1.033	0.455
	D	0.674	1.620	0.993
	D/E	0.677	1.606	1.208

Table A1.2: Probabilities of Liquefaction at Terminal 6.

Return Period	Site Class	Contributions	Probability of Liquefaction (Liq.)	
			p(Liq. = True)	p(Liq. = False)
72	B/C	WUS Shallow Gridded	0.0000	1.0000
	B/C	Was-Oreg Faults	0.0000	1.0000
	B/C	Slab	0.0000	1.0000
	B/C	CSZ	0.0000	1.0000
	D	WUS Shallow Gridded	0.0000	1.0000
	D	Was-Oreg Faults	0.0000	1.0000
	D	Slab	0.0000	1.0000
	D	CSZ	0.0000	1.0000

	D/E	WUS Shallow Gridded	0.0000	1.0000
	D/E	Was-Oreg Faults	0.0000	1.0000
	D/E	Slab	0.0000	1.0000
	D/E	CSZ	0.0000	1.0000
225	B/C	WUS Shallow Gridded	0.0705	0.9295
	B/C	Was-Oreg Faults	0.0759	0.9241
	B/C	Slab	0.0829	0.9171
	B/C	CSZ	0.1047	0.8953
	D	WUS Shallow Gridded	0.3186	0.6814
	D	Was-Oreg Faults	0.3434	0.6566
	D	Slab	0.3750	0.6250
	D	CSZ	0.4733	0.5267
	D/E	WUS Shallow Gridded	0.3863	0.6137
	D/E	Was-Oreg Faults	0.4164	0.5836
	D/E	Slab	0.4548	0.5452
	D/E	CSZ	0.5739	0.4261
475	B/C	WUS Shallow Gridded	0.4794	0.5206
	B/C	Was-Oreg Faults	0.5203	0.4797
	B/C	Slab	0.5641	0.4359
	B/C	CSZ	0.7100	0.2900
	D	WUS Shallow Gridded	0.6140	0.3860
	D	Was-Oreg Faults	0.6664	0.3336
	D	Slab	0.7225	0.2775
	D	CSZ	0.9093	0.0907
	D/E	WUS Shallow Gridded	0.6140	0.3860
	D/E	Was-Oreg Faults	0.6664	0.3336
	D/E	Slab	0.7225	0.2775
	D/E	CSZ	0.9093	0.0907
975	B/C	WUS Shallow Gridded	0.6195	0.3805
	B/C	Was-Oreg Faults	0.6782	0.3218
	B/C	Slab	0.7250	0.2750
	B/C	CSZ	0.9109	0.0891
	D	WUS Shallow Gridded	0.6195	0.3805
	D	Was-Oreg Faults	0.6782	0.3218
	D	Slab	0.7250	0.2750
	D	CSZ	0.9109	0.0891

	D/E	WUS Shallow Gridded	0.6195	0.3805
	D/E	Was-Oreg Faults	0.6782	0.3218
	D/E	Slab	0.7250	0.2750
	D/E	CSZ	0.9109	0.0891
2475	B/C	WUS Shallow Gridded	0.6285	0.3715
	B/C	Was-Oreg Faults	0.6913	0.3087
	B/C	Slab	0.7286	0.2714
	B/C	CSZ	0.9123	0.0877
	D	WUS Shallow Gridded	0.6285	0.3715
	D	Was-Oreg Faults	0.6913	0.3087
	D	Slab	0.7286	0.2714
	D	CSZ	0.9123	0.0877
	D/E	WUS Shallow Gridded	0.6285	0.3715
	D/E	Was-Oreg Faults	0.6913	0.3087
	D/E	Slab	0.7286	0.2714
	D/E	CSZ	0.9123	0.0877
475	B/C	WUS Shallow Gridded	0.6341	0.3659
	B/C	Was-Oreg Faults	0.6984	0.3016
	B/C	Slab	0.7310	0.2690
	B/C	CSZ	0.9132	0.0868
	D	WUS Shallow Gridded	0.6341	0.3659
	D	Was-Oreg Faults	0.6984	0.3016
	D	Slab	0.7310	0.2690
	D	CSZ	0.9132	0.0868
	D/E	WUS Shallow Gridded	0.6341	0.3659
	D/E	Was-Oreg Faults	0.6984	0.3016
	D/E	Slab	0.7310	0.2690
	D/E	CSZ	0.9132	0.0868

Table A1.3: Estimates of PGD at Terminal 6.

Return Period	Contributions	Peak Ground Deformation (inches)					
		Site Class B/C		Site Class D		Site Class D/E	
		Liq. = True	Liq. = False	Liq. = True	Liq. = False	Liq. = True	Liq. = False
72	WUS Shallow Gridded	0.0	12.0	0.0	12.0	0.0	12.0
72	Was-Oreg Faults	0.0	12.0	0.0	12.0	0.0	12.0
72	Slab	0.0	12.0	0.0	12.0	0.0	12.0

72	CSZ	0.0	12.0	0.0	12.0	0.0	12.0
225	WUS Shallow Gridded	0.0	12.0	0.3	12.0	0.4	12.0
225	Was-Oreg Faults	0.0	12.0	0.3	12.0	0.5	12.0
225	Slab	0.0	12.0	0.4	12.0	0.7	12.0
225	CSZ	0.0	12.0	1.3	15.2	2.0	18.4
475	WUS Shallow Gridded	0.5	12.0	3.3	12.0	4.2	12.0
475	Was-Oreg Faults	0.7	12.0	4.2	13.5	5.4	15.0
475	Slab	0.9	12.0	5.7	18.1	7.2	20.1
475	CSZ	2.5	12.0	15.6	48.3	19.7	53.6
975	WUS Shallow Gridded	4.8	12.0	10.2	39.7	10.5	43.5
975	Was-Oreg Faults	6.2	12.0	13.1	56.2	13.5	61.6
975	Slab	8.3	12.0	17.4	71.4	18.0	78.2
975	CSZ	22.8	22.8	47.9	191.2	49.4	209.5
2475	WUS Shallow Gridded	12.9	12.9	16.1	42.1	16.3	46.1
2475	Was-Oreg Faults	18.5	18.5	23.0	60.2	23.3	66.0
2475	Slab	22.1	22.1	27.6	72.6	28.0	79.5
2475	CSZ	62.8	62.8	78.3	194.6	79.3	213.2
4750	WUS Shallow Gridded	17.0	17.0	22.3	43.6	22.4	47.8
4750	Was-Oreg Faults	24.2	24.2	31.9	62.5	32.0	68.5
4750	Slab	29.1	29.1	38.2	73.5	38.4	80.5
4750	CSZ	82.4	82.4	108.3	197.1	108.8	215.9

Table A1.4: Estimates of Ground Shaking at the Astoria-Megler Bridge.

Return Period	PGA	Spectral Acceleration (g)	
		SA 0.3 Sec	SA 1.0 Sec
72	0.0336	0.0602	0.0212
225	0.0969	0.1700	0.0578
475	0.2359	0.4118	0.1687
975	0.4515	0.7941	0.3685
2475	0.7580	1.4015	0.6643
4750	1.0117	1.8747	0.8880

Table A1.5: Probabilities of Liquefaction at the Astoria-Megler Bridge.

Return Period	Site Class	Contributions	Probability of Liquefaction (Liq.)	
			p(Liq. = True)	p(Liq. = False)
72	B/C	WUS Shallow Gridded	0.0000	1.0000

72	B/C	Was-Oreg Faults	0.0000	1.0000
72	B/C	Slab	0.0000	1.0000
72	B/C	CSZ	0.0000	1.0000
72	B/C	Null	0.0000	1.0000
225	B/C	WUS Shallow Gridded	0.0000	1.0000
225	B/C	Was-Oreg Faults	0.0000	1.0000
225	B/C	Slab	0.0000	1.0000
225	B/C	CSZ	0.0000	1.0000
225	B/C	Null	0.0000	1.0000
475	B/C	WUS Shallow Gridded	0.3715	0.6285
475	B/C	Was-Oreg Faults	0.0000	1.0000
475	B/C	Slab	0.4143	0.5857
475	B/C	CSZ	0.5202	0.4798
475	B/C	Null	0.0000	1.0000
975	B/C	WUS Shallow Gridded	0.6513	0.3487
975	B/C	Was-Oreg Faults	0.0000	1.0000
975	B/C	Slab	0.7322	0.2678
975	B/C	CSZ	0.9089	0.0911
975	B/C	Null	0.0000	1.0000
2475	B/C	WUS Shallow Gridded	0.6582	0.3418
2475	B/C	Was-Oreg Faults	0.0000	1.0000
2475	B/C	Slab	0.7407	0.2593
2475	B/C	CSZ	0.9097	0.0903
2475	B/C	Null	0.0000	1.0000
4750	B/C	WUS Shallow Gridded	0.6524	0.3476
4750	B/C	Was-Oreg Faults	0.0000	1.0000
4750	B/C	Slab	0.7455	0.2545
4750	B/C	CSZ	0.9101	0.0899
4750	B/C	Null	0.0000	1.0000

Table A1.5: Estimates of PGD at the Astoria-Megler Bridge.

Return Period	Site Class	Contributions	PGD (inches)	
			Liq. = True	Liq. = False
72	B/C	WUS Shallow Gridded	2.0	0.0
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	2.0	0.0

	B/C	CSZ	2.0	0.0
225	B/C	WUS Shallow Gridded	2.0	0.0
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	2.0	0.0
	B/C	CSZ	2.0	0.0
475	B/C	WUS Shallow Gridded	3.5	3.5
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	5.2	5.2
	B/C	CSZ	13.6	13.6
975	B/C	WUS Shallow Gridded	16.0	16.0
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	24.4	24.4
	B/C	CSZ	61.8	61.8
2475	B/C	WUS Shallow Gridded	26.3	26.3
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	42.7	42.7
	B/C	CSZ	108.3	108.3
4750	B/C	WUS Shallow Gridded	35.4	35.4
	B/C	Was-Oreg Faults	2.0	0.0
	B/C	Slab	57.5	57.5
	B/C	CSZ	145.9	145.9

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APPENDIX C.2: CRITICAL INFRASTRUCTURE COMPONENT DAMAGE STATES, FRAGILITY CURVES, AND RESTORATION FUNCTIONS

This appendix summarizes the damage states, fragility curves, and restoration functions used in this study. The primary source of these functions is FEMA's HAZUS MH-2.1 Earthquake Model. The potential damage states of CIC in the infrastructure network are described in Table A2.1. The functionality of infrastructure components was inferred from the damage state descriptions. The parameters of fragility curves are summarized in Table A2.2 for CIC that are sensitive to ground shaking and in Table A2.3 for CIC that are sensitive to ground deformation. The parameters of the fragility curve for seismically retrofit wharves was developed by the authors with the understanding that structures located in seismically active should, in general, be designed to withstand seismic loads associated with return periods of 2475 years. Restoration functions are listed in Table A2.4. HAZUS restoration functions for bridges describe the length of time to restore those bridges to a functional state. This study is concerned with removing bridges from the navigation channel. Therefore, restoration functions were created specifically for this study. Given the status quo condition, six months is required to contract for removal of bridges. Under the advance contracting alternative, no lead time is required to prepare the contract.

Table A2.1: Damage State Descriptions (FEMA 2012). Note: F = Functional, NF = Non-functional.

Category	**Component**	**Damage State**	**Description of Damage State**	**Function State**
Bridges		Complete	Any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse, tilting of substructure due to foundation failure.	NF
Buildings, Structural components	Wood, Light Frame (W1) *Building* *7545*	Slight	Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.	F
		Moderate	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.	F
		Extensive	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-story” configurations; small foundations cracks.	NF
		Complete	Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with Complete damage is expected to be collapsed.	NF
	Steel Moment Frame, Low Rise (S1L) *OCR Shed*	Slight	Minor deformations in connections or hairline cracks in a few welds.	F
		Moderate	Some steel members have yielded exhibiting observable permanent rotations at connections. A few welded connections may exhibit major cracks through welds. A few bolted connections may exhibit broken bolts or enlarged bolt holes.	F
		Extensive	Most steel members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.	NF
		Complete	A significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building. Approximately 8% of the total area of S1 buildings with Complete damage is expected to be collapsed.	NF
		Slight	The most vulnerable equipment (e.g., unanchored or on spring isolators) moves and damages attached piping or ducts.	F

Category	Component	Damage State	Description of Damage State	Function State
Buildings, Non-structural components	Electrical and communication components	Moderate	Movements are larger and damage is more extensive. Piping leaks at a few locations.	F
		Extensive	Equipment on spring isolators topples and falls. Other unanchored equipment slides or falls breaking connections to piping and ducts. Leaks develop at many locations. Anchored equipment indicate stretched bolts or strain at anchorages.	NF
		Complete	Equipment is damaged by sliding, overturning or failure of their supports and is not operable. Piping is leaking at many locations. Some pipe and duct supports have failed causing pipes and ducts to fall or hang down. Elevator rails are buckled or have broken supports and/or counterweights have derailed.	NF
Cranes	Ship to shore gantry cranes	Slight	Minor derailment or misalignment without any major structural damage to the rail mount. Minor repair and adjustments may be required before the crane becomes operable.	F
		Moderate	Derailment due to differential displacement of parallel track. Rail repair and some repair to structural members is required	NF
		Extensive	Considerable damage to equipment. Toppled or totally derailed cranes are likely to occur. Replacement of structural members is required.	NF
		Complete	Considerable damage to equipment. Toppled or totally derailed cranes are likely to occur. Replacement of structural members is required. (Description is the same as Extensive)	NF
Electrical	Substations	Slight	The failure of 5% of the disconnect switches (i.e., misalignment), or the failure of 5 % of the circuit breakers (i.e., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter head falling to the ground), or by the building being in minor damage state.	F
		Moderate	Failure of 40% of disconnect switches (e.g., misalignment), or 40% of circuit breakers (e.g., circuit breaker phase sliding off its pad, circuit breaker tipping over, or interrupter-head falling to the ground), or failure of 40% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by the building being in moderate damage state.	NF
		Extensive	Failure of 70% of disconnect switches (e.g., misalignment), 70% of circuit breakers, 70% of current transformers (e.g., oil leaking from transformers, porcelain cracked), or by failure of 70% of transformers (e.g., leakage of transformer radiators), or by the building being in extensive damage state.	NF
		Complete	Failure of all disconnect switches, all circuit breakers, all transformers, or all current transformers, or by the building being in complete damage state.	NF
	Circuits	Slight	Failure of 4 % of all circuits.	U(0.04, 0.12)
		Moderate	Failure of 12% of circuits.	U(0.12, 0.5)

Category	Component	Damage State	Description of Damage State	Function State
		Extensive	Failure of 50% of all circuits.	U0.5, 0.8)
		Complete	Failure of 80% of all circuits.	U(0.8, 1.0)
Pavement	Urban roads	Slight	Slight settlement (a few inches) or offset of the ground.	F
		Moderate	Moderate settlement (several inches) or offset of the ground.	F
		Extensive	Major settlement (a few feet) of the ground.	NF
Railroad	Track segments	Slight	Minor (localized) derailment due to slight differential settlement of embankment or offset of the ground.	F
		Moderate	Considerable derailment due to differential settlement or offset of the ground. Rail repair is required.	NF
		Extensive	Major differential settlement of the ground resulting in potential derailment over extended length.	NF
Waterfront Structures	Wharves	Slight	Minor ground settlement resulting in a few piles (for piers/seawalls) getting broken and damaged. Cracks are formed on the surface of the wharf. Repair may be needed.	F
		Moderate	Considerable ground settlement with several piles (for piers/seawalls) getting broken and damaged.	F
		Extensive	Failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.	NF
		Complete	Failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.	NF

Table A2.2. Parameters of Fragility Curves for Infrastructure Components Sensitive to Ground Shaking (PGA) (m_x, g)

Infrastructure Component				**Damage State**							
				Slight		**Moderate**		**Extensive**		**Complete**	
				m_x	β	m_x	β	m_x	β	m_x	β
Bridges	Astoria-Megler Bridge			-	-	-	-	-	-	1.0125	0.6
	Lewis and Clark Bridge			-	-	-	-	-	-	1.0125	0.6
	Burlington Northern Railroad Bridge			-	-	-	-	-	-	0.7063	0.6
	Interstate 5 Bridge (North & South Bound)			-	-	-	-	-	-	0.9225	0.6
	Interstate 205 Bridge			-	-	-	-	-	-	1.197	0.6
	New Lock Swing Bridge, Bonneville Lock			-	-	-	-	-	-	1.197	0.6
Buildings	Electrical and communications components	OCR and Radiation Sheds		0.25	0.67	0.5	0.66	1.0	0.67	2.0	0.67
		Building 7545 (CY Gate Building)		0.25	0.73	0.5	0.68	1.0	0.67	2.0	0.64
Cranes	Ship to Shore Gantry Cranes			0.15	0.6	0.35	0.6	0.8	0.7	-	-
Electrical	Circuits		Standard	0.24	0.25	0.33	0.2	0.58	0.15	0.89	0.15
			Seismically Retrofit	0.28	0.3	0.4	0.2	0.72	0.15	1.1	0.15
	Substations	Low voltage (422 & 423)	Standard	0.13	0.65	0.26	0.5	0.34	0.4	0.74	0.4
			Seismically Retrofit	0.15	0.7	0.29	0.55	0.45	0.45	0.9	0.45
		Medium voltage (A & B)	Standard	0.1	0.6	0.2	0.5	0.3	0.4	0.5	0.4
			Seismically Retrofit	0.15	0.6	0.25	0.5	0.35	0.4	0.7	0.4

Table A2.3. Parameters of Fragility Curves for Infrastructure Components Sensitive to Ground Deformation (PGD) (m_x, inches).

Infrastructure Component			**Damage State**							
			Slight		**Moderate**		**Extensive**		**Complete**	
			m_x	β	m_x	β	m_x	β	m_x	β
Bridges	Astoria-Megler Bridge		-	-	-	-	-	-	13.8	0.2
	Lewis and Clark Bridge		-	-	-	-	-	-	13.8	0.2
	Burlington Northern Railroad Bridge		-	-	-	-	-	-	13.8	0.2
	Interstate 5 Bridge (North and South Bound)		-	-	-	-	-	-	13.8	0.2
	Interstate 205 Bridge		-	-	-	-	-	-	13.8	0.2
	New Lock Swing Bridge, Bonneville Lock		-	-	-	-	-	-	13.8	0.2
Buildings	Structural components	OCR and radiation Sheds	1.3	0.8	2.24	0.75	5.08	0.74	12.96	0.88
		Building 7545 (CY Gate Building)	0.5	0.84	1.25	0.86	3.86	0.89	9.45	1.04
Cranes	Ship to shore gantry cranes		2	0.6	4	0.6	10	0.7	-	-
Pavement	Urban roads (Roadways, container storage area, FSA)		6	0.7	12	0.7	24	0.7	-	-
Railroad	Railroad tracks		12	0.7	24	0.7	60	0.7	-	-
Waterfront Structures	Wharves	Standard	5	0.5	12	0.5	17	0.5	43	0.5
		Seismically retrofit	15	0.5	22	0.5	27	0.5	53	0.5

Table A2.4: Restoration Functions for CIC (FEMA 2012).

Category	Component	Damage State	Parameters		Number of Days Following the Seismic Event									
			Mean	Standard Deviation	1	3	7	30	90	120	180	210	240	365
Bridges	No contract	Complete	194	30	0.00	0.00	0.00	0.00	0.00	0.01	0.32	0.70	0.94	1.00
	Advance contract	Complete	14	3	0.00	0.00	0.01	0.99	1.00	1.00	1.00	1.00	1.00	1.00
Buildings	Structural and Non-structural components	Slight	5	1	0.00	0.02	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	20	2	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	90	10	0.00	0.00	0.00	0.00	0.50	1.00	1.00	1.00	1.00	1.00
		Complete	180	20	0.00	0.00	0.00	0.00	0.00	0.00	0.5	0.93	1.00	1.00
Cranes	Ship to shore gantry cranes	Slight	0.4	0.35	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	6	6	0.20	0.31	0.57	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	30	30	0.17	0.18	0.22	0.50	0.98	1.00	1.00	1.00	1.00	1.00
		Complete	75	55	0.09	0.10	0.11	0.21	0.61	0.79	0.97	0.99	1.00	1.00
Electrical	Substations	Slight	1	0.5	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	3	1.5	0.09	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	7	3.5	0.04	0.13	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Complete	30	15	0.03	0.04	0.06	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	Circuits	Slight	0.3	0.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	1	0.5	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	3	1.5	0.09	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Complete	7	3	0.02	0.09	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pavement	Urban roads	Slight	0.9	0.05	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	2.2	1.8	0.25	0.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	21	16	0.11	0.13	0.19	0.71	1.00	1.00	1.00	1.00	1.00	1.00

Category	**Component**	**Damage State**	**Parameters**		**Number of Days Following the Seismic Event**									
			Mean	**Standard Deviation**	**1**	**3**	**7**	**30**	**90**	**120**	**180**	**210**	**240**	**365**
Railroad	Tracks	Slight	0.9	0.07	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	3.3	3	0.22	0.46	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	15	13	0.14	0.18	0.27	0.88	1.00	1.00	1.00	1.00	1.00	1.00
		Complete	65	45	0.08	0.08	0.10	0.22	0.71	0.89	0.99	1.00	1.00	1.00
Waterfront Structures	Wharves	Slight	0.98	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Moderate	0.24	0.44	0.84	0.24	0.44	0.84	1.00	1.00	1.00	1.00	1.00	1.00
		Extensive	0.17	0.19	0.25	0.17	0.19	0.25	0.64	1.00	1.00	1.00	1.00	1.00
		Complete	0.12	0.13	0.14	0.12	0.13	0.14	0.23	0.53	0.68	1.00	1.00	1.00

ANNEX D. U.S. PORT NETWORK CONNECTIVITY AND RAMIFICATIONS FOR PORT RESILIENCE

CONTENTS

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Disclaimer: The information contained in this report is summarized from Young et al. 2021 and Kress et al. 2021. Please see those documents for more thorough discussion.

PURPOSE

The maritime transportation system (MTS) of the U.S. is a pillar of the national supply chain. The MTS transports over 90% percent of U.S. imports/exports and is responsible for more than $4.6 trillion in economic activity every year (USCG 2018). Due to its criticality to the U.S. economy, the MTS's operators and regulators are tasked with ensuring that it is reliable and efficient. The MTS is vulnerable to a wide range of environmental and non-environmental disruptions. Many of these vulnerabilities will be exacerbated by worsening climate extremes, increasing demand, and advancements in technology (PIANC 2020). As a result, resilient strategies and designs are being increasingly emphasized by the U.S. federal agencies charged with maintaining the nation's MTS (PPD 2013; NSS 2017; USACE 2020A). Four parameters are used to estimate the resilience of managed systems (including the MTS): robustness to withstand unforeseen demands; redundancy to tolerate the loss or damage to a component; resourcefulness to identify a problem and respond effectively; and rapidity to restore functionality quickly (Bruneau et al. 2003). This study demonstrates a means to describe two of these four resilience parameters for the MTS at both a nationwide and regional scale: robustness and redundancy.

METHODS

A firm grasp of the connectivity of a network is key to understanding how network structure can impact robustness/redundancy, and therefore, resilience (Touzinsky et al. 2018; Scully and Chambers 2019). Fortunately, the increased availability of publically accessible shipping and vessel data provides opportunities to observe the patterns and functions of the MTS. In this study the U.S. MTS is modeled by identifying port-to-port movements of vessels across a network of 62 U.S. ports using an open source nationwide Automatic Identification System (AIS) data product called Marine Cadastre (BOEM and NOAA 2018). The data are filtered to retain a time-stamped list of arrivals and departures for every AIS-equipped vessel transiting the U.S. MTS, thereby capturing the connectivity between U.S. ports over the study duration (see Fig. 1). With this quantitative network model in place, the nationwide and regional traffic patterns at any location in the United States can be fully described. Two further analyses can be utilized to assess network robustness and redundancy.

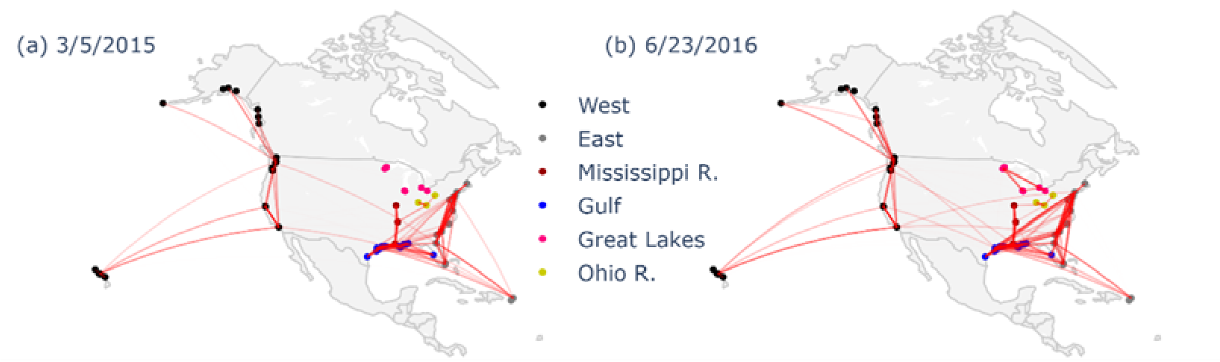

Figure 1: Vessel exchanges between U.S. Ports. Reprinted from Young et al. 2021 with permission.

First, community detection via label propagation (Cordasco and Gargano 2010; Malliaros and Vazirgiannis 2013) is applied to identify regions of the port network based on shared vessel traffic rather than physical proximity. Community detection allows for a more in-depth understanding of the trade relationships of a given port or regional grouping of ports, as well as the trade-partner ports or regions likely to be impacted if it is disrupted. Second, the PageRank algorithm (Page et al. 1999) is applied to identify ports that are more critical to regional or network-wide traffic flow than might be anticipated from their traffic numbers alone. The combination of these two capabilities allows for the identification of more robust network regions due to the presence of redundant regional ports. It is also relevant when considering which ports are most vulnerable and may be good candidates to harden to improve the overall robustness of a given network region.

RESULTS

Improved Understanding of Traffic Patterns

As described above, this network model allows for a more quantitative description of regional and national traffic patterns than possible with the traditional gross tonnage metrics. Kress et al. (2021) demonstrated this capability for the Great Lakes maritime navigation system by describing the port-to-port connectivity within the Great Lakes region. Connectivity describes multiple properties of the port network, such as its geographic reach and its interconnectivity as defined by the traffic levels and vessel types between ports. Fig. 2 depicts the monthly vessel departures from Calumet Harbor area over the study duration.

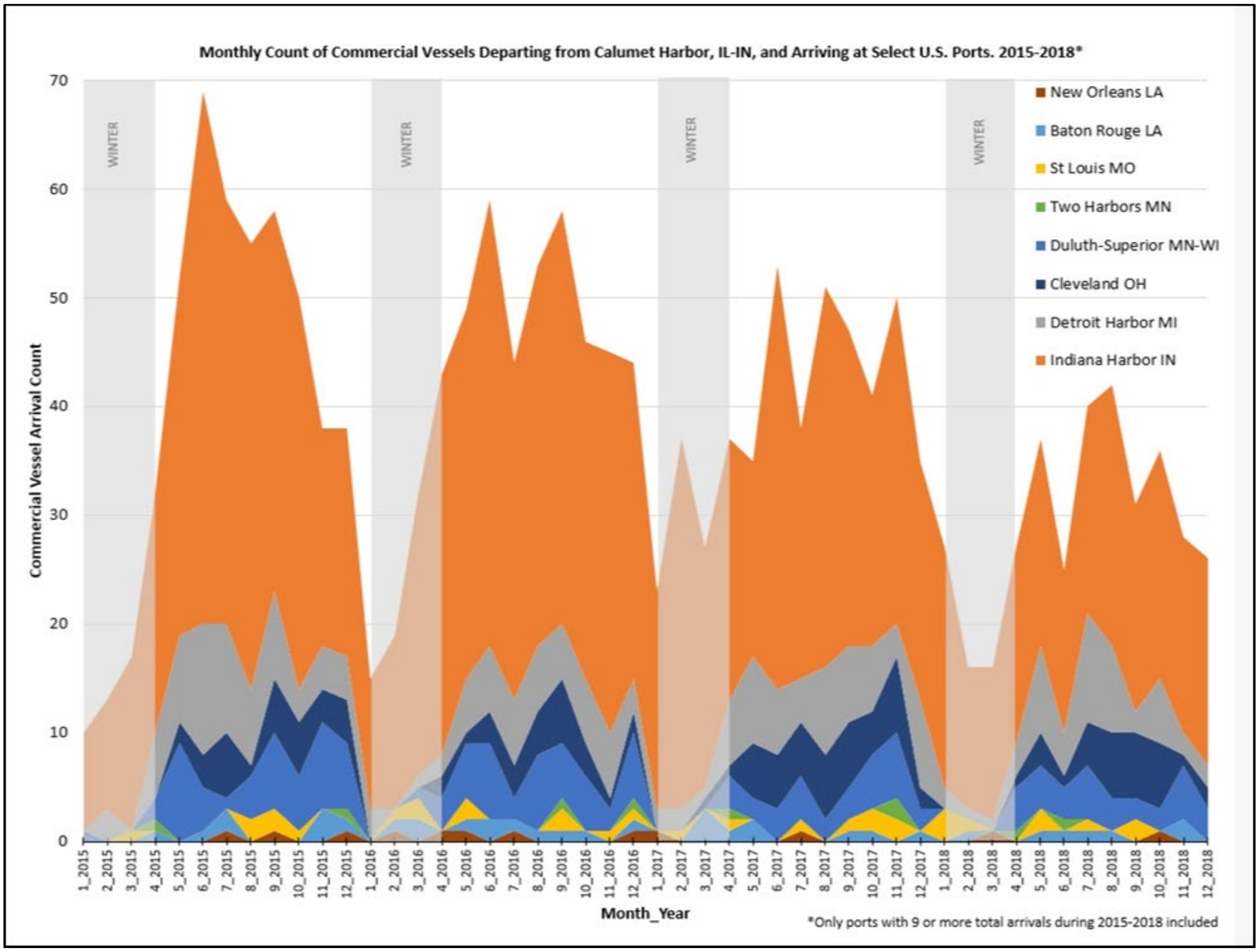

Figure 2. Monthly counts for select commercial vessels departing from the Calumet Harbor, located in Illinois and Indiana (IL and IN), Port Area and arriving at selected port areas, 2015 – 2018. Reprinted from Kress et al. 2021 with permission.

Fig. 2 highlights the fact that, while Calumet Harbor traffic is predominantly confined to the Great Lakes region, the port does trade substantially with ports almost 1,000 mi away. Fig. 2 also highlights the seasonality of vessel traffic and, presumably, the effect disruption timing has on the impacts to regional vessel traffic. As noted in Kress et al. (2021) there is a distinct cyclical pattern of a decline in transits during winter months for the Great Lakes ports. The results from the network model also describe the vessel migration by vessel type, as illustrated for the Great Lakes ports by Fig. 3. As described below, vessel type can have a larger impact on trading partners and port connectivity than physical proximity in many cases.

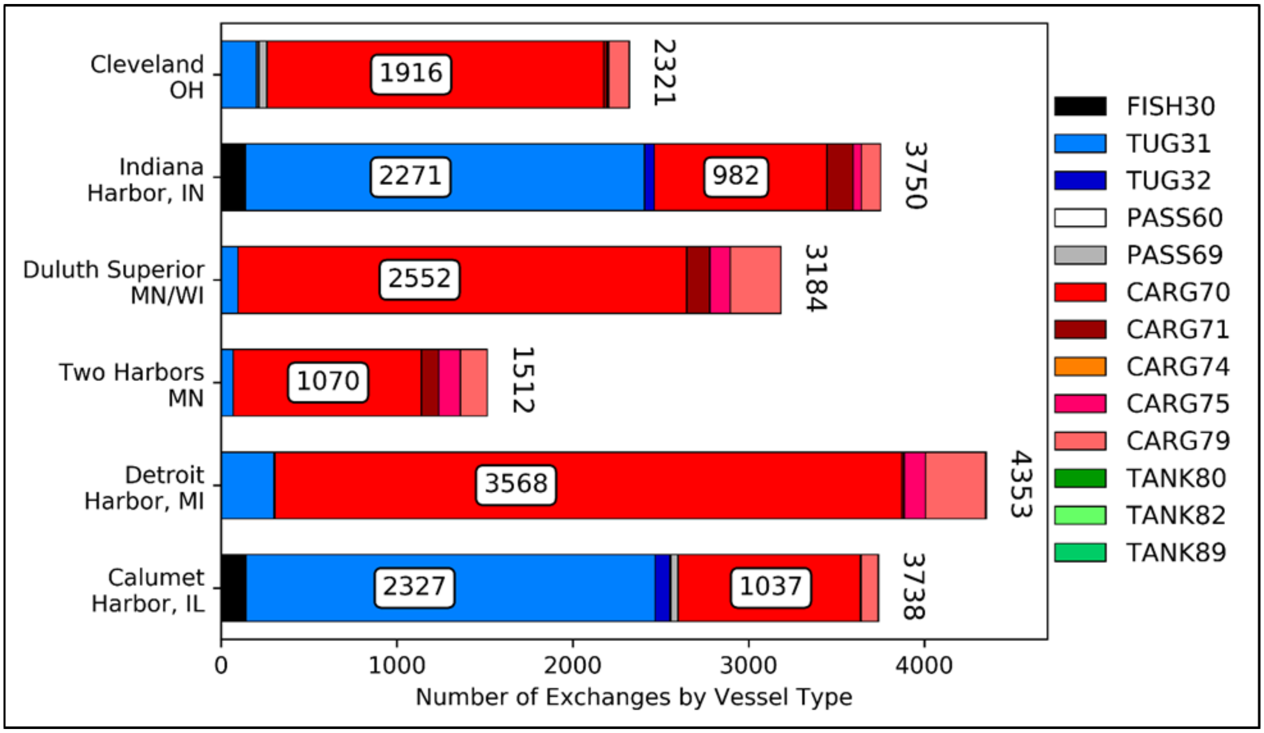

Figure 3. Total Vessel Exchanges (arrivals and departures) by AIS Vessel Type Code from 2015 through 2018 in select port areas. Abbreviations are as follows: FISH = Fishing; TUG = Tug; PASS = Passenger; CARG = Cargo; TANK = Tanker-type vessels. Numbers in the legend refer to specific AIS vessel type codes (USCG 2020). Reprinted from Kress et al. 2021 with permission.

Community Detection

Fig. 4 displays a network graph describing the results of the label-propagation-based community detection algorithm performed on the nationwide portfolio of ports. The algorithm identified distinct communities for the Great Lakes and Ohio River ports. The ports along the East Coast were also assigned a distinct community, although substantial cross-traffic is observed between the East Coast and ports along the Gulf Coast. The community detection algorithm was very discerning of geographic region on the West Coast, assigning the Columbia River ports to a community distinct from the larger West coast community. This distinction further highlights the effect of vessel traffic. For example, riverine systems like Columbia River have a high percentage of total vessel exchanges made by Tugs (77% for the Columbia River Community), similar to the other riverine communities (Mississippi R./East Gulf - 71% and Ohio R. - 95%) and distinct from the West Coast (41% traffic by Tugs).

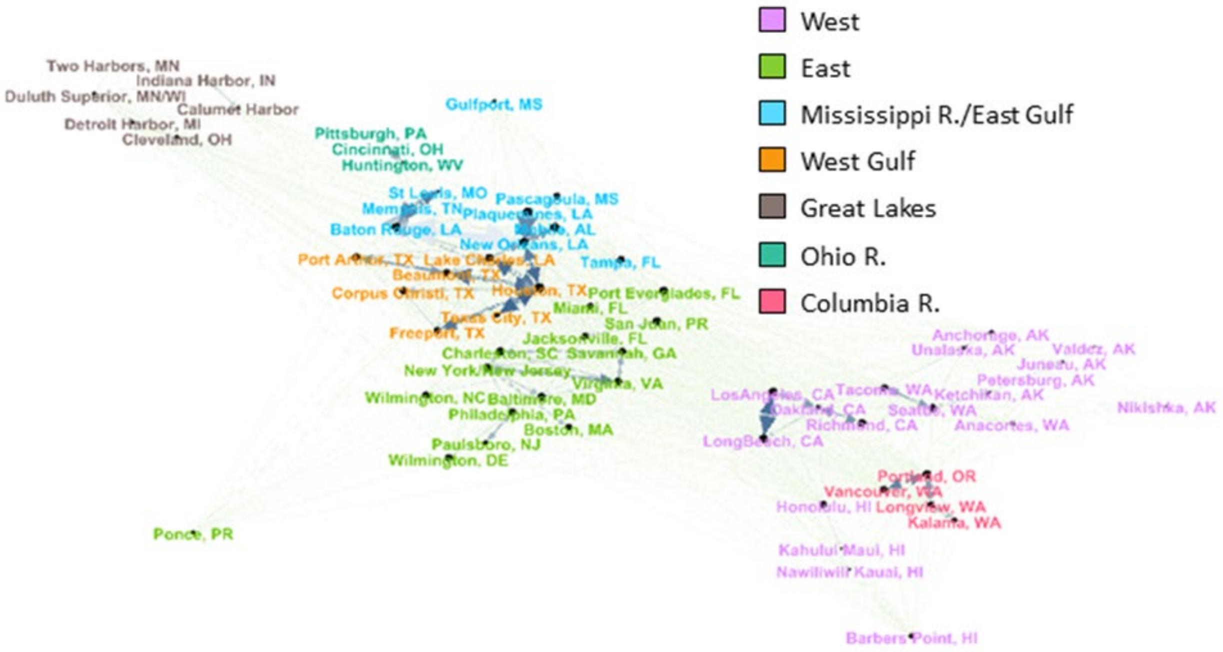

Figure 4. Undirected network graph describing port connectivity. Ports are colored by detected community. Reprinted from Young et al. 2021 with permission.

The detected communities of ports along the Gulf Coast and along the Mississippi River provided some notable results. There were two distinct communities detected for these ports, one with all ports along the Mississippi River and all Gulf Coast ports eastward of Lake Charles, LA ("Mississippi R./East Gulf"), and another that includes all the Texas coastal ports and Lake Charles, LA ("West Gulf"). The detection of a community combining Mississippi River and specific Gulf Coast ports is perhaps not surprising to those familiar with U.S. maritime commerce patterns - the Mississippi River transports a substantial portion of inland U.S. cargo to the Gulf coast (USACE WCSC 2021). This is further supported by the dominant vessel type in this community - a large majority of the vessels at these Mississippi R./East Gulf ports are Tug vessels (71%), indicating that this detected community describes inland riverine traffic being fed to East Gulf coast ports. The West Gulf community is likely distinguished from the Mississippi R./East Gulf community by predominant commodity, specifically the petrochemical vessel traffic associated with the prominence of the petroleum industry in Texas (USACE 2020B). This West Gulf community has the most tanker traffic (20%) of any of the 7 detected communities. Despite these differences, the West Gulf and Mississippi R./East Gulf ports are the most closely linked of any pair of detected communities - 30% of the Mississippi R./East Gulf vessels are exchanged with West Gulf ports and 30% of West Gulf vessels are exchanged with Mississippi R./East Gulf ports.

PageRank

The second analysis run in this study is the PageRank algorithm. PageRank was originally developed to rank webpages by importance for a search engine. To use it on a network of ports, the port areas are conceptualized as webpages and the vessel migration as links between pages (Scully and Chambers 2019). PageRank can identify: (a) individual ports that may have an outsized impact on overall vessel traffic across the network if they are disrupted and (b) regions of the port network whose traffic patterns indicate increased resistance to disruption than apparent from the traffic volume alone. A comparison between port ranking by the total number of vessel arrivals and by

PageRank score is shown in Table 1. This comparison is shown over the full study duration for selected ports. Table 1 demonstrates that the highest trafficked ports are critical to nationwide commerce by either metric. The top three most-trafficked ports by total number of arrivals (Houston, TX, New Orleans, LA, and Baton Rouge, LA) also received the three highest PageRank scores. Disruptions to traffic at any of these three extremely large ports can reasonably be expected to have a large effect on nationwide vessel traffic, as well as the respective regions to which these ports belong.

Table 1. Comparison between port ranking by total number of arrivals and PageRank score (from 2015 - 2018) for selected ports. Reprinted from Young et al. 2021 with permission.

Port	# Arrivals (Rank)	PageRank Score $\times 10^{-2}$ (Rank)	Community
Houston, TX	40,405 (1)	6.40 (1)	West Gulf
New Orleans, LA	36,382 (2)	5.77 (2)	Mississippi R./East Gulf
Baton Rouge, LA	28,670 (3)	4.50 (3)	Mississippi R./East Gulf
Beaumont, TX	16,607 (4)	2.68 (8)	West Gulf
Lake Charles, LA	14,123 (6)	2.27 (12)	West Gulf
Los Angeles, CA	11,829 (7)	3.16 (5)	West
Long Beach, CA	11,211 (9)	2.99 (7)	West
Port Arthur, TX	11,026 (10)	1.81 (18)	West Gulf
Texas City, TX	9,212 (14)	1.58 (26)	West Gulf
Oakland, CA	8,986 (15)	2.61 (10)	West
Freeport, TX	8,498 (17)	1.48 (32)	West Gulf
Mobile, AL	7,663 (18)	1.47 (33)	Mississippi R./East Gulf
Seattle, WA	7,416 (19)	3.24 (4)	West
Tacoma, WA	5,770 (27)	2.35 (11)	West

A more complex relationship between arrivals and PageRank score is shown for ports outside the top three. Mississippi R./East Gulf and West Gulf ports that rank in the range of 4 – 30 (by arrivals) consistently receive lower PageRank scores than might expected from vessel counts alone. In contrast, West coast ports in a similar range consistently receive higher PageRank scores than might expected from vessel counts. The apparent contrast in port rankings of the West coast community and the two Gulf-related communities by arrivals and by PageRank is a direct result of the traffic pattern structure of the West coast region relative to the two Gulf regions. This difference is pertinent to the concepts of regional redundancy and robustness, and PageRank is well-suited to illuminate it. In brief, the total PageRank score of the West coast region is concentrated in a smaller number of large-to-medium sized ports, and the vessel traffic is largely self-contained within the region, such that regional ports do not send PageRank score to other regions. In contrast, the total PageRank score in the two Gulf regions is heavily concentrated in three extremely large ports (larger than any found in the West Coast region), rather than those ports of comparable size (by arrivals) to those found on the West coast. Furthermore, the two Gulf regions are more closely linked to other regions of the network than the West coast, thus the total PageRank score of the two regions is shared among a larger pool of ports.

CONCLUSION

The model of the U.S. MTS presented in this study allows the full description of vessel traffic migration between U.S. ports providing far more detail on connectivity than possible with traditional gross tonnage metrics. With this connectivity model in place, this study has successfully demonstrated two capabilities required to understand and describe national or regional marine traffic resilience. First, it has been demonstrated that community detection via label propagation can quantitatively delineate network regions based on shared vessel traffic. These groupings compares interestingly with a geographically defined regions. In many cases, geographic and community-detected regions overlapped (Great Lakes, Ohio River, East Coast). However, for Gulf of Mexico and Mississippi River ports, the detected communities quite different from the regions that would be predicted from geographic proximity. These results suggest a re-framing of any “regional resilience” study interested in supply chain movements or redundancy to consider traffic flow instead of geographic proximity when defining a “region”.

Second, it has been demonstrated that the PageRank algorithm identifies critical ports whose disruption would have a debilitating effect on traffic flow within a port network. PageRank accounts for both network structure and connectivity. As a result, it provides insights on network-wide robustness that are not available through typical vessel counts or tonnage. This is also relevant to discussions of “hardening” individual ports - specifically expending money and resources to make a given port more resistant to disruption. Ideally the hardened port would improve both the robustness of regional traffic flow as well as its own traffic. These PageRank metrics may be used in addition to overall tonnage to identify ports that are not just commercially critical to their respective regions, but also have a large role in providing robustness to nationwide commerce and trade.

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