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Towards a Comparative Index of Seaport Climate Vulnerability: Developing Indicators from Open-Data

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TOWARDS A COMPARATIVE INDEX OF SEAPORT CLIMATE VULNERABILITY: DEVELOPING INDICATORS FROM OPEN-DATA

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ABSTRACT

This work was motivated in part by Austin Becker's 2013 dissertation, *Building Seaport Resilience for Climate Change Adaptation: Stakeholder Perceptions of the Problems, Impacts, and Strategies*, which surveyed global port authorities' perceptions and plans for climate change adaptation and found a disconnect between perceptions of climate impacts and a lack of policies to address them. That work called for the development of a nationwide risk and vulnerability index for ports as a next step in the climate adaptation process for seaports. Climate change adaptation was found to be in the early planning phase for most ports globally, and assessing vulnerabilities is a recommended first step in risk-reduction.

In the face of climate change impacts projected over the coming century, seaport decision makers have the responsibility to manage risks for a diverse array of stakeholders and enhance seaport resilience against climate and weather impacts. At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their own port the number one priority. But, at the multi-port (regional or national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of the marine transportation system as a whole. Such multi-port decisions can be supported by information products such as indicator-based composite indices that allow for objective assessment of relative vulnerabilities among a sample of ports.

To that end, this work, consisting of three distinct but theoretically related manuscripts, advances the state of data-driven Climate Impact Adaptation and

Vulnerability (CIAV) decision-support products for the seaport sector by assessing the current state of vulnerability assessments for seaports (manuscript 1), compiling and refining a set of candidate indicators of seaport climate and extreme-weather vulnerability from open-data sources for 23 major seaports of the United States' North Atlantic region and creating and applying a Visual Analogue Scale (VAS) instrument for expert-evaluation of the candidate indicators (manuscript 2), and finally by applying the Analytic Hierarchy Process (AHP) with port-experts to weight a selection of the indicators to examine the suitability of the indicator-based vulnerability assessment (IBVA) approach and available open-data to create a composite index of relative climate and extreme-weather vulnerability for the sample of ports.

The first manuscript in this work provides an overview of a variety of approaches that set out to quantify various aspects of seaport vulnerability. It begins with discussion of the importance of a "multi-port" approach to complement the single case study approach more commonly applied to port assessments. It then addresses the components of climate vulnerability assessments and provides examples of a variety of approaches. Finally, it suggests an opportunity exists for further research and development of standardized, comparative CCVA methods for seaports and the marine transportation system that can support CIAV decisions and allow decision-makers to compare mechanisms and drivers of climate change across multiple ports.

When comparing vulnerabilities of multiple disparate systems such as ports in a region, IBVA methods can yield standardized metrics, allowing for high-level analysis to identify areas or systems of concern. To advance IBVA for the seaport sector, the second manuscript in this work investigates the suitability of publicly available open-data, generally collected for other purposes, to serve as indicators of climate and extreme-weather vulnerability for 23 major seaports in the Northeast United States, addressing the question: How sufficient is the current state of data reporting for and about the seaport sector to develop expert-supported vulnerability indicators for a regional sample of ports? To address this question, researchers developed a framework for expert-evaluation of candidate indicators that can be replicated to develop indicators in other sectors and for other purposes. Researchers first identified candidate indicators from the CCVA and seaport-studies literature and vetted them for data-availability for the sample ports. Candidate indicators were then evaluated by experts via a mind-mapping exercise, and finally via a visual analogue scale measurement instrument. Researchers developed a VAS instrument to elicit expert perception of the magnitude and direction of correlation between candidate indicators and each of the three dimensions of vulnerability that have become standard in the CCVA literature, e.g., exposure, sensitivity, and adaptive capacity. For candidate indicators selected from currently available open-data sources, port-expert respondents found notably stronger correlation with the exposure and sensitivity of a port than with the adaptive capacity. Results suggests that better data reporting and sharing within the maritime transportation sector will be necessary before IBVA will become feasible for seaports.

The third manuscript in this work describes a method of weighting indicators for assessing the exposure and sensitivity of seaports to climate and extreme-weather impacts. To examine the suitability of IBVA methods and available data to discriminate relative vulnerabilities among a sample of ports, researchers employed AHP to generate weights for a subset of expert-selected indicators of seaport exposure and sensitivity to climate and extreme-weather. The indicators were selected from the results of the VAS survey of port-experts who ranked candidate indicators by magnitude of perceived correlation with the three components of vulnerability; exposure, sensitivity, and adaptive capacity. As those port-expert respondents found significantly stronger correlation between candidate indicators and the exposure and sensitivity of a port than with a port's adaptive capacity, this AHP exercise did not include indicators of adaptive capacity. The weighted indicators were then aggregated to generate composite indices of seaport exposure and sensitivity to climate and extreme weather for 23 major ports in the North East United States. Rank order generated by AHP-weighted aggregation was compared to a subjective expert-ranking of ports by perceived vulnerability to climate and extreme weather. For the sample of 23 ports, the AHP-generated ranking matched three of the top four most vulnerable ports as assessed subjectively by port-experts. These results suggest that a composite index based on open-data may eventually prove useful as a data-driven tool for identifying outliers in terms of relative seaport vulnerabilities, however, improvements in the standardized reporting and sharing of port data will be required before such an indicator-based assessment method can prove decision-relevant.

Overall, this body of work began with a call to develop a method to assess the relative vulnerabilities of seaports to climate and extreme-weather impacts. In the first of three manuscripts, this research identifies an opportunity to contribute to the CCVA literature for the seaport sector by piloting a multi-port vulnerability assessment method based on the use of indicators. The second manuscript in this work contributes to the field of IBVA for seaports by identifying from open-data sources and refining via expert-elicitation methods a set of expert-evaluated candidate indicators of seaport climate and extreme-weather vulnerability. This indicator-evaluation resulted in the finding that adaptive capacity is considered by port-experts as the most difficult of the three components of vulnerability (i.e., exposure, sensitivity, and adaptive capacity) to represent with quantitative data. The final manuscript of this work contributes to the body of CCVA and seaport-studies literature by building and trialing a composite-index of seaport climate and extreme-weather vulnerability based on the evaluated indicators and using AHP to generate component weights. By modeling seaport vulnerability with an indicator-based composite index and comparing results to expert expectations, this work has shown the potential of indicator-based methods to bring a data-driven approach to the CIAV decision-making process, however, results suggest that the current state of publicly available data for and about the seaport sector is not currently sufficient for a robust, expert-supported index.

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PREFACE

This dissertation is written in manuscript form. Each chapter is written as a separate manuscript and prepared for publication separately in different scientific journals; as such, they are formatted as required for submission to each journal. Manuscript 1 was published by Springer Publishing 3 August 2017 in *Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains*, NATO Science for Peace and Security Series C. Manuscript 2 is prepared for submission to the Journal of Regional Environmental Change. Manuscript 3 is prepared for submission to the Journal of Environment Systems and Decisions.

Manuscript 1: Seaport Climate Vulnerability Assessment at the Multi-Port Scale: A Review of Approaches

Manuscript 2: Expert Evaluation of Open-Data Indicators of Seaport Vulnerabilities to Climate and Extreme Weather Impacts

Manuscript 3: Using AHP to Weight Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic Ports

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Abstract

In the face of climate change impacts projected over the coming century, seaport decision makers have the responsibility to manage risks for a diverse array of stakeholders and enhance seaport resilience against climate and weather impacts. At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their port the number one priority. But, at the multi-port (regional or national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of the marine transportation system as a whole. This chapter provides an overview of a variety of approaches that set out to quantify various aspects of seaport vulnerability. It begins with discussion of the importance of a "multi-port" approach to complement the single case study approach more commonly applied to port assessments. It then addresses the components of climate vulnerability assessments and provides examples of a variety of approaches. Finally, it concludes with recommendations for next steps.

Key Findings:

- Sparse examples exist of comparative CCVA for ports
- Expert-elicitation has been a common method to select indicators
- Most efforts at CCVA to date focus on the single-port scale

Seaports Are Critical, Constrained, and Exposed

Seaports represent an example of spatially defined, large scale, coast-dependent infrastructure with high exposure to projected impacts of global climate change (Becker et al. 2013, Hanson et al. 2010, Melillo, Richmond, and Yohe 2014). Seaports play a critical role in the global economy, as more than 90% of global trade is carried by sea (IMO 2012). A disruption to port activities can interrupt supply chains, which can have far reaching consequences (Becker, Newell, et al. 2011, Becker et al. 2013, IPCC 2014a). Seaports are inextricably linked with land-based sectors of transport and trade, and serve both the public and private good. Globally, climate change adaptation is still in the planning stages for most seaports (Becker, Inoue, et al. 2011), yet the inevitable imperative for climate resiliency looms, as atmospheric concentrations of greenhouse gasses, the primary driver of climate change (IPCC 2013), continue to accumulate (WMO 2015). Indeed, most aspects of climate change will persist for centuries even if anthropogenic emissions of carbon dioxide were halted today (IPCC 2013).

Functionally restricted to the water's edge, seaports will face impacts driven by changes in water-related parameters like mean sea level, wave height, salinity and acidity, tidal regime, and sedimentation rates, yet they can also be affected directly by changes in temperature, precipitation, wind, and storm frequency and intensity (Koppe, Schmidt, and Strotmann 2012). The third U.S. National Climate Assessment (NCA) (Melillo, Richmond, and Yohe 2014) of the U.S. Global Change Research Program notes that impacts from sea level rise (SLR), storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, and other climatic conditions are already affecting the reliability and capacity of the U.S. transportation system. While the U.S. NCA predicts that climate change impacts will increase the total costs to the nation's transportation systems, the report also finds that adaptive actions can reduce these impacts.

In the face of these challenges, port decision makers have the responsibility to manage risks for a diverse array of stakeholders and enhance seaport resilience against climate and weather impacts. At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their port the number one priority. But, at the multi-port (regional or national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of the marine transportation system as a whole.

Recognizing a regional or national set of ports and waterways as part of an interconnected marine transportation system (MTS)[1], how should responsible decision makers prioritize the climate adaptation decisions for systems that involve multiple ports? This chapter provides an overview of a variety of approaches that set out to quantify various aspects of seaport vulnerability. It begins with discussion of the importance of a "multi-port" approach to complement the single case study approach more commonly applied to port assessments. It then addresses the components of climate vulnerability assessments and provides examples of a variety of approaches. Finally, it concludes with recommendations for next steps.

[1] The marine transportation system, or MTS, consists of waterways, ports, and inter-modal land-side connections that allow the various modes of transportation to move people and goods to, from, and on the water. (MARAD 2016)

Impediments to Multi-Port Adaptation

A 2016 study which quantified the resources, time and cost of engineering minimum-criteria "hard" protections against sea level rise for 223 of the world's most economically important seaports, suggested insufficient global capacity for constructing the proposed protective structures within 50-60 years (Becker et al. 2016). As individual actors and governments consider climate-adaptation solutions for seaports, a global uncoordinated response involving heavy civil infrastructure construction may be unsustainable simply from a resource availability perspective (Becker et al. 2016, Becker, Newell, et al. 2011, Peduzzi 2014). Given limited financial and construction resources for the implementation of engineered protection across many ports, some form of prioritization for national and regional-scale climate-adaptation will likely be necessary. Port authorities have expressed that although general concern for climate change exists, awareness of sea level rise is limited and the planning for adaptation is lacking (Becker et al. 2010).

The implementation of strategic adaptation on a multi-port scale is further challenged by complex and dynamic regional differences defined by varying landscapes and geographies that are far from uniform in their climate change vulnerability. Some ports, for example, may by surrounded by lowlands at risk to inundation from sea level rise. For these ports, the ground transportation systems may by more threatened than the port itself (e.g., Port of Gulfport, MS). In other areas, storm surge might be amplified by the geomorphology of an estuarine system (e.g., Providence, RI).

At the single port scale, the design of engineering protection during a port's expansion can benefit by estimating how long the infrastructure will last and withstand future impacts (Becker, Toilliez, and Mitchell 2015). However, justifying major investments is challenged by the uncertainty involved in projecting the extent to which ports will be impacted this century (Becker and Caldwell 2015). In the following section, we first discuss the concept of measuring vulnerability, risk, and resilience, then describe assessment methods employed by individual ports. Following, we discuss the need for multi-port assessment approaches and work in this area to date.

Assessing Climate Vulnerabilities to Facilitate Far-Sighted Resilience Planning

Vulnerability and resilience are two theoretical concepts, sometimes defined complementarily, other times described as opposite sides of the same coin, (Gallopín 2006, Linkov et al. 2014) that have gained increasing attention in the climate change adaptation and hazard risk reduction literature. As theoretical notions, resilience and vulnerability are not directly measurable, and some researchers (Barnett, Lambert, and Fry 2008, Eriksen and Kelly 2007, Hinkel 2011, Klein 2009, Gudmundsson 2003) have criticized attempts to assess them as unscientific and or biased. However, policymakers are increasingly calling for the development of methods measure relative risk, vulnerability, and resilience (Cutter, Burton, and Emrich 2010, Hinkel 2011, Rosati 2015).

The International Association of Ports and Harbors (IAPH) defines seaport vulnerability using three components: *exposure*, *sensitivity*, and *adaptation capacity* (Koppe, Schmidt, and Strotmann 2012). Measuring a port's *exposure* requires downscaled regional climate projections which may not yet be available for some port regions, and where they are available, necessarily contain uncertainty. A port on the west coast of the U.S., for example, may be considered less exposed to hurricanes than a port on the east coast. Port exposure, then, may be analyzed using a multiple scenario approach, with a range of values for the applicable climate variables. Measuring port *sensitivity* and *adaptation capacity* generally requires site-specific analyses. By analyzing the impacts of projected changes in regional or even local climate variables and evaluating a port's design criteria in light of those impacts, the sensitivity to those changes can be determined for a port and its assets. Recently constructed infrastructure designed for higher intensity storms, for example, may be considered as less sensitive to a given storm event than infrastructure that is in a state of disrepair already. An assessment of a port's adaptive capacity, taking into account the port system's planning parameters, management flexibility and existing stresses, can reveal obstacles to a port system's ability to cope with climate change impacts. A port with robust planning procedures and more wealth, for example, may be considered to have a higher adaptive capacity than a port that has lesser planning and resources. In 2011, Becker and collaborators made a first attempt at quantifying international seaport adaptive capacity by developing a scoring system based on port authority responses regarding climate adaptation policies currently in place (Becker, Inoue, et al. 2011).

Because exposure and vulnerability are dynamic (IPCC 2012), varying across spatial and temporal scales, and individual ports are differentially vulnerable and exposed, assessments should be iterative with multiple feedbacks, shaped by people and knowledge (IPCC 2014a), and take a "bottom up" approach by including input from a diverse stakeholder cluster to ensure that the variables representing exposure, sensitivity and adaptive capacity are empirically identified by and important to the stakeholders, rather than presupposed by the researchers or available data (Smit and Wandel 2006).

A concept related to vulnerability, *risk* is a measure of the potential for consequences where something of value is at stake and where the outcome is uncertain (IPCC 2014b). Risk can be quantitatively modeled as $Risk = p(L)$, where L is potential loss and p the probability of occurrence, however, both can be speculative and difficult to measure in the climate-risk context. Risk, in the context of climate change, is often defined similarly to vulnerability (Preston 2012, IPCC 2014a), but with the added component of *probability,* thus making *vulnerability* a component of *risk.*

Resilience, another closely related term with a more positive connotation than *vulnerability*, is defined by the IPCC as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation" (IPCC 2014b). The National Academy of Science (The National Academies 2012) and the President of the United States (Obama 2013) define critical infrastructure resilience as, "the ability to prepare, resist, recover, and more successfully adapt to the impacts of adverse events." With *resilience* defined in terms of ability, and *vulnerability* defined in terms of susceptibility, it is tempting to consider them polar opposites (Gallopín 2006), however, resilience can also be considered a broader concept than vulnerability. Most working definitions of resilience involve a process that begins before a hazardous impact, but also includes temporal periods during and after the impact. Resilience, like vulnerability, can also encompass coping with adverse effects from a multitude of hazards in addition to climate change. By increasing our understanding of the distribution of seaport climate vulnerabilities, the overall *resilience* of the MTS may be enhanced.

CIAV Decision-Support for the Seaport Sector

As port decision makers face climate impact, adaptation, and vulnerability (CIAV)[2] decisions, climate change vulnerability assessments (CCVA), including risk and resilience assessments support those decisions by addressing the "adapt to what" question (IPCC 2014a). The process enables a dialog among stakeholders and practitioners on planning and implementation of adaptation measures to enhance resilience. The Intergovernmental Panel on Climate Change (IPCC) describes vulnerability and risk assessment as "the first step for risk reduction, prevention, and transfer, as well as climate adaptation in the context of extremes." [p. 90] (IPCC 2012) The U.S. NCA considers vulnerability and risk assessment an "especially important" [p. 137] (Melillo, Richmond, and Yohe 2014) area in consideration of adaptation strategies in the transportation sector. Such assessments can be made at the single-port scale or at the multi-port scale, with each approach having benefits for different types of decision makers.

Single-Port Scale

Among climate change vulnerability, resilience, and risk assessment methods applied to seaports, most efforts to date have been limited in scope to exposure-only assessments (Hanson et al. 2010, Nicholls et al. 2008), or limited in scale to a single port; either as case studies (Koppe, Schmidt, and Strotmann 2012, Cox, Panayotou, and

[2] Climate impact, adaptation, and vulnerability (CIAV) decisions are choices, the results of which are expected to affect or be affected by the interactions of the changing climate with ecological, economic, and social systems.

Cornwell 2013, USDOT 2014, Messner et al. 2013, Chhetri et al. 2014) or as self-assessment tools (NOAA OCM 2015, Semppier et al. 2010, Morris and Sempier 2016).

While single-port scale CCVA inform CIAV decisions within the domain of one port (e.g., Which specific adaptations are recommended for my port?), a CCVA approach that objectively compares the relative vulnerabilities of multiple ports in a region could support CIAV decisions at the multi-port scale (e.g., Which ports in a region are the *most* vulnerable and urgently in need of adaptation?). The hitherto focus on individual port scale assessments presents a challenge for how to describe the *distribution* of climate-vulnerabilities across multiple ports.

Multi-Port Scale

At the multi-port scale, an evaluation of *relative* climate-vulnerabilities or the *distribution* of those vulnerabilities among a regional or national set of ports requires standard measures (e.g. indicators, or metrics). Directly immeasurable, concepts such as resilience and vulnerability are instead made operational by mapping them to functions of observable variables called indicators. *Indicators* are measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly, adequately measured (Gallopin 1997, Hinkel 2011). Indicator-based assessment methods, therefore, are generally applied to assess or 'measure' features of a system that are described by theoretical concepts. The indicator-based assessment process of operationalizing immeasurable aspects of a system consists (Hinkel 2011) of two or sometimes three steps: 1) defining the response to be indicated, 2) selecting the indicators, 3) aggregating the indicators (this step is sometimes omitted but necessary to yield a numerical 'score' or create a comparative index). In this section, we investigate examples of indicator-based assessment methods applied to multi-port systems to aid the further development of such methods for the port sector, which can yield benefits including the ability to not only ‘measure’ immeasurable concepts like vulnerability and resilience, but also to index and compare them across entities.

Factors Considered in Port Resilience Evaluation

The US National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM) along with the federal interagency Committee on the Marine Transportation System (CMTS) produced a port resilience planning web-based tool (NOAA OCM 2015), tailored towards communities undergoing a port expansion or reconstruction, that assembles resilience indicators and their datasets. This web-based prototype tool came online in 2015 with the stated purpose of assisting transportation planners, port infrastructure planners, community planners, and hazard planners to explore resilience considerations and options in developing marine transportation projects. Inspired by and aligned with broader resilience objectives called for in the CMTS’s strategic action plan (USCMTS 2011), this tool shows port communities what to look for in resilient freight transportation infrastructure. While the Port Tomorrow resilience planning tool assembles seaport resilience indicators, provides links to their potential data sources, and organizes them with categories and subcategories into a framework for assessing port resilience, the tool stops short of providing a method to normalize and aggregate the indicators into a comparative score.

Assessing Global Port City *Exposure*

One of the few CCVA to comparatively assess multiple ports, the 2010 work by Hanson, Nichols, et al. (Hanson et al. 2010) made some of the first progress towards comparative seaport CCVA by focusing on assessing the *exposure* component of seaport climate-vulnerability. Part of a larger project on Cities and Climate Change that was sponsored by the Organization for Economic Cooperation and Development (OECD), this global screening study assesses the exposure[3] of all 136 international port cities with over one million inhabitants in 2005 to coastal flooding. The analysis considers exposure to present-day extreme water levels (represented by a 100-year flood) as well as six future scenarios (represented by the decade 2070 – 2080) that include projected changes in sea level and population. The researchers base the methods used on determining the numbers of people who would be exposed to the water level of interest and then using that number to estimate the potential assets exposed within each city. The researchers then rank the cities by number of people exposed and by 2005 U.S. dollar value of assets exposed. These two response variables, i.e. people and dollar value of assets, are semi-empirical quantities rather than theoretical concepts, and as such, the methods involved in this study are not directly analogous to other indicator-based assessment methods. Instead of using indicators to serve as proxies for some immeasurable concept, this study uses indicators to approximate concrete numbers that, due to scale, are difficult to measure.

This study took the form of a Geographic Information System (GIS) elevation-based analysis, after authors (McGranahan, Balk, and Anderson 2007). The researchers used 100-year historic flood levels taken from the Dynamic Interactive Vulnerability Assessment (DIVA) database as current extreme water levels to be modeled in GIS for each city. For the future water levels, the researchers calculate two different scenarios,

[3] Exposure refers to the nature and extent to which a system is subjected to a source of harm, taking no account of any defenses or other adaptation.

one that considers only natural factors (i.e. a calculated "storm enhancement factor," historic subsidence rates, and sea level rise (SLR)), and another that adds to those factors one representing anthropogenic subsidence.

For current population, the study takes the ambient population distribution estimates from LandScan 2002 (Bright and Coleman 2003) for each city, delimited by city extents from post code data. The postcodes are taken from geocoding data and, for cities in the USA, from Metropolitan Statistical Areas (MSAs) from Census data. The authors resample the 1km LandScan 2002 data to 30m for all cities in the US and UK and resampled to 100m for the remaining cities. To determine population distribution by elevation, the authors use 90m resolution topographic data from the Shuttle Radar Topography Mission (SRTM) for most cities, 30m SRTM data for the US, and a 10m Digital Elevation Model (DEM) provided by Infoterra for the UK. The authors then overlay each LandScan population distribution over the relevant Digital Terrain Model (DTM), yielding for each city a map of geographical cells with defined population and elevation. From these maps, the authors are able to isolate total population within 1m vertical bands of elevation. To represent future population, the authors start with baseline population projections from the OECD ENV-Linkages model, which itself is based on United Nations (UN) medium variant projections to 2050. To bring these projections to 2070, the authors extrapolate them forward using national growth rates and UN projected rates of urbanization.

To indicate the dollar value of assets, the researchers use what they describe as a "widely used assumption in the insurance industry" (Hanson et al. 2010, 92) (p 92) that as urban areas are typically more affluent than rural areas, each person in a city has assets that are 5 times the national Gross Domestic Product (GDP). This simple calculation is based on the national per capita GDP Purchasing Power Parity (PPP) values for 2005 from the International Monetary Fund (IMF) database. To indicate future GDP, the study uses OECD baseline projections to 2075. To find the total value of assets exposed then, the researchers take the number of people exposed (from the GIS maps described above) and multiply that number by a country's GDP PPP times five.

Using the indicators described above, and organized in Table 1, this study is ultimately able to produce rankings of port cities exposed to coastal flooding by number of people and by dollar value of assets exposed to extreme water levels in 2005 and for projected extreme water levels in 2075.

Table 1 Indicators, categories and data sources used in (Hanson et al. 2010)

Indicator Categories	Indicator Sub-Categories	Indicators	Data Source
Elevation	Elevation	elevation	Shuttle Radar Topography Mission (SRTM)
Population	Population	population distribution	Landscan 2002
Future Population	Future Population	Projected Population in 2075	OECD ENV-Linkages Model
	Projected Urbanization Rate (assumed uniform within country)	2005–2030 trends extrapolated to 2075, assuming that urbanization rates will saturate at 90%, except where it is already larger than this value (e.g. in special cases like Hong Kong)	UN projected urbanization rates 2005-2030 (are then extrapolated to 2075)
Current Water Level	Current Water Level	100 yr storm surge	DIVA
Future Water Level	SLR	assumes a homogenous global rise of 0.5m by 2070	assumed from lit.

Indicator Categories	Indicator Sub-Categories	Indicators	Data Source
	Anthropogenic Subsidence	assumes uniform 0.5m decline in land level (from 2005-2070) in port cities located in deltas	assumed
	Natural Subsidence	Annual Rate of subsidence extrapolated to 2070	used annual sub. Rate from DIVA
	Storm Enhancement Factor	10% increase in extreme water level assumed for cities exposed to TC, 10% increase assumed for cities bet. 45 and 70 deg latitude which are assumed exposed to Extra-TC	CHRR (Columbia), historical TC tracks, Munich Re
Value of Assets	Value of Assets	national per capita GDP PPP (assuming each person in a city has assets 5 x annual GDP per capita)	www.imf.org
Future Value of Assets	Future Value of Assets	Projected GDP per capita	OECD Baseline projections to 2075

Assessing Regional Port *Interdependency* Vulnerabilities

Another example of CCVA that extends beyond the single-port scale is the 2013 work by Hsieh et al. that examines the vulnerability of port failures from an interdependency perspective using four commercial ports in Taiwan as empirical case studies (Hsieh, Tai, and Lee 2013). The method determines factors vulnerable to disasters by reviewing literature and conducting an in-depth interview process with port experts; in this way, the researchers developed 14 ‘vulnerable factors’ that can be considered similar to our described indicators (Berle, Asbjørnslett, and Rice 2011).

To develop the 14 indicators, the authors held a series of discussions in open participatory meetings. Eleven experts participated, including port officials, government officials, planners, and scholars. The discussions classified the indicators into four categories: accessibility, capability, operational efficiency, and industrial cluster/energy supply, as shown in Table 2. The process to determine weights for the indicators followed the analytic network process (ANP) of Jharkharia and Shankar (2007) (Jharkharia and Shankar 2007), and involved constructing an impact matrix via fuzzy cognitive maps (FCMs) developed and evaluated during these participatory meetings. The impact matrix represents magnitudes of causal effects of each indicator compared to every other indicator.

Table 2 Indicators, categories, and data sources used in (Hsieh, Tai, and Lee 2013)

Indicator Categories	**Indicators**	**Data Source**
Accessibility	Ground access system (%)	GIS maps
	Travel time (minute)	GIS maps
	Shipping route density (lines)	port annual statistics overviews
Capability	Gantry crane capacity (TEUs)	Ministry of Transportation and Communications
	Facility supportability (%)	port annual statistics overviews
	Wharf productivity (10^3 tons/meter)	Ministry of Transportation and Communications
Operational Efficiency	EDI connectivity (%)	Ministry of Transportation and Communications
	Turnaround time (hr)	Ministry of Transportation and Communications
	Labor productivity (tons/person)	port annual statistics overviews
	Berth occupancy rate (%)	port annual statistics overviews
Industrial Cluster/Energy Supply	Investment growth (10^9 NTD[4])	national industry, commerce, and service census
	FTZ business volume (10^9 NTD)	national industry, commerce, and service census
	Electric power supply (%)	GIS maps
	Gas supply (%)	GIS maps

To standardize the indicators, the experts completed a questionnaire that had them identify threshold values for each indicator. The researchers provided a scale from

[4] NTD = New Taiwan Dollars

0-4, with 0 indicating that the port can operate normally, 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 value (i.e. minimum or maximum value, depending upon whether the indicator indicates vulnerability or competitiveness) for each indicator that would lead the port to each of the five results described in the scale 0-4. 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. Table 3 shows the standardized indicators (called "Vulnerable factors"), their units, and their threshold values.

Table 3 Standardized indicators showing threshold values from (Hsieh, Tai, and Lee 2013)

Vulnerable factors		Rating				
		0	1	2	3	4
(1)	Ground access system (%)	>90	90–80	80–50	50–20	<20
(2)	Travel time (minute)	<90	90–120	120–150	150–180	>180
(3)	Shipping route density (lines)	<15	15–100	100–200	200–300	>300
(4)	Gantry crane capacity (TEUs*)	>90	90–70	70–50	50–35	<35
(5)	Facility supportability (%)	>80	80–70	70–50	50–40	<40
(6)	Wharf productivity (10^3 tons/meter)	>5	5–4	4–2	2–1.5	<1.5
(7)	EDI connectivity (%)	>90	90–80	80–50	50–20	<20
(8)	Turnaround time (hr)	<24	24–36	36–48	48–72	>72
(9)	Labor productivity (tons/person)	>350	350–250	250–150	150–100	<100
(10)	Berth occupancy rate (%)	>70	70–50	50–30	30–10	<10
(11)	Investment growth (10^9 NTD**)	>10	10–8	8–4	4–2	<2
(12)	FTZ business volume (10^9 NTD**)	>10	10–8	8–4	4–2	<2
(13)	Electric power supply (%)	>90	90–80	80–50	50–20	<20
(14)	Gas supply (%)	>50	50–30	30–20	20–5	<5

The data for the indicators come from published statistics, literature, and GIS maps. Table 2 shows the specific data source for each of the 14 indicators. To score a port's vulnerability, the researchers standardize a port's raw indicator data using Table 3, then sum the standardized indicators multiplied by their weights to produce a total vulnerability score. The results for the 4 Taiwanese case study ports are show in Table 4.

Table 4 Results of port vulnerability analysis from (Hsieh, Tai, and Lee 2013)

Score of vulnerable factors		Keelung	Taipei	Taichung	Kaohsiung
(1)	Ground access system	3	2	2	1
(2)	Travel time	2	1	0	0
(3)	Shipping route density	1	1	1	4
(4)	Gantry crane capacity	3	3	1	0
(5)	Facility supportability	0	3	2	0
(6)	Wharf productivity	0	2	0	1
(7)	EDI connectivity	1	1	1	1
(8)	Turnaround time	0	1	1	1
(9)	Labor productivity	0	0	1	1
(10)	Berth occupancy rate	3	1	2	2
(11)	Investment growth	4	2	0	0
(12)	FTZ business volume	4	1	0	0
(13)	Electric power supply	2	0	1	0
(14)	Gas supply	1	0	0	0
Port vulnerability		1.6131	1.8063	0.8746	0.7724

In addition to the vulnerability assessment method herein described, Hsieh et al. also conducted an interdependency analysis to determine how strongly each indicator affects and is affected by the other indicators of the port system. This analysis uses groups of experts who fill out a matrix form during an iterative Delphi-style process, similar to that used during the first stages of this project.

Assessing Relative Port Performance

At the multi-port, MTS scale, CCVA have been sparse. Indicator-based multi-port assessments to date have tended to focus on port *performance* rather than *vulnerabilities* or *resilience.* Here, we investigate some of the methods used to assess relative port *performance* in an effort to inform new CCVA methods at the multi-port scale.

Port Performance Indicators: Selection and Measurement (PPRISM)

Carried out from 2010 to 2011 by the European Seaports Organization (ESPO) and co-funded by the European Commission, the Port Performance Indicators: Selection and Measurement (PPRISM) program was designed to take a first step towards establishing a culture of performance measurement in European ports by identifying a set of relevant and feasible performance indicators for the European port system. The aim of this project was to develop indicators that allow the port industry to measure, assess, and communicate the impact of the European port system on society, the environment, and the economy. Although PPRISM does document equations (ESPO 2011) used to aggregate numbers used for individual indicators, this study does not aggregate the indicators themselves into a total performance score. The future plans for PPRISM include the establishment of a Port Sector Performance Dashboard (as part of a European Port Observatory website) that will not publish or compare interport performance, but illustrate the performance of the whole European system of ports.

The indicator selection process began with input from five European Universities: University of the Aegean, Institute of Transport and Maritime Management Antwerp, Eindhoven University of Technology, Vrije Universiteit Brussel, and Cardiff University. These academic partners came up with 159 port performance indicators based on a literature review and industry current practices and organized them under the following five categories: Market Trends, Logistic Chain and Operations, Environmental Indicators, Socio-economic Indicators, and Governance Indicators. The academic partners excluded indicators that did not fulfill one of the following criteria (ESPO 2010):

P: Policy relevance - Monitor the key outcomes of strategies, policies and legislation and measure progress towards policy goals. Provides information to a level appropriate for policy decision – making.

I: Informative – Supplies relevant information with respect to the port's activities.

M: Measurable – Is readily available or made available at a response cost/benefit ratio. Updated at regular intervals in accordance with reliable procedures.

R: Representative – Gives clear information and is simple to interpret. Accessible, publicly appealing and therefore likely to meet acceptance.

F: Feasible / Practical - Requires limited numbers of parameters to be established. Uses existing data and information wherever possible. Simple to monitor.

Following the academic pre-selection process, the 159 indicators were assessed by ESPO members. ESPO organized four special workshop sessions for this purpose in combination with its Technical Committee meetings. During these workshops, ESPO members screened the pre-selected indicators and discussed their proposed definitions and calculation methods with the academic partners. ESPO members considered and provided qualitative feedback on the data availability and relevance of the proposed indictors. Additionally, ESPO members provided quantitative feedback on the feasibility and acceptability of each indicator by using a five point Linkert-style scale during two rounds, following the Delphi methodology[5]. The first round of this Delphi-style assessment process by ESPO members narrowed the 159 indicators down to 39. The second round with the modified indicators resulted in additional indicators, adjustments to indicator definitions and calculation formulas, renamed indicators, and produced a new list of 45 indicators.

The four rounds involved in the Delphi-style indicator assessment included only internal stakeholders (i.e. representatives of the European port authorities). In an effort

[5] The Delphi method is an iterative, multistage response process designed to generate expert consensus.

to increase the validity and reliability of the work, the scope was then expanded to include external stakeholders, targeting a “representative external stakeholder response panel” (ESPO 2011) to include port users, government, and academics. This external stakeholder assessment made use of an online survey that was freely available without restrictions on who was invited to participate. The survey was advertised in social media, specialized presses, and personal networks and remained open for four months (February – May 2011). This external stakeholder assessment helped to narrow the list of indicators further to 42.

The results of the internal and external stakeholder assessments guided the final choice of 14 indicators that were then tested in a pilot phase. The 42 indicators were narrowed down to 14 (Table 5) through a process of weighing stakeholders’ acceptance vs the feasibility of implementation of each indicator.

The pilot consisted of an EU-wide project to test the feasibility of the 14 selected indicators, with the intent to uncover the real-world availability of data and the willingness of port authorities to provide data. For the pilot study, the PPRISM group sent an electronic form to all port authorities associated with ESPO accompanied by an explanatory letter from ESPO Secretary General Patrick Verhoeven and received back a total of 58 forms fully or partially filled out. The pilot revealed problems with data availability, unclear data requests, and port participation. Given that data provision is voluntary, and hence, the number of ports submitting could fluctuate from year to year, the pilot study recommended that, at least for the initial stages of any port performance dashboard, reporting data in the form of trends rather than single values is the best approach. The results of the pilot study are shown in Table 5.

Table 5 Findings and conclusions for each piloted indicator (ESPO 2012)

Indicators	Pilot result	Next steps
1. Maritime traffic	Relevant and feasible	Building a "time series" mainly focusing on the relative changes in traffic volumes over time. A three dimensional approach is suggested with respect to the dimension of 'time', (quarterly figures), of 'commodity'[total throughput plus 5 categories of cargoes plus passenger traffic (7 in total)] and 'geography'(all European ports)
2. Call size	Relevant and feasible	Building a "time series" mainly focusing on the relative changes in traffic volumes over time. A three dimensional approach is suggested with respect to the dimension of 'time', (yearly figures), of 'commodity'[total throughput plus 5 categories of cargoes plus passenger traffic (7 in total)] and 'geography'(all European ports)
3. Employment (Direct)	Relevant and feasible	Getting data from a larger number of ports
4. Added value (Direct)	Relevant and feasible	Getting data from a larger number of ports
5. Carbon footprint	Relevant and feasible	Make Tool available to port associations and authorities. Provide training support where requested.
6. Total water consumption	Relevant and feasible	
7. Amount of waste	Relevant and feasible	
8. Environmental management	Relevant and feasible	Promote using Tool (see above) and populate from SDM and PERS responses.
9. Maritime connectivity	Relevant and	Building a 'time series' to monitor maritime connectivity over time.
10. Intermodal connectivity	Relevant and feasible	Getting data from a larger number of European ports.
11. Quality of customs procedures	Relevant and feasible	This indicator can be substituted by something more detailed in the medium run. Until then, this is the best available indicator.

Indicators	Pilot result	Next steps
12. Integration of port cluster	Relevant and feasible	Revision of criteria used. The need to reduce the number of criteria is already anticipated. More detailed info for each criteria will be asked. Efforts to standardize and collect quantitative data as well. In the long run the objective is to measure the efficiency of a PAs initiatives related to the respective indicators. .
13. Reporting Corporate and Social Responsibility	Relevant and feasible	
14. Autonomous management	Relevant and feasible	

Upon conclusion of the pilot study, the PPRISM project group published its executive report (ESPO 2012), with the recommendation that the development of European Ports Observatory be phased in over time, starting small. Though a printed version of a Dashboard was presented at the 2012 ESPO Conference in Sopot, Poland, the current status of the dashboard remains unclear.

USCMTS Marine Transportation System Performance Measures

The World Association for Waterborne Transport Infrastructure (PIANC) report, *Performance Measures for Inland Waterways Transport (PIANC Inland Navigation Commission 2010)*, identifies three general purposes for performance measures (operational, informational, referential) and nine thematic areas (infrastructure, ports, environment, fleet and vehicles, cargo and passengers, information and communication, economic development, safety, and security). Building upon the PIANC report and aiming to create an initial picture of the overall state of the U.S. MTS using authoritative data, the United States Committee on the Marine Transportation System (USCMTS) Research and Development Integrated Action Team in 2015 published a compilation of MTS *performance measures* (USCMTS 2015) developed from publicly available data sources. Serving as standard metrics, such indicators allow standardized comparison of the components of port *performance* including; Economic Benefits to the Nation, Capacity and Reliability, Safety and Security, Environmental Stewardship, and Resilience.

While the USCMTS study suggests two "Resilience Performance Measures," (i.e., *Age of Federally Owned and Operated Navigation Locks*, and *Physical Condition Rating of Critical Coastal Navigation Infrastructure owned by USACE*[6]), these measures do not consider private, state, or locally owned container terminals or port facilities, and the authors conclude that more work is needed to capture the concept of port or MTS resilience using standard metrics. Table 6 compares the indicator selection and aggregation methods of the aforementioned indicator-based seaport assessments.

Discussion

To date, there are relatively few examples of multi-port assessments. The approaches discussed in this chapter, and summarized in Table 6, tend to lean heavily on expert judgement in the selection and evaluation for indicators of climate vulnerability or focus exclusively on the "exposure" aspect of vulnerability.

Worth note is the use of indicators to develop a score or rating of climate vulnerability (or resilience). Such assessment may be welcome or rejected, depending on the goals and objectives of the audience. For example, a high "vulnerability" score may help a port petition a funding agent to build a case for needed resilience investments. On the other hand, a high score could also leave a port at a competitive disadvantage if tenants perceive higher levels of storm risk. Thus, while aggregations, scores, and rankings may be desired by regional or national-level decision makers, creating multi-port assessment tools is not without controversy.

[6] United States Army Corps of Engineers

That said, such tools *can* help inform the decision-making process. And, as demand for climate-critical resources (both funding and materials) increases, the need to better understand relative vulnerability of coastal systems, such as ports, will also increase. Our review of the literature suggests a need for better tools that can be used to gain an objective understanding of various aspects of port vulnerability. Although expert judgement will likely be necessary to a certain extent, due to the inherent difficulty of measuring and quantifying fuzzy concepts such as “adaptive capacity,” publicly available data (e.g., historical storm tracks, types of cargo handled, throughput) can also be leveraged to help decision makers gain a better sense of which areas are more vulnerable, in what ways, and how this vulnerability might be reduced.

Table 6 - Examples of multi-port, indicator-based assessments

Study	Response Indicated	Indicator Selection Method	Indicator Aggregation Method
PPRISM	Port performance	i. Academic pre-selection ii. Delphi Method with internal stakeholders iii. Delphi Method with external stakeholders	Not aggregated
USCMTS Performance Measures	Port performance	Internal review: An ideal MTS performance measure would be collected locally, using the same method across all areas of responsibility, so that state, regional, and national summaries could be easily compiled for comparison.	Not aggregated
Nichols and Hanson et al.	Coastal flood exposure measured in number of people and dollar value of assets	Response variables are semi-empirical quantities rather than theoretical concepts.	Does not involve selecting and aggregating indicators; rather it involves a more straightforward calculation of the responses.
Hsieh et al.	Port interdependency vulnerability	i. Participatory discussion process with experts ii. Delphi method with experts	i. Experts develop weights via analytic network process (ANP) ii. Raw indicator data is standardized, weighted, and summed to yield a vulnerability score
NOAA Port Tomorrow	Port resilience	Indicator selection is led by a guiding question for each indicator subcategory	Not aggregated

Conclusion

Seaports are critical to global trade and national security yet sit on the front-line for extreme coastal weather and climate impacts, and such impacts are projected to worsen globally. As port decision-makers wrestle with the myriad of climate adaptation options (including the option of making no adaptations at all), their CIAV decisions can and should be supported with data. For CIAV decision-support, the first step often involves assessing vulnerabilities. For an individual seaport, this process tends to take the shape of CCVA, either as a participatory self-assessment, or as a site-specific case study. For multiple port systems, however, we suggest an opportunity exists for further research and development of standardized, comparative CCVA methods for seaports and the marine transportation system, with the objective of supporting CIAV decisions with information products that allow decision makers to compare mechanisms and drivers of climate change across multiple ports.

Works Cited

Barnett J, Lambert S, Fry I (2008) The hazards of indicators: insights from the environmental vulnerability index. Annals of the Association of American Geographers 98 (1):102-119

Becker A, Acciaro M, Asariotis R, Cabrera E, Cretegny L, Crist P, Esteban M, Mather A, Messner S, Naruse S, Ng AKY, Rahmstorf S, Savonis M, Song DW, Stenek V, Velegrakis AF (2013) A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Climatic Change 120 (4):683-695. doi:DOI 10.1007/s10584-013-0843-z

Becker A, Caldwell MR (2015) Stakeholder Perceptions of Seaport Resilience Strategies: A Case Study of Gulfport (Mississippi) and Providence (Rhode Island). Coastal Management 43 (1):1-34

Becker A, Chase NT, Fischer M, Schwegler B, Mosher K (2016) A method to estimate climate-critical construction materials applied to seaport protection. Global Environmental Change 40:125-136

Becker A, Inoue S, Fischer M, Schwegler B (2011a) Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Climatic Change 110 (1-2):5-29. doi:10.1007/s10584-011-0043-7

Becker A, Newell D, Fischer M, Schwegler B (2011b) Will Ports Become Forts? Climate Change Impacts, Opportunities and Challenges. Terra et Aqua 122:11-17

Becker A, Toilliez J, Mitchell T (2015) Considering Sea Level Change When Designing Marine Civil

Works: Recommendations for Best Practices. In: Esteban M, Takagi H, Shibayama T (eds) Handbook of Coastal Disaster Mitigation for Engineers and Planners. Elsevier, Waltham ,MA,

Becker A, Wilson A, Bannon R, McCann J, Robadue D (2010) Rhode Island Ports & Commercial Harbors: A GIS-based Inventory of Current Uses and Infrastructure. Rhode Island Statewide Planning Program, US Department of Transportation, Federal Highway Administration,

Berle Ø, Asbjørnslett BE, Rice JB (2011) Formal vulnerability assessment of a maritime transportation system. Reliability Engineering & System Safety 96 (6):696-705

Bright EA, Coleman PR (2003) LandScan 2002. 2002 edn. Oak Ridge National Laboratory, Oak Ridge, TN

Chhetri P, Corcoran J, Gekara V, Maddox C, McEvoy D (2014) Seaport resilience to climate change: mapping vulnerability to sea-level rise. Journal of Spatial Science:1-14. doi:10.1080/14498596.2014.943311

Cox RJ, Panayotou K, Cornwell RM (2013) Climate Risk Assessment for Avatiu Port and Connected Infrastructure. Water Research Lab, University of New South Wales,

Cutter SL, Burton CG, Emrich CT (2010) Disaster Resilience Indicators for Benchmarking Baseline Conditions. Journal of Homeland Security and Emergency Management 7 (1). doi:10.2202/1547-7355.1732

Eriksen S, Kelly PM (2007) Developing credible vulnerability indicators for climate adaptation policy assessment. Mitigation and Adaptation Strategies for Global Change 12 (4):495-524

ESPO (2010) Work Package 1 (WP1): Pre-Selection of an initial set of indicators. PPRISM: Port PeRformance Indicators : Selection and Measurement, vol WP1. European Sea Ports Organization (ESPO),

ESPO (2011) Work Package 2 (WP2): Stakeholders' dialogue to evaluate and select a shortlist of indicators. PPRISM: Port PeRformance Indicators : Selection and Measurement, vol WP1. European Sea Ports Organization (ESPO),

ESPO (2012) Project Executive report (PPRISM WP4 D4.2). PPRISM: Port PeRformance Indicators : Selection and Measurement, vol WP4. European Sea Ports Organization (ESPO),

Gallopin GC (1997) Indicators and their use: information for decision-making. In: Boldan B, Bilharz S (eds) Sustainability Indicators. A Report on the Project on Indicators of Sustainable Development, vol 58. SCOPE, Chichester, pp 13-27

Gallopín GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. Global environmental change 16 (3):293-303

Gudmundsson H (2003) The policy use of environmental indicators—learning from evaluation research. The Journal of Transdisciplinary Environmental Studies 2 (2):1-12

Hanson S, Nicholls R, Ranger N, Hallegatte S, Corfee-Morlot J, Herweijer C, Chateau J (2010) A Global Ranking of Port Cities with High Exposure to Climate Extremes. Climatic Change 104 (1):89-111. doi:10.1007/s10584-010-9977-4

Hinkel J (2011) "Indicators of vulnerability and adaptive capacity": Towards a clarification of the science-policy interface. Global Environmental Change-Human and Policy Dimensions 21 (1):198-208. doi:DOI 10.1016/j.gloenvcha.2010.08.002

Hsieh C-H, Tai H-H, Lee Y-N (2013) Port Vulnerability Assessment from the Perspective of Critical Infrastructure Interdependency. Maritime Policy & Management 41 (6):589-606. doi:10.1080/03088839.2013.856523

IMO (2012) International Shipping Facts and Figures – Information Resources on Trade , Safety , Security , Environment (trans: Centre MK). International Maritime Organization, Maritime Knowledge Centre

IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change (SREX). Cambridge University Press, Cambridge. doi:10.1017/CBO9781139177245

IPCC (2013) Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge, UK; New York, NY, USA

IPCC (2014a) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, United Kingdom and New York, NY, USA

IPCC (2014b) WGII AR5 Glossary. Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland

Jharkharia S, Shankar R (2007) Selection of logistics service provider: An analytic network process (ANP) approach. Omega-International Journal of Management Science 35 (3):274-289. doi:DOI 10.1016/j.omega.2005.06.005

Klein RJ (2009) Identifying countries that are particularly vulnerable to the adverse effects of climate change: an academic or political challenge. Carbon & Climate L Rev:284

Koppe B, Schmidt M, Strotmann T (2012) IAPH-Report on Seaports and Climate Change and Implementation Case Study for the Port of Hamburg.

Linkov I, Bridges T, Creutzig F, Decker J, Fox-Lent C, Kröger W, Lambert JH, Levermann A, Montreuil B, Nathwani J, Nyer R, Renn O, Scharte B, Scheffler A, Schreurs M, Thiel-Clemen T (2014) Changing the resilience paradigm. Nature Climate Change 4 (6):407-409. doi:10.1038/nclimate2227

MARAD (2016) Marine Transportation System (MTS). Maritime Administration. https://www.marad.dot.gov/ports/marine-transportation-system-mts/. Accessed 5/25/2016

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environment and urbanization 19 (1):17-37

Melillo JM, Richmond TTC, Yohe GW (2014) Climate Change Impacts in the United States. The Third National Climate Assessment. US Global Change Research Program. doi:10.7930/j0z31WJ2

Messner S, Moran L, Reub G, Campbell J (2013) Climate change and sea level rise impacts at ports and a consistent methodology to evaluate vulnerability and risk. ENVIRON International Corp. doi:10.2495/CP130131

Morris LL, Sempier T (2016) Ports Resilience Index: A Port Management Self-Assessment. U.S. Department of Commerce, Gulf of Mexico Alliance,

Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Château J, Muir-Wood R (2008) Ranking port cities with high exposure and vulnerability to climate extremes: Exposure Estimates. OECD Environment Working Papers, vol No. 1. Organization for Economic Cooperation and Development,

NOAA OCM (2015) Port Tomorrow: Port Resilience Planning Tool [Prototype]. NOAA Office for Coastal Management. http://www.coast.noaa.gov/port/. Accessed 3 April 2015 2015

Obama B (2013) Presidential Policy Directive 21: Critical Infrastructure Security and Resilience. Washington, DC

Peduzzi P (2014) Sand, rarer than one thinks. Environmental Development 11:208-218

PIANC Inland Navigation Commission (2010) Performance Indicators for Inland Waterways Transport: User Guideline. PIANC Report No. 111. The World Association for Waterborne Transport Infrastructure (PIANC), Bruxelles, Belgium

Preston B (2012) Climate change vulnerability assessment: From conceptual frameworks to practical heuristics. CSIRO Climate Adaptation Flagship Working paper,

Rosati JD (2015) PhD, PE, D.CE, Coastal & Hydraulics Laboratory, Engineer Research & Development Center, U.S. Army Corps of Engineers. USACE, Personal Communication

Semppier TT, Swann DL, Emmer R, Sempier SH, Schneider M (2010) Coastal Community Resilience Index: A Community Self-Assessment. Mississippi-Alabama Sea Grant Consortium,

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Global environmental change 16 (3):282-292

The National Academies (2012) Disaster Resilience: A National Imperative. vol 55. Washington, D.C.

USCMTS (2011) Strategic Action Plan for Research and Development in the Marine Transportation System. US Committee on the Marine Transportation System, Washington, DC

USCMTS (2015) Marine Transportation System Performance Measures: Executive Summary. U.S. Committee on the Marine Transportation System, Research and Development Integrated Action Team, 1200 New Jersey Ave SE. Washington, D.C. 20590

USDOT (2014) Impacts of Climate Change and Variability on Transportation Systems and Infrastructure The Gulf Coast Study, Phase 2 Screening for Vulnerability Final Report, Task 3.1. US Department of Transportation, Washington, DC

WMO (2015) The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2014 (trans: Atmospheric Environment Research Division RD). Greenhouse Gas Bulletin, vol 11. World Meteorological Organization, Geneva

MANUSCRIPT 2: Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic Ports

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Abstract

When comparing vulnerabilities of multiple disparate systems, indicator-based vulnerability assessment (IBVA) methods can yield standardized metrics, allowing for high-level analysis to identify areas or systems of concern. To advance IBVA for the seaport sector, researchers investigated the suitability of publicly available open-data, generally collected for other purposes, to serve as indicators of climate and extreme-weather vulnerability for 23 major seaports in the North East United States, addressing the question: How sufficient is the current state of data reporting for and about the seaport sector to develop expert-supported vulnerability indicators for a regional sample of ports? To address this question, researchers developed a framework for expert-evaluation of candidate indicators that can be replicated to develop indicators in other sectors and for other purposes. Researchers first identified candidate indicators from the climate change vulnerability assessment (CCVA) and seaport-studies literature and vetted them for data-availability for the sample ports. Candidate indicators were then evaluated by experts via a mind-mapping exercise, and finally via a visual analogue scale measurement instrument. Researchers developed a visual analogue scale (VAS) instrument to elicit expert perception of the magnitude and direction of correlation between candidate indicators and each of the three dimensions of vulnerability that have become standard in the CCVA literature, e.g., exposure, sensitivity, and adaptive capacity. For candidate indicators selected from currently available open data sources, port-expert respondents found notably stronger correlation with the exposure and sensitivity of a port than with the adaptive capacity. Results suggest that more open

reporting and sharing of port-specific data within the maritime transportation sector will be necessary before IBVA will become feasible for seaports.

Key Findings:

- Open-data can be developed into expert-supported indicators of seaport climate *exposure* and *sensitivity*.
- Experts found relatively little perceived correlation between open-data candidate indicators and a port's *adaptive capacity*.
- Experts found higher levels of perceived correlation for *place-based* indicators than for *port-specific* indicators.

Introduction

Indicator-Based Assessments

Indicators are measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly, adequately measured (Gallopin 1997, Hinkel 2011). Indicator-based assessment methods are generally applied to assess or 'measure' features of a system that are described by theoretical concepts. Directly immeasurable, concepts such as resilience and vulnerability are instead made operational by mapping them to functions of observable variables called indicators (McIntosh and Becker 2017). When comparing vulnerabilities of multiple disparate systems, indicator-based vulnerability assessment (IBVA) methods can yield standardized metrics, allowing for high-level analysis to identify areas or systems of concern. To advance IBVA for the seaport sector, researchers investigated the suitability of publicly available open-data, generally collected for other purposes, to serve as indicators of climate and extreme-weather vulnerability for 23 major seaports in the North East United States, addressing the question: How sufficient is the current state of data reporting for and about the seaport sector to develop expert-supported vulnerability indicators for a regional sample of ports?

The indicator-based assessment process of operationalizing immeasurable aspects of a system (Hinkel 2011) consists of two or sometimes three steps: 1) defining the response to be indicated, 2) selecting the indicators, and 3) aggregating[7] the indicators. (Hinkel 2011) describes three kinds of arguments for developing vulnerability indicators and notes that developments of indicators generally combine the different types: (i) deductive ones, which are based on existing theory, (ii) inductive ones, based on data of both the indicating variables as well as observed harm, and (iii) normative ones, which are based on value judgements.

The indicator development process described in this work combines a deductive approach with a normative one. To develop indicators using an inductive argument would require a response variable (e.g., drop in revenue, port downtime, loss in throughput), that could allow for building statistical models to test for correlation with candidate indicators. Inductive arguments are generally only available when systems can be defined using only a few variables and sufficient data is available to serve as a response, or dependent variable, and this is rarely the case for the development of indicators of climate change vulnerability (Hinkel 2011). Hinkel argues that deductive arguments are only available for selecting indicators, not for aggregating them, and notes that deductive arguments are generally applied as a first step in indicator development. Accordingly, the approach described in this paper begins with the application of a deductive argument to selecting indicators that is grounded in the framework established in the third assessment report of the IPCC (IPCC 2001), which defined climate change vulnerability in terms of three components: exposure, sensitivity, and adaptive capacity. In this research, an initial

[7] This step is sometimes omitted but necessary to yield a heat map or create a comparative index.

deductive approach to identifying candidate indicators is then followed by a normative one, where expert-elicitation is applied to seek expert consensus on the value judgements required to determine perceived correlation between the candidate indicators and the components of vulnerability taken from the deductive framework.

Expert-elicitation has become a common approach to applying a normative argument to the indicator development process, and examples include the "new indicators of vulnerability and adaptive capacity" (Adger et al. 2004), "determinants of vulnerability and adaptive capacity at the national level" (Brooks, Adger, and Kelly 2005), climate change vulnerability for South Korea (Kim and Chung 2013), performance appraisal indicators for mobility of the service industries (Kuo and Chen 2008), and indicators for fisheries management (Rice and Rochet 2005) among others. Additionally, research indicates (White et al. 2010, Schroth, Pond, and Sheppard 2011), that involving stakeholders in the process of developing knowledge systems (i.e., decision support tools) can lead to improvements in their perceived credibility, salience, and legitimacy.

The IPCC considers indicators an important part of vulnerability and risk analysis, and recommends that quantitative approaches be complimented with qualitative approaches to capture the full complexity of climate vulnerability in its different dimensions (environmental, social, economic) (IPCC 2014a). This investigation contributes to the ongoing work of developing CCVA indicators by applying expert-elicitation methods to develop and evaluate a set of indicators for each of the three components of seaport climate vulnerability.

To date there have been relatively few examples of comparative CCVA for the seaport sector (McIntosh and Becker 2017). Most indicator-based assessments for ports have stopped short of comparative CCVA, e.g., the elevation-based, exposure-only assessment of global port cities of (Nicholls et al. 2008), or have focused on assessing other concepts, e.g., (ESPO 2012) which aimed to measure port performance. While understanding how a port or a port-city's elevation affects its exposure to climate-impacts like SLR, it is only one piece of the puzzle that describes how a port is or is not vulnerable to climate and extreme weather impacts. By assessing the sensitivity and adaptive capacity of a port along with its exposure to a wide array of impacts in addition to SLR, a more complete picture of the mechanisms and drivers of seaport climate vulnerability may be better understood.

Why Seaports?

Seaports sit on the front lines of the climate-change challenge. Critical to national economies, global trade and national security, yet restricted to the hazardous land-sea interface, seaports face impacts from today's weather extremes as well as impacts from projected changes in temperature, precipitation, wind, storm frequency and intensity, mean sea level, wave height, salinity and acidity, tidal regime, and sedimentation rates (Koppe, Schmidt, and Strotmann 2012). Among climate change vulnerability, resilience, and risk assessment methods applied to seaports, most efforts to date have been limited in scope to exposure-only assessments (Hanson et al. 2010, Nicholls et al. 2008, Klein, Nicholls, and Thomalla 2003), or limited in scale to a single port (either as case studies (Koppe 2012, Cox, Panayotou, and Cornwell 2013, USDOT 2014, Messner et al. 2013, Chhetri et al. 2014) or as self-assessment tools (NOAA OCM 2015, Semppier et al. 2010, Morris and Sempier 2016)), thus making comparisons of climate vulnerability among ports difficult. Climate impact, adaptation, and vulnerability (CIAV)[8] decisions at the multi-port (regional or national) scale may be supported by information products that allow decision makers to compare mechanisms and drivers of climate change among ports.

[8] CIAV decisions are choices, the results of which are expected to affect or be affected by the interactions of the changing climate with ecological, economic, and social systems.

To advance the ability of seaport decision makers to compare levels of vulnerability among ports, and to further the development of IBVA for the seaport sector, this research investigates the suitability of publicly available open-data[9] to serve as indicators of climate and extreme-weather vulnerability for 23 major seaports in the North East United States (Figure 3). This investigation seeks to examine the suitability of the current state of data reporting for and about the seaport sector to determine how sufficient it may or may not be to develop expert-supported vulnerability indicators for a regional sample of ports.

Vulnerability, Risk, and Resilience

This section describes several of the terms and concepts that are often used in discussions of the concepts of vulnerability, resilience, and risk. In the context of projected changes and current variability[10] in the earth's climate system, the meaning of the term *vulnerability* continues to evolve in the research literature (Füssel and Klein 2006, Smit and Wandel 2006). In the third assessment report of the IPCC (IPCC 2001), vulnerability is defined in terms of susceptibility:

> **Vulnerability** *is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.* (IPCC 2001)

According to this definition, a system's vulnerability to climate change consists of external and internal dimensions. The external dimensions of vulnerability, i.e., the *character*, *magnitude* and

[9] Open-data refers to publicly available data structured in a way that enables the data to be fully discoverable and usable by end users without having to pay fees or be unfairly restricted in its use.
[10] Whereas *climate change* encompasses long-term (decades or longer) continuous changes to average weather conditions or to the range of weather, *climate variability* refers to yearly fluctuations above or below a long-term average.

rate of climate change, are commonly represented in the CCVA literature collectively as the *exposure* of the system in question, while the internal dimensions of vulnerability are represented by the system's *sensitivity* and *adaptive capacity*. (Clark and Parson 2000, Turner et al. 2003). In its 2014 fifth assessment report, the IPCC simplified its definition of *vulnerability* to, "the propensity or predisposition to be adversely affected," [p. 5] (IPCC 2014a) however, the three components of vulnerability (Figure 1) remain relevant. In a 2012 report on seaports and climate change, the International Association of Ports and Harbors[11] (IAPH) defines seaport vulnerability using the same three components, i.e., *exposure*, *sensitivity*, and *adaptation capacity* (Koppe 2012).

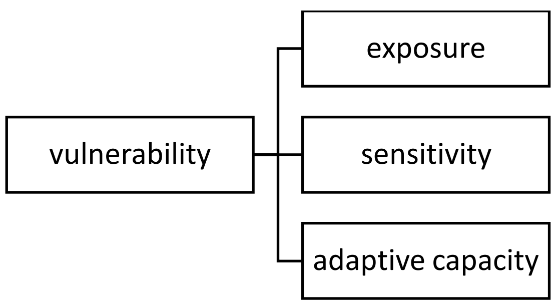


Figure 1Three components of vulnerability

For the purposes of this research, vulnerability to climate and extreme weather is defined according to the IPCC definition of vulnerability quoted above, and the components of vulnerability are defined as follows:

> **Exposure:** *The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.* (IPCC 2014b)

[11] IAPH is an industry-based non-governmental organization representing over 180 member-ports and 140 port related businesses in 90 countries.

Sensitivity: *The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.* (IPCC 2001)

Adaptive Capacity: *The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.* (IPCC 2014b)

A concept related to vulnerability, *risk* is a measure of the potential for consequences where something of value is at stake and where the outcome is uncertain (IPCC 2014b). Risk can be quantitatively modeled as $Risk = p(L)$, where L is potential loss and p the probability of occurrence, however, both can be speculative and difficult to measure in the climate-risk context. Risk, in the context of climate change, is often defined similarly to vulnerability (Preston 2012, IPCC 2014a), but with the added component of *probability*, thus making *vulnerability* a component of *risk* (Figure 2). From the risk analysis perspective, the indicators developed by this research focus on measuring the L rather than the p. From the CCVA perspective, the indicators are developed to measure *vulnerability* and its three components, but not likelihood nor probability of occurrence. By measuring vulnerability, then, this work aims to inform the measurement of the magnitude of a risk, but not it's probability.

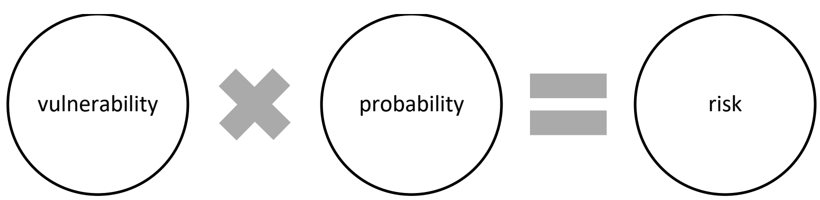


Figure 2 Vulnerability as a component of risk

Resilience, another closely related term with a more positive connotation than *vulnerability*, is defined by the IPCC as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation" (IPCC 2014b). The National Academy of Sciences (The National Academies 2012) and the President of the United States (Obama 2013) define critical infrastructure resilience as, "the ability to prepare, resist, recover, and more successfully adapt to the impacts of adverse events." With *resilience* defined in terms of ability, and *vulnerability* defined in terms of susceptibility, it is tempting to consider them polar opposites (Gallopín 2006), however, resilience can also be considered a broader concept than vulnerability. Most working definitions of resilience involve a process that begins before a hazardous impact, but also includes temporal periods during and after the impact. Resilience, like vulnerability, can also encompass coping with adverse effects from a multitude of hazards in addition to climate change. While this research will further the development of indicators of seaport climate *vulnerability,* the objective is that by increasing our understanding of the regional distribution of seaport climate and extreme weather vulnerability, the overall *resilience* of the marine transportation system[12] (MTS) may be enhanced.

[12] The Marine Transportation System, or MTS, consists of waterways, ports, and inter-modal land-side connections that allow the various modes of transportation to move people and goods to, from, and on the water. (MARAD 2016)

Methodology

To refine a set of high-level indicators of seaport climate and extreme weather vulnerability, and to determine the suitability of available open-data to differentiate ports within a region in terms of relative climate vulnerabilities, researchers developed a visual analogue scale[13] (VAS) survey instrument for expert-evaluation of selected candidate indicators of seaport vulnerability to climate and extreme weather impacts for the 23 medium and high-use ports of the USACE North Atlantic Division.

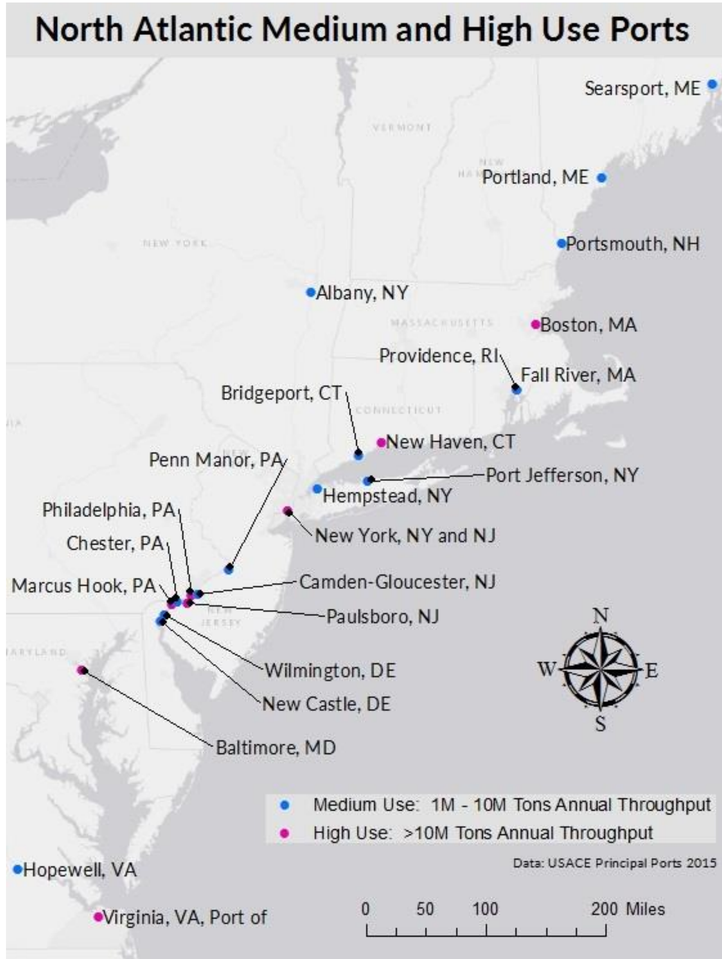


Figure 3 Study Area Ports

Rather than taking a purely theoretical approach to developing indicators, e.g., that used in the development of the Social Vulnerability Index (SoVI) (Cutter, Boruff, and Shirley 2003), this work takes a stakeholder-driven approach to indicator development by including port-experts in the selection, evaluation, and weighting of the indicators, as this has been shown to increase the creditability of the indicators as tools (Barnett, Lambert, and Fry 2008, Sagar and Najam 1998). By including stakeholders in the design-stage of decision-support tool or boundary-object development, the

[13] In visual analogue scale (VAS), respondents measure their level of agreement by indicating a position along a continuous line segment

stakeholders' perceptions of the credibility, salience, and legitimacy of the tool can be increased (White et al. 2010).

For evaluating candidate indicators of seaport vulnerability, this research was designed to take a holistic approach to vulnerability assessment by considering impacts that extend beyond the borders of the port property. To that end, this research in both the identification and evaluation of candidate indicators considered potential multimodal vulnerabilities at the port location as well as impacts to a port's surrounding community and economy (socio-economic systems) and ecological and environmental surroundings (environmental systems).

A VAS is a measurement instrument that tries to measure a characteristic or attitude that is believed to range across a continuum of values and cannot easily be directly measured. A VAS is usually a horizontal line, 100 mm in length, anchored by word descriptors at each end, as illustrated in Figure 6. The respondent marks on the line the point that they feel represents their perception of their current state. The VAS score is determined by measuring in millimeters from the left-hand end of the line to the point that the respondent marks. As a continuous, or analogue scale, the VAS is differentiated from discrete scales such as the Likert scale by the fact that a VAS contains a real distance measure, and as such, a wider range of statistical methods can be applied to the measurement.

The selection and evaluation of indicators involved four steps which will be described in the following sections:

Step 1. Literature review to compile candidate indicators

Step 2. Vetting for data availability

Step 3. Mind mapping exercise

Step 4. VAS survey instrument

This research focuses on the thirteen *medium-use*[14] and nine *high-use*[15] ports found in the United States Army Corp of Engineers (USACE) North Atlantic Division[16] (CENAD) as the sample population for which to develop indicators (Figure 3). The U.S. Army Engineer Research and Development Center (ERDC) has expressed (Rosati 2015) an interest in piloting port resilience and vulnerability assessment methods with high use ports, and by adding medium use ports and restricting the selection to the Northeast region researchers were able to create a manageable sample of 23 ports. Though this assessment was tailored to the US NE region, the framework was developed with the intent that it could be applicable (with modifications) to other regions.

Step 1: Literature Review to Compile Candidate Indicators

Candidate indicators of seaport climate vulnerability were first identified from an extensive literature review of the CCVA and seaport studies research literature. Indicators were sought for their potential to represent one of the three components of vulnerability, i.e., *exposure*, *sensitivity*, and *adaptive capacity* in terms of weather extremes, current variability, and projected changes in earth's climate and their impact on seaports and seaports' surrounding socioeconomic and environmental systems. The exposure component of vulnerability captures the geographic proximity of a port to projected climate and extreme weather impacts, while the sensitivity component captures the degree to which a port is affected by those impacts. Adaptive capacity indicators are not specific to individual climate impacts (USDOT 2014) but capture a port's ability to cope with and respond to stress by measuring redundancies within the port, duration of downtime, and ability to bounce back quickly.

[14] USACE definition of medium use port: annual throughput between 1M and 10M tons
[15] USACE definition of high use port: annual throughput greater than 10M tons
[16] The North Atlantic Division is one of nine USACE divisions and encompasses the U.S. Eastern Seaboard from Virginia to Maine (USACE 2014).

Step 2: Vetting for Data Availability

Once identified, candidate indicators were vetted for their data availability from sources of open data. Adopting open data for indicator development increases transparency, facilitates reproducibility, and can enhance reliability when using standardized data sources (Janssen, Charalabidis, and Zuiderwijk 2012, CMTS 2015). Only those indicators with data available for at least 16 of the study's sample of 23 ports were considered further. Table 9 shows the 108 candidate indicators of seaport climate-exposure, sensitivity, and adaptive capacity that were uncovered during this first step, as well as each indicator's preliminary categorization and its open data source. These candidate indicators include a mix of those that measure vulnerability of place at the county scale, à la the hazards-of-place model of vulnerability (Cutter 1996, Cutter et al. 2008, Cutter, Burton, and Emrich 2010), e.g., *population inside floodplain*, and those that measure vulnerability via a characteristic of the port itself, e.g., *containership capacity*. For a comprehensive review of the data sources used, see (Mclean et al. 2017a). Of the 108 candidate indicators originally compiled, 48 (24 place-based and 24 port-specific) were found to have sufficient data available for the 23 sample ports.

Step 3: Mind Mapping Exercise to Refine the Set of Candidate Indicators

After compiling the 48 candidate indicators that were deemed to have sufficient data availability, researchers mapped them to the components of seaport climate vulnerability using the mind mapping software FreeMind (Muller et al. 2013) (Figure 16). Researchers then held a workshop with nine members of the Resilience Integrated Action Team[17] (RIAT) of the United

[17] The MTS Resilience IAT (R-IAT) was established to focus on cross-Federal agency knowledge co-production and governance in order to incorporate the concepts of resilience into the operation and management of the U.S. Marine Transportation System.

States Committee on the Marine Transportation System[18] (US CMTS) in Washington, D.C. to elicit MTS-expert opinion on which of the candidate indicators to include in the VAS survey instrument.

On the mind maps, each of the 48 candidate indicators with available data was hierarchically mapped to one of the three components of vulnerability, and for each indicator, the research team provided its description, data source, and units (Figure 4).

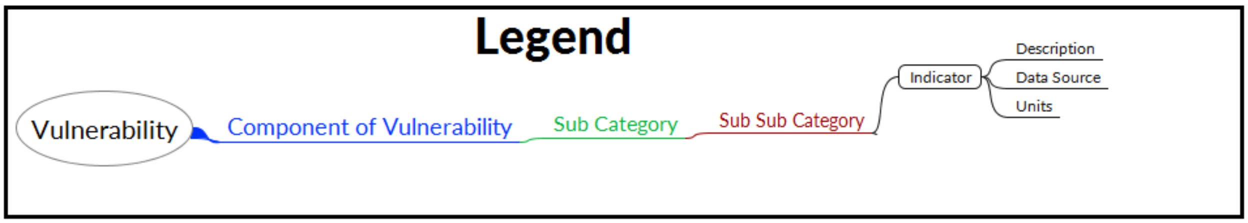


Figure 4 Mind map legend showing how each indicator was hierarchically mapped to a component of vulnerability. The mind map also listed a description, data source, and units for each indicator.

During the mind mapping exercise, for each candidate indicator, experts from the USCMTS RIAT denoted with a plus or a minus whether an increase in that indicator correlates to an increase or decrease in the component of vulnerability it was mapped to, or with a zero if no correlation could be determined. In addition to evaluating the 48 candidate indicators with sufficient data availability, participants were also asked to brainstorm other potential data sources for those indicators without sufficient data and to add additional indicators that may have been overlooked.

The mind mapping exercise concluded with 14 candidate indicators marked as having no correlation to vulnerability, 25 marked as having positive correlation, and 9 candidate indicators marked as having negative correlation (Table 9). As a result of the mind mapping exercise, 34 candidate indicators were selected to be evaluated via the VAS expert survey: 14 port-specific

[18] The United States' CMTS is a Federal Cabinet-level, inter-departmental committee chaired by the Secretary of Transportation. The purpose of the CMTS is to create a partnership of Federal departments and agencies with responsibility for the Marine Transportation System (MTS).

indicators and 20 place-based indicators. Table 7 lists the 34 selected candidate indicators alphabetically, along with their descriptions, units, and data sources. For a more comprehensive description of each of the 34 indicators, see (Mclean et al. 2017b). The RIAT participants suggested one additional candidate indicator, "age of infrastructure," however, they and the research team were unable to identify a data source that contains data on the age of infrastructure for the sample ports.

*Table 7 Thirty-four candidate indicators selected via mind mapping exercise for inclusion in the VAS survey, with each indicator's description, units, and data source. Port-specific candidate indicators in **bold**.*

Indicator	Description	Units	Data Source
Air.Pollution.Days	Number of Days with Air Quality Index value greater than 100 for the port city	Days	EPA Air Quality Report
Average.Cost.of.Hazmat.Incidents	Average cost per incident of total damage from the 10 most costly Hazardous Materials Incidents in the port city since 2007	$	U.S. DOT Pipeline and Hazardous Materials Safety Administration
Average.Cost.of.Storm.Events	Average cost of property damage from storm events in the port county since 1950 with property damage > $1 Million	$	NOAA Storm Events Database
Channel.Depth	The controlling depth of the principal or deepest channel at chart datum	A (over 76 ft) to Q (0 – 5 ft) in 5-foot increments	World Port Index (Pub 150)
Containership.Capacity	Container Vessel Capacity	calls x DWT	MARAD: Vessel Calls at U.S. Ports by Vessel Type
Disaster.Housing.Assistance	The total disaster housing assistance of Presidential Disaster Declarations for the port county since 1953	Declarations	FEMA: Disaster Declarations
Entrance.Restrictions	Presence or absence of entrance restrictions	Tide, Swell, Ice, Other	World Port Index (Pub 150)
Environmental.Index..ESI.	Environmental Sensitivity Index (ESI) shoreline sensitivity to an oil spill for the most sensitive shoreline within the port	ESI Rank (1.00 - 10.83)	NOAA Office of Response and Restoration
Gas.Carrier.Capacity	Gas Carrier Capacity	calls x DWT	MARAD: Vessel Calls at U.S. Ports by Vessel Type
Harbor.Size	Harbor Size	Large, Medium, Small, Very-Small	World Port Index (Pub 150)
Hundred.Year.High.Water	1% annual exceedance probability high water level which corresponds to the level that would be exceeded one time per century, for the nearest NOAA tide station to the port	m above MHHW	NOAA Tides and Currents: Extreme Water Levels
Hundred.Year.Low.Water	1% annual exceedance probability low water level for the nearest NOAA tide station to the port, which corresponds to the level that would be exceeded one time per century	m below MLLW	NOAA Extreme Water Levels
Marine.Transportation.GDP	County Marine Transportation GDP	$	NOAA Office for Coastal Management
Marine.Transportation.Jobs	Number of Marine Transportation Jobs in the port county	number of jobs	NOAA Office for Coastal Management
Number.of.Critical.Habitat.Areas	Number of Critical Habitat Areas within 50 miles of the port	Areas	U.S. Fish & Wildlife Service
Number.of.Cyclones	Number of cyclones that have passed within 100 nm of the port since 1842	Number of cyclones	NOAA Historical Hurricane Tracks Tool
Number.of.Disasters	Number of Presidential Disaster Declarations for the port county since 1953	Disaster Type	FEMA: Disaster Declarations
Number.of.Endangered.Species	Number of Threatened or Endangered Species found in port county	Species	U.S. Fish & Wildlife Service

Indicator	Description	Units	Data Source
Number.of.Hazmat.Incidents	Number of Hazardous Materials Incidents in port city since 2007	Number of Incidents	U.S. DOT Pipeline and Hazardous Materials Safety Administration
Number.of.Storm.Events	Number of storm events in port county w/ property damage > $1M	events	NOAA Storm Events Database
Overhead.Limits	Presence or absence of overhead limitations	Y/N	World Port Index (Pub 150)
Percent.of.Bridges.Deficient	Percent of bridges in the port county that are structurally deficient or functionally obsolete	%	US DOT FHA National Bridge Inventory
Pier.Depth	The greatest depth at chart datum alongside the respective wharf/pier. If there is more than one wharf/pier, then the one which has greatest usable depth is shown.	A (over 76 ft) to Q (0 – 5 ft) in 5-foot increments	World Port Index (Pub 150)
Population.Change	Rate of population change (from 2000-2010) in the port county, expressed as a percent change	%	NOAA Office for Coastal Management
Population.Inside.Floodplain	Percent of the port county population living inside the FEMA Floodplain	%	NOAA Coastal County Snapshots
Projected.Change.in.Days.Above.Baseline.Extremely.Hot.Temperature	The percent change from observed baseline of the average number of days per year above baseline “Extremely Hot” temperature projected for the end-of-century, downscaled to 12km resolution for the port location	%	US DOT CMIP Climate Data Processing Tool
Projected.Change.in.Number.of.Extremely.Heavy.Precipitation.Events	The percent change from observed baseline of the average number of “Extremely Heavy” Precipitation Events projected for the end-of-century, downscaled to 12km resolution for the port location	%	US DOT CMIP Climate Data Processing Tool
Sea.Level.Trend	Local Mean Sea Level Trend	mm / yr	NOAA Tides and Currents: Sea Level Trends
Shelter.Afforded	The shelter afforded from wind, sea, and swell, refers to the area where normal port operations are conducted, usually the wharf area.	Excellent (5), Good (4), Fair (3), Poor (2), None (1)	World Port Index (Pub 150)
SoVI.Social.Vulnerability.Score	Port County Social Vulnerability (SoVI) Score	score number	SoVI® Social Vulnerability Index
Tanker.Capacity	Tanker Capacity	calls x DWT	MARAD: Vessel Calls at U.S. Ports by Vessel Type
Tide.Range	Mean tide range at the port	feet	World Port Index (Pub 150)
Tonnage	Total Throughput	Tons	USACE Navigation Data Center (pports)
Vessel.Capacity	Vessel Capacity (vessels > 10k DWT)	calls x DWT	MARAD: Vessel Calls at U.S. Ports by Vessel Type

Selection of Experts for VAS Survey

Because expert elicitation relies on expert knowledge rather than a statistical sample, the selection of qualified experts is considered one of most crucial steps in the process for insuring the internal validity of the research (Delbecq, Van de Ven, and Gustafson 1975, Hasson, Keeney, and McKenna 2000, Keeney, Hasson, and McKenna 2006, Okoli and Pawlowski 2004). Candidates for the port-expert group were selected according to recommended best practices in expert selection developed by (Delbecq, Van de Ven, and Gustafson 1975) and expanded by (Okoli and Pawlowski 2004). Researchers first prepared a knowledge resource nomination worksheet

(KRNW) (Table 10) modified from (Okoli and Pawlowski 2004) to help categorize the experts prior to identifying them and to help avoid overlooking any important class of expert.

The KRNW was then populated with names, beginning with the professional network of the research team and that of the RIAT and identifying other candidate experts via a review of the relevant literature. This initial group of candidate experts was then contacted, provided a brief description of the study, queried for basic biographical information (e.g., number of papers published, length of practice, or number of years of tenure in government or NGO positions), and asked to nominate other candidate experts for inclusion on the list. Experts were asked to nominate peers with expertise in the fields of seaport operations, planning, policy, seaport data, and/or the vulnerability of the Northeast U.S. Marine Transportation System to climate and extreme weather impacts. This first round of contacts did not include invitations, but was aimed at extending the KRNW to ensure that it included as many experts as could be accessed. Upon completion of snowball sampling, researchers identified a total of 154 candidate experts to invite for participation in the VAS survey.

For this survey, 154 experts were invited and 64 participated, for a response rate of 42%. Participating experts self-identified their affiliation (Figure 5) as: *Federal Government* (n=28), *Academic* (n=13), *Consultant* (n=10), *Port/MTS Practitioner* (n=4), *Non-governmental Organization* (n=2), *State Government* (n=1), and *Other* (n=6). The "other" category of expert affiliation was specified as: Attorney (n=1), Consultant/port director/District engineer/Academic (n=1), Contractor supporting the federal government (n=1), Federal Government Academic (n=1), Port Authority (n=1), and Local Government (n=1).

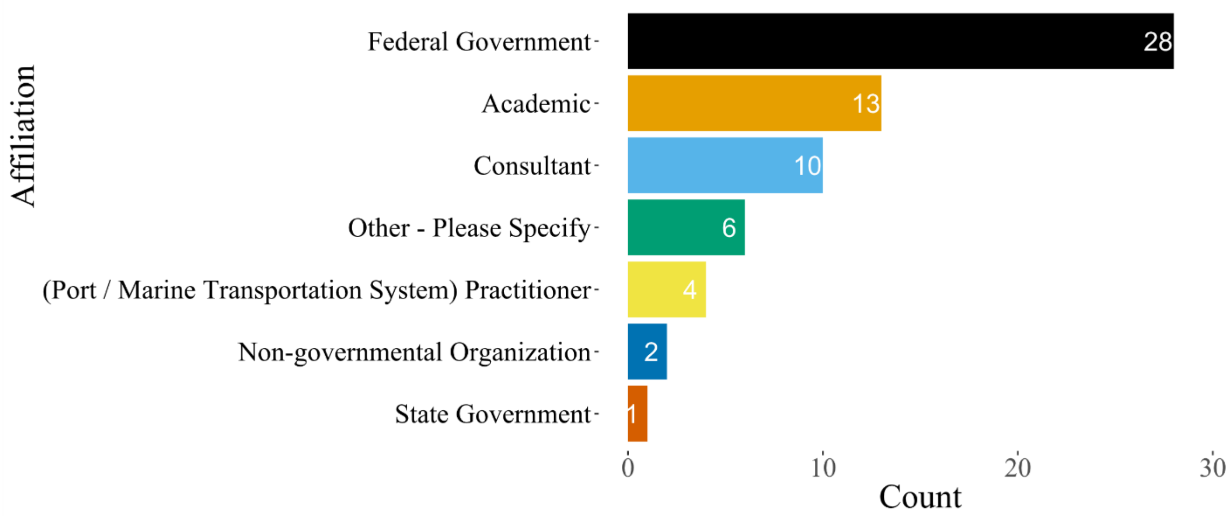


Figure 5 Count of respondents' self-identified affiliations. Total n=64

Step 4: Expert-Elicitation VAS Survey

The objective of this survey was to measure port-expert perceptions of the suitability of available data to serve as indicators of seaport vulnerabilities to climate and extreme weather impacts. The survey consisted of 34 candidate indicators to evaluate for correlation with the components of seaport vulnerability. For each candidate indicator, respondents were given the indicator's description, units, data source, and example values, and respondents were asked to determine whether the candidate indicator could be correlated with the exposure, sensitivity, and/or the adaptive capacity of ports in the study area. In evaluating candidate indicators, respondents were instructed to consider port vulnerability holistically, inclusive of the port's surrounding socioeconomic and environmental systems. Respondents indicated the magnitude and direction of correlation by dragging a slider along a VAS line segment (Figure 6). To indicate "no correlation," respondents were to leave the slider in the center of the line. Dragging the slider to the left indicated a negative correlation and dragging the slider to the right indicated a positive correlation (Figure 6). The distance measure of how far the slider was moved was indicative of the magnitude of perceived correlation. As a second check on the comprehensiveness of the set of candidate indicators, experts were also asked to suggest additional candidate indicators and data sources.

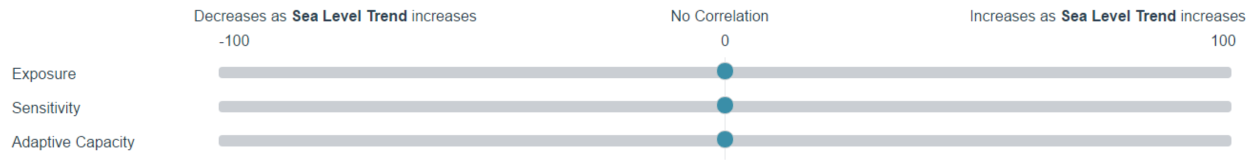


Figure 6 VAS slider for indicating expert-perceived correlation between a candidate indicator and each of the components of vulnerability.

While the initial search for candidate indicators was guided by the components (exposure, sensitivity, adaptive capacity) of vulnerability and subsequent sub-categories of those components specific to seaports, the VAS survey did not limit the candidate indicators to a single category or component of vulnerability. On the VAS survey, candidate indicators were presented with their metadata, but without assignment to a single component of vulnerability; instead, respondents denoted each indicator's correlation (or lack of correlation) with each of the three components of vulnerability (Figure 6). This prevented respondents from inheriting the researchers' notions of correlation between candidate indicator and component of vulnerability. This feature also resulted in some indicators scoring high in correlation with more than one component of vulnerability.

Results

For each of the 34 candidate indicators evaluated, Figure 7 shows the median expert-perceived magnitude of correlation with each of the three components of vulnerability, stacked, in descending order of correlation. To reduce the effect of outliers on the measure of central tendency, this work considers the median rather than the mean of responses when aggregating scores for each candidate indicator. Interestingly, respondents reserved their highest levels of aggregate perceived correlation for place-based indicators; though 14 of the 34 candidate indicators were port-specific, the top 12 candidate indicators ranked by total correlation were all place-based

(Figure 7). Also of note in Figure 7 is the low level of perceived correlation with adaptive capacity (pink) compared to exposure (green) and sensitivity (blue).

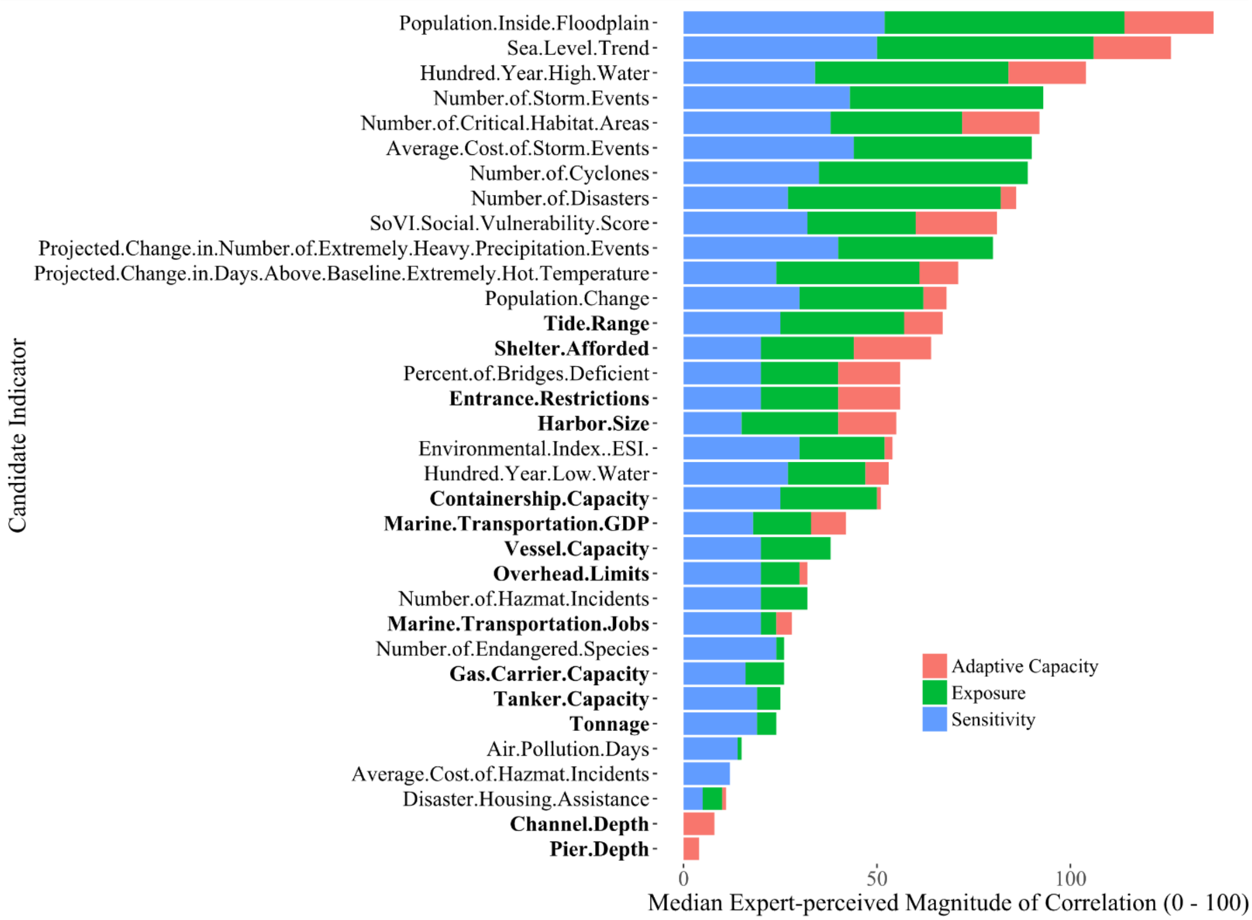


*Figure 7 Candidate indicators of seaport vulnerability to climate and extreme weather, sorted by total median expert-perceived magnitude of correlation with each of the three components of vulnerability. Port-specific candidate indicators in **bold**.*

The indicator with the highest median expert-perceived correlation was the same for all three components of vulnerability, i.e., *population inside floodplain*. The indicator, *sea level trend* also scored high, rated second highest in median correlation with exposure and sensitivity, and fourth highest with adaptive capacity. In Figure 7, the highest scoring port-specific indicator (bold) was *tide range*, followed by *shelter afforded*, both metrics available from the World Port Index (NGIA 2015).

The following three figures illustrate the median expert-percieved magnitude of correlation seperately for each component of vulnerability, revealing expert preferences for the most suitable candidate indicators to represent each concept for the sample set of CENAD ports. Figure 8, Figure 9, and Figure 10 show the top 15 scoring indicators in descending order for correlation with exposure, sensitivity, and adaptive capacity, respectively.

In Figure 8, the ten indicators with the highest median perceived correlation with port exposure were all place based. The port-specific indicator rated highest perceived correlation with exposure was *tide range*, ranked 11/34, followed by *harbor size*, ranked 14/34.

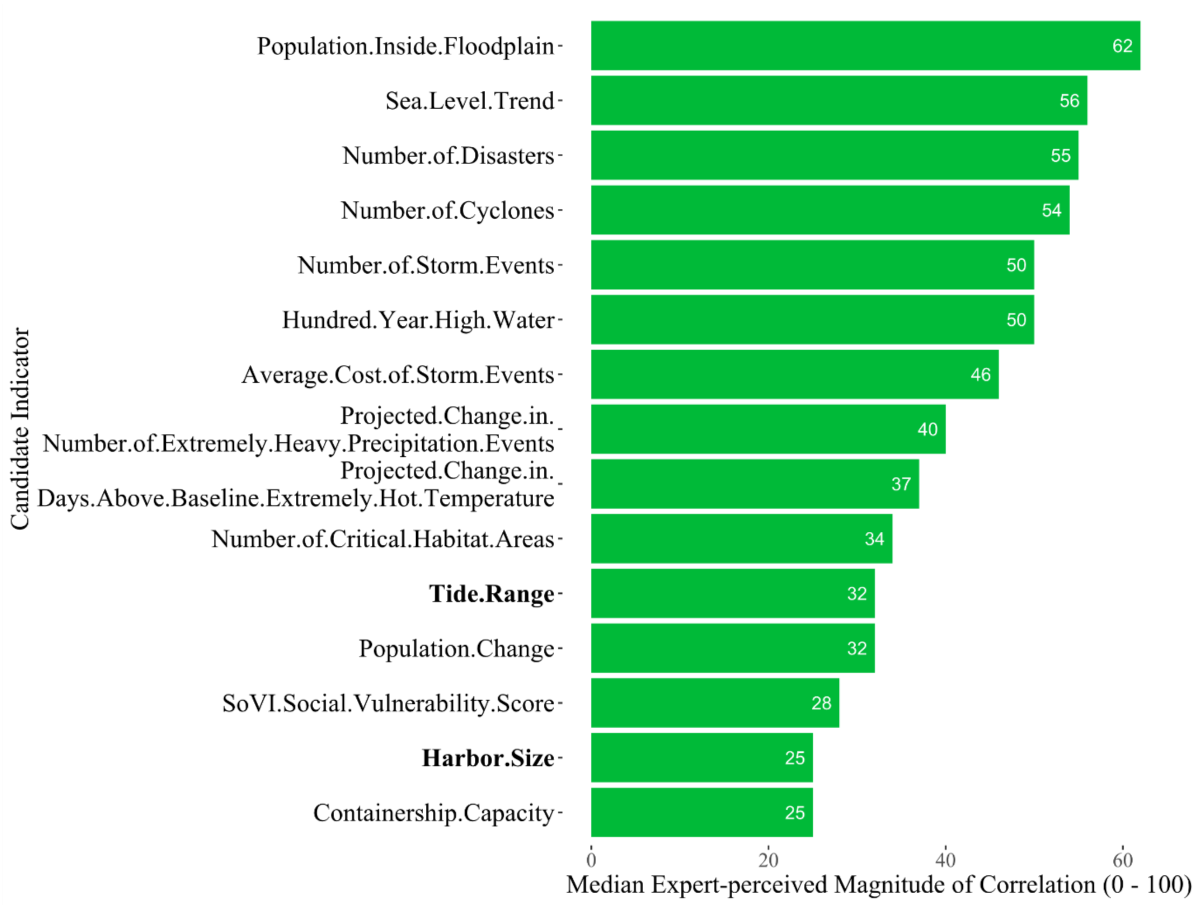


Figure 8 Top 15 candidate indicators for exposure*. In descending order of median expert-perceived magnitude of correlation with seaport* exposure *to climate and extreme weather impacts. Port-specific candidate indicators in* ***bold****.*

In Figure 9, the top 13 indicators with the highest median perceived correlation with port sensitivity were all place based. As was the case with exposure, the two highest scoring indicators for correlation with sensitivity were also *population inside floodplain*, and *sea level trend*, respectively. The port-specific indicator rated highest perceived correlation with sensitivity was also the same as that for exposure, i.e., *tide range*, ranked 14/34, followed by *containership capacity*, ranked 15/34.

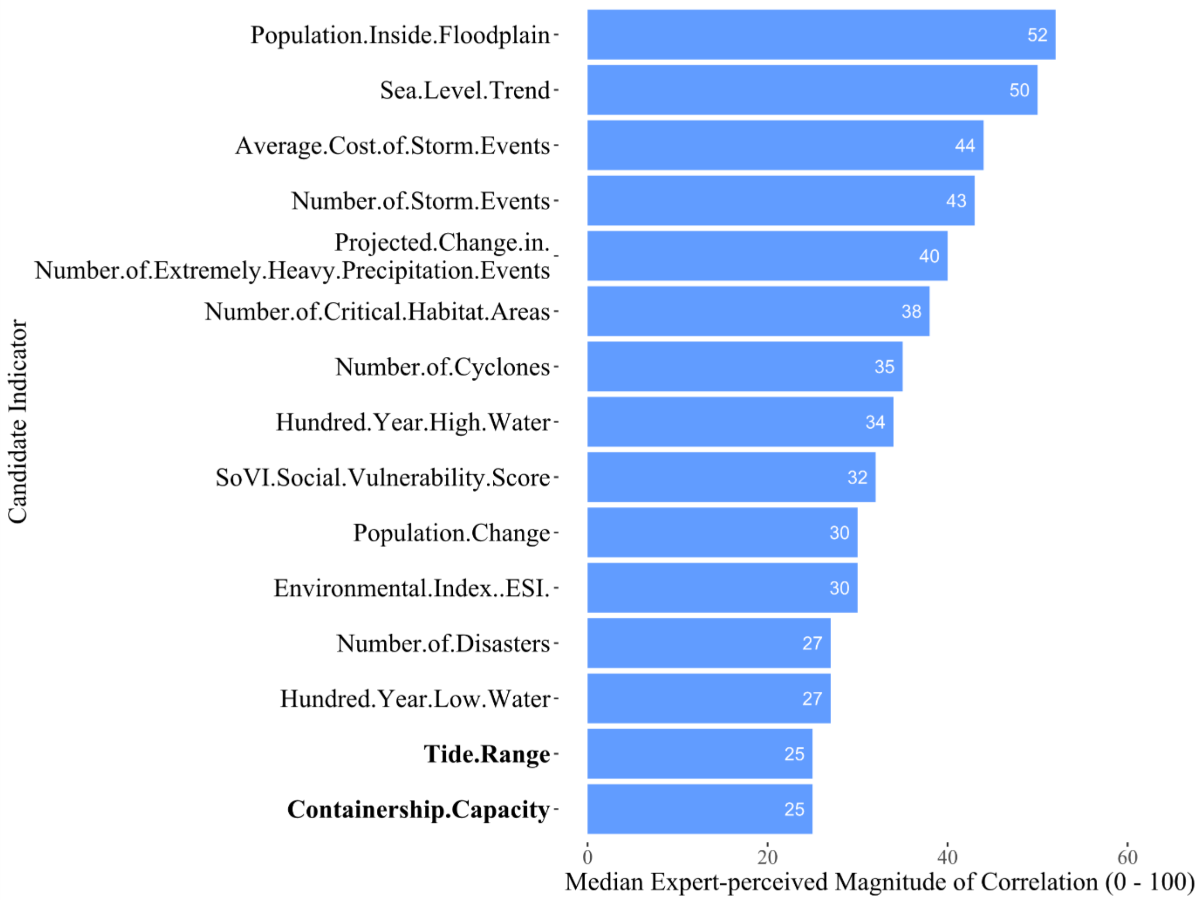


Figure 9 Top 15 candidate indicators for sensitivity*, sorted by median expert-perceived magnitude of correlation with seaport* sensitivity *to climate and extreme weather impacts. Port-specific candidate indicators in **bold***

While the top ten scoring indicators for correlation with exposure and sensitivity were all place-based, the same was not true for adaptive capacity. For correlation with adaptive capacity (Figure 10), port-specific indicators scored relatively high. The port-specific indicator rated highest perceived correlation with adaptive capacity was *shelter afforded*, ranked 3/34, followed by *entrance restrictions*, ranked 8/34, *harbor size*, ranked 9/34, *tide range*, ranked 10/34, *marine transportation GDP*, ranked 12/34, and *channel depth*, ranked 13/34.

Although the distance measure of the VAS sliders is unitless, the results indicate an overall low level of expert-perceived correlation between candidate indicators and seaports' adaptive capacity (Figure 10), significantly lower than that for exposure (Figure 8) and sensitivity (Figure 9). The highest scoring candidate indicator for adaptive capacity, *population inside floodplain*, only scored 23 on the unitless VAS, which is lower than 16th place for exposure and lower than 17th place for sensitivity. Interestingly, although candidate indicators scored generally low with adaptive capacity, port-specific indicators fared much better with adaptive capacity than with the other two components of vulnerability, with 4 of the top ten indicators in Figure 10 representing port-specific indicators.

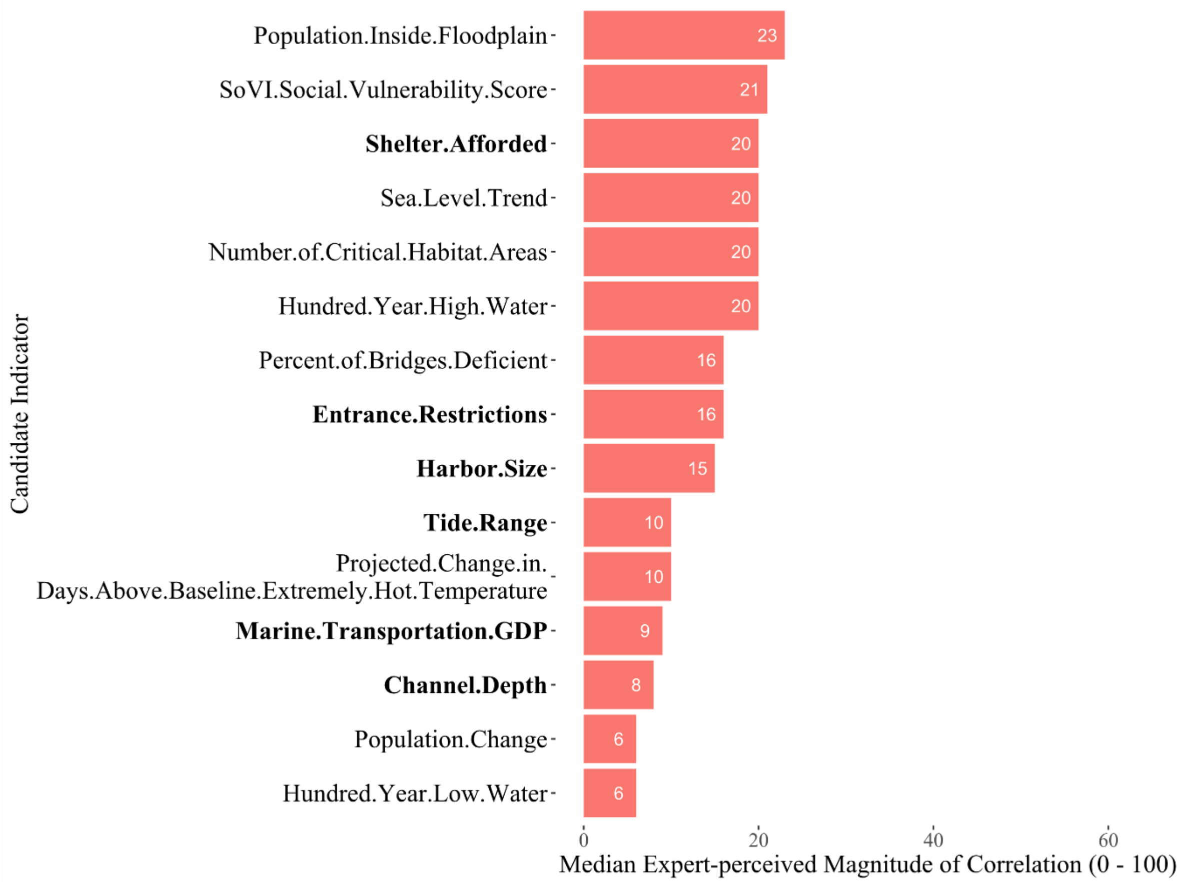


Figure 10 Top 15 candidate indicators for adaptive capacity*, sorted by median expert-perceived magnitude of correlation with seaport adaptive capacity to climate and extreme weather impacts. Port-specific candidate indicators in **bold**. Overall, experts found significantly lower correlation with adaptive capacity than with the other two components of vulnerability.*

Because the VAS expert group was disproportionately represented by those with Federal affiliations (Figure 5), the median aggregate group response considered in the previous four figures is necessarily dominated by those experts. Further insights may be gained by filtering results by expert type, revealing differences in the perceptions of the differently affiliated experts. For example, academically affiliated experts (Figure 12) found more and higher levels of correlation with adaptive capacity than did other types of expert (Figures 11, 13-15). This may be due to academically affiliated experts having more familiarity with the concept of adaptive capacity than other types of expert, as adaptive capacity has become a more common subject in the academic literature.

Asked to suggest additional candidate indicators, respondent experts suggested seven indicators (Table 8) that may warrant further development but were not sufficiently supported by data for our study area ports to be included in this study. As this study aimed to evaluate the current state of openly-available data, candidate indicators required an identifiable open data source with data coverage for greater than 75% of the ports in the CENAD sample to be immediately applicable to this work. Some of the suggested indicators that currently lack sufficient data coverage could potentially be synthesized from a combination of other available data sources, derived via geographic information systems (GIS), or compiled via additional computation for evaluation in future studies. For example, *robustness of transportation infrastructure*, measured in terms of the number of back-up routes, may be determinable via GIS analysis of each ports' multimodal connections' elevations, however, such indicators will be highly sensitive to the value-judgement of how to delimit each port. Port interdependencies also present potential for inclusion in indicator development, e.g., the suggested indicator *distance to nearest alternative seaport*, which would capture the availability of backup ports available to handle a port's primary cargo should that port experience downtime. Though not presently identifiable in openly available data sources, such an indicator could be synthesized from data records of port cargo types, with a similar caveat that it will also require the value judgement of what qualifies as an "alternative" port in terms of ability to handle similar cargo.

Table 8 Expert-suggested candidate indicators of seaport vulnerability to climate and extreme weather impacts. While these suggested candidate indicators lacked the readily available data required to be included in the VAS survey, they may hold promise for further development provided data can be synthesized or compiled from identifiable sources.

Indicator	Units	Description	Data Source
Real estate values	% of tax base at risk	SLR changes in Nuisance and Repetitive Flooding	NA
Distance to nearest alternative seaport	Nautical or statute miles	Based on type of cargo received at the primary seaport	GIS, nautical charts, customs cargo records
Alternative freight transportation modes between seaports	Transportation modes for freight (Pipeline, rail, highway)	As paucity of alternative transportation modes increases, so does the criticality and therefore vulnerability of the primary port	USDOT
Robustness of redundancy for transportation options	number of back-up routes	Robustness of port area to a shock to operations	GIS Mapping
land use	industrial/mixed use	low value vs. high value infrastructure	NA
Age of infrastructure	Years	Average age of critical port infrastructure	NA
Surface Transportation Vulnerability	NA	Ports are dependent on surface access	Local, perhaps FHWA

Discussion

To further IBVA development for the seaport sector and to determine the suitability of available open-data to differentiate ports within a region in terms of relative climate vulnerabilities, researchers applied expert-elicitation methods to refine and evaluate a set of high-level indicators of seaport climate vulnerability. Researchers first held a mind mapping exercise with MTS experts to refine a set of candidate indicators, then developed and tested a visual analogue scale (VAS) survey instrument for expert-evaluation of the selected candidate indicators of seaport vulnerability to climate and extreme weather impacts for the 23 medium and high-use ports of the USACE North Atlantic Division. The results of the VAS survey reveal which indicators port-experts found relatively more correlated with the components of climate vulnerability for seaports. The results can be used to aid in indicator selection for IBVA and CCVA development work in the seaport sector, and the indicators themselves can serve as high-level screening tools for quick comparative analyses among multiple ports.

This research fist identified a gap in the literature for the development of CCVA applied to ports at the multi-port scale. The researchers then performed a first pass of the openly available data for and about the seaport sector to evaluate to what extent it can support the development of expert-supported indicators that can measure the relative climate vulnerabilities of seaports. Open-data here refers to data that is publicly available without fees or restrictions. The use of open-data for indicator development can increase transparency and facilitate the reproducibility of the results. This first-pass of open-data, then, is considered a first step in the development of indicators for seaport climate vulnerability. By starting with examining open-data generally collected for other purposes to assess to assess to what extent it can be developed into expert-supported indicators, an envisioned next step would be to identify what types of bespoke data might be synthesized into new additional indicators to supplement those developed here.

To date there have been relatively few examples of comparative CCVA for the seaport sector (McIntosh and Becker 2017). Most indicator-based assessments for ports have stopped short of comparative CCVA, e.g., the elevation-based, exposure-only assessment of global port cities of (Nicholls et al. 2008), or have focused on assessing other concepts, e.g., (ESPO 2012) which aimed to measure port performance. This research builds upon this body of literature by contributing a set of 34 expert-evaluated indicators of seaport climate vulnerability that can be monitored to assess relative vulnerabilities across ports.

Low Expert-Perceived Correlation with Adaptive Capacity

Results indicate that available open-data can be developed into expert-supported indicators of seaport climate exposure and sensitivity, however, results also indicate relatively little expert-perceived correlation between open-data and a port’s adaptive capacity. For the 34 candidate indicators that were evaluated, none scored a median rating higher than 23 on the unitless VAS scale of correlation with adaptive capacity, compared to a high of 62 with exposure and 52 with sensitivity. This low level of perceived correlation with adaptive capacity suggests a dearth of open-data sources suitable for representing the adaptive capacity of seaports to climate and extreme weather impacts. It also suggests that the concept of adaptive capacity is considered by port-experts to be more difficult to represent with quantitative data than the concepts of exposure or sensitivity.

Expert Preference for Place-Based Indicators

Results of the VAS survey also indicate that respondents reserve their highest levels of aggregate perceived correlation for place-based indicators; though 14 of the 34 candidate indicators were port-specific, the top 12 candidate indicators ranked by total correlation were all place-based. While port-specific indicators scored low overall, they fared better with adaptive capacity than with exposure or sensitivity, which suggests that more or different port-specific data reporting may lead to improvements in the ability to measure a port's relative adaptive capacity.

While the 34 candidate indicators encompassed a combination of 14 port-specific indicators (i.e., those that capture a specific aspect of the port) and 20 place-based indicators (i.e., those that capture the hazards-of-place at the county scale), respondents found higher levels of correlation with the components of vulnerability for place-based indicators than for port-specific ones. For both correlation with exposure (Figure 8) and with sensitivity (Figure 9), the ten highest rated candidate indicators were all place-based. For correlation with adaptive capacity, however, while noticeably lower in magnitude, four of the top ten indicators were port-specific, and a port-specific indicator scored second highest overall (Figure 10). This suggests that of the 34 candidate indicators evaluated, respondents generally preferred the place-based indicators for representing the exposure and sensitivity of a seaport but preferred a mixture of place-based and port-specific indicators for representing a port's adaptive capacity.

This finding suggests that while adaptive capacity is considered by port experts the most difficult component of seaport climate vulnerability to quantify, if expert-supported indicators of seaport adaptive capacity are to be developed, they will most likely be developed from port-specific data, rather than place-based data. As the current selection of port-specific data openly available for the CENAD sample of ports was found to have little expert-perceived correlation with the components of seaport climate vulnerability, efforts will have to be made to identify and share additional port-specific data that can better capture these concepts, and adaptive capacity in particular.

Variation of Results for Different Expert-Affiliation Groups

Filtering responses by expert affiliation revealed differences in the perceptions of the different types of expert. Academically affiliated experts were more willing to indicate correlation with adaptive capacity than other types of expert, while federally affiliated experts indicated the least amount of correlation with adaptive capacity. This discrepancy may reveal a higher familiarity with adaptive capacity as an abstract concept in the academic sphere than in other port-expert professions. This finding highlights the importance of a diverse expert group when using expert-elicitation methods.

Limitations and Next Steps

As the population of experts with the requisite knowledge of the climate vulnerabilities of N.E. U.S. seaports is limited, this study was limited by the sample size of respondent experts. While the total response rate was satisfactory, the total number of experts was not evenly distributed among the seven expert-affiliation categories (Figure 5). Accordingly, comparisons of responses by expert-affiliation suffer from this small sample size. These expert-related limitations are a function of applying a stakeholder-driven approach, as opposed to a purely data-drive approach, e.g., SoVI (Cutter, Boruff, and Shirley 2003). Instead of the purely theoretical approach described by the SoVI, this work takes a stakeholder-driven approach by including port-experts in the development and weighting of the indicators, as this has been shown to increase the creditability of the index as a tool (Barnett, Lambert, and Fry 2008, Sagar and Najam 1998).

An additional limitation stems from the difficulty of achieving true comprehensiveness in the process of seeking and compiling the candidate indicators for experts to evaluate. To lessen the risk of excluding potential candidate indicators, researchers asked experts, at both the mind map stage and the VAS survey stage, to suggest additional or better indicators. At neither stage were experts able to suggest an indicator with a known data source with sufficient data availability for the sample of ports, suggesting that our search for open-data candidate indicators was suitably comprehensive. Next steps for future studies may involve furthering the development of those candidate indicators suggested by respondents in Table 8, exploring non-open or proprietary sources of data for those indicators identified in Table 9 but lacking available open data sources, or synthesizing novel indicators from combinations of available data.

Conclusion

Seaports are critical to global trade and national security yet sit on the front-line for extreme coastal weather and climate impacts, and such impacts are projected to worsen globally. As port decision-makers wrestle with the myriad of climate adaptation options (including the option of making no adaptations at all), their CIAV decisions can and should be supported with data. For CIAV decision-support, the first step often involves assessing vulnerabilities. For an individual seaport, this process tends to take the shape of CCVA, either as a participatory self-assessment, or as a site-specific case study. For multiple port systems, however, CCVA often rely on indicators. This research has presented a general method for developing and evaluating candidate indicators based on aggregate expert-elicitation that could be applicable in other fields of study beyond the seaport sector.

While the research literature currently lacks examples of multi-port, comparative CCVA for the seaport sector, this body of work has developed and contributed a set of 34 expert-evaluated indicators of seaport climate-vulnerability from open-data that can be monitored to assess relative vulnerabilities across ports. Further, this work quantified expert preferences for weighting indicators and the components of climate vulnerability for seaports and identified adaptive capacity as lacking representation in the available data. Additionally, the stakeholder-driven method of identifying and evaluating candidate indicators could be replicated to develop new indicators for other port regions or other non-port sectors.

This expert-evaluation of candidate indicators of seaport vulnerability to climate and extreme weather impacts explored the sufficiency of the current state of data reporting for and about the seaport sector to develop expert-supported vulnerability indicators for a regional sample of ports. Expert-evaluation of 34 candidate indicators in the context of a sample of 23 CENAD ports resulted in port-experts having found significantly stronger correlation with the exposure and sensitivity of a port than with the adaptive capacity, suggesting a lack of open-data sources available for representing the adaptive capacity of seaports in the sample. This finding also suggests that port-experts consider the concept of adaptive capacity to be less amenable to representation with quantitative data than the remaining two components of vulnerability, i.e., exposure and sensitivity. Regarding the question of sufficiency of currently available open-data to serve as vulnerability indicators for the seaport sector, then, results suggest that while exposure and sensitivity can currently be represented by expert-supported indicators, this research was unable to identify currently available data sources that could yield expert-supported indicators of adaptive capacity. These results suggest an opportunity exists for further research and development of standardized, comparative CCVA methods for seaports and the marine transportation system, with the objective of supporting CIAV decisions with information products that allow decision makers to compare mechanisms and drivers of climate change across multiple ports. Before a complete IBVA framework for seaports can be developed, however, further work on the development of indicators of adaptive capacity will be needed.

Works Cited

Adger, W Neil, Nick Brooks, Graham Bentham, Maureen Agnew, and Siri Eriksen. 2004. New indicators of vulnerability and adaptive capacity. Tyndall Centre for Climate Change Research.

Brooks, Nick, W Neil Adger, and P Mick Kelly. 2005. "The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation." *Global environmental change* 15 (2):151-163.

Chhetri, Prem, Jonathan Corcoran, Victor Gekara, Chris Maddox, and Darryn McEvoy. 2014. "Seaport resilience to climate change: mapping vulnerability to sea-level rise." *Journal of Spatial Science*:1-14. doi: 10.1080/14498596.2014.943311.

Clark, William C., and Edward A. Parson. 2000. *Assessing vulnerability to global environmental risks*: Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University.

CMTS, U.S. 2015. Marine Transportation System Performance Measures: Executive Summary. 1200 New Jersey Ave SE. Washington, D.C. 20590: U.S. Committee on the Marine Transportation System, Research and Development Integrated Action Team.

Cox, R. J., K. Panayotou, and R. M. Cornwell. 2013. Climate Risk Assessment for Avatiu Port and Connected Infrastructure. Water Research Lab, University of New South Wales.

Cutter, S. L. 1996. "Vulnerability to environmental hazards." *Progress in Human Geography* 20 (4):529-539. doi: Doi 10.1177/030913259602000407.

Cutter, S. L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb. 2008. "A place-based model for understanding community resilience to natural disasters." *Global Environmental Change* 18 (4):598-606. doi: DOI 10.1016/j.gloenvcha.2008.07.013.

Cutter, S. L., C. G. Burton, and C. T. Emrich. 2010. "Disaster Resilience Indicators for Benchmarking Baseline Conditions." *Journal of Homeland Security and Emergency Management* 7 (1). doi: 10.2202/1547-7355.1732.

Delbecq, Andre L, Andrew H Van de Ven, and David H Gustafson. 1975. *Group techniques for program planning: A guide to nominal group and Delphi processes*: Scott, Foresman Glenview, IL.

Füssel, Hans Martin, and R. J. T. Klein. 2006. "Climate change vulnerability assessments: An evolution of conceptual thinking." *Climatic Change* 75:301-329. doi: 10.1007/s10584-006-0329-3.

Gallopín, Gilberto C. 2006. "Linkages between vulnerability, resilience, and adaptive capacity." *Global environmental change* 16 (3):293-303.

Gallopin, Gilberto Carlos. 1997. "Indicators and their use: information for decision-making." In *Sustainability Indicators. A Report on the Project on Indicators of Sustainable Development*, edited by Bedrich Boldan and Suzanne Bilharz, 13-27. Chichester: SCOPE.

Hanson, Susan, Robert Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau. 2010. "A Global Ranking of Port Cities with High Exposure to Climate Extremes." *Climatic Change* 104 (1):89-111. doi: 10.1007/s10584-010-9977-4.

Hasson, Felicity, Sinead Keeney, and Hugh McKenna. 2000. "Research guidelines for the Delphi survey technique." *Journal of advanced nursing* 32 (4):1008-1015.

Hinkel, J. 2011. ""Indicators of vulnerability and adaptive capacity": Towards a clarification of the science-policy interface." *Global Environmental Change-Human and Policy Dimensions* 21 (1):198-208. doi: DOI 10.1016/j.gloenvcha.2010.08.002.

IPCC. 2001. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.

IPCC. 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change.

IPCC. 2014b. WGII AR5 Glossary. In *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Janssen, Marijn, Yannis Charalabidis, and Anneke Zuiderwijk. 2012. "Benefits, adoption barriers and myths of open data and open government." *Information Systems Management* 29 (4):258-268.

Keeney, Sinead, Felicity Hasson, and Hugh McKenna. 2006. "Consulting the oracle: ten lessons from using the Delphi technique in nursing research." *Journal of advanced nursing* 53 (2):205-212.

Kim, Yeonjoo, and Eun-Sung Chung. 2013. "Assessing climate change vulnerability with group multi-criteria decision making approaches." *Climatic change* 121 (2):301-315.

Koppe, Baerbel. 2012. "IAPH-Report on Seaports and Climate Change and Implementation Case Study for the Port of Hamburg."

Kuo, Ying-Feng, and Pang-Cheng Chen. 2008. "Constructing performance appraisal indicators for mobility of the service industries using Fuzzy Delphi Method." *Expert Systems with Applications* 35 (4):1930-1939.

MARAD. 2016. "Marine Transportation System (MTS)." Maritime Administration, accessed 5/25/2016. https://www.marad.dot.gov/ports/marine-transportation-system-mts/.

McIntosh, R. Duncan, and Austin Becker. 2017. "Seaport Climate Vulnerability Assessment at the Multi-port Scale: A Review of Approaches." In *Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains*, edited by Igor Linkov and José Manuel Palma-Oliveira, 205-224. Dordrecht: Springer Netherlands.

Mclean, Elizabeth, Austin Becker, R. Duncan McIntosh, and Julie Dean Rosati. 2017a. Measuring Risk Database for 23 North Atlantic Ports. A Technical Report for ERDC, Version 1.0. Project: W912HZ-16-C-0019. United States Army Corps of Engineers.

Mclean, Elizabeth, Austin Becker, R. Duncan McIntosh, and Julie Dean Rosati. 2017b. Selection of Seaport Vulnerability Indicators for 23 Medium and High Use North Atlantic Ports United States Army Corps of Engineers.

Messner, S., L. Moran, G. Reub, and J. Campbell. 2013. Climate change and sea level rise impacts at ports and a consistent methodology to evaluate vulnerability and risk. ENVIRON International Corp.

Morris, Lauren L., and Tracie Sempier. 2016. Ports Resilience Index: A Port Management Self-Assessment. U.S. Department of Commerce, Gulf of Mexico Alliance.

Muller, Jorg, Daniel Polansky, Petr Novak, Christian Foltin, and Dimitry Polivaev. 2013. Freemind - free mind mapping and knowledge building software.

NGIA. 2015. *WORLD PORT INDEX - 150 PUB. - TWENTY-FOURTH EDITION*. Springfield, Virginia: NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY.

Nicholls, Robert J, Susan Hanson, Celine Herweijer, Nicola Patmore, Stéphane Hallegatte, Jan Corfee-Morlot, Jean Château, and Robert Muir-Wood. 2008. Ranking port cities with high exposure and vulnerability to climate extremes: Exposure Estimates. In *OECD Environment Working Papers*: Organization for Economic Cooperation and Development.

NOAA OCM. 2015. "Port Tomorrow: Port Resilience Planning Tool [Prototype]." NOAA Office for Coastal Management, accessed 3 April 2015. http://www.coast.noaa.gov/port/.

Obama, Barack. 2013. "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience." *Washington, DC*.

Okoli, Chitu, and Suzanne D Pawlowski. 2004. "The Delphi method as a research tool: an example, design considerations and applications." *Information & management* 42 (1):15-29.

Preston, BL. 2012. Climate change vulnerability assessment: From conceptual frameworks to practical heuristics. CSIRO Climate Adaptation Flagship Working paper.

Rice, Jake C, and Marie-Joëlle Rochet. 2005. "A framework for selecting a suite of indicators for fisheries management." *ICES Journal of Marine Science* 62 (3):516-527.

Rosati, Julie Dean. 2015. "PhD, PE, D.CE, Coastal & Hydraulics Laboratory, Engineer Research & Development Center, U.S. Army Corps of Engineers." Personal Communication, 1/10/15.

Schroth, Olaf, Ellen Pond, and Stephen RJ Sheppard. 2011. "Integration of Spatial Outputs from Mathematical Models in Climate Change Visioning Tools for Community-Decision Making on the Landscape Scale." *DLA-Digital Landscape Architecture*:246-255.

Semppier, T. T., D.L. Swann, R. Emmer, S. H. Sempier, and M. Schneider. 2010. Coastal Community Resilience Index: A Community Self-Assessment. Mississippi-Alabama Sea Grant Consortium.

Smit, Barry, and Johanna Wandel. 2006. "Adaptation, adaptive capacity and vulnerability." *Global environmental change* 16 (3):282-292.

The National Academies. 2012. Disaster Resilience: A National Imperative. edited by Committee on Increasing National Resilience to Hazards and Disasters; Committee and Engineering on Science, and Public Policy. Washington, D.C.

Turner, Billie L, Roger E Kasperson, Pamela A Matson, James J McCarthy, Robert W Corell, Lindsey Christensen, Noelle Eckley, Jeanne X Kasperson, Amy Luers, and Marybeth L Martello. 2003. "A framework for vulnerability analysis in sustainability science." *Proceedings of the national academy of sciences* 100 (14):8074-8079.

USACE. 2014. USACE Civil Works Division Boundaries. http://geoplatform.usace.army.mil/home/item.html?id=c3695249909c45a2b2e2c3993aff3edb: U.S. Army Corps of Engineers.

USDOT. 2014. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure The Gulf Coast Study, Phase 2 Screening for Vulnerability Final Report, Task 3.1. edited by ICF International. Washington, DC: US Department of Transportation.

White, Dave D, Amber Wutich, Kelli L Larson, Patricia Gober, Timothy Lant, and Clea Senneville. 2010. "Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater." *Science and Public Policy* 37 (3):219-232.

Appendix

Table 9 Candidate Indicators Identified from Literature Review

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
Exposure	Storm Hazard	Storm Frequency	1	Number of storm events in port county w/ property damage > $1M	**NumberStormEvents**	events	NOAA Storm Events Database	yes	yes	place
		Storm Damage	2	Cost of property damage from the most costly storm event in the port county since 1950	**MaxCostStormEvents**	$	NOAA Storm Events Database	yes	no	place
		Wind Hazard	3	Non-convective high winds	**NA**	kts	NOAA Storm Events Database	no	no	place
			4	1% annual exceedance wind speed	**NA**	kts	NA	no	no	place
		Storm Surge Hazard	5	Max historical storm surge	**NA**	meters	SurgeDAT	no	no	place
			6	Highest historical water level	**NA**	m above MHHW	Top Ten Highest Water Levels for long-term stations	no	no	place
			7	1% annual exceedance probability high water level which corresponds to the level that would be exceeded one time per century, for the nearest NOAA tide station to the port	**HundredYearHighWater**	m above MHHW	NOAA Tides and Currents: Extreme Water Levels	yes	yes	place
		Tropical Cyclone Frequency	8	Number of cyclones that have passed within 100 nm of the port since 1842	**NumberCyclones**	Number of cyclones	NOAA Historical Hurricane Tracks Tool	yes	yes	place

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			9	Tropical cyclone return period	**NA**	years	National Hurricane Center	no	no	place
	Sea Level Rise Hazard	Empirical SLR	10	Local Mean Sea Level Trend	**SeaLevelTrend**	mm / yr	NOAA Tides and Currents: Sea Level Trends	yes	yes	place
		Projected SLR	11	Local SLR Projections	**NA**	mm / yr	Global Sea Level Rise Scenarios for the United States: National Climate Assessment	no	no	place
		Rate of vertical land motion due to Glacial Isostatic Adjustment (GIA)	12	annual uplift/subsidence rate	**NA**	mm / yr	Permanent Service for Mean Sea Level (PSMSL) Peltier GIA data sets	no	no	place
	Temperature Hazard	Sea Temperature Anomaly	13	Average Annual Sea Surface Temp Anomaly	**NA**	°F	NOAA National Centers For Environmental Information NCDC	no	no	place
		Projected Temperature	14	The percent change from observed baseline of the average number of days per year above baseline "Extremely Hot" temperature projected for the end-of-century, downscaled to 12km resolution for the port location	**CMIP_DaysAboveBaselineExtrememlyHotTemperature**	%	US DOT CMIP Climate Data Processing Tool	yes	yes	place

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
	Precipitation Hazard	Projected Precipitation	15	The percent change from observed baseline of the average number of “Extremely Heavy” Precipitation Events projected for the end-of-century, downscaled to 12km resolution for the port location	**CMIP_NumberOfExtremelyHeavyPrecipEvents**	%	US DOT CMIP Climate Data Processing Tool	yes	yes	place
	Disasters	Disaster Frequency	16	Number of Presidential Disaster Declarations for the port county since 1953	**NumberDisastersCounty**	Disaster Type	FEMA, Historical Disaster Declarations	yes	yes	place
		Disaster Intensity	17	The total disaster housing assistance of Presidential Disaster Declarations for the port county since 1953	**DisasterHousingAssistanceCounty**	Declarations	FEMA, Historical Disaster Declarations	yes	yes	place
Sensitivity	Environmental Sensitivity	Surrounding Environment	18	Nearby Federally/State Managed Water	**NA**	Acres	NOAA National Estuary Research Reserve System	no	no	place
			19	Number of Threatened or Endangered Species found in port county	**NumberEndangeredSpeciesCounty**	Species	U.S. Fish & Wildlife Service: Endangered Species	yes	yes	place
			20	Nearby Wildlife Refugees	**NA**	Acres	U.S. Fish and Wildlife Refugees	no	no	place
			21	Number of Critical Habitat Areas within 50 miles of the port	**NumberCriticalHabitat**	Areas	U.S. Fish & Wildlife Service: Critical Habitat Portal	yes	yes	place

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			22	Proximity to nearest MPA with a Protection level including “No Take,” “No Impact,” or “No Access”	**MilesToMPA**	Miles	NOAA National MPA Center	yes	no	place
			23	Environmental Sensitivity Index (ESI) shoreline sensitivity to an oil spill for the most sensitive shoreline within the port	**ESI**	ESI Rank (1.00 - 10.83)	NOAA Office of Response and Restoration: Shoreline Rankings	yes	yes	place
		Air Quality	24	Number of Days with Air Quality Index value greater than 100 for the port city	**AirPollutionDays**	Days	EPA Air Quality Report	yes	yes	place
		Port Consumption	25	Energy Consumption	**NA**	Watts	NA	no	no	port
			26	Water Consumption	**NA**	Gallons	NA	no	no	port
			27	Soild Waste Production	**NA**	Tons	NA	no	no	port
		Hazmat	28	EPA Brownfields near port	**NA**	Number of sites	EPA Cleanups in My Community	no	no	place
			29	Number of Hazardous Materials Incidents in port city since 2007	**NumberHazmatIncidents**	Number of Incidents	U.S. DOT Pipeline and Hazardous Materials Safety Administration: Incident Statistics	yes	yes	place
			30	Average cost per incident of total damage from the 10 most costly Hazardous Materials Incidents in the port city since 2007	**AvgCostHazmatIncidents**	$	U.S. DOT Pipeline and Hazardous Materials Safety Administration: Incident Statistics	yes	yes	place

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
	Built Asset Sensitivity	Land-Side Built Asset Sensitivity	31	Average age of gantry cranes	**NA**	years	NA	no	no	port
			32	Average age of buildings	**NA**	years	NA	no	no	port
			33	Average age of berthing infrastructure	**NA**	years	NA	no	no	port
			34	Average cost of property damage from storm events in the port county since 1950 with property damage > $1 Million	**AvgCostStormEvents**	$	NOAA Storm Events Database	yes	yes	place
			35	Percent of bridges in the port county that are structurally deficient or functionally obsolete	**PercentDeficientBridgesCounty**	%	US DOT FHA National Bridge Inventory: Deficient Bridges by County	yes	yes	place
		Water-Side Built Asset Sensitivity	36	Shelter Afforded	**Shelter**	Excellent (5), Good (4), Fair (3), Poor (2), None (1)	World Port Index (Pub 150)	yes	yes	port
			37	Presence or absence of entrance restrictions	**EntranceRestrictions**	Tide, Swell, Ice, Other	World Port Index (Pub 150)	yes	yes	port
			38	Presence or absence of overhead limitations	**OverheadLimits**	Y/N	World Port Index (Pub 150)	yes	yes	port
			39	The controlling depth of the principal or deepest channel at chart datum	**ChannelDepth**	A (over 76 ft) to Q (0 – 5 ft) in	World Port Index (Pub 150)	yes	yes	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
						5-foot increments				
			40	The greatest depth at chart datum alongside the respective wharf/pier. If there is more than one wharf/pier, then the one which has greatest usable depth is shown.	**PierDepth**	A (over 76 ft) to Q (0 – 5 ft) in 5-foot increments	World Port Index (Pub 150)	yes	yes	port
			41	Mean tide range at the port	**TideRange**	feet	World Port Index (Pub 150)	yes	yes	port
			42	1% annual exceedance probability low water level for the nearest NOAA tide station to the port, which corresponds to the level that would be exceeded one time per century	**HundredYearLowWater**	m below MLLW	NOAA Extreme Water Levels	yes	yes	place
			43	Type of Harbor	**HarborType**	Coastal Natural, Coastal Breakwater, Coastal Tide Gate, River Natural, River Basis, None, River	World Port Index (Pub 150)	yes	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
						Tide Gate, Lake or Canal, Open Roadstead, Typhoon Harbor				
			44	Time since last dredged	**NA**	months	NA	no	no	port
	Economic Sensitivity	Regional Economic Sensitivity	45	Number of Marine Transportation Jobs in the port county	**MTJobsCounty**	number of jobs	NOAA Office for Coastal Management: Economics: National Ocean Watch (ENOW)	yes	yes	port
			46	Average Marine Transportation Wage per employee in port county	**MTWagesCounty**	$	NOAA Office for Coastal Management: Economics: National Ocean Watch (ENOW)	yes	no	port
			47	County Marine Transportation GDP	**MTGDPCounty**	$	NOAA Office for Coastal Management: Economics: National Ocean Watch (ENOW)	yes	yes	port
			48	Port Indirect Regional Employment	**NA**	number of jobs	NA	no	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
		Port Economic Sensitivity	49	Port Direct Employment	**NA**	number of jobs	NA	no	no	port
			50	Port Market Share	**NA**	%	NA	no	no	port
			51	Port Insurance Acutarial Rate	**NA**	$	NA	no	no	port
	Social Sensitivity	Surrounding Population's Sensitivity	52	Rate of population change (from 2000-2010) in the port county, expressed as a percent change	**PopulationChangeCounty**	%	NOAA Office for Coastal Management: Quick Report Tool for Socioeconomic Data	yes	yes	place
			53	Percent of the port county population over age 65	**PopulationOver65**	%	NOAA Coastal County Snapshots	yes	no	place
			54	Percent of the port county population living below poverty thresholds	**PopulationPovertyCounty**	%	NOAA Coastal County Snapshots	yes	no	place
			55	Percent of the port county population living inside the FEMA Floodplain	**PopulationInsideFloodplain**	%	NOAA Coastal County Snapshots	yes	yes	place
			56	Port County Social Vulnerability (SoVI) Score	**SoVI**	score number	SoVI® Social Vulnerability Index	yes	yes	place
		Surrounding Structures / Asset Sensitivity	57	National Flood Insurance Program Community Rating System Score	**NA**	score number	FEMA National Flood Insurance Program Community Rating System: Communities and Their Classes	no	no	place
Adaptive Cap			58	Vessel turnaround time	**NA**	hours	NA	no	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
	Operational Efficiency	Port Opperational Efficiency	59	Wharf productivity	**NA**	TEU / Foot of Berth	NA	no	no	port
			60	Port Container Productivity	**NA**	moves / hour	NA	no	no	port
			61	average container lifts per hour	**NA**	TEU	NA	no	no	port
			62	annual Crane Capacity	**NA**	TEU	NA	no	no	port
			63	annual TEU/Crane	**NA**	TEU	NA	no	no	port
			64	Avg annual TEU / CY Slot (Turns)	**NA**	TEU / CY slot	NA	no	no	port
			65	average drayage wait times	**NA**	minutes	NA	no	no	port
			66	Berth occupancy rate (Berth Utilization - Vessel Call Basis)	**NA**	%	NA	no	no	port
		Efficiency of Transport Connections	67	annual Truck Congestion Cost	**NA**	$ millions	Texas A&M University Texas Transportation Institute Urban Mobility Information, Congestion Data for Your City	no	no	place
			68	Roadway Congestion Index	**NA**	unitless	Texas A&M University Texas Transportation Institute Urban Mobility Information, Congestion Data for Your City	no	no	place

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			69	Travel Time Index	**NA**	unitless	Texas A&M University Texas Transportation Institute Urban Mobility Information, Congestion Data for Your City	no	no	place
	Water-Side Capacity	Vessels	70	Number of Annual Vessel Calls (vessels > 1k DWT) at the port	**VesselCalls**	ship calls	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	no	port
			71	Harbor Size	**HarborSize**	Large, Medium, Small, Very-Small	World Port Index (Pub 150)	yes	yes	port
			72	Vessel Capacity (vessels > 10k DWT)	**VesselCapacity**	calls x DWT	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	yes	port
			73	Tanker Calls	**TankerCalls**	ship calls	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			74	Tanker Capacity	**TankerCapacity**	calls x DWT	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	yes	port
			75	Gas Carrier Calls	**GasCalls**	ship calls	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	no	port
			76	Gas Carrier Capacity	**GasCapacity**	calls x DWT	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	yes	port
			77	Container Vessel Calls	**ConatinerCalls**	ship calls	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	no	port
			78	Container Vessel Capacity	**ContainerCapacity**	calls x DWT	U.S. DOT Maritime Administration, Vessel Calls at U.S. Ports by Vessel Type	yes	yes	port
			79	Cruise-Ship Calls	**NA**	ship calls	North American Cruise Traffic 2013-2014	no	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			80	Cruise-Ship Passengers	**NA**	passengers	North American Cruise Traffic 2013-2015	no	no	port
		Cargo	81	Total Throughput	**Tonnage**	Tons	USACE Navigation Data Center (pports)	yes	yes	port
			82	Containerized Throughput	**NA**	TEU	Western Hemisphere Port TEU Container Volumes 1980-2013	no	no	port
			83	Domestic Throughput	**Domestic**	Tons	USACE Navigation Data Center: Principal Ports of the U.S.	yes	no	port
			84	Foreign Throughput	**Foreign**	Tons	USACE Navigation Data Center: Principal Ports of the U.S.	yes	no	port
			85	Foreign Imports	**Imports**	Tons	USACE Navigation Data Center: Principal Ports of the U.S.	yes	no	port
			86	Foreign Exports	**Exports**	Tons	USACE Navigation Data Center: Principal Ports of the U.S.	yes	no	port
			87	Top Foreign Import By Value	**NA**	6 digit HS code	USA Trade Online: HS Port-level Data	no	no	port
			88	Top Foreign Import By Weight	**NA**	6 digit HS code	USA Trade Online: HS Port-level Data	no	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			89	Top Foreign Export By Value	**NA**	6 digit HS code	USA Trade Online: HS Port-level Data	no	no	port
			90	Top Foreign Export By Weight	**NA**	6 digit HS code	USA Trade Online: HS Port-level Data	no	no	port
	Land-Side Capacity	Flexibility	91	Ability to Shift Operations	**NA**	Likert scale	NA	no	no	port
			92	Gross Acres	**NA**	acres	NA	no	no	port
			93	Container Yard Acres	**NA**	acres	NA	no	no	port
			94	Container Yard / Gross Ratio	**NA**	%	NA	no	no	port
			95	Avg CY Slots / Acre - Density	**NA**	slots per acre	NA	no	no	port
			96	Yard area per berth	**NA**	area	NA	no	no	port
			97	Number of Berths	**NA**	Number of berths	NA	no	no	port
			98	Total Berth Feet	**NA**	feet	NA	no	no	port
			99	Number of Gantry Cranes	**NA**	Number of cranes	NA	no	no	port
			100	Gantry crane max height	**NA**	feet	NA	no	no	port
			101	Gantry crane max outreach	**NA**	feet	NA	no	no	port
			102	Gantry crane max tonnage capacity	**NA**	Tons	NA	no	no	port
			103	Presence of direct Rail Connections	**NA**	yes / no	NA	no	no	port
		Port Planning	104	Do port Master Plans consider resilience?	**NA**	yes / no	NA	no	no	port

Category	Sub-Category	Sub-Sub-Category	No.	Description	Indicator	Units	Data Source	Sufficient Data: Included in Mind Map	Selected via Mind Map: Included in VAS Survey	Place-Based / Port-Specific
			105	Do State and Local Adaptations Plans consider resilience?	**NA**	yes / no	NA	no	no	port
			106	Does the port have sustainability plan?	**NA**	yes / no	NA	no	no	port
		Port Growth	107	annual % change in throughput	**NA**	%	USACE Navigation Data Center: Principal Ports of the U.S.	no	no	port
			108	annual % change in Port Market Share	**NA**	%	NA	no	no	port

Table 10 Knowledge Resource Nomination Worksheet (KRNW) modified from (Okoli and Pawlowski 2004).

Disciplines or skills	**Organizations**	**Related literature**

• Academics
  ○ from review of literature
• Practitioners
  ○ from professional societies
• Government
  ○ Federal
  ○ State
• NGOs
	• American Association of Ports Authorities (AAPA)
	• North Atlantic Ports Association
	• International Association of Ports and Harbors (IAPH)
	• American Society of Civil Engineers (ASCE)
	  ○ Coasts, Oceans, Ports, and Rivers Institute (COPRI)
	• Inner City Fund (ICF) International
	• Stromberg Associates
	• World Association for Waterborne Transport Infrastructure (PIANC)
	• U.S. Army Corps of Engineers (USACE)
	  ○ Engineer Research and Development Center (ERDC)
	  ○ Institute for Water Resources (IWR)
	• Committee on the Marine Transportation System (CMTS)
	• U.S. Department of Transportation
	  ○ U.S. Maritime Administration (MARAD)
	• National Academies of Sciences, Engineering, and Medicine
	  ○ Transportation Research Board (TRB)
	• U.S. Coast Guard (USCG)
		Academic literature:
		• CCVA
		• Hazard risk assessment
		• Seaport related research
		• Indicator development research
		
		Grey literature:
		• Trade journals
		• White papers
		• Non-academic port studies

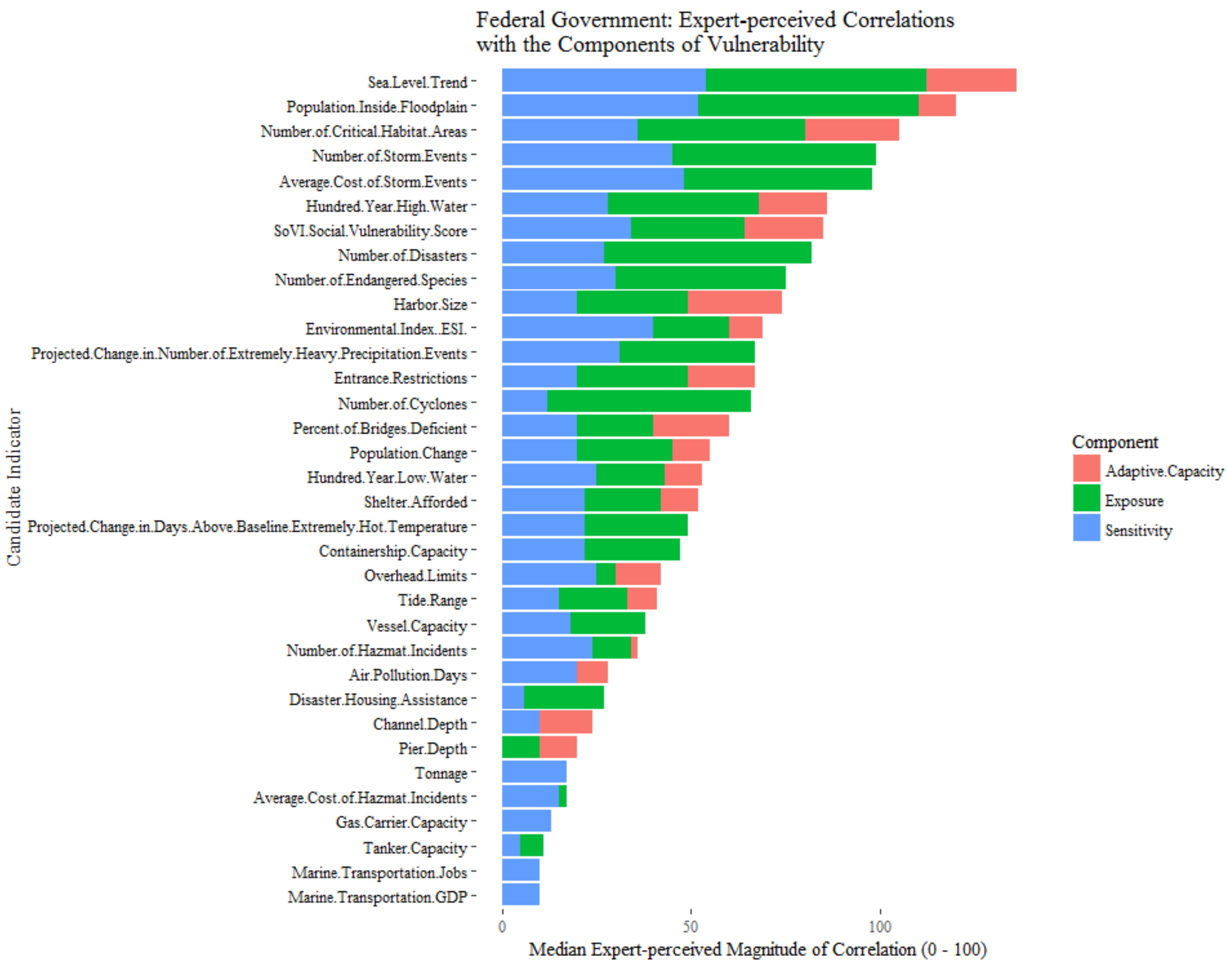


Figure 11 Median Federal expert-perceived magnitude of correlation with each of the three components of vulnerability

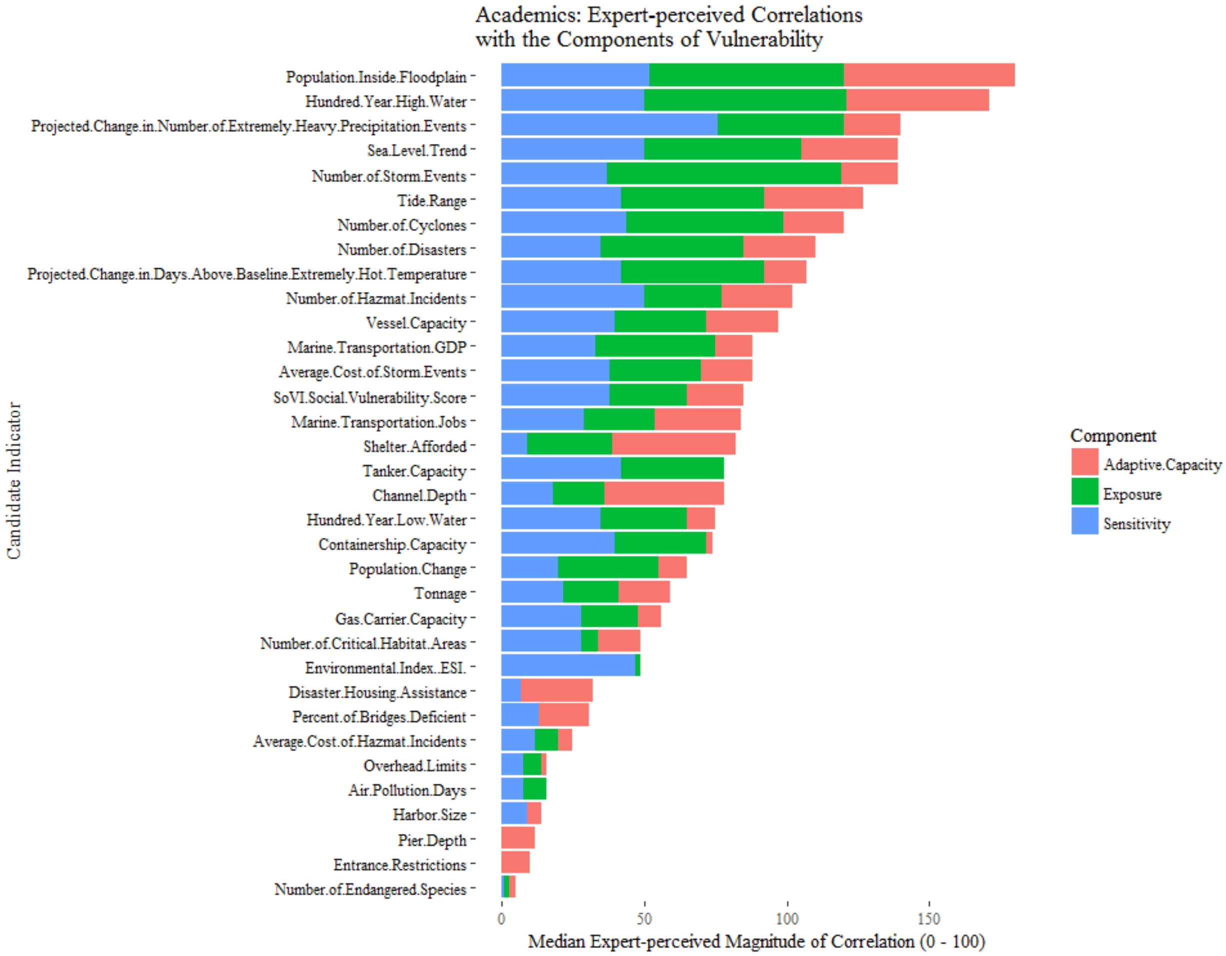


Figure 12 Median Academic expert-perceived magnitude of correlation with each of the three components of vulnerability

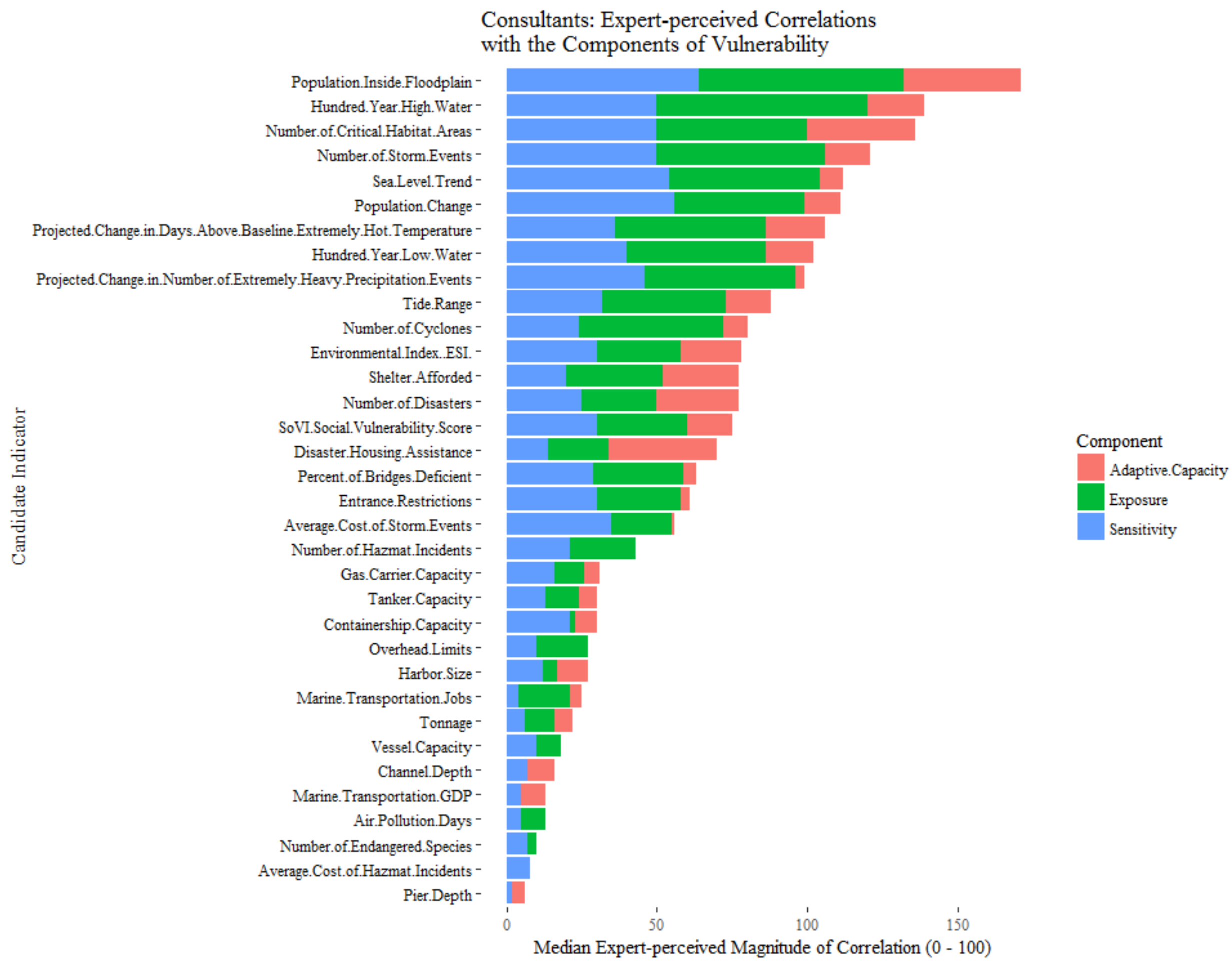


Figure 13 Median Consultant expert-perceived magnitude of correlation with each of the three components of vulnerability

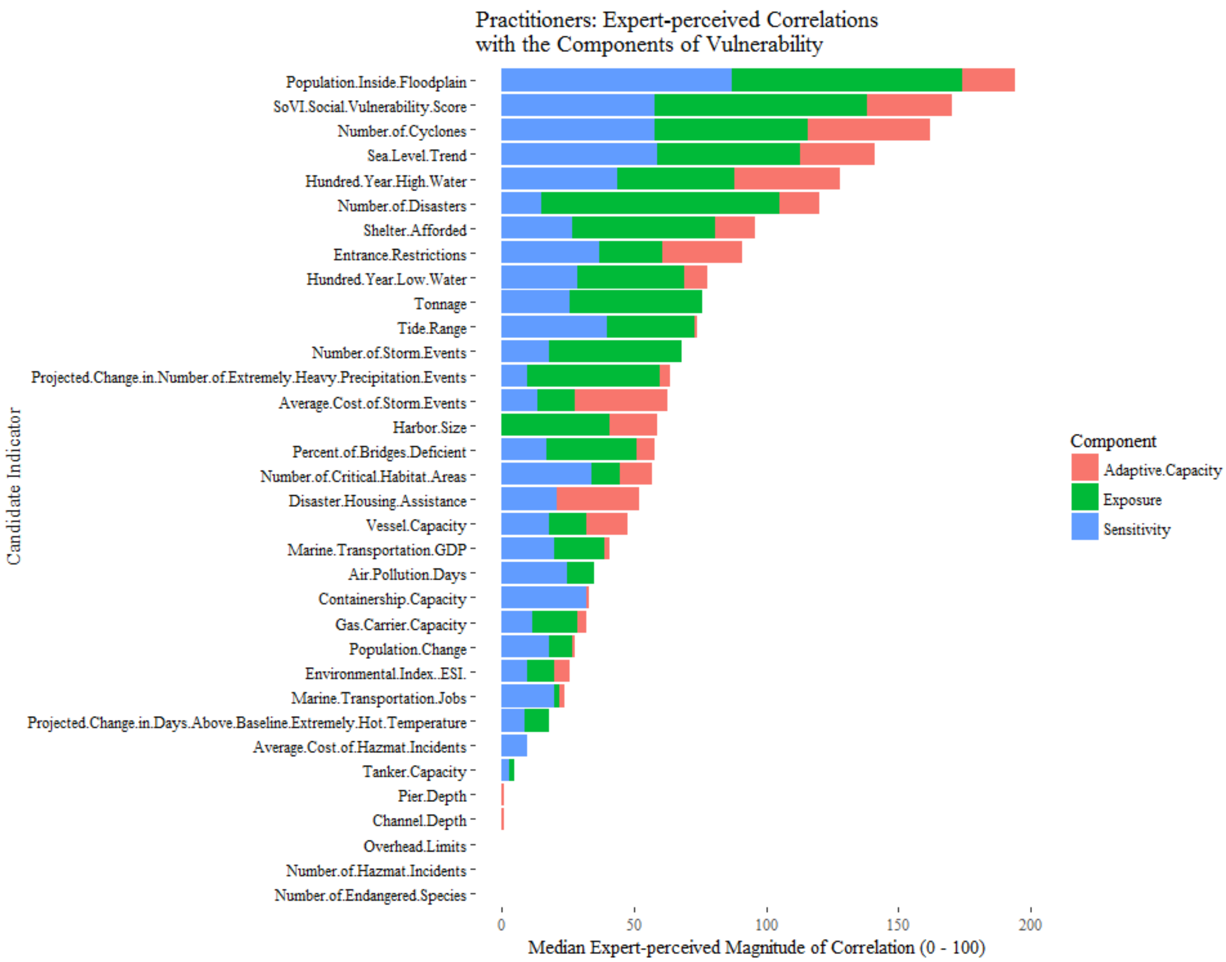


Figure 14 Median Practitioner expert-perceived magnitude of correlation with each of the three components of vulnerability

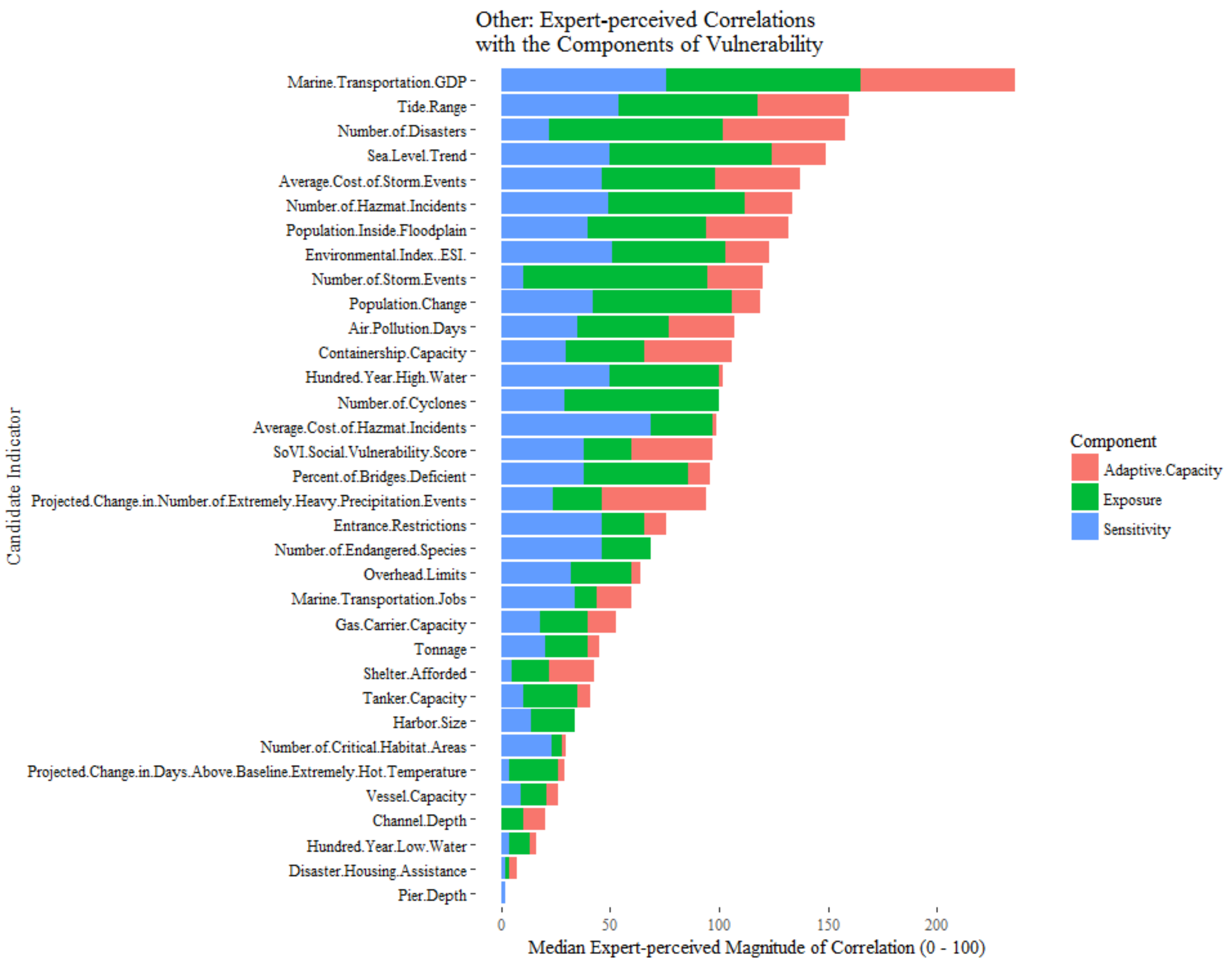
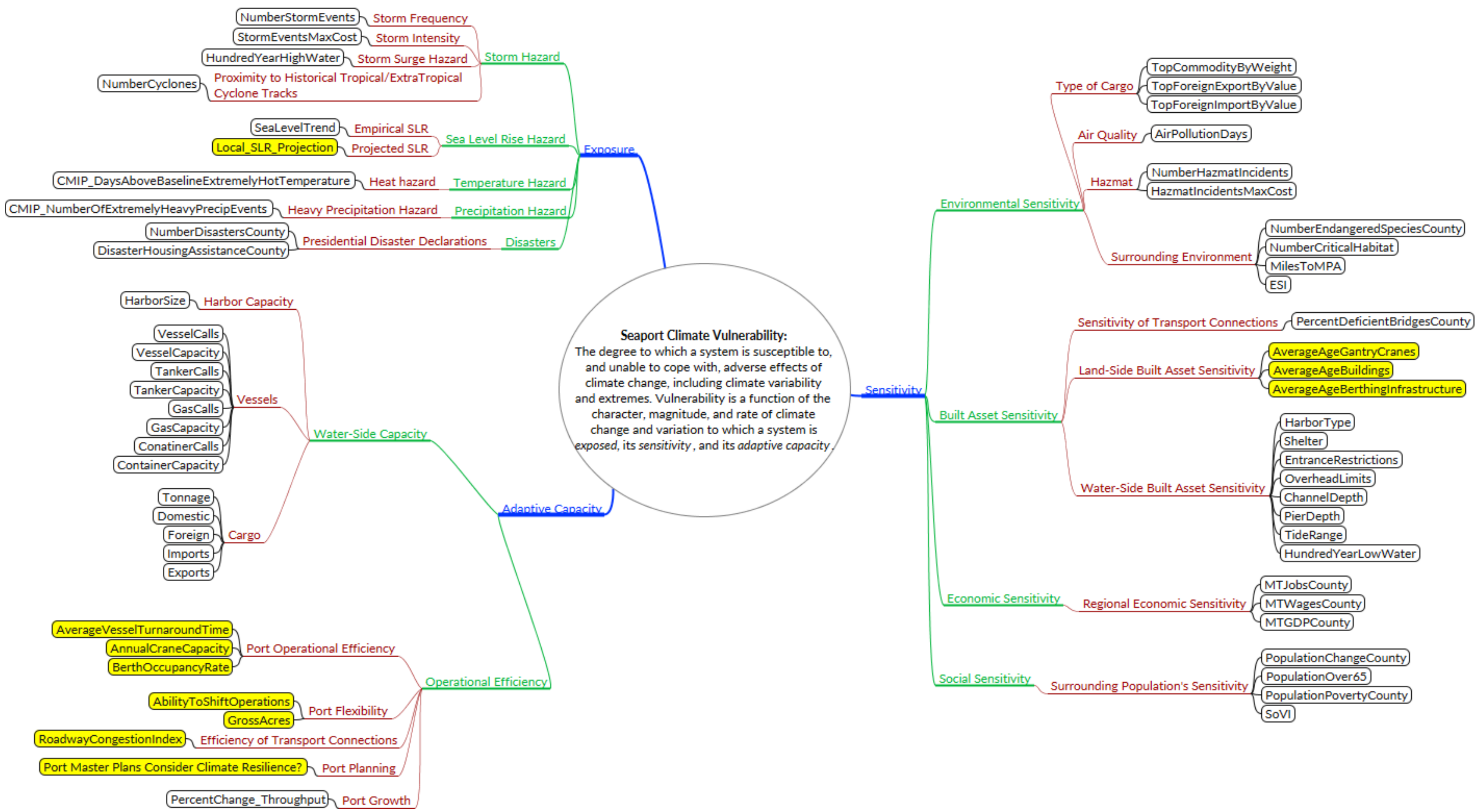


Figure 15 Median Other expert-perceived magnitude of correlation with each of the three components of vulnerabilit

Figure 16 Mind map of candidate indicators of Seaport Climate Vulnerability. Candidate indicators lacking a data-source are highlighted in yellow.



MANUSCRIPT 3: Using AHP to Weight Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic Ports

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Abstract

This paper describes a method of weighting indicators for assessing the exposure and sensitivity of seaports to climate and extreme weather impacts. Researchers employed the Analytic Hierarchy Method (AHP) to generate weights for a subset of expert-selected indicators of seaport exposure and sensitivity to climate and extreme weather. The indicators were selected from the results of a previous survey of port-experts who ranked candidate indicators by magnitude of perceived correlation with the three components of vulnerability; exposure, sensitivity, and adaptive capacity. As those port-expert respondents found significantly stronger correlation between candidate indicators and the exposure and sensitivity of a port than with a port's adaptive capacity, this AHP exercise did not include indicators of adaptive capacity. The weighted indicators were then aggregated to generate composite indices of seaport exposure and sensitivity to climate and extreme weather for 23 major ports in the North East United States. Rank order generated by AHP-weighted aggregation was compared to a subjective expert-ranking of ports by perceived vulnerability to climate and extreme weather. For the sample of 23 ports, the AHP-generated ranking matched three of the top four most vulnerable ports as assessed subjectively by port-experts. These results suggest that a composite index based on open-data may eventually prove useful as a data-driven tool for identifying outliers in terms of relative seaport vulnerabilities, however, improvements in the

standardized reporting and sharing of port data will be required before such an indicator-based assessment method can prove decision-relevant.

Key Findings:

- Experts weighted *adaptive capacity* higher than *sensitivity* and nearly equal with *exposure* in terms of importance to seaport climate vulnerability, yet, *adaptive capacity* lacks expert-supported indicators.
- Prototype composite-index matched the most vulnerable port and three of the top four most vulnerable ports as subjectively ranked by port experts.
- An indicator-based composite-index approach, weighted via AHP shows promise for identifying relative outliers among a sample of ports in terms of vulnerability.

Introduction

Seaport Vulnerability to Climate and Extreme Weather

Seaports sit on the frontlines of our shores, consigned to battle the elements at the hazardous intersection of land and sea. Ports face projected increases in the frequency and severity of impacts driven by changes in water-related parameters like mean sea level, wave height, salinity and acidity, tidal regime, and sedimentation rates, and port functions are expected to be increasingly affected directly by changes in temperature, precipitation, wind, and storm frequency and intensity (Koppe, Schmidt, and Strotmann 2012, Becker et al. 2013). At the same time, ports are often located in environmentally sensitive ecosystems such as estuaries and river mouths, which provide important nursery habitat for juvenile marine organisms (Beck et al. 2001).

As infrastructure assets, ports are critical to both the public and the private good, playing a key role in the network of both intranational and international supply-chains. Ports serve as catalysts of economic growth locally and regionally, as they create jobs and promote the expansion of nearby industries and cities (Asariotis, Benamara, and Mohos-Naray 2017).

Port decision-makers have a responsibility to manage a multitude of risks and enhance port resilience to achieve the minimum downtime safely possible in any given circumstance. When regional systems of ports are considered, responsible decision-makers may wish to prioritize limited resources, or to identify outliers among a set of ports in terms of vulnerability to certain hazards. At the single-port scale, port decision-makers (e.g., a local port authority) may be questioning which specific adaptation actions to take, or where to start with climate-adaptation. At the multi-port scale, port decision-makers (e.g., the U.S. Army Corps of Engineers) may be questioning which ports in a certain jurisdiction are the most vulnerable and hence the most in need of urgent attention. As climate adaptation decisions often involve conflicting priorities (e.g., politics, national priorities, local priorities), providing a data-driven, standard metric can help bring objectivity into the process.

Indicator-Based Composite Indices

Indicators are measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly, adequately measured (Gallopin 1997, Hinkel 2011). Indicator-based assessment methods are generally applied to assess or ‘measure’ features of a system that are described by theoretical concepts. Directly immeasurable, concepts such as resilience and vulnerability are instead made operational by mapping them to functions of observable metrics called indicators (McIntosh and Becker 2017). Indicator-based composite indices are multidimensional tools that synthesize multiple indicators into a single composite indicator that can represent a relative value of a theoretical concept (Dedeke 2013, McIntosh and Becker 2017). Examples of indicator-based composite indices include the Social Vulnerability Index (SoVI) (Cutter, Boruff, and Shirley 2003, Cutter, Burton, and Emrich 2010), the Earthquake Disaster Risk Index (EDRI) (Davidson and Shah 1997), and the Disaster Risk Index (Peduzzi et al. 2009) among others. Indicator-based composite indices are meant to yield a high-level overview of the relative values of a concept of interest, e.g., vulnerability, and as such, are more suited to high-level identification of relative outliers than to in-depth analyses of the concept of interest.

The SoVI, for example, compiles 29 input variables from the U.S. Census for over 66,000 census tracts to construct an index (Cutter, Boruff, and Shirley 2003). The large number of variables is reduced using Principal Component Analysis (PCA), and the resulting 6-8 principal components are named according to the highest loading factors for each component. The SoVI produces a score by summing the indicators into components and the components into the total score. The SoVI weights each indicator and component equally as the researchers lacked a theoretical basis for determining weights. For the research described in this paper, the SoVI recipe was considered, but deemed to be unsuitable for ports as the small sample size and the sparseness of available data (compared to Census data) led to difficulty in identifying and naming the principal components. Instead of the purely theoretical approach described by the SoVI, this work takes a stakeholder-driven approach by including port-experts in the development and weighting of the indicators, as this has been shown to increase the creditability of the index as a tool (Barnett, Lambert, and Fry 2008, Sagar and Najam 1998). By including stakeholders in the design-stage of decision-support tool or boundary-object development, the stakeholders' perceptions of the credibility, salience, and legitimacy of the tool can be increased (White et al. 2010).

Indicator-based assessments and indices have provoked debate in the literature, and some researchers (Barnett, Lambert, and Fry 2008, Eriksen and Kelly 2007, Hinkel 2011, Klein 2009, Gudmundsson 2003) have criticized attempts to assess theoretical concepts with them as lacking scientific rigor or lacking consistency. Nonetheless, policymakers are increasingly calling for the development of methods to measure relative risk, vulnerability, and resilience (Cutter, Burton, and Emrich 2010, Hinkel 2011, Rosati 2015), and developing better indicators and expert-driven weighting schemes through participatory processes like AHP may lead to improvements in this field. Despite these criticisms of indicator-based vulnerability assessments (IBVA) and indicator-based composite indices in particular, such decision-support tools can play an important role in bringing objective data into the complex decision-making process. The use of such indicator-based decision-support products can provide guidance in identifying areas of concern, but they should always be supplemented with additional expertise as they lack the high-resolution found in more detailed case-study assessment approaches.

Whereas low-level, high-resolution analyses are better served by more comprehensive case-study approaches, e.g., (Hallegatte et al. 2011, McLaughlin, Murrell, and DesRoches 2011, USDOT 2014), indicator-based composite indices are well suited to provide high-level overviews of relative outliers among a sample. Indicator-based assessments and indices, then, are simply one tool among a suite of tools that decision-makers should have at their disposal.

Port decision-makers faced with climate impact, adaptation and vulnerability (CIAV) [19] decisions involving multiple ports can benefit from information products that allow them to compare the mechanisms and drivers of vulnerability among ports. Indicator-based assessments provide an example of such a product that can quantify complex issues and bring a standardized data-driven approach to measuring theoretical concepts, with the caveat that the decision-relevance of their results hinges on the quality of data available to serve as indicators.

[19] CIAV decisions are choices, the results of which are expected to affect or be affected by the interactions of the changing climate with ecological, economic, and social systems.

Selection of Indicators

This paper describes the process of deriving weights for previously selected indicators. As described in more detail in the second manuscript of this dissertation, researchers previously worked with port-experts to develop from open-sources and evaluate a set of high-level indicators of seaport vulnerability[20] to climate and extreme weather impacts for the 23 medium[21] and high[22] use ports of the United States Army Corps of Engineers' (USACE) North Atlantic Division[23] (CENAD). The steps involved in compiling and evaluating this set of candidate indicators is also illustrated in Figure 18, below.

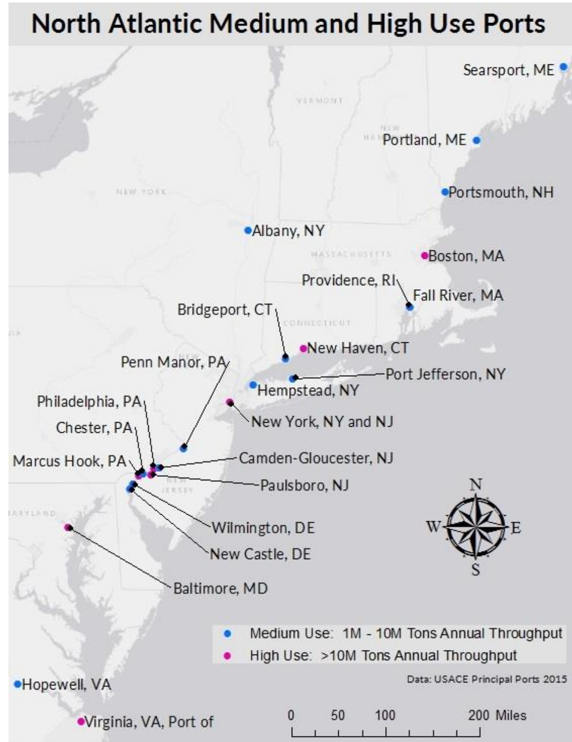

Figure 17 Study area ports

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[20] The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity. (IPCC 2001)

[21] Medium use here refers to ports with annual throughput > 1M tons

[22] High use here refers to ports with annual throughput > 10M tons

[23] The North Atlantic Division is one of nine USACE divisions and encompasses the U.S. Eastern Seaboard from Virginia to Maine (USACE 2014).

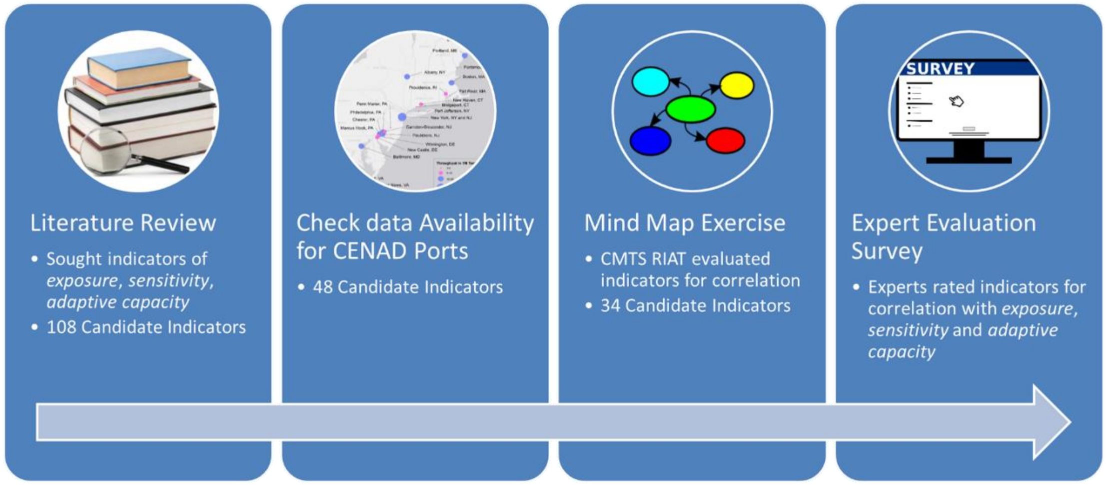

Figure 18 Steps involved in compiling and evaluating candidate indicators. The AHP described in this paper uses the highest scoring indicators from the last step (survey) portrayed in this figure

Researchers began by conducting a review of climate change vulnerability assessment (CCVA) and seaport-studies literature which identified 108 candidate indicators (see the second manuscript of this dissertation). Of the 108 candidate indicators identified, 48 were found to have sufficient data for the sample of CENAD ports (Figure 17). These 48 indicators were then further distilled to 34 viable candidate indicators via a mind mapping exercise with members of the Resilience Integrated Action Team[24] (RIAT) of the United States Committee on the Marine Transportation System[25] (US CMTS). The 34 candidate indicators chosen via this mind map exercise were then evaluated via a visual analogue scale[26] (VAS) survey instrument by 64 port experts (see the second manuscript of this dissertation). For each candidate indicator in

[24] The MTS Resilience IAT (R-IAT) was established to focus on cross-Federal agency knowledge co-production and governance to incorporate the concepts of resilience into the operation and management of the U.S. Marine Transportation System.
[25] The United States' CMTS is a Federal Cabinet-level, inter-departmental committee chaired by the Secretary of Transportation. The purpose of the CMTS is to create a partnership of Federal departments and agencies with responsibility for the Marine Transportation System (MTS).
[26] In visual analogue scale (VAS), respondents measure their level of agreement by indicating a position along a continuous line segment

the VAS survey, respondents were given the indicator's description, units, data source, and example values, and respondents were asked to determine whether the candidate indicator could be correlated with the exposure[27], sensitivity[28], and/or the adaptive capacity[29] of ports in the study area. Respondents indicated the magnitude and direction of correlation by dragging a slider along a VAS line segment (Figure 6). In addition to evaluating 34 indicators of seaport vulnerability, respondents of the VAS survey also subjectively ranked the CENAD ports by magnitude of perceived vulnerability to climate and extreme weather impacts.

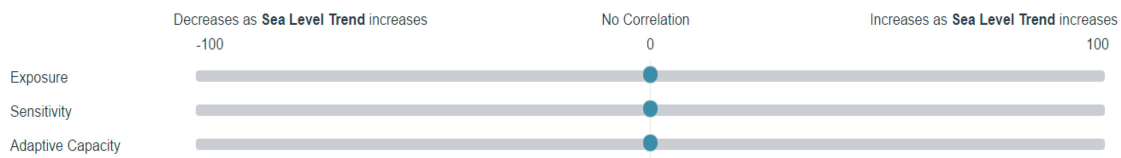

Figure 19 VAS slider for indicating expert-perceived correlation between a candidate indicator and each of the components of vulnerability.

For the 34 candidate indicators that were evaluated, none scored a median rating higher than 23 on the unitless VAS scale of correlation with adaptive capacity, compared to a high of 62 with exposure and 52 with sensitivity. This low level of perceived correlation with adaptive capacity suggests a dearth of open-data[30] sources suitable for representing the adaptive capacity of seaports to climate and extreme weather impacts. It also suggests that the concept of adaptive capacity is considered by port-experts to be more difficult to represent with quantitative data than the concepts of

[27] The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC 2014b)
[28] The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli (IPCC 2001)
[29] The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC 2014b)
[30] Open-data refers to publicly available data structured in a way that enables the data to be fully discoverable and usable by end users without having to pay fees or be unfairly restricted in its use.

exposure or sensitivity. For these reasons, this AHP exercise did not include indicators of adaptive capacity but focused instead on generating weights for indicators of exposure and sensitivity.

As AHP best-practice recommends each category should have at least 4, but not more than 7 to 10 sub-categories (Goepel 2013), researchers selected the 6 highest scoring indicators for exposure and the 6 highest scoring indicators for sensitivity for inclusion in the AHP exercise (Table 11) described in the following section.

Table 11The six indicators rated highest for correlation with seaport exposure and sensitivity to climate and extreme weather impacts from (see the second manuscript of this dissertation).

Category	**Description**	**Indicator**	**Units**	**Data Source**
Exposure	Number of storm events in port county w/ property damage > $1M	**NumberStormEvents**	events	NOAA Storm Events Database
	1% annual exceedance probability high water level which corresponds to the level that would be exceeded one time per century, for the nearest NOAA tide station to the port	**HundredYearHighWater**	m above MHHW	NOAA Tides and Currents: Extreme Water Levels
	Number of cyclones that have passed within 100 nm of the port since 1842	**NumberCyclones**	Number of cyclones	NOAA Historical Hurricane Tracks Tool
	Local Mean Sea Level Trend	**SeaLevelTrend**	mm / yr	NOAA Tides and Currents
	The percent change from observed baseline of the average number of “Extremely Heavy” Precipitation Events projected for the end-of-century, downscaled to 12km resolution for the port location	**CMIP_NumberOfExtremelyHeavyPrecipEvents**	%	US DOT CMIP Climate Data Processing Tool
	Number of Presidential Disaster Declarations for the port county since 1953	**NumberDisastersCounty**	Disaster Type	FEMA, Historical Declarations
Sensitivity	Number of Critical Habitat Areas within 50 miles of the port	**NumberCriticalHabitat**	Areas	U.S. Fish & Wildlife Service
	Environmental Sensitivity Index (ESI) shoreline sensitivity to an oil spill for the most sensitive shoreline within the port	**ESI**	ESI Rank	NOAA Office of Response and Restoration
	Average cost of property damage from storm events in the port county since 1950 with property damage > $1 Million	**AvgCostStormEvents**	$USD	NOAA Storm Events Database

Category	Description	Indicator	Units	Data Source
	Rate of population change (from 2000-2010) in the port county, expressed as a percent change	**PopulationChangeCounty**	%	NOAA Office for Coastal Management
	Percent of the port county population living inside the FEMA Floodplain	**PopulationInsideFloodplain**	%	NOAA Office for Coastal Management
	Port County Social Vulnerability (SoVI) Score	**SoVI**	score number	SoVI® Social Vulnerability Index

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a method to support multi-criteria decision-making first described by Thomas Saaty (Saaty 1977) that is based on the solution of an eigenvalue problem. Participants make pairwise comparisons, the results of which are arranged in a matrix where the dominant normalized right eigenvector gives the ratio scale (weighting) and the eigenvalue determines the consistency ratio (Goepel 2013, Saaty 1977, 1990b, 2006). AHP has become well established for group decisions based on the aggregation of individual judgements (Ramanathan and Ganesh 1994, Dedeke 2013, Goepel 2013). Psychologists have noted that respondents have an easier time making judgements on a pair of alternatives at a time than simultaneously on all the alternatives (Ishizaka and Labib 2011). AHP also allows consistency cross checking between the pairwise comparisons. Additionally, AHP uses a ratio scale, which, unlike methods using interval scales, does not require units in the comparison (Kainulainen et al. 2009, Hovanov, Kolari, and Sokolov 2008).

AHP has also proven useful as a standardized method for generating the weights of indicators in composite indices in a variety of different fields, e.g., environmental performance index (EPI) (Dedeke 2013), disaster-resilience index (Orencio and Fujii 2013), composite indicator of agricultural sustainability (Gómez-Limón and Riesgo

2009), and the urban public transport system quality (Pticina and Yatskiv 2015). While these studies assessed different theoretical concepts from performance, to disaster-resilience, to agricultural sustainability, they all employed AHP as a means of quantifying expert-preferences for weighting the relative importance of the indicators used. AHP simplifies the process of quantifying subjective weight preferences based on multiple criteria by using pairwise comparisons. Participants are given two items at a time and asked which is more important with respect to the given category. Using pairwise comparisons not only helps discover and correct logical inconsistencies (Goepel 2013), it also allows for translating subjective opinions into numeric relations, helping make group decisions more rational, transparent, and understandable (Goepel 2013, Saaty 2008).

Methodology

Expert Selection

Researchers invited the same group of 64 experts who contributed to the evaluation of candidate indicators via the previous VAS survey (see the second manuscript of this dissertation) to participate in this AHP weighting exercise. These experts were sought for their specialized knowledge and experience in seaport operations, planning, policy, data, and the vulnerability of the U.S. marine transportation system (MTS) to climate and extreme weather impacts. This

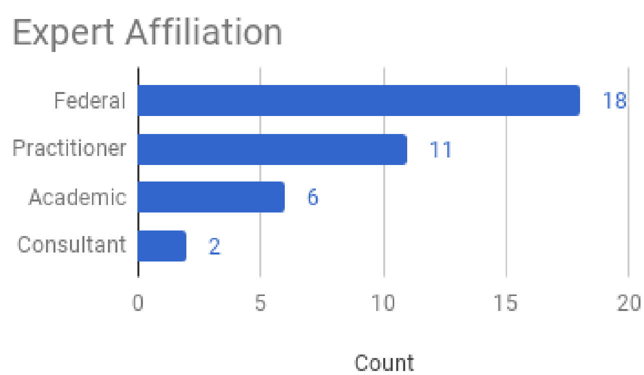

Figure 20 Count of participating experts' affiliations

group of expert-respondents was compiled via a knowledge resource nomination worksheet and peer snowball sampling described in more detail in (see the second manuscript of this dissertation). Out of this expert pool, 37 experts participated in this AHP exercise, representing the expert-affiliation categories of: federal (e.g., US Coast Guard, NOAA, USACE, MARAD), practitioners (e.g., port authorities), academics (e.g., professors, research analysts), and consultants (Figure 20).

AHP

In the spring and summer of 2017, researchers held 21 separate webinars with a total of 37 participating port-experts. During each webinar, participants were guided through the steps of the AHP using a web-based AHP system (Goepel 2017). Experts were given a data dictionary with descriptions, units, data sources, and example values for each of the 12 indicators to be weighted. For the AHP exercise, as with the previous VAS survey, respondents were instructed to consider port vulnerability holistically, inclusive of the port's surrounding socioeconomic and environmental systems, and to focus on 23 the ports of the CENAD (Figure 17).

The AHP involved two levels; the first comprised weighting the three components of vulnerability (i.e., exposure, sensitivity, and adaptive capacity), and the

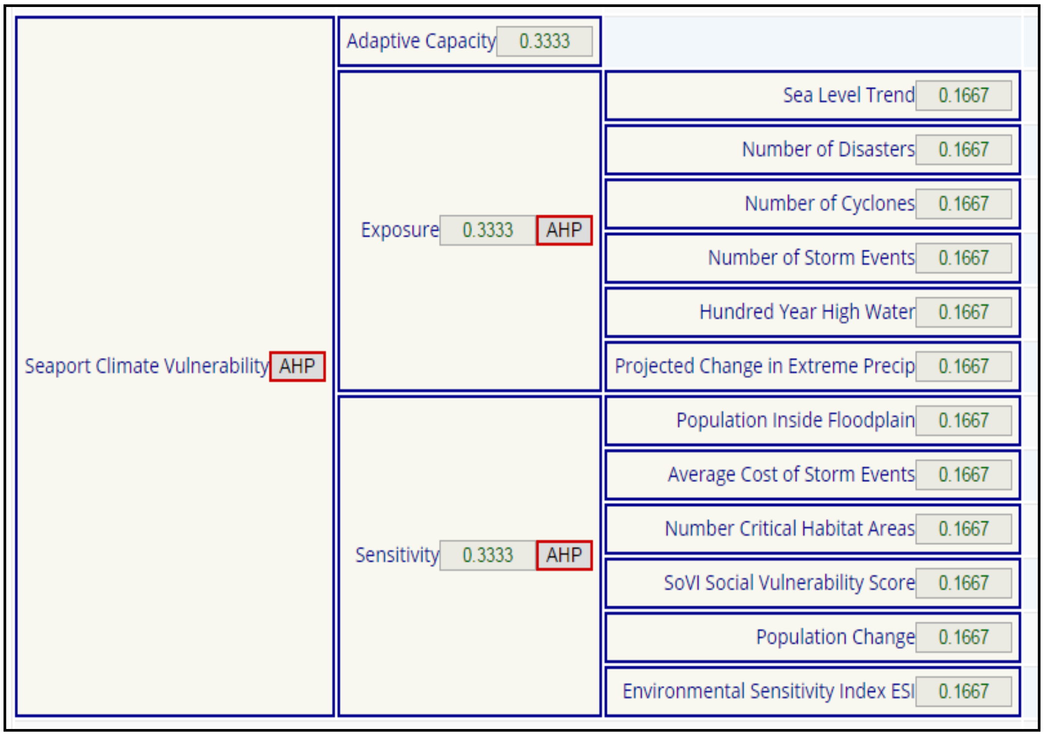

Figure 21 AHP hierarchy showing equal weighting prior to pairwise comparisons. Each column represents a level of the AHP, and each red rectangle indicates a node (for which a priority vector will be calculated).

second comprised weighting the six indicators of exposure and the six indicators of sensitivity (Figure 21). Because the earlier VAS survey failed to develop expert-supported indicators of adaptive capacity for seaport climate and extreme weather vulnerability, researchers were unable to include indicators of adaptive capacity for weighting in this AHP. The lack of indicators of adaptive capacity, however, did not prevent the derivation of weight for adaptive capacity as a component of seaport vulnerability to climate and weather extremes.

For the first level of the AHP, respondents weighted the three components of seaport vulnerability via pairwise comparisons. Respondents were given two components at a time and asked, "With respect to seaport climate vulnerability, which criterion is more important, and how much more on a scale 1 to 9," where '1' represents equal importance (Figure 22).

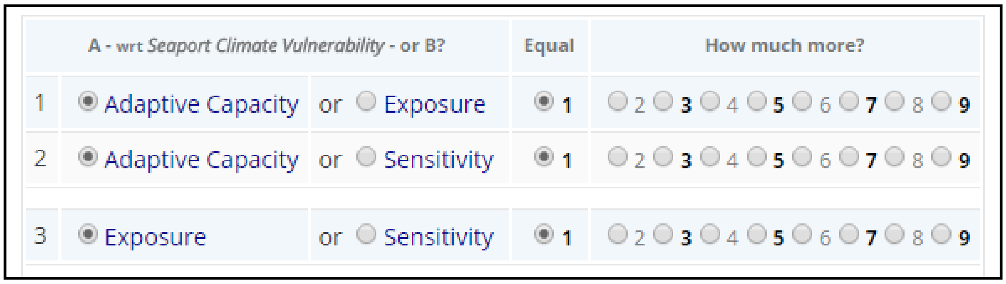

Figure 22 Pairwise comparisons of the three components of seaport vulnerability

The second level of the AHP involved two nodes; weighting six indicators of exposure, and weighting six indicators of sensitivity. For the former, respondents were given two indicators at a time and asked, “With respect to seaport climate exposure, which criterion is more important, and how much more on a scale 1 to 9.” For calculating the number of pairwise comparisons required, Equation 1 is used where *n* is the number of components or indicators (Saaty 1977, 1990a, Orencio and Fujii 2013).

Equation 1 Number of pairwise comparisons required for n *indicators*

$$(n)(n-1)/2$$

For the six indicators of exposure (Figure 21), respondents completed 15 pairwise comparisons, contrasting the relative importance of each indicator to every other indicator, one pair at a time. Similarly, the second node of this level of the AHP repeated this process with respect to sensitivity for the six indicators of seaport climate and extreme weather sensitivity. For each respondent at each level of the AHP, the product of each paired comparison was recorded in a *n* x *n* square matrix, with *n* equaling the number of indicators or components.

Let us denote the criteria that were ranked by experts as $[I_1, I_2, \ldots I_n]$, where *n* is the number of components of vulnerability or the number of indicators compared. Based on experts’ responses, a preference matrix was derived for each respondent, of the form:

Equation 2 Preference matrix for AHP

$$A = [a_{ij}] \begin{bmatrix} 1 & a_{ij} & \cdots & a_{1n} \\ 1/a_{ij} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

Where a_{ij} is the preference for indicator I_i over I_j when both were compared pairwise, for i, j = 1, 2, … n. If a respondent decided that indicator i was equally important to another indicator j, a comparison of $a_{ij} = a_{ji} = 1$ was recorded. If a respondent considered indicator i extremely more important than indicator j, the preference-matrix score was based on $a_{ij} = 9$ and its reciprocal given as $a_{ji} = 1/9$, where $a_{ij} > 0$.

After compiling a preference matrix for each expert for each node of the AHP, the dominant eigenvector of each matrix was then calculated using the power method (Larson 2016, Goepel 2013) with the number of iterations limited to 20, for an approximation error of 1×10^{-7} (Goepel 2013). This normalized principal eigenvector, also called a priority vector[31], gives the relative weights of the indicators and components of vulnerability that were compared.

The consistency of a respondent's answers was checked using the linear fit method (Equation 3) proposed by (Alonso and Lamata 2006) to calculate the consistency ratio, *CR*, for each respondent's preference matrix for each node of the AHP, where λ_{max} represents the principal eigenvalue obtained from the summation of products between each element of the priority vector and the sum of columns of the preference matrix, and n represents the number of dimensions of the matrix.

[31] Because the vector is normalized, the sum of all elements in a priority vector is equal to one.

Equation 3 Linear fit method of calculating consistency ratio

$$CR = \frac{\lambda_{max} - n}{2.7699 \ \cdot n - 4.3513 - n}$$

If a respondent completed a node of pairwise comparisons that yielded a CR greater than 10%, the software prompted the respondent to correct the inconsistencies by highlighting the three most inconsistent judgements and allowing adjustments.

Aggregation of individual judgements (AIJ) was based on the weighted geometric mean (WGM) of all participants' judgements (Aull-Hyde, Erdogan, and Duke 2006). The software calculated the geometric mean and standard deviation of all *K* participants' individual judgements pwc_k to derive a consolidated preference matrix, a_{ij}^{cons}. The WGM-AIJ process consisted of summing individual judgements, *pwc*, over *K* participants, squaring the sum, calculating the geometric mean of each *pwc*, and using the means to create a consolidated preference matrix (Equation 4).

Equation 4 Consolidated preference matrix based on the geometric mean of individual judgements

$$a_{ij}^{cons} = (\Pi_{k=1}^{K} a_{ij})^{\frac{1}{K}}$$

To measure the consensus for the aggregated group result, the AHP software used Shannon entropy and its partitioning in two independent components (alpha and beta diversity) to derive an AHP consensus indicator based on relative homogeneity *S* (Goepel 2013). The consensus of the complete hierarchy was calculated as the weighted arithmetic mean of the consensus of all hierarchy nodes. This similarity measure, *S*, is zero when the priorities of all *pwc* are completely distinct and *S=1*, when the priorities of all *pwc* are identical (Goepel 2013).

Aggregating Weighted Indicators

After generating the indicator and component weights via AHP, the next step was to create a composite index of seaport vulnerability based on the weightings. Due to the lack of expert-supported indicators of adaptive capacity, the AHP-based composite index was limited to the aggregation of two of the three components of vulnerability: exposure and sensitivity, yielding a composite score that may be considered similar to vulnerability minus the component of adaptive capacity. Researchers aggregated the indicators into a composite indicator of vulnerability (minus adaptive capacity) using a weighted sum model (WSM) (Equation 5). In Equation 5, n represents the number of decision criteria (i.e., indicators or components), m represents the number of ports, w_j represents the relative weight of indicator I_j, and p_{ij} represents the performance of port A_i when evaluated in terms of indicator I_j.

Equation 5 Weighted sum model

$$A_i^{WSM-score} = \sum_{j=1}^{n} w_j p_{ij}, for\ i = 1, 2, 3 \dots, m.$$

To create the composite index for CENAD ports based on this WSM, researchers first compiled data on all 12 indicators for the 23 ports of the CENAD. Missing values were imputed with the indicator's mean value. The input variables were then standardized using z-score standardization (Equation 6), generating variables with a mean of 0 and a standard deviation of 1. This standardization allows for indicators with disparate units to be combined (Cutter, Boruff, and Shirley 2003).

Equation 6 Z-score standardization

$$z = \frac{X - \mu}{\sigma}$$

A composite indicator for exposure was then created by summing the products of each exposure indicator and its weight. Next, a composite indicator for sensitivity was created by summing the products of each sensitivity indicator and its weight. The two composite indicators of exposure and sensitivity were then each multiplied by their respective component weights and summed together. The resultant composite indicator represents the combined exposure and sensitivity of the sample ports and was used to compile a composite index of seaport vulnerability (minus adaptive capacity) for the CENAD sample of ports based on publicly available data. The port-rankings generated by the composite index were then compared to the experts' subjective raking of port vulnerability obtained from the previous VAS survey (see the second manuscript of this dissertation).

Results

AHP-Generated Weights

The aggregation of judgements from the first level of the AHP, which weighted the three components of seaport vulnerability to climate and extreme weather, resulted in exposure ranked most important, with a ratio scale (weight) of .394 (Table 12). Adaptive capacity was ranked a close second, with a weight of .390, which is noteworthy since the component of adaptive capacity lacks expert-supported indicators. Sensitivity was ranked least important of the three components, with a weight of .216. For this node, the maximum consistency ratio, *CR*, was 0.1% (highly consistent) and the group consensus, *S*, was 50.1% (low)[32].

[32] (Goepel 2013) considers the following interpretation of AHP consensus; <50% (very low), 50%-65% (low), 65%-75% (moderate), 75%-85% (high), >85% (very high)

Table 12 Results of AHP consolidated group preferences for the relative importance of the components of seaport climate and extreme weather vulnerability

Component	Weight	Rank
Exposure	0.394	1
Adaptive Capacity	0.390	2
Sensitivity	0.216	3

The second level of the AHP consisted of two nodes, the first evaluated six indicators for relative importance in terms of seaport exposure to climate and weather extremes, and the second node evaluated six indicators in terms of seaport sensitivity. The first node resulted in the indicator "number of disasters," ranked most important for the component of exposure with a weight of .200, and resulted in weights for the remaining indicators of exposure as shown in Table 13. For this node, the maximum consistency ratio, *CR*, was 0.3% (highly consistent) and the group consensus, *S*, was 53.6% (low).

Table 13 Consolidated group preferences for the relative importance of indicators of seaport exposure to climate and weather extremes

Indicator of Exposure	Weight	Rank
Number of Disasters	0.200	1
Number of Storm Events	0.196	2
Sea Level Trend	0.180	3
Hundred Year High Water	0.163	4
Number of Cyclones	0.143	5
Projected Change in Extreme Precip	0.118	6

The second node of the second AHP level resulted in the indicator "population inside floodplain," ranked most important for the component of sensitivity with a weight of .229, and resulted in the remaining indicators of sensitivity weighted as shown in Table

14. For this node, the maximum consistency ratio, *CR*, was 0.5% (highly consistent) and the group consensus, *S*, was 61.1% (low).

Table 14 Consolidated group preferences for the relative importance of indicators of seaport sensitivity to climate and weather extremes

Indicator of Sensitivity	Weight	Rank
Population Inside Floodplain	0.229	1
SoVI Social Vulnerability Score	0.213	2
Average Cost of Storm Events	0.210	3
Environmental Sensitivity Index ESI	0.125	4
Population Change	0.119	5
Number Critical Habitat Areas	0.104	6

These indicator weights were then used to generate a composite index of seaport vulnerability (minus adaptive capacity) to climate and extreme weather impacts with a WSM (Equation 5).

Composite Index of CENAD Ports

To test the degree to which a ranking of ports by level of vulnerability to climate and extreme weather, created by a WSM using AHP-generated weights, would or would not resemble an a priori ranking generated[33] subjectively by the same participating experts, researchers compiled a composite index for the CENAD sample of ports. Applying the AHP-generated indicator weights to the z-score-standardized input variables for 23 CENAD ports, and aggregating them in a WSM yielded the following ranking (Table 15) where a larger number corresponds to a higher degree of

[33] As part of the VAS survey described in the second chapter of this dissertation, port-experts were asked to rank the top ten most vulnerable ports out of the sample of 22 CENAD ports. The rank distribution (Table 16) was generated from a sum of weighted values, which were weighted as the inverse of the number of ports the respondent chose to rank.

vulnerability. In Table 15, a score of zero represents the mean, a negative number represents a vulnerability score below the mean, and a positive number represents a vulnerability score above the mean.

Table 15 Model-generated ranking of CENAD ports by vulnerability to climate and weather extremes. Note that here, vulnerability includes exposure and sensitivity, but not adaptive capacity

Port	**Vulnerability Score**
Virginia.VA.Port.of	0.46
Boston.MA	0.24
Philadelphia.PA	0.11
New.Haven.CT	0.10
Port.Jefferson.NY	0.10
Portland.ME	0.10
Hopewell.VA	0.07
Searsport.ME	0.04
Fall.River.MA	0.02
Camden-Gloucester.NJ	0.02
Baltimore.MD	0.00
Bridgeport.CT	-0.03
Hempstead.NY	-0.04
Paulsboro.NJ	-0.04
Albany.NY	-0.05
Wilmington.DE	-0.07
Marcus.Hook.PA	-0.09
Chester.PA	-0.10
Penn.Manor.PA	-0.11
Portsmouth.NH	-0.12
New.York.NY.and.NJ	-0.12
Providence.RI	-0.13

Interestingly, the most vulnerable port according to the model-generated port vulnerability rankings matches the most vulnerable port as subjectively ranked by experts in the VAS survey (Table 16). While the second most vulnerable port according to the subjective expert-ranking, the Port of New York and New Jersey, was second to least vulnerable according to the model rank, the model did capture three out of four of the most vulnerable ports consistent with the experts' rankings.

Table 16 Port-experts' consolidated subjective ranking of the top ten CENAD ports most vulnerable to climate and extreme weather, from (see the second manuscript of this dissertation).

Port	Experts' Rank
Virginia.VA.Port.of	1
New.York.NY.and.NJ	2
Boston.MA	3
New.Haven.CT	4
Baltimore.MD	5
Providence.RI	6
Portland.ME	7
Portsmouth.NH	8
Philadelphia.PA	9
Hempstead.NY	10

One benefit of indicator-based composite indices is their ability to synthesize multiple variables into a single, measurable concept while still retaining the ability to explore the disaggregated substructure behind the composite construct. As such, their users are able to ask, "*Why* does a particular entity score high or low according to this index?" Figure 23 shows the disaggregated substructure behind the composite 'vulnerability scores' of the three highest scoring ports from the composite index, in which the relative performance of a port can be explored in terms of the individual indicators. Similarly, Figure 24 shows the disaggregated substructure for the three lowest scoring ports of the composite index.

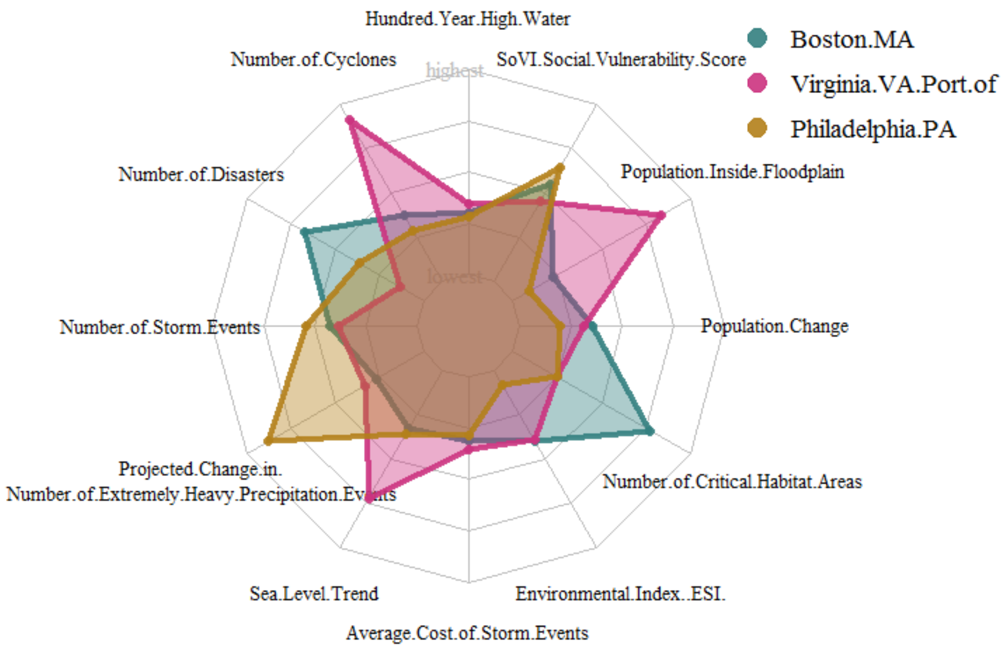

Figure 23 Disaggregated substructure of the composite-index vulnerability scores of the three highest scoring ports. Indicators of exposure are shown on the left half of the plot, and indicators of sensitivity are shown on the right half.

Comparing the three ports of Figure 23, reveals sharp differences in the underlying performance of each port in terms of the individual indicators. Whereas the port of Virginia scored high (i.e. relatively more vulnerable) in the 'number of cyclones' indicator and relatively low with respect to the 'number of disasters,' the opposite is seen for the port of Philadelphia. This type of differentiation can assist decision-makers in understanding the mechanisms and drivers behind a 'composite score,' and tools that allow exploration of the underlying substructure may add to the decision-relevance of indicator-based assessment efforts and especially indicator-based composite indices.

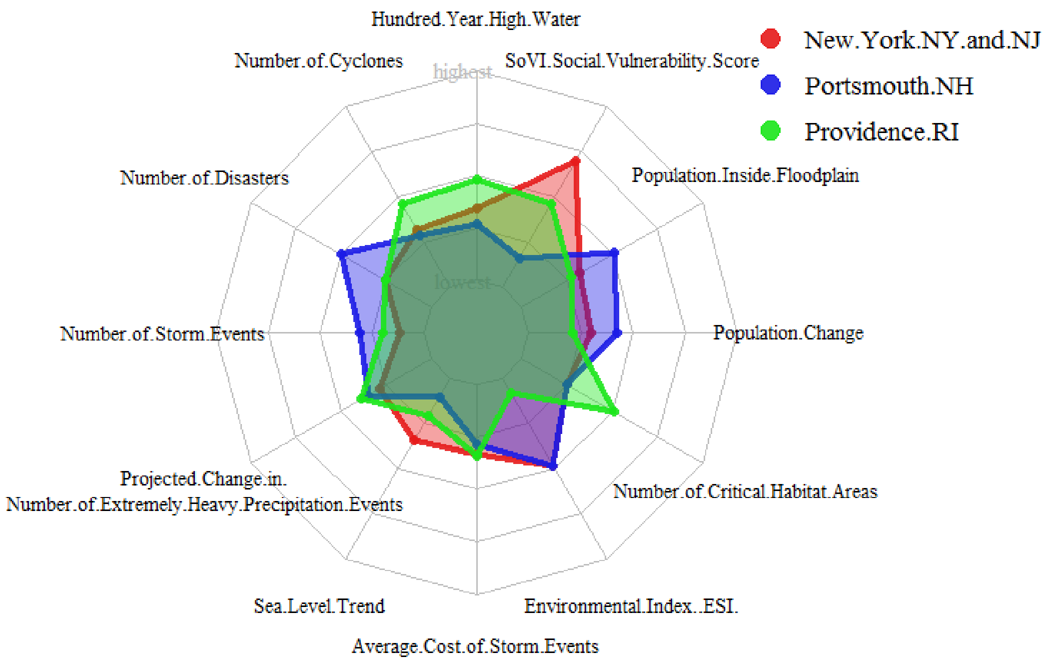

Figure 24 Disaggregated substructure of the composite-index vulnerability scores of the three lowest *scoring ports. Indicators of exposure are shown on the left half of the plot, and indicators of sensitivity are shown on the right half.*

Figure 24, showing the substructure of the three least vulnerable ports per the composite index, yields insight into the discrepancy between the index rankings and the subjective, expert-rankings. While the port of New York and New Jersey was considered second most vulnerable according to expert-perception, the weighted-index scored it second *least* vulnerable. Looking at Figure 24, we can see that while the port of New York and New Jersey scored high (i.e., relatively more vulnerable) in the "SoVI social vulnerability score" indicator, it scored near the bottom of the sample in nearly every other indicator. This may be an artifact of the method of compiling the indicator data for the sample of ports. Most indicators were measured at the county-level, and while the port of New York and New Jersey spans multiple counties, for this experiment, the port of New York and New Jersey was represented solely by New York County. Similarly, the port of Providence was subjectively ranked sixth most vulnerable by port-experts, yet scored least vulnerable of all in the composite index.

Figure 24 reveals that while Providence scored near the middle of the sample for "number of critical habitat areas," "hundred year high water," and "number of cyclones," it scored near the bottom of the sample for "number of disasters," "number of storm events," and "environmental sensitivity index ESI," and did not score higher than average for any indicator.

Discussion

The method of generating indicator weights based on aggregated expert-preferences using AHP described in this paper has shown both promise and limitations. Port rankings generated by a composite index based on a WSM using the AHP-derived weights, was compared to an a priori subjective ranking generated by port experts. Though the model lacked indicators of adaptive capacity, it matched (Table 15) the experts' ranking for the most vulnerable port, and also matched three of the four ports ranked most vulnerable by the experts (Table 16).

Whereas previous work on assessing the climate vulnerability of seaports has tended to focus on the single port scale, either as case studies (Koppe, Schmidt, and Strotmann 2012, Cox, Panayotou, and Cornwell 2013, USDOT 2014, Messner et al. 2013, Chhetri et al. 2014) or as self-assessment tools (NOAA OCM 2015, Semppier et al. 2010, Morris and Sempier 2016), this work contributes a first attempt at constructing an indicator-based composite-index for the purpose of developing seaport CCVA at the multi-port scale.

To the observed problem (i.e., the current difficulty of comparing relative vulnerability across ports), this work contributes a prototype composite-index (and a method to replicate such an index for other sectors) that allows rudimentary quantitative comparisons of exposure and sensitivity levels across ports. This prototype index was able to capture relative outliers in the sample of ports (i.e., the main objective of composite-indices) and shows the promise of an indicator-based approach to address this problem.

Adaptive Capacity Considered Highly Important

Adaptive capacity is defined in the glossary of the IPCC Fifth Assessment Report (IPCC 2014b) as ‘‘The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.” As noted by Siders (Siders 2016), this definition bears some resemblance to generally accepted definitions of resilience, i.e., the ability to bounce back from an impact (McIntosh and Becker 2017). As such, Siders recommends that adaptive capacity can be distinguished from resilience by ascribing the latter to maintaining stability by "bouncing back" to pre-shock conditions, and by taking adaptive capacity, to refer to the broader ability of a system to self-organize, learn, and embrace change to limit future harms (Klein, Nicholls, and Thomalla 2003, Siders 2016).

It may be significant that the AHP resulted in adaptive capacity ranked a close second to exposure in terms of importance with respect to seaport climate and extreme weather vulnerability (Table 12). This suggests that port-experts consider adaptive capacity to be more important than sensitivity and practically equal in importance to exposure with respect to seaport vulnerability. Though experts place a high degree of importance on adaptive capacity as a component of vulnerability, a previous study (see the second manuscript of this dissertation) found that adaptive capacity may be the most difficult of the three components of seaport vulnerability to represent with quantitative data. While this discrepancy may point to a need to improve the data collection and sharing of metrics that can capture the concept of adaptive capacity for ports, it also suggests that the concept of adaptive capacity may be better captured by other, less quantitative assessment methods. This finding also suggests a disconnect between what experts perceive as an important component to understanding seaport vulnerability to meteorological and climatological threats and the types of data that are currently being reported and available to represent that component.

As noted by Brooks et al. (Brooks, Adger, and Kelly 2005), adaptive capacity is a component of vulnerability primarily associated with governance. Hence, next-step efforts to assess relative levels of seaport adaptive capacity should start by examining ports' governance structures to find measurable metrics to assess and compare the ports' ability to adjust, take advantage, or respond to climate and weather impacts.

Limitations

A limitation of this AHP method can be the difficulty of achieving high levels of group consensus. For each of the three nodes of this AHP, the consensus indicator, *S*, was low (50.1%, 53.6%, 61.1%), suggesting low relative homogeneity of expert preferences. Improvements in group consensus may be achieved by using iterative approaches such as the Delphi[34] method, in which participants are shown descriptive

[34] The Delphi method is a structured communication technique designed to obtain opinion consensus of a group of experts by subjecting them to a series of questionnaires interspersed with feedback in the form of a statistical representation of the group response. The goal of employing the Delphi method is to reduce the range of responses and arrive at something closer to expert consensus.

statistics of the group responses and given the opportunity to revise their answers during subsequent iterations of the AHP, as was employed in (Orencio and Fujii 2013). A drawback of this iterative approach, however, is the additional time required to complete the process. For this study, researchers held 20 different webinars with a total of 34 experts to complete the AHP, lasting approximately 30 minutes to one hour each webinar. Experts may be more reluctant to participate the longer the process proposes to take. As the number of pairwise comparisons increases quickly due to Equation 1, even a single-round AHP can become a considerable imposition on the time constraints of busy professional experts.

Though the aggregation of weighted indicators into a composite index was performed mainly as a means to validate the AHP-generated weights by comparing the port-rankings they produced via a WSM to a subjective port-ranking, the process also yielded insight into the benefits and limitations of such methods. As a means to identify relative outliers among a sample, this method showed promise by successfully matching the most vulnerable port and three of the four most vulnerable ports as ranked subjectively by port-experts. While partially successful at identifying the relative outliers among our sample of ports, the composite index also ranked several ports (e.g., Providence, New York and New Jersey) near the bottom of the sample that experts had subjectively ranked near the top. Some of this discrepancy may be due to the sensitivity of indicator-based composite indices to differences in the interpretation of data used for the indicators. For example, an indicator for an entity that spans multiple counties, like the port of New York and New Jersey, could be represented by a measure of central tendency of the data for the collection of counties, by the data from the county with most extreme value, or by a single representative county. In this experiment, the single county of New York was taken to represent the port of New York and New Jersey for the purposes of compiling the indicator data, which may have resulted in lower than expected values for that port in some of the indicators. Additionally, indicator-based assessments are always limited by the quality of data available to incorporate into them.

Although the AHP weighted all three components of vulnerability, including adaptive capacity, and the composite index incorporated the weights for the components of exposure and sensitivity into the WSM, it should be noted that this composite index of seaport vulnerability to climate and extreme-weather did not include indicators of adaptive capacity. As such, the composite index is more accurately described as a weighted measure of seaport exposure and sensitivity to climate and weather extremes. This may have also contributed to some of the discrepancy between model results and the subjective ranking of ports (see the second manuscript of this dissertation) which was based on a definition of vulnerability that included all three components (e.g., exposure, sensitivity, adaptive capacity).

Additionally, indicator-based methods are inherently limited by the availability of data. The second manuscript of this dissertation, which describes the identification, development, and evaluation of candidate indicators of seaport climate vulnerability, illustrates these data availability limitations in more detail. For example, the lack of openly available data to serve as indicators of adaptive capacity resulted in the reduction of the composite index described here from an assessment of holistic vulnerability to one of exposure and sensitivity only.

Conclusion

To further the development of indicator-based assessment methods for the port sector, this study performed an AHP with 37 port-experts that developed weights for the three components of vulnerability (i.e., exposure, sensitivity, and adaptive capacity), and for a selection of 12 indicators of seaport exposure and sensitivity to climate and extreme weather impacts. The AHP resulted in adaptive capacity weighted higher than sensitivity and nearly equal to exposure in importance with respect to seaport climate and extreme weather vulnerability. This finding suggests a disconnect between what experts believe is an important component to understanding seaport vulnerability to meteorological and climatological threats and the types of data that are currently being reported and available to represent that component. An opportunity for future research may exist to develop an answer to what types of data, if any, experts would accept as more representative of the concept of seaport adaptive capacity than what data is currently available.

To validate the results of the AHP, the AHP-generated weighting scheme was applied using a WSM to create a composite index for 23 CENAD ports that was compared to a subjective ranking of the ports by the same experts. This comparison revealed that while the model showed promise in fulfilling the main objective of composite indices (i.e., identification of relative outliers among a sample) by matching the top port and three out of the top four ports subjectively chosen as most vulnerable by the experts, there were considerable discrepancies between the model rank and the subjective, expert rank that point to some of the limitations of this method. Those limitations include the potential for low group consensus during the AHP, for which the remedy, Delphi-style iterations, contains its own limitation of increased time-cost. Indicator-based methods are also limited by their sensitivity to small changes in the methods used to compile the individual indicators. Variations in spatial scale of available data can require subjective choices regarding the compilation of indicator data, e.g., how to compile indicator data for ports that span multiple counties. Additionally, the process of compiling indicators introduces other subjective decisions that affect model sensitivity, such as whether to use the max value or a measure of central tendency of a concept as an indicator. Because of both the sensitivity and subjectivity of these decisions, researchers recommend a stakeholder-based approach for the early stages of indicator development such as the expert-elicitation methods applied in (Mcleod et al. 2015, Teck et al. 2010). While this research has furthered the development of indicator-based assessment methods for the port sector by constructing and trialing a prototype composite-index of seaport climate vulnerability, it should be noted that further work exploring the sensitivity of results to data compilation methods and developing a measure of adaptive capacity will be needed before such methods are robust enough for use in critical decision-making. Finally, the main caveat of these methods is that they are always limited by the quality of the data that they incorporate.

Works Cited

Adger, W Neil, Nick Brooks, Graham Bentham, Maureen Agnew, and Siri Eriksen. 2004. New indicators of vulnerability and adaptive capacity. Tyndall Centre for Climate Change Research.

Alonso, Jose Antonio, and M Teresa Lamata. 2006. "Consistency in the analytic hierarchy process: a new approach." *International journal of uncertainty, fuzziness and knowledge-based systems* 14 (04):445-459.

Asariotis, Regina, Hassiba Benamara, and Viktoria Mohos-Naray. 2017. Port Industry Survey on Climate Change Impacts and Adaptation. In *UNCTAD Research Paper No. 18*: United Nations Conference on Trade and Development.

Aull-Hyde, Rhonda, Sevgi Erdogan, and Joshua M Duke. 2006. "An experiment on the consistency of aggregated comparison matrices in AHP." *European Journal of Operational Research* 171 (1):290-295.

Barnett, Jon, Simon Lambert, and Ian Fry. 2008. "The hazards of indicators: insights from the environmental vulnerability index." *Annals of the Association of American Geographers* 98 (1):102-119.

Beck, Michael W, Kenneth L Heck Jr, Kenneth W Able, Daniel L Childers, David B Eggleston, Bronwyn M Gillanders, Benjamin Halpern, Cynthia G Hays, Kaho Hoshino, and Thomas J Minello. 2001. "The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: a better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas." *Bioscience* 51 (8):633-641.

Becker, A., J. Toilliez, and T. Mitchell. 2015. "Considering Sea Level Change When Designing Marine Civil

Works: Recommendations for Best Practices." In *Handbook of Coastal Disaster Mitigation for Engineers and Planners*, edited by Miguel Esteban, Hiroshi Takagi and Tomoya Shibayama. Waltham ,MA: Elsevier.

Becker, Austin, M. Acciaro, R. Asariotis, E. Cabrera, L. Cretegny, P. Crist, M. Esteban, A. Mather, S. Messner, S. Naruse, A. K. Y. Ng, S. Rahmstorf, M. Savonis, D. W. Song, V. Stenek, and A. F. Velegrakis. 2013. "A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society." *Climatic Change* 120 (4):683-695. doi: DOI 10.1007/s10584-013-0843-z.

Becker, Austin, and Margaret R Caldwell. 2015. "Stakeholder Perceptions of Seaport Resilience Strategies: A Case Study of Gulfport (Mississippi) and Providence (Rhode Island)." *Coastal Management* 43 (1):1-34.

Becker, Austin, Nathan TL Chase, Martin Fischer, Ben Schwegler, and Keith Mosher. 2016. "A method to estimate climate-critical construction materials applied to seaport protection." *Global Environmental Change* 40:125-136.

Becker, Austin, Satoshi Inoue, Martin Fischer, and Ben Schwegler. 2011. "Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators." *Climatic Change* 110 (1-2):5-29. doi: 10.1007/s10584-011-0043-7.

Becker, Austin, David Newell, Martin Fischer, and Ben Schwegler. 2011. "Will Ports Become Forts? Climate Change Impacts, Opportunities and Challenges." *Terra et Aqua* 122:11-17.

Becker, Austin, Angela Wilson, Rebecca Bannon, Jennifer McCann, and Don Robadue. 2010. Rhode Island Ports & Commercial Harbors: A GIS-based Inventory of Current Uses and Infrastructure. edited by Susan Kennedy: Rhode Island Statewide Planning Program, US Department of Transportation, Federal Highway Administration.

Berle, Øyvind, Bjørn Egil Asbjørnslett, and James B Rice. 2011. "Formal vulnerability assessment of a maritime transportation system." *Reliability Engineering & System Safety* 96 (6):696-705.

Bright, Eddie A., and Phil R. Coleman. 2003. LandScan 2002. Oak Ridge, TN: Oak Ridge National Laboratory.

Brooks, Nick, W Neil Adger, and P Mick Kelly. 2005. "The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation." *Global environmental change* 15 (2):151-163.

Chhetri, Prem, Jonathan Corcoran, Victor Gekara, Chris Maddox, and Darryn McEvoy. 2014. "Seaport resilience to climate change: mapping vulnerability to sea-level rise." *Journal of Spatial Science*:1-14. doi: 10.1080/14498596.2014.943311.

Clark, William C., and Edward A. Parson. 2000. *Assessing vulnerability to global environmental risks*: Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University.

CMTS, U.S. 2015. Marine Transportation System Performance Measures: Executive Summary. 1200 New Jersey Ave SE. Washington, D.C. 20590: U.S. Committee on the Marine Transportation System, Research and Development Integrated Action Team.

Cox, R. J., K. Panayotou, and R. M. Cornwell. 2013. Climate Risk Assessment for Avatiu Port and Connected Infrastructure. Water Research Lab, University of New South Wales.

Cutter, S. L. 1996. "Vulnerability to environmental hazards." *Progress in Human Geography* 20 (4):529-539. doi: Doi 10.1177/030913259602000407.

Cutter, S. L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb. 2008. "A place-based model for understanding community resilience to natural disasters." *Global Environmental Change* 18 (4):598-606. doi: DOI 10.1016/j.gloenvcha.2008.07.013.

Cutter, S. L., C. G. Burton, and C. T. Emrich. 2010. "Disaster Resilience Indicators for Benchmarking Baseline Conditions." *Journal of Homeland Security and Emergency Management* 7 (1). doi: 10.2202/1547-7355.1732.

Cutter, Susan L., Bryan J. Boruff, and W. Lynn Shirley. 2003. "Social Vulnerability to Environmental Hazards*." *Social Science Quarterly* 84 (2):242-261. doi: 10.1111/1540-6237.8402002.

Davidson, Rachel A, and Haresh C Shah. 1997. An urban earthquake disaster risk index. John A. Blume Earthquake Engineering Center Standford University.

Dedeke, N. 2013. "Estimating the weights of a composite index using AHP: Case of the environmental performance index." *British Journal of Arts & Social Sciences* 11:199-221.

Delbecq, Andre L, Andrew H Van de Ven, and David H Gustafson. 1975. *Group techniques for program planning: A guide to nominal group and Delphi processes*: Scott, Foresman Glenview, IL.

Eriksen, SH, and P Mick Kelly. 2007. "Developing credible vulnerability indicators for climate adaptation policy assessment." *Mitigation and Adaptation Strategies for Global Change* 12 (4):495-524.

ESPO. 2010. Work Package 1 (WP1): Pre-Selection of an initial set of indicators. In *PPRISM: Port PeRformance Indicators : Selection and Measurement*: European Sea Ports Organization (ESPO).

ESPO. 2011. Work Package 2 (WP2): Stakeholders' dialogue to evaluate and select a shortlist of indicators. In *PPRISM: Port PeRformance Indicators : Selection and Measurement*: European Sea Ports Organization (ESPO).

ESPO. 2012. Project Executive report (PPRISM WP4 D4.2). In *PPRISM: Port PeRformance Indicators : Selection and Measurement*: European Sea Ports Organization (ESPO).

Füssel, Hans Martin, and R. J. T. Klein. 2006. "Climate change vulnerability assessments: An evolution of conceptual thinking." *Climatic Change* 75:301-329. doi: 10.1007/s10584-006-0329-3.

Gallopín, Gilberto C. 2006. "Linkages between vulnerability, resilience, and adaptive capacity." *Global environmental change* 16 (3):293-303.

Gallopin, Gilberto Carlos. 1997. "Indicators and their use: information for decision-making." In *Sustainability Indicators. A Report on the Project on Indicators of Sustainable Development*, edited by Bedrich Boldan and Suzanne Bilharz, 13-27. Chichester: SCOPE.

Goepel, Klaus D. 2013. "Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new AHP excel template with multiple inputs." Proceedings of the international symposium on the analytic hierarchy process.

Goepel, Klaus D. 2017. "AHP Online System - BPMSG." Last Modified Sep 8, 2017. https://bpmsg.com/academic/ahp.php.

Gómez-Limón, José A, and Laura Riesgo. 2009. "Alternative approaches to the construction of a composite indicator of agricultural sustainability: an application to irrigated agriculture in the Duero basin in Spain." *Journal of Environmental Management* 90 (11):3345-3362.

Gudmundsson, Henrik. 2003. "The policy use of environmental indicators—learning from evaluation research." *The Journal of Transdisciplinary Environmental Studies* 2 (2):1-12.

Hallegatte, Stéphane, Nicola Ranger, Olivier Mestre, Patrice Dumas, Jan Corfee-Morlot, Celine Herweijer, and Robert Muir Wood. 2011. "Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen." *Climatic change* 104 (1):113-137.

Hanson, Susan, Robert Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau. 2010. "A Global Ranking of Port Cities with High Exposure to Climate Extremes." *Climatic Change* 104 (1):89-111. doi: 10.1007/s10584-010-9977-4.

Hasson, Felicity, Sinead Keeney, and Hugh McKenna. 2000. "Research guidelines for the Delphi survey technique." *Journal of advanced nursing* 32 (4):1008-1015.

Hinkel, J. 2011. ""Indicators of vulnerability and adaptive capacity": Towards a clarification of the science-policy interface." *Global Environmental Change-Human and Policy Dimensions* 21 (1):198-208. doi: DOI 10.1016/j.gloenvcha.2010.08.002.

Hovanov, Nikolai V, James W Kolari, and Mikhail V Sokolov. 2008. "Deriving weights from general pairwise comparison matrices." *Mathematical Social Sciences* 55 (2):205-220.

Hsieh, Cheng-Hsien, Hui-Huang Tai, and Yang-Ning Lee. 2013. "Port Vulnerability Assessment from the Perspective of Critical Infrastructure Interdependency." *Maritime Policy & Management* 41 (6):589-606. doi: 10.1080/03088839.2013.856523.

IMO. 2012. International Shipping Facts and Figures – Information Resources on Trade , Safety , Security , Environment. Maritime Knowledge Centre: International Maritime Organization.

IPCC. 2001. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.

IPCC. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change (SREX). Cambridge: Cambridge University Press.

IPCC. 2013. Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by Thomas Stocker, Dahe Qin, Gian-Kasper Plattner, M Tignor, Simon K Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex and Pauline M Midgley. Cambridge, UK; New York, NY, USA: Intergovernmental Panel on Climate Change.

IPCC. 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change.

IPCC. 2014b. WGII AR5 Glossary. In *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Ishizaka, Alessio, and Ashraf Labib. 2011. "Review of the main developments in the analytic hierarchy process." *Expert systems with applications* 38 (11):14336-14345.

Janssen, Marijn, Yannis Charalabidis, and Anneke Zuiderwijk. 2012. "Benefits, adoption barriers and myths of open data and open government." *Information Systems Management* 29 (4):258-268.

Jharkharia, S., and R. Shankar. 2007. "Selection of logistics service provider: An analytic network process (ANP) approach." *Omega-International Journal of Management Science* 35 (3):274-289. doi: DOI 10.1016/j.omega.2005.06.005.

Kainulainen, T, Pekka Leskinen, Pekka Korhonen, A Haara, and Teppo Hujala. 2009. "A statistical approach to assessing interval scale preferences in discrete choice problems." *Journal of the Operational Research Society* 60 (2):252-258.

Keeney, Sinead, Felicity Hasson, and Hugh McKenna. 2006. "Consulting the oracle: ten lessons from using the Delphi technique in nursing research." *Journal of advanced nursing* 53 (2):205-212.

Kim, Yeonjoo, and Eun-Sung Chung. 2013. "Assessing climate change vulnerability with group multi-criteria decision making approaches." *Climatic change* 121 (2):301-315.

Klein, Richard JT. 2009. "Identifying countries that are particularly vulnerable to the adverse effects of climate change: an academic or political challenge." *Carbon & Climate L. Rev.*:284.

Klein, Richard JT, Robert J Nicholls, and Frank Thomalla. 2003. "Resilience to natural hazards: How useful is this concept?" *Global Environmental Change Part B: Environmental Hazards* 5 (1-2):35-45.

Koppe, Baerbel. 2012. "IAPH-Report on Seaports and Climate Change and Implementation Case Study for the Port of Hamburg."

Koppe, Baerbel, Maja Schmidt, and Thomas Strotmann. 2012. "IAPH-Report on Seaports and Climate Change and Implementation Case Study for the Port of Hamburg."

Kuo, Ying-Feng, and Pang-Cheng Chen. 2008. "Constructing performance appraisal indicators for mobility of the service industries using Fuzzy Delphi Method." *Expert Systems with Applications* 35 (4):1930-1939.

Larson, Ron. 2016. *Elementary linear algebra*: Nelson Education.

Linkov, Igor, Todd Bridges, Felix Creutzig, Jennifer Decker, Cate Fox-Lent, Wolfgang Kröger, James H. Lambert, Anders Levermann, Benoit Montreuil, Jatin Nathwani, Raymond Nyer, Ortwin Renn, Benjamin Scharte, Alexander Scheffler, Miranda Schreurs, and Thomas Thiel-Clemen. 2014. "Changing the resilience paradigm." *Nature Climate Change* 4 (6):407-409. doi: 10.1038/nclimate2227.

MARAD. 2016. "Marine Transportation System (MTS)." Maritime Administration, accessed 5/25/2016. https://www.marad.dot.gov/ports/marine-transportation-system-mts/.

McGranahan, Gordon, Deborah Balk, and Bridget Anderson. 2007. "The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones." *Environment and urbanization* 19 (1):17-37.

McIntosh, R. Duncan, and Austin Becker. 2017. "Seaport Climate Vulnerability Assessment at the Multi-port Scale: A Review of Approaches." In *Resilience and Risk: Methods and Application in Environment, Cyber and Social Domains*, edited by Igor Linkov and José Manuel Palma-Oliveira, 205-224. Dordrecht: Springer Netherlands.

McLaughlin, Brian J, Scott D Murrell, and Susanne DesRoches. 2011. "Case study: Assessment of the vulnerability of Port Authority of NY & NJ facilities to the impacts of climate change." First Congress of Transportation and Development Institute (TDI).

Mclean, Elizabeth, Austin Becker, R. Duncan McIntosh, and Julie Dean Rosati. 2017a. Measuring Risk Database for 23 North Atlantic Ports. A Technical Report for ERDC, Version 1.0. Project: W912HZ-16-C-0019. United States Army Corps of Engineers.

Mclean, Elizabeth, Austin Becker, R. Duncan McIntosh, and Julie Dean Rosati. 2017b. Selection of Seaport Vulnerability Indicators for 23 Medium and High Use North Atlantic Ports. United States Army Corps of Engineers.

Mcleod, Elizabeth, Brian Szuster, Emma L Tompkins, Nadine Marshall, Thomas Downing, Supin Wongbusarakum, Anand Patwardhan, Mo Hamza, Cheryl Anderson, and Sukaina Bharwani. 2015. "Using Expert Knowledge to Develop a Vulnerability and Adaptation Framework and Methodology for Application in Tropical Island Communities." *Coastal Management* 43 (4):365-382.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe. 2014. Climate Change Impacts in the United States. In *The Third National Climate Assessment*: US Global Change Research Program.

Messner, S., L. Moran, G. Reub, and J. Campbell. 2013. Climate change and sea level rise impacts at ports and a consistent methodology to evaluate vulnerability and risk. ENVIRON International Corp.

Morris, Lauren L., and Tracie Sempier. 2016. Ports Resilience Index: A Port Management Self-Assessment. U.S. Department of Commerce, Gulf of Mexico Alliance.

Muller, Jorg, Daniel Polansky, Petr Novak, Christian Foltin, and Dimitry Polivaev. 2013. Freemind - free mind mapping and knowledge building software.

NGIA. 2015. *WORLD PORT INDEX - 150 PUB. - TWENTY-FOURTH EDITION*. Springfield, Virginia: NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY.

Nicholls, Robert J, Susan Hanson, Celine Herweijer, Nicola Patmore, Stéphane Hallegatte, Jan Corfee-Morlot, Jean Château, and Robert Muir-Wood. 2008. Ranking port cities with high exposure and vulnerability to climate extremes: Exposure Estimates. In *OECD Environment Working Papers*: Organization for Economic Cooperation and Development.

NOAA OCM. 2015. "Port Tomorrow: Port Resilience Planning Tool [Prototype]." NOAA Office for Coastal Management, accessed 3 April 2015. http://www.coast.noaa.gov/port/.

Obama, Barack. 2013. "Presidential Policy Directive 21: Critical Infrastructure Security and Resilience." *Washington, DC*.

Okoli, Chitu, and Suzanne D Pawlowski. 2004. "The Delphi method as a research tool: an example, design considerations and applications." *Information & management* 42 (1):15-29.

Orencio, Pedcris M, and Masahiko Fujii. 2013. "A localized disaster-resilience index to assess coastal communities based on an analytic hierarchy process (AHP)." *International Journal of Disaster Risk Reduction* 3:62-75.

Peduzzi, P., H. Dao, C. Herold, and F. Mouton. 2009. "Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index." *Nat. Hazards Earth Syst. Sci.* 9 (4):1149-1159. doi: 10.5194/nhess-9-1149-2009.

Peduzzi, Pascal. 2014. "Sand, rarer than one thinks." *Environmental Development* 11:208-218.

PIANC Inland Navigation Commission. 2010. Performance Indicators for Inland Waterways Transport: User Guideline. PIANC Report No. 111. Bruxelles, Belgium: The World Association for Waterborne Transport Infrastructure (PIANC).

Preston, BL. 2012. Climate change vulnerability assessment: From conceptual frameworks to practical heuristics. CSIRO Climate Adaptation Flagship Working paper.

Pticina, Irina, and Irina Yatskiv. 2015. "Weighting the urban public transport system quality index (UPTQI) using the analytical hierarchy process." *International Journal of Society Systems Science* 7 (2):107-126.

Ramanathan, R, and LS Ganesh. 1994. "Group preference aggregation methods employed in AHP: An evaluation and an intrinsic process for deriving members' weightages." *European Journal of Operational Research* 79 (2):249-265.

Rice, Jake C, and Marie-Joëlle Rochet. 2005. "A framework for selecting a suite of indicators for fisheries management." *ICES Journal of Marine Science* 62 (3):516-527.

Rosati, Julie Dean. 2015. "PhD, PE, D.CE, Coastal & Hydraulics Laboratory, Engineer Research & Development Center, U.S. Army Corps of Engineers." Personal Communication, 1/10/15.

Saaty, Thomas L. 1977. "A scaling method for priorities in hierarchical structures." *Journal of mathematical psychology* 15 (3):234-281.

Saaty, Thomas L. 1990a. "An exposition of the AHP in reply to the paper "remarks on the analytic hierarchy process"." *Management science* 36 (3):259-268.

Saaty, Thomas L. 1990b. "How to make a decision: the analytic hierarchy process." *European journal of operational research* 48 (1):9-26.

Saaty, Thomas L. 2006. "Rank from comparisons and from ratings in the analytic hierarchy/network processes." *European Journal of Operational Research* 168 (2):557-570.

Saaty, Thomas L. 2008. "Decision making with the analytic hierarchy process." *International journal of services sciences* 1 (1):83-98.

Sagar, Ambuj D, and Adil Najam. 1998. "The human development index: a critical review1." *Ecological economics* 25 (3):249-264.

Schroth, Olaf, Ellen Pond, and Stephen RJ Sheppard. 2011. "Integration of Spatial Outputs from Mathematical Models in Climate Change Visioning Tools for Community-Decision Making on the Landscape Scale." *DLA-Digital Landscape Architecture*:246-255.

Semppier, T. T., D.L. Swann, R. Emmer, S. H. Sempier, and M. Schneider. 2010. Coastal Community Resilience Index: A Community Self-Assessment. Mississippi-Alabama Sea Grant Consortium.

Siders, Anne. 2016. *Incoherent Resilience -- Towards a Common Language for Climate Change Adaptation, Disaster Risk Reduction, and Sustainable Development [Pre-Print Version]*.

Smit, Barry, and Johanna Wandel. 2006. "Adaptation, adaptive capacity and vulnerability." *Global environmental change* 16 (3):282-292.

Teck, Sarah J, Benjamin S Halpern, Carrie V Kappel, Fiorenza Micheli, Kimberly A Selkoe, Caitlin M Crain, Rebecca Martone, Christine Shearer, Joe Arvai, and Baruch Fischhoff. 2010. "Using expert judgment to estimate marine ecosystem vulnerability in the California Current." *Ecological Applications* 20 (5):1402-1416.

The National Academies. 2012. Disaster Resilience: A National Imperative. edited by Committee on Increasing National Resilience to Hazards and Disasters; Committee and Engineering on Science, and Public Policy. Washington, D.C.

Turner, Billie L, Roger E Kasperson, Pamela A Matson, James J McCarthy, Robert W Corell, Lindsey Christensen, Noelle Eckley, Jeanne X Kasperson, Amy Luers, and Marybeth L Martello. 2003. "A framework for vulnerability analysis in sustainability science." *Proceedings of the national academy of sciences* 100 (14):8074-8079.

USACE. 2014. USACE Civil Works Division Boundaries. http://geoplatform.usace.army.mil/home/item.html?id=c3695249909c45a2b2e2c3993aff3edb: U.S. Army Corps of Engineers.

USCMTS. 2011. Strategic Action Plan for Research and Development in the Marine Transportation System. Washington, DC: US Committee on the Marine Transportation System.

USCMTS. 2015. Marine Transportation System Performance Measures: Executive Summary. 1200 New Jersey Ave SE. Washington, D.C. 20590: U.S. Committee on the Marine Transportation System, Research and Development Integrated Action Team.

USDOT. 2014. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure The Gulf Coast Study, Phase 2 Screening for Vulnerability Final Report, Task 3.1. edited by ICF International. Washington, DC: US Department of Transportation.

White, Dave D, Amber Wutich, Kelli L Larson, Patricia Gober, Timothy Lant, and Clea Senneville. 2010. "Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater." *Science and Public Policy* 37 (3):219-232.

WMO. 2015. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2014. In *Greenhouse Gas Bulletin*. Geneva: World Meteorological Organization.

Comprehensive Conclusion

This work began with a call to develop a method to assess the relative vulnerabilities of seaports to climate and extreme-weather impacts. In the first of three manuscripts, this research identified an opportunity to contribute to the CCVA literature for the seaport sector by piloting a multi-port vulnerability assessment method based on the use of indicators. The second manuscript in this work contributes to the field of IBVA for seaports by identifying from open-data sources and refining via expert-elicitation methods a set of expert-evaluated candidate indicators of seaport climate and extreme-weather vulnerability. This indicator-evaluation resulted in the finding that adaptive capacity is considered by port-experts as the most difficult of the three components of vulnerability (i.e., exposure, sensitivity, and adaptive capacity) to represent with quantitative data. The final manuscript of this work contributes to the body of CCVA and seaport-studies literature by building and trialing a composite-index of seaport climate and extreme-weather vulnerability based on the evaluated indicators and using AHP to generate component weights. By modeling seaport vulnerability with an indicator-based composite index and comparing results to expert expectations, this work has shown the potential of indicator-based methods to bring a data-driven approach to the CIAV decision-making process, however, results suggest that the current state of publicly available data for and about the seaport sector is not currently sufficient for a robust, expert-supported index.

This research fist identified a gap in the literature for the development of CCVA applied to ports at the multi-port scale. The researchers then performed a first pass of the openly available data for and about the seaport sector to evaluate to what extent it can support the development of expert-supported indicators that can measure the relative climate vulnerabilities of seaports. Open-data here refers to data that is publicly available without fees or restrictions. The use of open-data for indicator development can increase transparency and facilitate the reproducibility of the results. This first-pass of open-data, then, is considered a first step in the development of indicators for seaport climate vulnerability. By starting with examining open-data generally collected for other purposes to assess to assess to what extent it can be developed into expert-supported indicators, and in turn a composite-index for ports, an envisioned next step would be to identify what types of bespoke data might be synthesized into new additional indicators to supplement those developed here.

Results indicate that available open-data can be developed into expert-supported indicators of seaport climate exposure and sensitivity, however, results also indicate relatively little expert-perceived correlation between open-data and a port's adaptive capacity. This finding suggests a lack of open-data sources available for representing the adaptive capacity of seaports in the sample. This finding also suggests that port-experts consider the concept of adaptive capacity to be less amenable to representation with quantitative data than the remaining two components of vulnerability, i.e., exposure and sensitivity.

Results of the VAS survey also indicate that respondents reserve their highest levels of aggregate perceived correlation for place-based indicators; though 14 of the 34 candidate indicators were port-specific, the top 12 candidate indicators ranked by total correlation were all place-based. While port-specific indicators scored low overall, they fared better with adaptive capacity than with exposure or sensitivity, which suggests that more or different port-specific data reporting may lead to improvements in the ability to measure a port's relative adaptive capacity.

After evaluating candidate indicators, researchers then constructed and trialed a prototype composite-index of seaport climate vulnerability using the highest scoring indicators from the VAS survey. The objective of this experiment was to investigate the ability of a data-driven composite-index approach to measure relative climate vulnerability for a sample of ports. Interestingly, during the AHP part of the index construction, respondents weighted adaptive capacity higher than sensitivity and nearly equal with exposure in terms of importance to seaport climate vulnerability. This finding is noteworthy because the previous VAS survey found a lack of expert-support for candidate indicators of adaptive capacity. This suggests a disconnect between those concepts experts consider important to capture when measuring vulnerability and what data is available to measure those concepts.

Finally, results of the prototype index were compared to experts' subjective port rankings to evaluate how well the model captured expert expectations. Although the model lacked indicators of adaptive capacity, it showed promise in fulfilling the main objective of composite indices (i.e., identification of relative outliers among a sample) by matching the most vulnerable port and three of the top four most vulnerable ports as subjectively ranked by port experts.

While the research literature currently lacks examples of multi-port, comparative CCVA for the seaport sector, this body of work has developed and contributed a set of 34 expert-evaluated indicators of seaport climate-vulnerability from open-data. Further, this work quantified expert preferences for weighting indicators and the components of climate vulnerability for seaports and identified adaptive capacity as lacking representation in the available data. Finally, this work contributes a first attempt at an indicator-based composite-index for seaport climate-vulnerability.

By trialing this approach for indicator development and piloting a prototype composite-index, researchers identified several limitations of the chosen approach. The results of the prototype composite-index are highly sensitive to value-judgements such as how to delimit each port (e.g., Where should the boundary be? Which terminal to include?) or how to compile indicator data (e.g., Use max value or average value? Take the value for the highest county or the average of counties when ports span multiple counties?) Additionally, the reproducibility of the expert-elicitation processes will necessarily be limited by expert subjectivity. A further limitation of the prototype composite-index stems from its lack of indicators of adaptive capacity.

To the observed problem (i.e., the current difficulty of comparing relative vulnerability across ports), this body of research contributes a set of 34 expert-evaluated indicators that can be monitored to assess relative vulnerabilities across ports. This work also contributes a prototype composite-index (and a method to replicate such an index for other sectors) that allows rudimentary quantitative comparisons of exposure and sensitivity levels across ports. This prototype index was able to capture relative outliers in the sample of ports (i.e., the main objective of composite-indices) and shows the promise of an indicator-based approach to address this problem.

Results of this research point to several recommended next steps for the purpose of comparing and assessing seaport climate vulnerability. Researchers recommend that future efforts focus on the development of methods to comparatively measure ports' adaptive capacity. Port-experts weight adaptive capacity high in importance with respect to seaport climate vulnerability, yet adaptive capacity lacks expert-supported representation in the available data. Because results of the VAS survey indicate that port-specific data is preferred by experts for representing adaptive capacity, researchers recommend that non-open (i.e., proprietary) port-specific data be explored for this purpose where possible. Additionally, researchers recommend that next steps involve the investigation of what types of bespoke data (e.g., GIS analysis of port elevation, or proprietary non-open data sources) might be synthesized into new, additional, or supplementary indicators. Finally, researchers recommend that theoretical investigations of port climate vulnerability, such as that presented here, be complimented with empirical investigations of historical impacts of climate and extreme weather on seaports to better understand the complete picture of what makes ports vulnerable and how ports empirically respond to such impacts.

APPENDICES

Manuscript 2

Procedure for Selecting Experts Using a KRNW

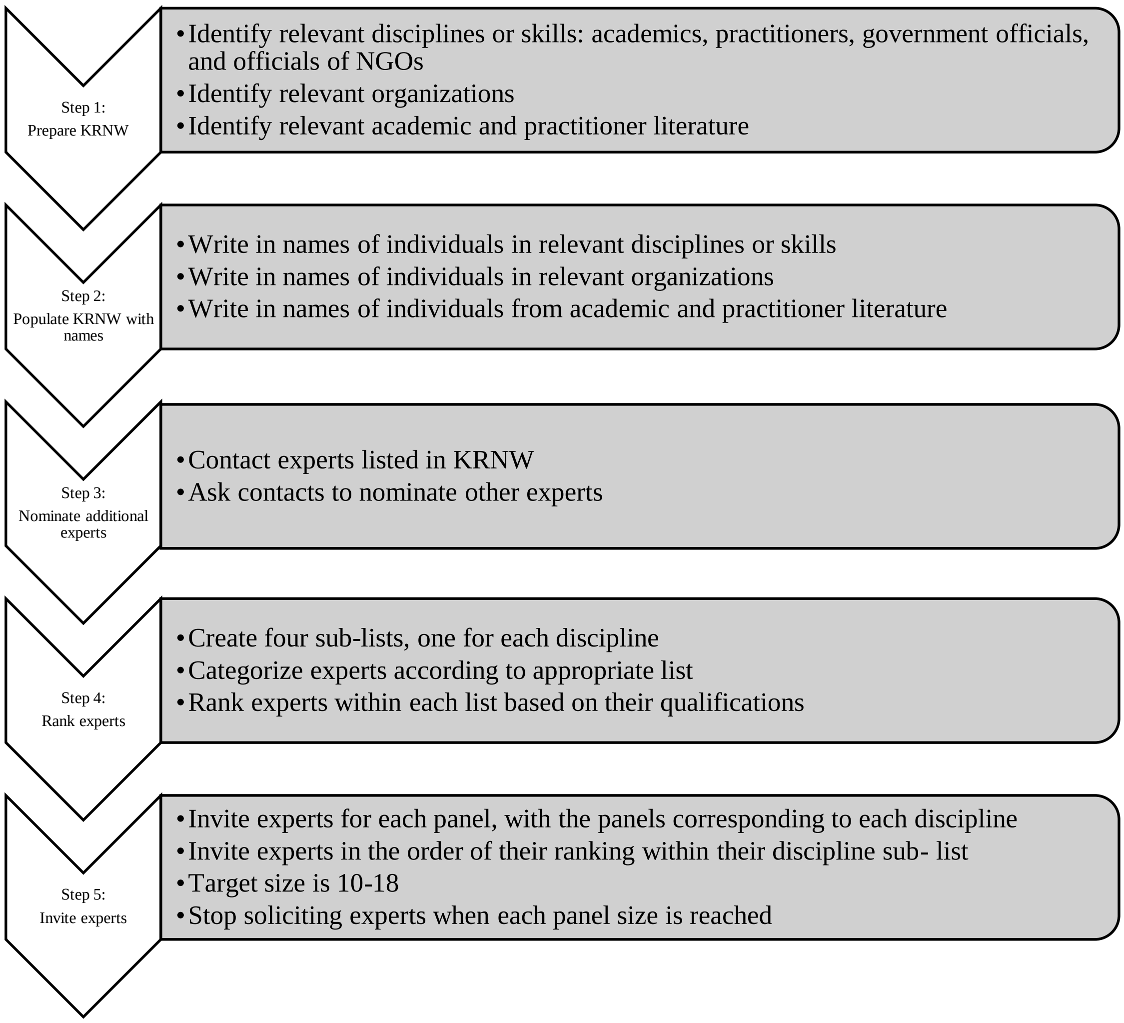

Figure 25 Procedure for selecting experts using a Knowledge Resource Nomination Worksheet. Modified from (Okoli and Pawlowski 2004).

VAS Survey Instrument

*Adapted from online version hosted via www.surveygizmo.com, internally tested December 2016 and January 2017, and open to invited experts from 25 January to 23 February 2017.

Indicating Seaport Vulnerabilities to Climate and Extreme Weather Impacts

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Informed Consent

Electronic Consent: Please select a choice below. Clicking on the "Agree" button indicates that
You have read the above information
You voluntarily agree to participate
*
( ) Agree - Enter Survey
( ) Disagree - Exit

Affiliation
Please select the category that best describes your professional affiliation:*
( ) Consultant
( ) Academic
( ) (Port / Marine Transportation System) Practitioner
( ) Federal Government
( ) State Government
( ) Non-governmental Organization
( ) Other - Please Specify:
____*

Instructions

Please consider whether this candidate indicator, (Measurable, observable quantity that serves as a proxy for an aspect of a system that cannot itself be directly, adequately measured [page("title")]), could be correlated (The condition of being interdependent; a mutual relation of two or more things such that a change in the value of one is associated with a change in the value or the expectation of the others) with one or more of the three components of climate vulnerability (The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity):

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected

Example: a port on the US East coast has a *higher exposure* to hurricanes than a port on the US West Coast; independent of the ports' sensitivity to damage

Sensitivity: The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli

Example: a port with a storm surge barrier may be *less sensitive* to storm driven flooding impacts than a similar port without a storm surge barrier; independent of the ports' exposure and/or the

Adaptive Capacity: The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences

Example: a port with a robust master plan that considers climate resilience and has a high degree of operational flexibility may have a *higher adaptive capacity* than a port with minimal planning and low redundancy; independent of the ports' exposure and sensitivity of a port, including the port's surrounding socioeconomic and environmental
systems.

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For each component of vulnerability: If you feel no correlation exists with [page("title")], click the slider, leaving it in the center (0) position.

.

If you feel the component may be correlated with [page("title")], then drag each slider-To the Right if the correlation is Positive (i.e., an increase in one correlates to an increase in the other)

-To the Left if the correlation is Negative (i.e., an increase in one correlates to a decrease in the other)

-In the Center if you feel there is No Correlation to indicate your opinion of the magnitude and direction of the correlation Positive Correlation: An increase in one correlates to an increase in the other

Negative Correlation: an increase in one correlates to a *decrease* in the other

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Study Area

Harbor Size

Shortname / Alias: Harbor Size
1)

Indicator	**HarborSize**
Units	Large, Medium, Small, Very Small

Description	The classification of harbor size is based on several applicable factors, including: area, facilities, and wharf space. It is not based on area alone or on any other single factor.
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries).
Example Values	**Port of NY/NJ**: Large **Port of Providence, RI**: Medium

Exposure	-100 ________________________[__]____________________________ 100
Sensitivity	-100 ________________________[__]____________________________ 100
Adaptive Capacity	-100 ________________________[__]____________________________ 100

Comments (Please also explain any extreme views)::

Number of Storm Events

Shortname / Alias: Number of Storm Events
2)

Indicator	**Number of Storm Events**
Units	Number of Events
Description	Number of storm events in the port county since 1950 that resulted in property damage > $1 Million
Data Source	The NOAA Storm Events Database is an official publication of the National Oceanic and Atmospheric Administration (NOAA) which documents the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. National Centers for Environmental Information (NCEI) Storm Events Database contains the records used to create the official NOAA Storm Data publication, documenting: a. The occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce;

	b. Rare, unusual, weather phenomena that generate media attention, such as snow flurries in South Florida or the San Diego coastal area; and c. Other significant meteorological events, such as record maximum or minimum temperatures or precipitation that occur in connection with another event. NCEI receives Storm Data from the National Weather Service.
Example Values	**Port of Boston, MA** (Suffolk County): 11 Events **Searsport, ME** (Waldo County): 4 Events

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Average Cost of Storm Events

Shortname / Alias: Average Cost of Storm Events

3)

Indicator	**Average Cost of Storm Events**
Units	$ Millions USD
Description	Average cost of property damage from storm events in the port county since 1950 with property damage > $1 Million
Data Source	The NOAA Storm Events Database is an official publication of the National Oceanic and Atmospheric Administration (NOAA) which documents the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. National Centers for Environmental Information (NCEI) Storm Events Database contains the records used to create the official NOAA Storm

	Data publication, documenting: a. The occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce; b. Rare, unusual, weather phenomena that generate media attention, such as snow flurries in South Florida or the San Diego coastal area; and c. Other significant meteorological events, such as record maximum or minimum temperatures or precipitation that occur in connection with another event. NCEI receives Storm Data from the National Weather Service.
Example Values	**Port of Boston, MA** (Suffolk County): $5.92 Million **Searsport, ME** (Waldo County): $7.05 Million

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Hundred Year High Water

Shortname / Alias: Hundred Year High Water
4)

Indicator	**Hundred Year High Water**
Units	Meters above Mean Higher High Water (MHHW)
Description	1% annual exceedance probability high water level which corresponds to the level that would be exceeded one time per century, for the nearest NOAA tide station to the port
Data Source	NOAA Extreme Water Levels Extremely high or low water levels at coastal locations are an important public concern and a factor in coastal hazard assessment, navigational safety, and ecosystem management. Exceedance

	probability, the likelihood that water levels will exceed a given elevation, is based on a statistical analysis of historic values. The Extreme Water Levels product provides web-based access to Exceedance Probability Statistics at approximately 110 NOAA Center for Operational Oceanographic Products and Services (CO-OPS) water level stations with at least 30 years of water level observations.
Example Values	**Port of Boston, MA**: 1.40 meters above MHHW **Providence, RI**: 2.73 meters above MHHW

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Hundred Year Low Water

Shortname / Alias: Hundred Year Low Water
5)

Indicator	**Hundred Year Low Water**
Units	Meters below Mean Lower Low Water (MLLW)
Description	1% annual exceedance probability low water level for the nearest NOAA tide station to the port, which corresponds to the level that would be exceeded one time per century.
Data Source	NOAA Extreme Water Levels Extremely high or low water levels at coastal locations are an important public concern and a factor in coastal hazard assessment, navigational safety, and ecosystem management. Exceedance probability, the likelihood that water levels will exceed a given elevation, is based on a statistical analysis of historic values. The Extreme Water Levels product provides web-based access to Exceedance Probability Statistics at approximately 110 NOAA Center

	for Operational Oceanographic Products and Services (CO-OPS) water level stations with at least 30 years of water level observations.
Example Values	**Fall River, MA**: 0.77 meters below MLLW **Penn Manor, PA**: 1.72 meters below MLLW

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Number of Cyclones

Shortname / Alias: Number of Cyclones
6)

Indicator	**Number of Cyclones**
Units	Number of cyclones
Description	Number of cyclones that have passed within 100 nautical miles (nm) of the port since 1842.
Data Source	NOAA Historical Hurricane Tracks Tool Storm track information is available from 1842 through the previous year's storms. The storm track data are from the NOAA National Climatic Data Center's International Best Track Archive for Climate Stewardship (IBTrACS) data set and the NOAA National Weather Service HURDAT2 data set.
Example Values	**Norfolk, VA**: 116 cyclones **Albany, NY**: 28 cyclones

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100

Adaptive Capacity	-100 ______________________[__]___________________________ 100	

Comments (Please also explain any extreme views)::

Sea Level Trend

Shortname / Alias: Sea Level Trend
7)

Indicator	**Sea Level Trend**
Units	millimeters per year (mm/yr)
Description	Local Mean Sea Level Trend
Data Source	NOAA Tides and Currents- Sea Level Trends The Center for Operational Oceanographic Products and Services has been measuring sea level for over 150 years, with tide stations of the National Water Level Observation Network operating on all U.S. coasts. Changes in Mean Sea Level (MSL), either a sea level rise or sea level fall, have been computed at 142 long-term water level stations using a minimum span of 30 years of observations at each location. These measurements have been averaged by month to remove the effect of higher frequency phenomena in order to compute an accurate linear sea level trend. Tide stations measure **Local Sea Level**, which refers to the height of the water as measured along the coast relative to a specific point on land. Water level measurements at tide stations are referenced to stable vertical points (or bench marks) on the land and a known relationship is established. However, **the measurements at any given tide station include both global sea level rise and vertical land motion**, such as subsidence, glacial rebound, or large-scale tectonic motion. Because the heights of both the land and the water are changing, the land-water interface can vary spatially and temporally and must be defined over time. Depending on the rates of vertical land motion relative to changes in sea level, observed local sea level trends may differ greatly from the average rate of global sea level rise, and vary widely from one location to the next. Relative Sea Level Trends reflect changes in local sea level over time and are typically the most critical sea level trend for many coastal applications, including coastal mapping, marine boundary delineation, coastal zone management, coastal engineering, sustainable habitat restoration design, and the general public enjoying their favorite beach. This website focuses on relative sea level trends, computed

	from monthly averages of hourly water levels observed at specific tide stations, called monthly mean sea level.
Example Values	**Norfolk, VA**: 4.6 mm/yr **Portland, ME**: 1.9 mm/yr

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Number of Disasters

Shortname / Alias: Number of Disasters
8)

Indicator	**Number of Disasters**
Units	Number of Disaster Declarations
Description	Number of Presidential Disaster Declarations for the port county since 1953
Data Source	FEMA Historical Disaster Declarations FEMA Disaster Declarations Summary is a summarized dataset describing all federally declared disasters. This information begins with the first disaster declaration in 1953 and features all three disaster declaration types: major disaster, emergency and fire management assistance.
Example Values	**Providence, RI** (Providence County): 18 disaster declarations **Portland, ME** (Cumberland County): 33 disaster declarations

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100

Adaptive Capacity	-100 ________________________[__]________________________________ 100	

Comments (Please also explain any extreme views)::

Disaster Housing Assistance

Shortname / Alias: Disaster Housing Assistance
9)

Indicator	**Disaster Housing Assistance**
Units	$ Millions of USD
Description	The total disaster housing assistance of Presidential Disaster Declarations in the port county since 1953
Data Source	FEMA Historical Disaster Declarations FEMA Disaster Declarations Summary is a summarized dataset describing all federally declared disasters. This information begins with the first disaster declaration in 1953 and features all three disaster declaration types: major disaster, emergency and fire management assistance. Disaster housing assistance funds are available through FEMA's Individual and Household Program.
Example Values	**Providence, RI** (Providence County): $9.98 Million **Portland, ME** (Cumberland County): $0.0

Exposure	-100 ________________________[__]________________________________ 100
Sensitivity	-100 ________________________[__]________________________________ 100
Adaptive Capacity	-100 ________________________[__]________________________________ 100

Comments (Please also explain any extreme views)::

Projected Change in Days Above Baseline Extremely Hot Temperature

Shortname / Alias: Projected Change in Days Above Baseline Extremely Hot Temperature
10)

Indicator	**Projected Change in Days Above Baseline Extremely Hot Temperature**
Units	%
Description	The **percent change** from observed baseline of the **average number of days per year above baseline "Extremely Hot" temperature** projected for the end-of-century, downscaled to 12km resolution for the port location. "**Extremely Hot**" Day Temperature defined as 99th Percentile Temp
Data Source	US DOT CMIP Climate Data Processing Tool The purpose of the U.S. DOT CMIP Climate Data Processing Tool is to process readily available downscaled climate data at the local level into relevant statistics for transportation planners. This tool works with data from the U.S. Bureau of Reclamation's Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) website, available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. This website houses climate model data from phase 3 (CMIP3) and phase 5 (CMIP5) of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP). The Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool, developed by the U.S. Department of Transportation, will process raw climate model outputs from the World Climate Research Programme's CMIP3 and CMIP5 into relevant statistics for transportation planners. These statistics include changes in the frequency of very hot days and extreme precipitation events and other climate characteristics that may affect transportation infrastructure and services by the middle and end of the century.
Example Values	**Providence, RI**: 440 % increase **Portland, ME**: 220 % increase

Exposure	-100 ________________________[__]______________________________ 100
Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Projected Change in Number of Extremely Heavy Precipitation Events

Shortname / Alias: Projected Change in Number of Extremely Heavy Precipitation Events
11)

Indicator	**Projected Change in Number of Extremely Heavy Precipitation Events**
Units	%
Description	The **percent change** from observed baseline of the **average number of "Extremely Heavy" Precipitation Events** projected for the end-of-century, downscaled to 12km resolution for the port location. **"Extremely Heavy" Precipitation Events** >= (1.5 inches in 24 hrs)
Data Source	US DOT CMIP Climate Data Processing Tool The purpose of the U.S. DOT CMIP Climate Data Processing Tool is to process readily available downscaled climate data at the local level into relevant statistics for transportation planners. This tool works with data from the U.S. Bureau of Reclamation's Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) website, available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. This website houses climate model data from phase 3 (CMIP3) and phase 5 (CMIP5) of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP). The Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool, developed by the U.S. Department of Transportation, will process raw climate model outputs from the World Climate Research Programme's CMIP3 and CMIP5 into relevant statistics for transportation planners. These statistics include changes in the frequency of very hot days and extreme precipitation events and other climate characteristics that may affect transportation infrastructure and services by the middle and end of the century.
Example Values	**Providence, RI**: 122 % increase **Portland, ME**: 77 % increase

Exposure	-100 ________________________[__]_____________________________ 100

Sensitivity	-100 ______________________[__]__________________________ 100	
Adaptive Capacity	-100 ______________________[__]__________________________ 100	

Comments (Please also explain any extreme views)::

Number of Endangered Species

Shortname / Alias: Number of Endangered Species
12)

Indicator	**Number of Endangered Species**
Units	Number of Species
Description	Number of Threatened or Endangered Species found in port county
Data Source	U.S. Fish & Wildlife Service, Endangered Species An endangered species is an animal or plant species in danger of extinction throughout all or a significant portion of its range. A threatened species is an animal or plant species likely to become endangered within the foreseeable future throughout all or a significant portion of its range.
Example Values	**Providence, RI** (Providence County): 8 species **Portland, ME** (Cumberland County): 11 species

Exposure	-100 ______________________[__]__________________________ 100
Sensitivity	-100 ______________________[__]__________________________ 100
Adaptive Capacity	-100 ______________________[__]__________________________ 100

Comments (Please also explain any extreme views)::

Number of Critical Habitat Areas

Shortname / Alias: Number of Critical Habitat Areas
13)

Indicator	**Number Critical Habitat Areas**
Units	Number of Areas
Description	Number of Critical Habitat Areas within 50 miles of the port
Data Source	U.S. Fish & Wildlife Service, Critical Habitat Portal Critical Habitat for Threatened & Endangered Species: A specific geographic area(s) that contains features essential for the conservation of a threatened or endangered species and that may require special management and protection and that have been formally designated by rule published in the Federal Register. Critical Habitat Online Mapper
Example Values	**New Castle, DE**: 0 areas **Boston, MA**: 22 areas

Exposure	-100 ________________________[__]____________________________ 100
Sensitivity	-100 ________________________[__]____________________________ 100
Adaptive Capacity	-100 ________________________[__]____________________________ 100

Comments (Please also explain any extreme views)::

Environmental Sensitivity Index (ESI)

Shortname / Alias: Environmental Sensitivity Index (ESI)
14)

Indicator	**ESI**
Units	ESI Rank (1.00 - 10.83; the higher the number, the *more sensitive* the shoreline is to an oil spill)
Description	Environmental Sensitivity Index (ESI) shoreline sensitivity to an oil spill. Using the ranking for the most sensitive shoreline within the port
Data Source	NOAA Office of Response and Restoration: ESI Shoreline Rankings Environmental Sensitivity Index (ESI) maps use shoreline rankings to rate how sensitive an area of shoreline would be to an oil spill. The ranking scale goes from 1 to 10. A rank of 1 represents shorelines with the *least susceptibility to damage* by oiling. Examples include steep, exposed rocky cliffs and

	banks. The oil cannot penetrate into the rock and will be washed off quickly by the waves and tides. A rank of 10 represents shorelines *most likely to be damaged* by oiling. Examples include protected, vegetated wetlands, such as mangrove swamps and saltwater marshes. Oil in these areas will remain for a long period of time, penetrate deeply into the substrate, and inflict damage to many kinds of plants and animals.
Example Values	**Philadelphia, PA**: 1.25 **Albany, NY**: 9.25

Exposure	-100 _________________________[__]______________________________ 100
Sensitivity	-100 _________________________[__]______________________________ 100
Adaptive Capacity	-100 _________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Air Pollution Days

Shortname / Alias: Air Pollution Days
15)

Indicator	**Air Pollution Days**
Units	Number of days per year
Description	Number of days per year with Air Quality Index value greater than 100 for the port city, averaged over the past five years
Data Source	EPA Air Quality Index Report The Air Quality Index (AQI) provides information on pollutant concentrations of ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide. The AQI is based on pollutant concentration data measured by the State and Local Air Monitoring Stations network and by other special purpose monitors. For most pollutants in the index, the concentration is converted into index values between 0 and 500, “normalized” so that an index value of 100 represents the short-term, health-based standard for that pollutant as established by EPA (U.S. EPA, 1999).

	The higher the index value, the greater the level of air pollution and health risk. An index value of 500 reflects a risk of imminent and substantial endangerment of public health. The level of the pollutant with the highest index value is reported as the AQI level for that day. **An AQI value greater than 100 means that at least one criteria pollutant has reached levels at which people in sensitive groups may experience health effects**.
Example Values	**Philadelphia, PA**: 32 days per year **Albany, NY**: 4 days per year

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Number of Hazmat Incidents

Shortname / Alias: Number of Hazmat Incidents
16)

Indicator	**Number of Hazmat Incidents**
Units	Number of Incidents
Description	Number of Hazardous Materials Incidents in port city since 2007
Data Source	U.S. DOT Pipeline and Hazardous Materials Safety Administration: Incident Statistics Hazardous material means a substance or material that the Secretary of Transportation has determined is capable of posing an unreasonable risk to health, safety, and property when transported in commerce, and has designated as hazardous under section 5103 of Federal hazardous materials transportation law (49 U.S.C. 5103). Each person in physical possession of a hazardous material at the time that any of the following incidents occurs during transportation (including loading, unloading, and temporary storage) must submit

	a Hazardous Materials Incident Report on DOT Form F 5800.1 (01/2004) within 30 days of discovery of the incident: An unintentional release of a hazardous material or the discharge of any quantity of hazardous waste; A specification cargo tank with a capacity of 1,000 gallons or greater containing any hazardous material suffers structural damage to the lading retention system or damage that requires repair to a system intended to protect the lading retention system, even if there is no release of hazardous material; An undeclared hazardous material is discovered; or A fire, violent rupture, explosion or dangerous evolution of heat (***i.e.***, an amount of heat sufficient to be dangerous to packaging or personal safety to include charring of packaging, melting of packaging, scorching of packaging, or other evidence) occurs as a direct result of a battery or battery-powered device. Hazardous materials in various forms can cause death, serious injury, long-lasting health effects and damage to buildings, homes and other property. Many products containing hazardous chemicals are used and stored in homes routinely. These products are also shipped daily on the nation's highways, railroads, waterways and pipelines.
Example Values	**Philadelphia, PA**: 1,981 incidents **Camden, NJ**: 154 incidents

Exposure	-100 ________________________[__]______________________________ 100
Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Average Cost of Hazmat Incidents

Shortname / Alias: Average Cost of Hazmat Incidents
17)

Indicator	**Average Cost of Hazmat Incidents**
Units	$ USD
Description	Average cost per incident of total damage from the 10 most costly Hazardous Materials Incidents in the port city since 2007

Data Source	U.S. DOT Pipeline and Hazardous Materials Safety Administration: Incident Statistics **Total Amount of Damages**. This figure includes the cost of the material lost, carrier damage, property damage, response costs, and remediation clean-up costs. Hazardous material means a substance or material that the Secretary of Transportation has determined is capable of posing an unreasonable risk to health, safety, and property when transported in commerce, and has designated as hazardous under section 5103 of Federal hazardous materials transportation law (49 U.S.C. 5103). Each person in physical possession of a hazardous material at the time that any of the following incidents occurs during transportation (including loading, unloading, and temporary storage) must submit a Hazardous Materials Incident Report on DOT Form F 5800.1 (01/2004) within 30 days of discovery of the incident: An unintentional release of a hazardous material or the discharge of any quantity of hazardous waste; A specification cargo tank with a capacity of 1,000 gallons or greater containing any hazardous material suffers structural damage to the lading retention system or damage that requires repair to a system intended to protect the lading retention system, even if there is no release of hazardous material; An undeclared hazardous material is discovered; or A fire, violent rupture, explosion or dangerous evolution of heat (***i.e.***, an amount of heat sufficient to be dangerous to packaging or personal safety to include charring of packaging, melting of packaging, scorching of packaging, or other evidence) occurs as a direct result of a battery or battery-powered device. Hazardous materials in various forms can cause death, serious injury, long-lasting health effects and damage to buildings, homes and other property. Many products containing hazardous chemicals are used and stored in homes routinely. These products are also shipped daily on the nation's highways, railroads, waterways and pipelines.
Example Values	**Port of NY/NJ**: $2,877,763 per incident **Baltimore, MD**: $5,099,343 per incident

Exposure -100 ________________________[__]____________________________ 100

Sensitivity	-100 ________________________[__]______________________________ 100	
Adaptive Capacity	-100 ________________________[__]______________________________ 100	

Comments (Please also explain any extreme views)::

Percent of Bridges Deficient

Shortname / Alias: Percent of Bridges Deficient
18)

Indicator	**Percent of Bridges that are Deficient**
Units	%
Description	Percent of bridges in the port county that are structurally deficient or functionally obsolete
Data Source	U.S. DOT Federal Highway Administration: National Bridge Inventory: Deficient Bridges by County "Structurally deficient" means that the condition of the bridge includes a significant defect, which often means that speed or weight limits must be put on the bridge to ensure safety; a structural evaluation of 4 or lower qualifies a bridge as "structurally deficient". The designation can also apply if the approaches flood regularly. "Functionally obsolete" means that the design of a bridge is not suitable for its current use, such as lack of safety shoulders or the inability to handle current traffic volume, speed, size, or weight.
Example Values	**Philadelphia, PA** (Philadelphia County): 22.50 % **Baltimore, MD** (Baltimore-City County): 3.46 %

Exposure	-100 ________________________[__]______________________________ 100
Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Shelter Afforded

Shortname / Alias: Shelter Afforded
19)

Indicator	**Shelter**
Units	Excellent (5), Good (4), Fair (3), Poor (2), None (1)
Description	Shelter afforded from wind, sea, and swell
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). The **shelter afforded** from wind, sea, and swell, refers to the area where normal port operations are conducted, usually the wharf area. Shelter afforded the anchorage area is given for ports where cargo is handled by lighters.
Example Values	**New Haven, CT**: Good (4) **Boston, MA**: Excellent (5)

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Entrance Restrictions

Shortname / Alias: Entrance Restrictions
20)

Indicator	**Number of Entrance Restrictions**
Units	Number of entrance restrictions (Tide, Swell, Ice, Other, or None)
Description	Entrance Restrictions are natural factors restricting the entrance of vessels, such as ice, heavy swell, etc.

Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). **Entrance Restrictions** are natural factors restricting the entrance of vessels, such as ice, heavy swell, etc.
Example Values	**Port of NY/NJ**: 1 (Tide) **Boston, MA**: 0 (None)

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

---

20 Candidate Indicators Evaluated, Thank You!

21) You have evaluated 20 candidate indicators so far, thank you!

Though 14 additional candidate indicators remain to be evaluated, we understand your time is valuable.
If you prefer to skip ahead to the final section of this survey you may do so by selecting the appropriate choice below:
( ) Yes, I can evaluate the remaining 14 candidate indicators.
( ) No, I wish to skip ahead to the final section of this survey.

Overhead Limits

Shortname / Alias: Overhead Limits
22)

Indicator	**Overhead Limits**
Units	Yes=1, No=0

Description	Overhead Limitations: indicates that bridge and overhead power cables exist.
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). This entry is shown only to indicate that bridge and overhead power cables exist. It is advisable to refer to the chart for particulars.
Example Values	**Port of NY/NJ**: 1 (Yes) **Norfolk, VA:** 0 (No)

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Channel Depth

Shortname / Alias: Channel Depth
23)

Indicator	**Channel Depth**
Units	A (over 76 ft) to Q (0 – 5 ft) in 5-foot increments
Description	The controlling depth of the principal or deepest channel at chart datum
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). Depth information is generalized into 5-foot units, with the equivalents in meters, for the main channel, the main anchorage, and the principal cargo pier and/or oil terminal. Depths refer to chart datum. Depths are given in increments of 5 feet (1.5 meters) in order to lessen the number of changes when a small

	change in depth occurs. A depth of 31 feet (9.5 meters) would use letter "K," a depth of 36 feet (11.0 meters) would use "J," etc. The letter "K" means a least depth of 31 feet (9.5 meters) or greater, but not as great as 36 feet (11.0 meters). **CHANNEL (controlling)**—The controlling depth of the principal or deepest channel at chart datum is given. The channel selected should lead up to the anchorage if within the harbor or to the wharf/pier. If the channel depth decreases from the anchorage to the wharf/pier and cargo can be worked at the anchorage, then the depth leading to the anchorage is taken. Large ports may have sub-ports (smaller) which have their own number and entry in the World Port Index. The controlling depth of the channel should refer to a smaller channel (if present) leading from the main channel into the sub-port facilities and anchorages. Note.—The depth of small shoals is not a controlling depth unless it limits the passage of vessels. For example, if a channel is charted as having a depth of 39 feet (11.9 meters), but there are small shoals noted or charted with depths of 30 feet (9.1 meters), then the controlling depth is still 39 feet (11.9 meters) unless a ship with a draft of 39 feet (12 meters) cannot pass around the shoals and navigate the channel safely.
Example Values	**Wilmington, DE**: M (21 - 25 feet) **Norfolk, VA**: H (41 - 45 feet)

Exposure	-100 _________________________[__]______________________________ 100
Sensitivity	-100 _________________________[__]______________________________ 100
Adaptive Capacity	-100 _________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Pier Depth

Shortname / Alias: Pier Depth
24)

Indicator	**Pier Depth**
Units	A (over 76 ft) to Q (0 – 5 ft) in 5-foot increments
Description	The greatest depth at chart datum alongside the respective wharf/pier. If there is more than one wharf/pier, then the one which has greatest usable depth is shown.
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). Depth information is generalized into 5-foot units, with the equivalents in meters, for the main channel, the main anchorage, and the principal cargo pier and/or oil terminal. Depths refer to chart datum. Depths are given in increments of 5 feet (1.5 meters) in order to lessen the number of changes when a small change in depth occurs. A depth of 31 feet (9.5 meters) would use letter "K," a depth of 36 feet (11.0 meters) would use "J," etc. The letter "K" means a least depth of 31 feet (9.5 meters) or greater, but not as great as 36 feet (11.0 meters). **CARGO PIER/WHARF**—The greatest depth at chart datum alongside the respective wharf/pier is given. If there is more than one wharf/pier, then the one which has greatest usable depth is shown. For example, if there are three cargo/container piers with depths of 23 feet (7.0 meters), 33 feet (10.1 meters), and 43 feet (13.1 meters), then Code H, representing the deepest depth of 43 feet (13.1 meters), would be entered into the World Port Index.
Example Values	**Baltimore, MD**: G (46 -51 feet) **Paulsboro, NJ**: K (31 - 35 feet)

Exposure	-100 ________________________[__]____________________________ 100
Sensitivity	-100 ________________________[__]____________________________ 100
Adaptive Capacity	-100 ________________________[__]____________________________ 100

Comments (Please also explain any extreme views)::

Tide Range

Shortname / Alias: Tide Range
25)

Indicator	**Tide Range**
Units	Feet
Description	The mean tidal range at the port
Data Source	The National Geospatial-Intelligence Agency (NGA) World Port Index (Pub 150) contains the location and physical characteristics of, and the facilities and services offered by major ports and terminals world-wide (approximately 3700 entries). **TIDES**—The mean range in meters is normally given for all ports outside of United States (U.S.) jurisdiction, but the mean rise is substituted if range data is not available. The distinction between range and rise can be disregarded without affecting the general utility of this publication. Note.—The mean range is given in feet for all US ports and ports under U.S. jurisdiction (Trust Territories, etc).
Example Values	Baltimore, MD: 1 foot Paulsboro, NJ: 6 feet

Exposure	-100 ________________________[__]______________________________ 100
Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Marine Transportation Jobs

Shortname / Alias: Marine Transportation Jobs
26)

Indicator	**Marine Transportation Jobs**
Units	Number of jobs
Description	Number of Marine Transportation Jobs in the port county

Data Source	The NOAA Office for Coastal Management: Economics: National Ocean Watch (ENOW) ENOW Explorer contains annual time-series data for over 400 coastal counties, 30 coastal states, 8 regions, and the nation, derived from the Bureau of Labor Statistics and the Bureau of Economic Analysis. It describes six economic sectors that depend on the oceans and Great Lakes and measures four economic indicators: Establishments, Employment, Wages, and Gross Domestic Product (GDP). **Marine Transportation** includes deep sea freight, marine passenger transportation, pipeline transportation, marine transportation services, search and navigation equipment, and warehousing.
Example Values	**Providence, RI** (Providence County): 979 jobs in 2013 **Searsport, ME** (Waldo County): 54 jobs in 2013

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Marine Transportation GDP

Shortname / Alias: Marine Transportation GDP
27)

Indicator	**Marine Transportation GDP**
Units	$ Millions USD
Description	Gross Domestic Product of Marine Tranportation in the port county
Data Source	The NOAA Office for Coastal Management: Economics: National Ocean Watch (ENOW) ENOW Explorer contains annual time-series data for over 400 coastal counties, 30 coastal states, 8 regions, and the nation, derived from the Bureau of Labor Statistics and the Bureau of Economic Analysis. It describes six economic sectors that depend on the oceans and Great Lakes and measures four economic indicators: Establishments, Employment, Wages, and Gross Domestic Product (GDP).

	MARINE TRANSPORTATION Includes deep sea freight, marine passenger transportation, pipeline transportation, marine transportation services, search and navigation equipment, and warehousing. **GDP** represents the monetary value of all goods and services produced within a county's geographic borders over a specified period of time.
Example Values	**Providence, RI** (Providence County): $59.8 Million in 2013 **Searsport, ME** (Waldo County): $4.5 Million in 2013

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Population Change

Shortname / Alias: Population Change

28)

Indicator	**Population Change**
Units	%
Description	Rate of population change (from 2000-2010) in the port county, expressed as a percent change
Data Source	The NOAA Office for Coastal Management: Quick Report Tool for Socioeconomic Data provides easy access to economic and demographic data for multiple coastal jurisdictions. Information is derived from several key socioeconomic sources, including the U.S. Census Bureau, Bureau of Economic Analysis, Bureau of Labor Statistics, and Federal Emergency Management Agency's Hazus database. In 2010, 123.3 million people, or 39 percent of the nation's population lived in Coastal Shoreline Counties. Population growth in these counties occurred at a lower rate than the nation as a whole

	from 1970 to 2010. The population in Coastal Shoreline Counties increased by 34.8 million people, a 39 percent increase, while the nation's entire population increased by 52 percent over the same time period. Within the limited space of the nation's coast, population density far exceeds the nation as a whole, and this trend will continue into the future. This situation presents coastal managers with the challenge of protecting both coastal ecosystems from a growing population and protecting a growing population from coastal hazards. The concentration of people impacts the integrity of coastal ecosystems, and at the same time, the lives and livelihoods of some of these residents and visitors can be at risk from natural processes at the coast – such as hurricanes, erosion, and sea level rise.
Example Values	**Baltimore, MD** (Baltimore-City County): -4.64 % *decrease* **Gloucester, NJ** (Gloucester County): +13.20 % *increase*

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Population Inside Floodplain

Shortname / Alias: Population Inside Floodplain
29)

Indicator	**Population Inside Floodplain**
Units	%
Description	Percent of the port county population living inside the FEMA Floodplain
Data Source	NOAA Office for Coastal Management: Coastal County Snapshots; based on 2009-2013 American Community Survey 5-year Summary File data **People + Floodplains = Not Good**

	The more homes and people located in a floodplain, the greater the potential for harm from flooding. Impacts are likely to be even greater when additional risk factors (age, income, capabilities) are involved, since people at greatest flood risk may have difficulty evacuating or taking action to reduce potential damage. **Floodplain = 100 Year Flood Elevation = Base Flood Elevation (BFE):** The elevation shown on the Flood Insurance Rate Map (FIRM) that indicates the water surface elevation resulting from a flood that has a 1% chance of equaling or exceeding that level in any given year.
Example Values	**Wilmington, DE** (New Castle County): 8 % **Norfolk, VA** (Norfolk County): 18 %

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

SoVI® Social Vulnerability Score

Shortname / Alias: SoVI Social Vulnerability Score
30)

Indicator	**SoVI® Score**
Units	The SoVI® Social Vulnerability score is classified using standard deviations. Social vulnerability scores that are greater than 2 standard deviations above the mean are considered the most socially vulnerable, and scores below 2 standard deviations less than the mean are the least vulnerable.
Description	The SoVI® Social Vulnerability score of the port county
Data Source	University of South Carolina Hazards and Vulnerability Research Institute: Social Vulnerability Index Data **Social Vulnerability** The hazards-of-place model (Cutter 1996) combines the biophysical vulnerability (physical characteristics of hazards and environment)

	and social vulnerability to determine an overall place vulnerability. Social vulnerability is represented as the social, economic, demographic, and housing characteristics that influence a community's ability to respond to, cope with, recover from, and adapt to environmental hazards. **The Social Vulnerability Index (SoVI®)** County-level socioeconomic and demographic data were used to construct an index of social vulnerability to environmental hazards, called the Social Vulnerability Index (SoVI®) for the United States **based on data collected from 2005 to 2009**. The majority of the sources used by the Hazards Research Lab are obtained from the five-year American Community Survey estimates compiled by the U.S. Census Bureau. After obtaining the relevant data, a principle components analysis is used to reduce the data into set of components. Slight adjustments are made to the components to ensure that the sign of the component loadings coincide with each individual population characteristic's influence on vulnerability. All components are added together to determine a numerical value that represents the social vulnerability for each county.
Example Values	**Philadelphia, PA** (Philadelphia County): 3.418284 (High) **Norfolk, VA** (Norfolk County): -0.207217 (Medium)

Exposure	-100 _________________________[__]______________________________ 100
Sensitivity	-100 _________________________[__]______________________________ 100
Adaptive Capacity	-100 _________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Vessel Capacity

Shortname / Alias: Vessel Capacity
31)

Indicator	**Vessel Capacity**

Units	(Number of Vessel Calls) x (Vessel Deadweight Tonnage)
Description	Annual vessel capacity at the port
Data Source	The U.S. DOT Maritime Administration: Vessel Calls in U.S. Ports, Selected Terminals and Lightering Areas is a report containing a calculation of vessel calls for privately-owned, oceangoing merchant vessels of all flags of registries over 1,000 gross tons (GT) calling at ports and selected ports/terminals within the contiguous United States, Hawaii, Alaska, Guam and Puerto Rico. Vessel Types: MARAD uses six vessel categories in this report: (1) Containerships, (2) Tanker, (3) Dry Bulk, (4) General Cargo, (5) Roll On – Roll Off (Ro-Ro), and (6) Gas. **Calls** are calculated by how many times a vessel arrived at a port, facility or terminal. This number may include berth shifts, movement to and from an anchorage while awaiting cargo and may also include other activities related to vessel, port or terminal operations. Calls do not include vessels arriving at a designated anchorage area. In addition, vessels calling on a port may not necessary be engaged in onloading/offloading of cargoes. **Capacity** is calculated as the sum of vessel calls weighted by vessel deadweight (DWT). DWT is defined as the total weight (metric tons) of cargo, fuel, fresh water, stores and crew which a ship can carry when immersed to its load line.
Example Values	**Albany, NY**: 223,943,760 in 2015 **Fall River, MA**: 14,707,900 in 2015

Exposure	-100 ________________________[__]_____________________________ 100
Sensitivity	-100 ________________________[__]_____________________________ 100
Adaptive Capacity	-100 ________________________[__]_____________________________ 100

Comments (Please also explain any extreme views)::

Tanker Capacity

Shortname / Alias: Tanker Capacity

32)

Indicator	**Tanker Capacity**
Units	(Number of Tanker Calls) x (Vessel Deadweight Tonnage)
Description	Annual tanker capacity at the port **Tankers** – CO2, Chemical, Chemical/Oil, Wine, Vegetable Oil, Edible Oil, Beer, Latex, Crude Oil, Oil Products, Bitumen, Coal/Oil, Water, Fruit Juice, Molasses, Glue, Alcohol, and Caprolacatam.
Data Source	The U.S. DOT Maritime Administration: Vessel Calls in U.S. Ports, Selected Terminals and Lightering Areas is a report containing a calculation of vessel calls for privately-owned, oceangoing merchant vessels of all flags of registries over 1,000 gross tons (GT) calling at ports and selected ports/terminals within the contiguous United States, Hawaii, Alaska, Guam and Puerto Rico. Vessel Types: MARAD uses six vessel categories in this report: (1) Containerships, (2) Tanker, (3) Dry Bulk, (4) General Cargo, (5) Roll On – Roll Off (Ro-Ro), and (6) Gas. **Calls** are calculated by how many times a vessel arrived at a port, facility or terminal. This number may include berth shifts, movement to and from an anchorage while awaiting cargo and may also include other activities related to vessel, port or terminal operations. Calls do not include vessels arriving at a designated anchorage area. In addition, vessels calling on a port may not necessary be engaged in onloading/offloading of cargoes. **Capacity** is calculated as the sum of vessel calls weighted by vessel deadweight (DWT). DWT is defined as the total weight (metric tons) of cargo, fuel, fresh water, stores and crew which a ship can carry when immersed to its load line.
Example Values	**Albany, NY**: 21,437,035 in 2015 **Fall River, MA**: 0 in 2015

Exposure	-100 _________________________[__]______________________________ 100
Sensitivity	-100 _________________________[__]______________________________ 100
Adaptive Capacity	-100 _________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Gas Carrier Capacity

Shortname / Alias: Gas Carrier Capacity
33)

Indicator	**Gas Capacity**
Units	(Number of Gas Carrier Calls) x (Vessel Deadweight Tonnage)
Description	Annual gas carrier capacity at the port **Gas** – Liquefied Petroleum and Liquefied Natural Gas Carriers
Data Source	The U.S. DOT Maritime Administration: Vessel Calls in U.S. Ports, Selected Terminals and Lightering Areas is a report containing a calculation of vessel calls for privately-owned, oceangoing merchant vessels of all flags of registries over 1,000 gross tons (GT) calling at ports and selected ports/terminals within the contiguous United States, Hawaii, Alaska, Guam and Puerto Rico. Vessel Types: MARAD uses six vessel categories in this report: (1) Containerships, (2) Tanker, (3) Dry Bulk, (4) General Cargo, (5) Roll On – Roll Off (Ro-Ro), and (6) Gas. **Calls** are calculated by how many times a vessel arrived at a port, facility or terminal. This number may include berth shifts, movement to and from an anchorage while awaiting cargo and may also include other activities related to vessel, port or terminal operations. Calls do not include vessels arriving at a designated anchorage area. In addition, vessels calling on a port may not necessary be engaged in onloading/offloading of cargoes. **Capacity** is calculated as the sum of vessel calls weighted by vessel deadweight (DWT). DWT is defined as the total weight (metric tons) of cargo, fuel, fresh water, stores and crew which a ship can carry when immersed to its load line.
Example Values	**Boston, MA**: 284,802 in 2015 **Port of NY/NJ**: 6,424 in 2015

Exposure -100 ________________________[__]_____________________________ 100

Sensitivity -100 ________________________[__]_____________________________ 100

Adaptive Capacity	-100 ______________________[__]___________________________ 100

Comments (Please also explain any extreme views)::

Containership Capacity

Shortname / Alias: Containership Capacity
34)

Indicator	**Containership Capacity**
Units	(Number of Containership Calls) x (Vessel Deadweight Tonnage)
Description	Annual containership capacity at the port **Containership** – Container Ship and Passenger/Container Ships
Data Source	The U.S. DOT Maritime Administration: Vessel Calls in U.S. Ports, Selected Terminals and Lightering Areas is a report containing a calculation of vessel calls for privately-owned, oceangoing merchant vessels of all flags of registries over 1,000 gross tons (GT) calling at ports and selected ports/terminals within the contiguous United States, Hawaii, Alaska, Guam and Puerto Rico. Vessel Types: MARAD uses six vessel categories in this report: (1) Containerships, (2) Tanker, (3) Dry Bulk, (4) General Cargo, (5) Roll On – Roll Off (Ro-Ro), and (6) Gas. **Calls** are calculated by how many times a vessel arrived at a port, facility or terminal. This number may include berth shifts, movement to and from an anchorage while awaiting cargo and may also include other activities related to vessel, port or terminal operations. Calls do not include vessels arriving at a designated anchorage area. In addition, vessels calling on a port may not necessary be engaged in onloading/offloading of cargoes. **Capacity** is calculated as the sum of vessel calls weighted by vessel deadweight (DWT). DWT is defined as the total weight (metric tons) of cargo, fuel, fresh water, stores and crew which a ship can carry when immersed to its load line.
Example Values	**Hampton Roads, VA**: 104,862,259,278 in 2015 **Providence, RI**: 0 in 2015

Exposure	-100 ______________________[__]___________________________ 100

Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Tonnage

Shortname / Alias: Tonnage
35)

Indicator	**Tonnage**
Units	Short Tons
Description	Total Annual Throughput at the port
Data Source	USACE Navigation Data Center: Principal Ports of the United States The Principal Port file contains USACE port codes, geographic locations (longitude, latitude), names, and commodity tonnage summaries (total tons, domestic, foreign, imports and exports) for Principal USACE Ports. The ports are politically defined by port limits or Corps projects, excluding non-Corps projects not authorized for publication. The determination for the published Principal Ports is based upon the total tonnage for the port for the particular year; therefore the top 150 list can vary from year to year.
Example Values	**Port of NY/NJ**: 126,690,317 tons in 2015 **Providence, RI**: 8,043,051 tons in 2015

Exposure	-100 ________________________[__]______________________________ 100
Sensitivity	-100 ________________________[__]______________________________ 100
Adaptive Capacity	-100 ________________________[__]______________________________ 100

Comments (Please also explain any extreme views)::

Most Vulnerable Ports

Shortname / Alias: Most Vulnerable Ports
Where are the highest levels of climate vulnerabilityThe degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity among the principal ports of the USACEUnited States Army Corps of Engineers North Atlantic Division?

Based on your present knowledge and opinion,
Please select from the following list and arrange the **5 MOST VULNERABLE** ports in **descending** order from highest to lowest level of relative climate vulnerabilityThe degree to which a system is susceptible to, and unable to cope with, adverse effects of

climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Please rank *at least* 5 ports - you are encouraged to rank more

________Searsport, ME
________Portland, ME
________Portsmouth, NH
________Albany, NY
________Boston, MA
________Providence, RI
________Fall River, MA
________New Haven, CT
________Bridgeport, CT
________Port Jefferson, NY
________Hempstead, NY
________New York, NY and NJ
________Penn Manor, PA
________Camden-Gloucester, NJ
________Philadelphia, PA
________Paulsboro, NJ
________Chester, PA
________Marcus Hook, PA
________Wilmington, DE
________New Castle, DE
________Baltimore, MD
________Hopewell, VA
________Virginia, VA, Port of
Comments (Please also explain any extreme views)::

Least Vulnerable Ports

Shortname / Alias: Least Vulnerable Ports
Where are the lowest levels of climate vulnerabilityThe degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity among the principal ports of the USACEUnited States Army Corps of Engineers North Atlantic Division?

Based on your present knowledge and opinion,
Please select from the following list and arrange the **5 LEAST VULNERABLE** ports in **ascending** order from lowest to highest level of relative climate vulnerabilityThe degree to which a system is susceptible to, and unable to cope with, adverse effects of

climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Please rank *at least* 5 ports - you are encouraged to rank more

________Searsport, ME
________Portland, ME
________Portsmouth, NH
________Albany, NY
________Boston, MA
________Providence, RI
________Fall River, MA
________New Haven, CT
________Bridgeport, CT
________Port Jefferson, NY
________Hempstead, NY
________New York, NY and NJ
________Penn Manor, PA
________Camden-Gloucester, NJ
________Philadelphia, PA
________Paulsboro, NJ
________Chester, PA
________Marcus Hook, PA
________Wilmington, DE
________New Castle, DE
________Baltimore, MD
________Hopewell, VA
________Virginia, VA, Port of
Comments (Please also explain any extreme views):

Help suggest additional candidate indicators

Shortname / Alias: Help suggest additional candidate indicators
Are there better indicators out there?

Can you suggest additional candidate indicators (Measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly, adequately measured) of seaport climate vulnerability (The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity)?*
( ) Yes, I have additional candidate indicators to suggest.
( ) No, I have no indicators to suggest.

Manuscript 3

AHP Group Results

Table 17 AHP decision hierarchy with consolidated priorities

Decision Hierarchy			
Level 0	**Level 1**	**Level 2**	**Global Priorities**
Seaport Climate Vulnerability	Adaptive Capacity 0.390		39.0%
	Exposure 0.394	Sea Level Trend 0.180	7.1%
		Number of Disasters 0.200	7.9%
		Number of Cyclones 0.143	5.6%
		Number of Storm Events 0.196	7.7%
		Hundred Year High Water 0.163	6.4%
		Projected Change in Extreme Precip 0.118	4.6%
	Sensitivity 0.216	Population Inside Floodplain 0.229	4.9%
		Average Cost of Storm Events 0.210	4.5%
		Number Critical Habitat Areas 0.104	2.3%
		SoVI Social Vulnerability Score 0.213	4.6%
		Population Change 0.119	2.6%
		Environmental Sensitivity Index ESI 0.125	2.7%
			1.0

AHP Node: Seaport Climate Vulnerability

CR: 0.1% - AHP group consensus: 50.1% low

Table 18 AHP decision hierarchy with consolidated priorities for node: Vulnerability

	Category	**Priority**	**Rank**
1	Adaptive Capacity	39.0%	2
2	Exposure	39.4%	1
3	Sensitivity	21.6%	3

AHP Node: Exposure

CR: 0.3% - AHP group consensus: 53.6% low

Table 19 AHP decision hierarchy with consolidated priorities for node: Exposure

	Category	Priority	Rank
1	Sea Level Trend	18.0%	3
2	Number of Disasters	20.0%	1
3	Number of Cyclones	14.3%	5
4	Number of Storm Events	19.6%	2
5	Hundred Year High Water	16.3%	4
6	Projected Change in Extreme Precip	11.8%	6

AHP Node: Sensitivity

CR: 0.5% - AHP group consensus: 61.1% low

Table 20 AHP decision hierarchy with consolidated priorities for node: Sensitivity

	Category	Priority	Rank
1	Population Inside Floodplain	22.9%	1
2	Average Cost of Storm Events	21.0%	3
3	Number Critical Habitat Areas	10.4%	6
4	SoVI Social Vulnerability Score	21.3%	2
5	Population Change	11.9%	5
6	Environmental Sensitivity Index ESI	12.5%	4