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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. Identification of indicators is often a first step in the development of coastal vulnerability indices (CVI). To advance IBVA for the seaport sector, researchers investigated the sufficiency of and elicited expert-evaluation of publicly available open-data to serve as indicators of climate and extreme-weather vulnerability for 22 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? 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 (VAS) 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 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 Words: indicator, seaport, climate vulnerability, mind map, visual analogue scale, expert elicitation

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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; McIntosh and Becker, 2017). Indicator-based assessment methods are employed when concepts to be measured are theoretical and not directly quantifiable. While the concepts of resilience and vulnerability are not directly measurable, such concepts may be operationalized by "mapping them to functions of observable variables called indicators" (Gallopin, 1997; Hinkel, 2011; 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. The comparative assessment of coastal vulnerability often leads to the development of coastal vulnerability indices (CVI), and the identification of indicators is commonly a first step in the development of CVI. Indicators are often combined into multidimensional tools known as indicator-based composite indices 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). Such 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. To advance IBVA for the seaport sector, researchers investigated the sufficiency and elicited expert-evaluation of publicly available open-data, generally collected for other purposes, to serve as indicators of climate and extreme-weather vulnerability for 22 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 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.

While CVI approaches offer advantages of comparability between disparate systems and allow for insightful disaggregation of components of vulnerability, indices have also been the subject of criticism. One critique of indices and CVI is that the set of indicators they use may not be equally applicable to all of the sites that will be assessed, since different sites have different characteristics, therefore the mechanisms and drivers of those vulnerabilities may not withstand such a standardized assessment approach (Bakkensen et al., 2016). While recognizing the limitations of CVI, this study proposed that indicators, nonetheless, are worth developing for their ability to provide high level insight into the comparative vulnerabilities, and that more detailed, bespoke risk assessments should follow.

Why Seaports?

Sitting on the front lines of the climate-change challenge, seaports provide an example of large-scale infrastructure that is indispensable to both global commerce and national security yet is restricted to the hazardous land-sea interface. Seaports face impacts from today's weather extremes as well as impacts from projected changes in temperature extremes, frequency and intensity of storm events, sea level, wave runup, ocean chemistry, tidal regime, frequency and

intensity of precipitation events, wind, and sedimentation rates (Koppe et al., 2012). Most previous efforts at assessing vulnerability, resilience, and risk due to climate change at seaports, have been limited (McIntosh and Becker, 2017) either by the scope of the assessment focusing on exposure only (Hanson et al., 2010; Klein et al., 2003; Nicholls et al., 2008), or by the scale of the assessment focusing on a single port (with some examples being case studies (Chhetri et al., 2014; Cox et al., 2013; Koppe, 2012; Messner et al., 2013; USDOT, 2014) and other examples being self-assessment tools (Morris and Sempier, 2016; NOAA OCM, 2015; Semppier et al., 2010)), thus making comparisons of climate vulnerability among ports difficult. Climate impact, adaptation, and vulnerability (CIAV)[1] decisions at the multi-port (regional or national) scale may be supported by information products that allow decision makers to compare driving mechanisms of climate change among ports.

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 multi-port scale, port decision-makers may question which ports in a certain regional jurisdiction are the most vulnerable and hence the most in need of urgent attention. As climate adaptation decisions often involve conflicting priorities and limited resources, data-driven, standardized indicators can help bring objectivity into the process.

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 sufficiency of and elicits expert-evaluation of publicly available open-data[2] to

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[1] 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.

[2] 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.

serve as indicators of climate and extreme-weather vulnerability for 22 major seaports in the North East United States (Figure 1). This investigation seeks to examine the sufficiency of the current state of data reporting for and about the seaport sector to determine how able 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[3] 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 *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

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[3] 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.

vulnerability to, "the propensity or predisposition to be adversely affected," [p. 5] (IPCC, 2014a) however, the three components of vulnerability remain relevant. In a 2012 report on seaports and climate change, the International Association of Ports and Harbors[4] (IAPH) defines seaport vulnerability using the same three components, i.e., *exposure*, *sensitivity*, and *adaptation capacity* (Koppe, 2012).

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)

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)

Related to vulnerability, *risk* measures the magnitude of loss within the probability of an uncertain outcome (IPCC, 2014b). Risk can be modeled quantitatively as *Risk = p(L)*, where *L* is potential loss and *p* the probability of occurrence, however, a challenge of assessing risk lies in the speculative nature of both *L* and *p*, as well as the difficulty of measuring them in the context of climate-risk. 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

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

probability of occurrence. By measuring vulnerability, then, this work aims to inform the measurement of the magnitude of a risk, but not its probability.

The concept of *Resilience,* also often associated with the above, yet commonly used in a more positive context 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). Resilience and vulnerability are sometimes taken as is polar opposites (Gallopín, 2006), however, resilience often describes a process that includes a timeframe prior to a loss-incurring event, and also includes temporal periods during and after the impact. Resilience, then may be considered a concept more expansive than, and even encompassing vulnerability. Accordingly, resilience is ultimately the goal, and assessing resilience involves assessments of risk along with recovery and adaptation, while assessing vulnerability is part of risk assessment (Linkov et al., 2018; Linkov and Trump, 2019).

Methodology

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

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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 defines climate change vulnerability in terms of three components: exposure, sensitivity, and adaptive capacity. In this research, an initial 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.

Researchers aimed to refine a set of high-level indicators of seaport climate and extreme weather vulnerability from available open-data and then to elicit expert assessment of these indicators' ability to differentiate ports within a region in terms of relative climate vulnerabilities. To accomplish this, researchers developed a visual analogue scale[5] (VAS) survey instrument for expert-evaluation of selected candidate indicators of seaport vulnerability to climate and extreme weather impacts for the 22 medium and high-use ports of the USACE North Atlantic Division (Figure 1).

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

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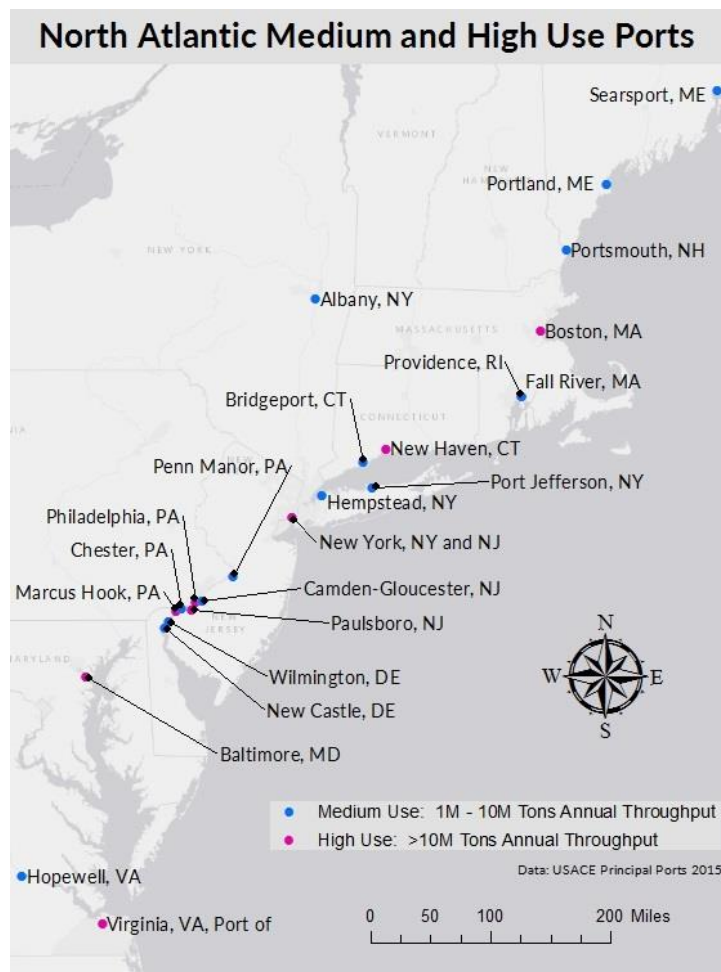
Figure 1 Study Area Ports

Rather than taking a purely theoretical approach to developing indicators, e.g., that used in the development of the Social Vulnerability Index (SoVI) (Cutter et al., 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 et al., 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).

For evaluating candidate indicators of seaport vulnerability, this research was designed to take a holistic approach to vulnerability assessment by considering impacts that extend

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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 3. 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*[6] and nine *high-use*[7] ports found in the United States Army Corp of Engineers (USACE) North Atlantic Division[8] (CENAD) as the

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[6] USACE definition of medium use port: annual throughput between 1M and 10M tons
[7] USACE definition of high use port: annual throughput greater than 10M tons
[8] The North Atlantic Division is one of nine USACE divisions and encompasses the U.S. Eastern Seaboard from Virginia to Maine USACE, 2014. USACE Civil Works Division Boundaries. U.S. Army Corps of Engineers, http://geoplatform.usace.army.mil/home/item.html?id=c3695249909c45a2b2e2c3993aff3edb, pp. Polygons showing USACE Civil Works Division boundaries. This dataset was digitized from the NRCS Watershed

sample population for which to develop indicators (Figure 1). 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.

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 (CMTS, 2015; Janssen et al., 2012). Only those indicators with data available for at least 16 of the study's sample of 22 ports were considered further. 108 candidate indicators of seaport climate-exposure, sensitivity, and adaptive capacity were compiled during this first step, as well as each

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Boundary Dataset (WBD). Where districts follow administrative boundaries, such as County and State lines, National Atlas and Census datasets were used. USACE District GIS POCs also submitted data to incorporate into this dataset. This dataset has been dissolved based on Division..

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 et al., 2010), e.g., *population inside floodplain*, and those that measure vulnerability via a characteristic of the port itself, e.g., *containership capacity*. In the hazards of place model of vulnerability, the various elements that constitute vulnerability interact to produce the vulnerability of specific places and the people or infrastructure that reside there (Cutter, 1996). Of the 108 candidate indicators originally compiled, 48 (24 place-based and 24 port-specific) were found to have sufficient data available for the 22 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). Researchers then held a workshop with nine members of the Resilience Integrated Action Team[9] (RIAT) of the United States Committee on the Marine Transportation System[10] (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 2).

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[9] 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.

[10] 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).

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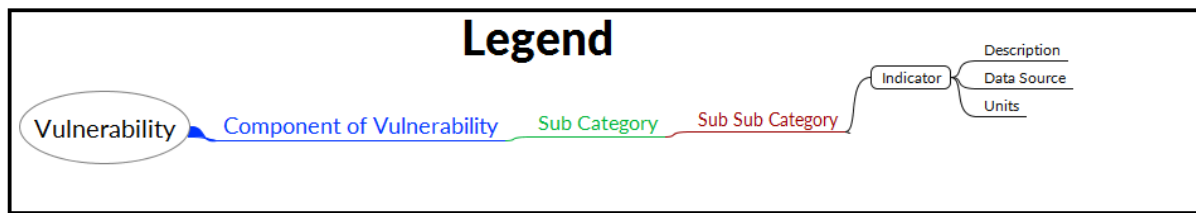

Figure 2 Mind map legend showing how each indicator was hierarchically mapped to a component of vulnerability. The mind map also listed a description, data source, and units for each indicator.

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. As a result of the mind mapping exercise, 34 candidate indicators were selected to be evaluated via the VAS expert survey: 14 port-specific indicators and 20 place-based indicators. Table 1 lists the 34 selected candidate indicators alphabetically, along with their descriptions, units, and data sources. 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 1 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

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Indicator	Description	Units	Data Source
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
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)

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Indicator	Description	Units	Data Source
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 Visual Analogue Scale 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 et al., 1975; Hasson et al., 2000; Keeney et al., 2006; Okoli and Pawlowski, 2004). Candidates for the port-expert group were selected according to recommended best practices in expert selection developed by (Delbecq et al., 1975) and expanded by (Okoli and Pawlowski, 2004). Researchers first prepared a knowledge resource nomination worksheet (KRNW) (Table 2) 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.

Table 2 Knowledge Resource Nomination Worksheet (KRNW) modified from (Okoli and Pawlowski 2004).

Disciplines or skills	Organizations	Related literature

• Academics
   o from review of literature
• Practitioners
   o from professional societies
• Government
   o Federal
   o 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)
	   o 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)
	   o Engineer Research and Development Center (ERDC)
	   o Institute for Water Resources (IWR)
		Academic literature:
		• CCVA
		• Hazard risk assessment
		• Seaport related research
		• Indicator development research
		
		Grey literature:
		• Trade journals
		• White papers
		• Non-academic port studies

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

Disciplines or skills	Organizations	Related literature

	• 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)	

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 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).

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

Step 4: Expert-Elicitation VAS Survey

The objective of this survey was to measure port-expert perceptions 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 3). 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 3). 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.
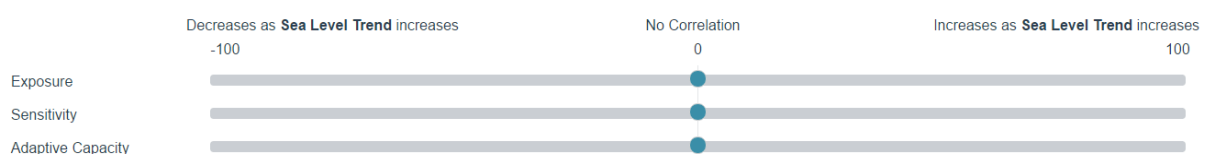
Figure 3 VAS slider for indicating expert-perceived correlation between a candidate indicator and each of the components of vulnerability.

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

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

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 3). 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 4 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 4). Also of note in Figure 4 is the low level of perceived correlation with adaptive capacity (pink) compared to exposure (green) and sensitivity (blue).
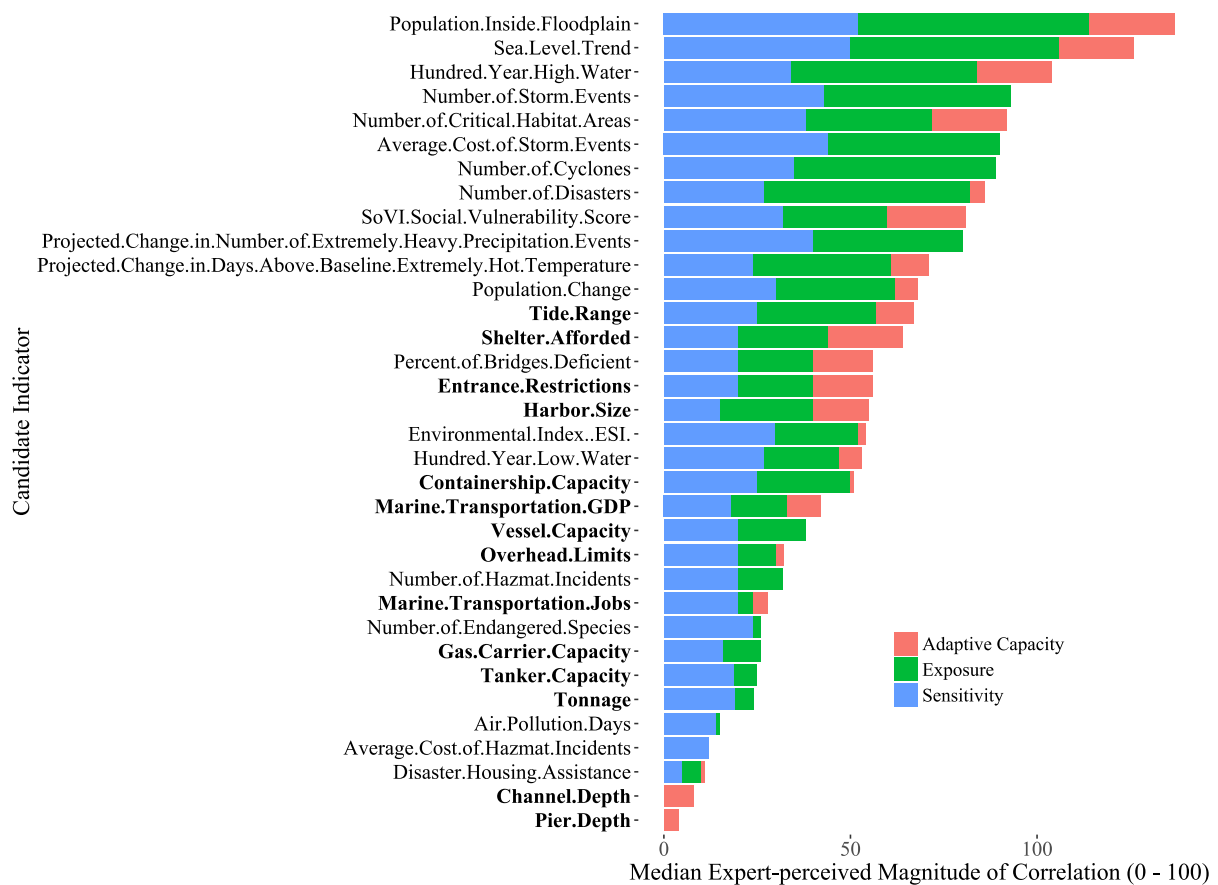
*Figure 4 Candidate indicators of seaport vulnerability to climate and extreme weather, sorted by total median expert-perceived magnitude of correlation with each of the three components of vulnerability. Port-specific candidate indicators in **bold**.*

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 4, 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

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

ports. Figure 5, Figure 6, and Figure 7 show the top 15 scoring indicators in descending order for correlation with exposure, sensitivity, and adaptive capacity, respectively.

In Figure 5, 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.
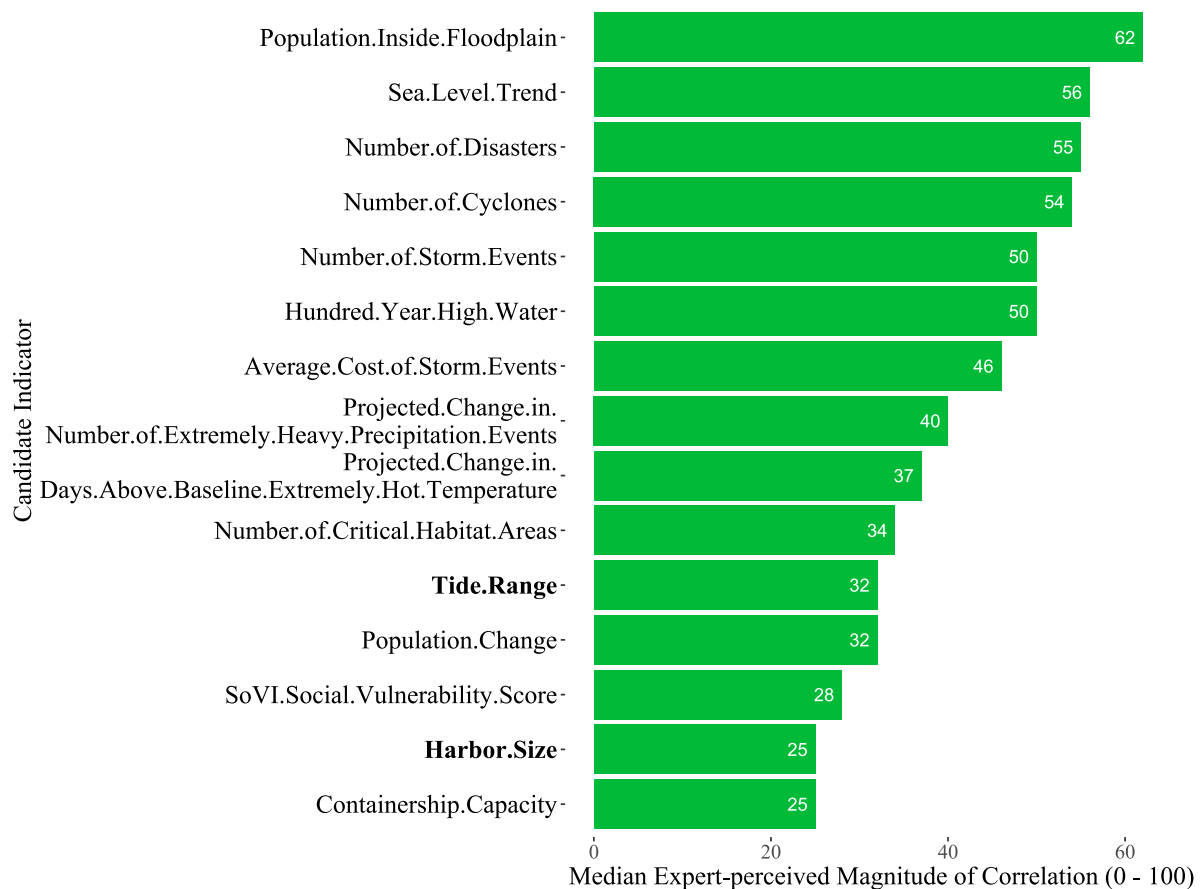
Figure 5 Top 15 candidate indicators for exposure*. In descending order of median expert-perceived magnitude of correlation with seaport* exposure *to climate and extreme weather impacts. Port-specific candidate indicators in* **bold***.*

In Figure 6, 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.

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.
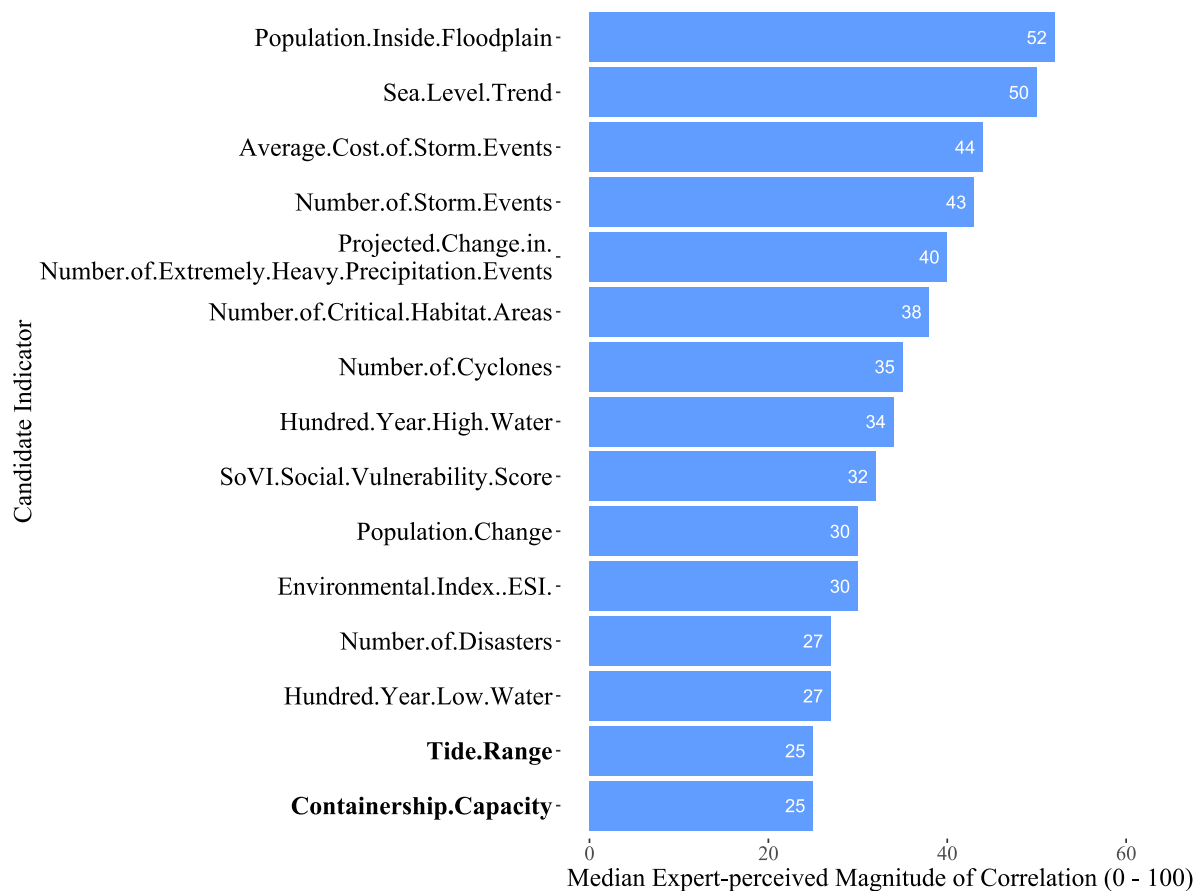
Figure 6 Top 15 candidate indicators for sensitivity*, sorted by median expert-perceived magnitude of correlation with seaport* sensitivity *to climate and extreme weather impacts. Port-specific candidate indicators in **bold***

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 7), 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 7), significantly lower than that for exposure (Figure 5) and sensitivity (Figure 6). 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 7 representing port-specific indicators.
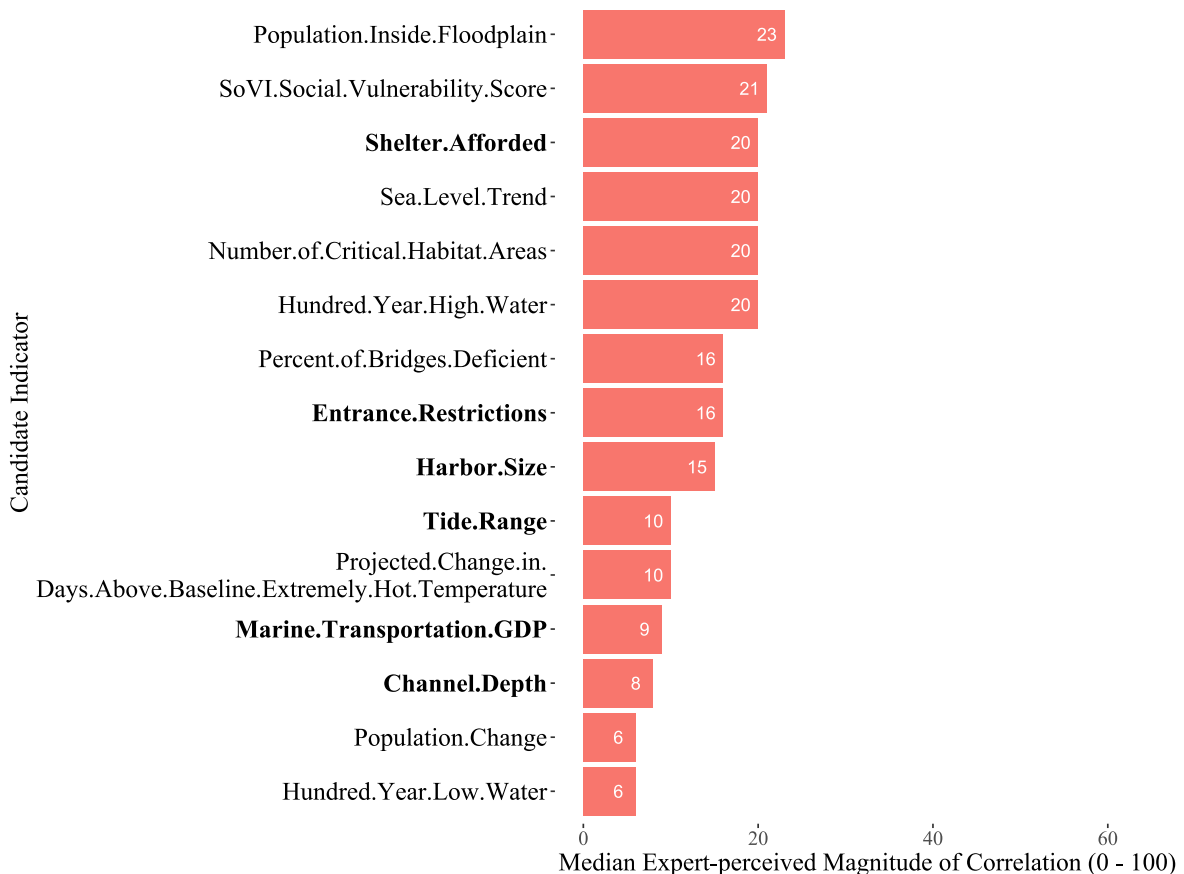
Figure 7 Top 15 candidate indicators for adaptive capacity*, sorted by median expert-perceived magnitude of correlation with seaport adaptive capacity to climate and extreme weather impacts. Port-specific candidate indicators in **bold**. Overall, experts found significantly lower correlation with adaptive capacity than with the other two components of vulnerability.*

Because the VAS expert group was disproportionately represented by those with Federal affiliations, 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 found more and higher levels of correlation with adaptive capacity than did other types of expert. This may be due to

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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 3) 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.

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

Table 3 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 22 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 first-pass

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of open-data 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.

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.

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

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 5) and with sensitivity (Figure 6), 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 7). 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

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

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. Accordingly, comparisons of responses by expert-affiliation suffer from this small sample size. A larger sample size of experts may have improved the distribution of experts among the expert categories. Further, political affiliation, gender, age, or other demographics of respondents may have influenced their responses, though, this was not catalogued during this exercise. 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 et al., 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 et al., 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 3, exploring

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

non-open or proprietary sources of data for those indicators identified during the literature review but lacking available open data sources, or synthesizing novel indicators from combinations of available data.

Conclusion

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. This method can be reproduced with relatively low cost using online tools for the VAS evaluation. While the mind mapping exercise to refine the initial set of candidate indicators would be difficult to reproduce using a remote-only approach, this can be accomplished with a smaller, more select group of experts or by the research team without the necessity of gathering the larger expert group involved with the VAS evaluation. This type of approach to indicator evaluation could be reproduced in other countries or regions by seeking experts with more local expertise and tailoring the expert elicitation to the region of interest.

Expert-evaluation of 34 candidate indicators in the context of a sample of 22 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 that while open-data can be developed into expert-supported indicators of seaport climate *exposure* and *sensitivity*, more

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.

open reporting and sharing of port-specific data within the maritime transportation sector will

be necessary before IBVA and CVI will become feasible for seaports, and specifically further

work on the development of indicators of adaptive capacity will be needed.

Acknowledgements

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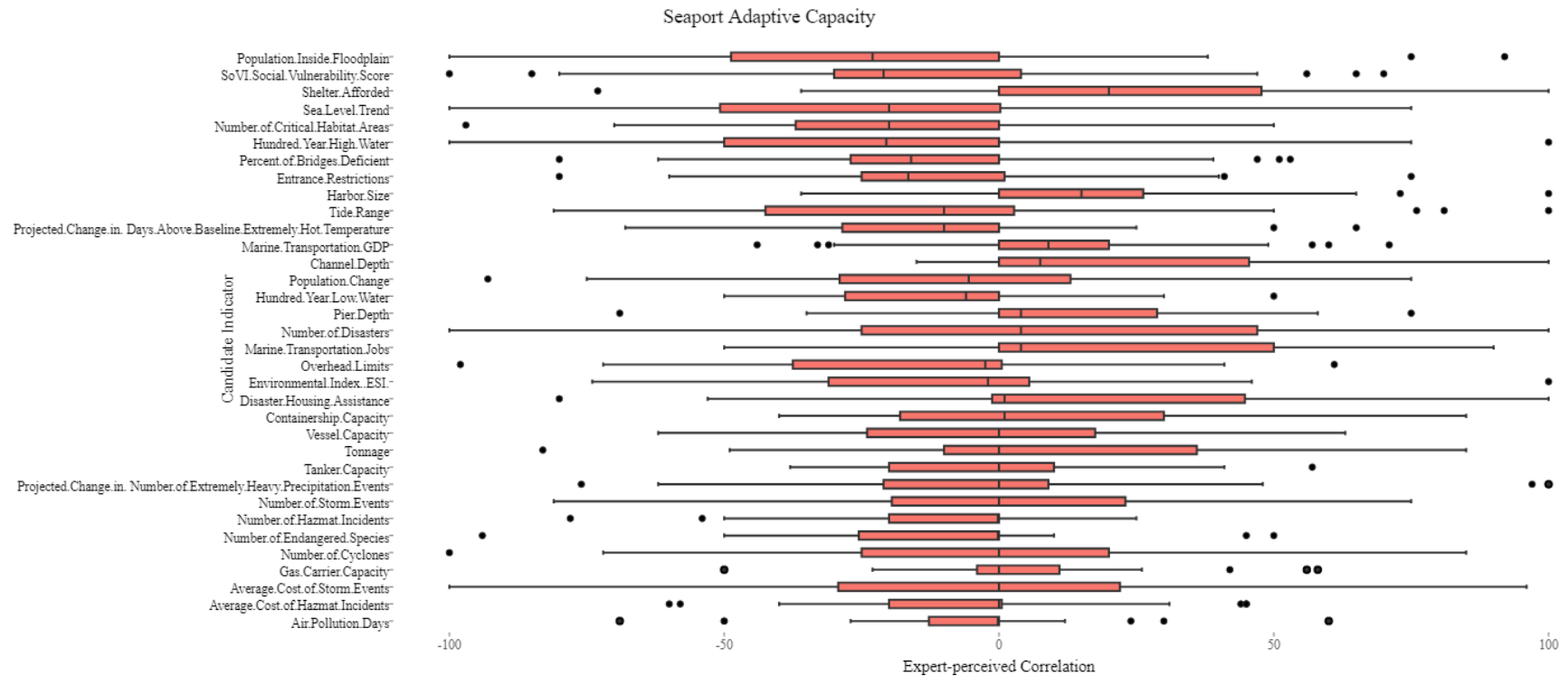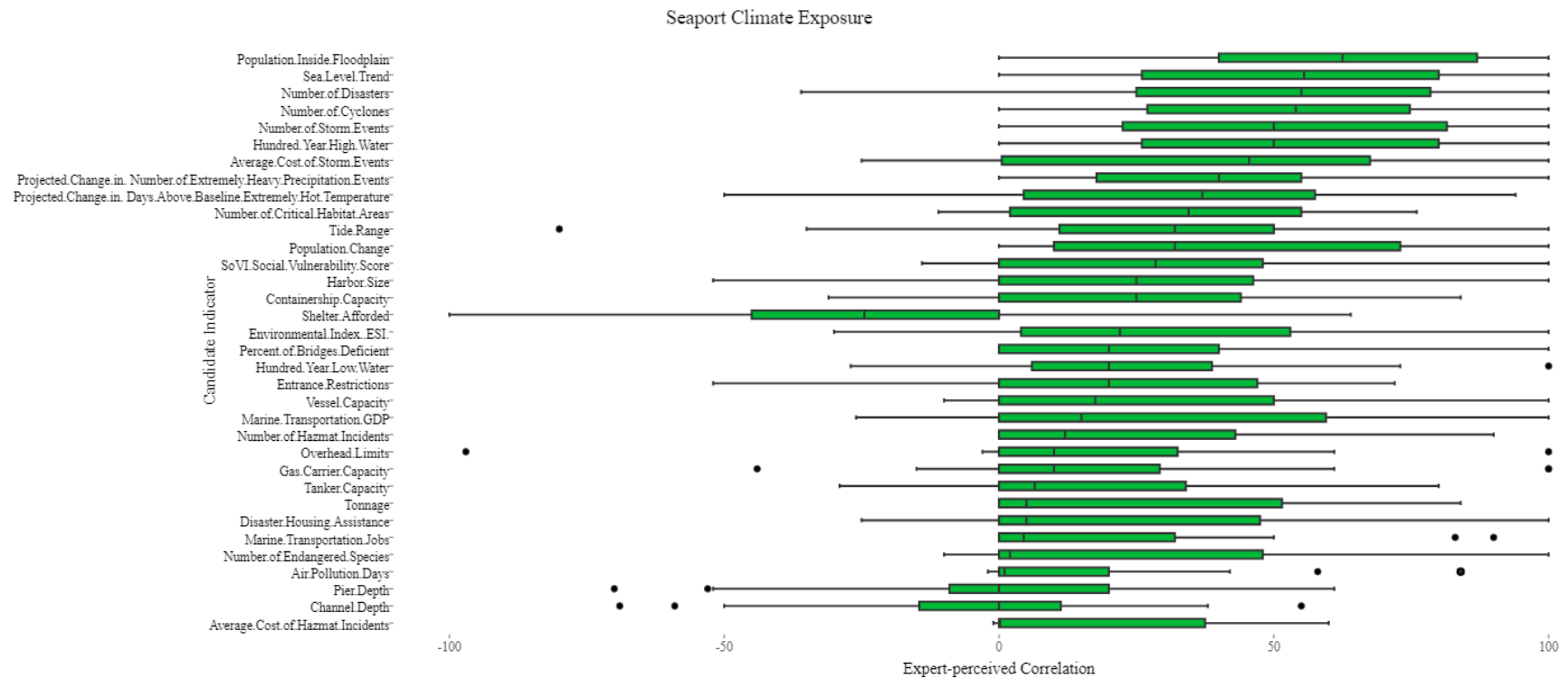
Appendix

Figure 8: Distribution of responses for adaptive capacity

McIntosh, R.D., Becker, A., (2019), "Expert Evaluation of Open-Data Indicators of Seaport Vulnerability to Climate and Extreme Weather Impacts for U.S. North Atlantic." Ocean and Coastal Management. Volume 180, 1 October 2019, 104911.
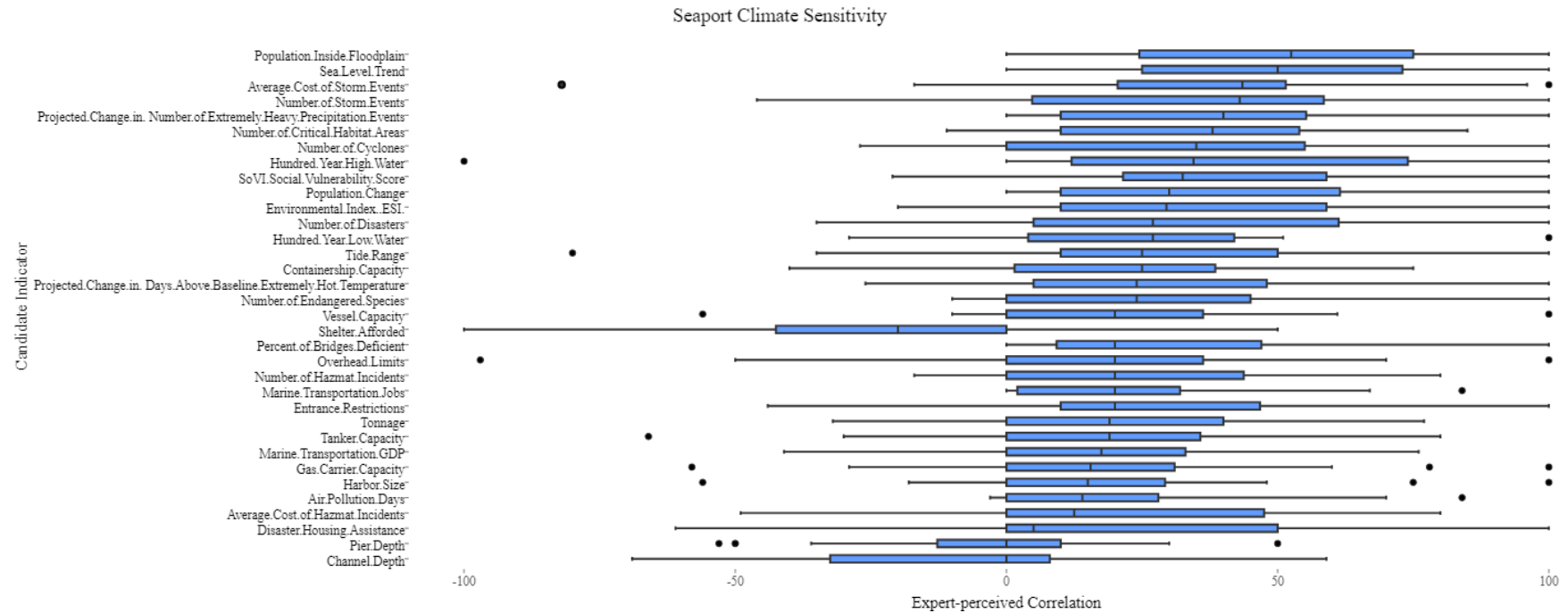

Figure 9: Distribution of responses for exposure.

Figure 10: Distribution of responses for sensitivity.