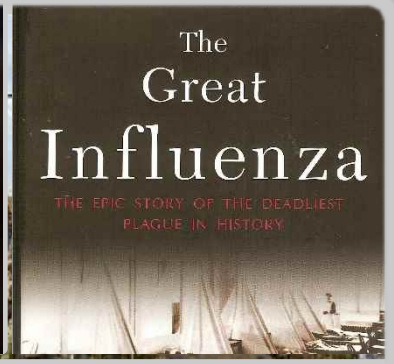
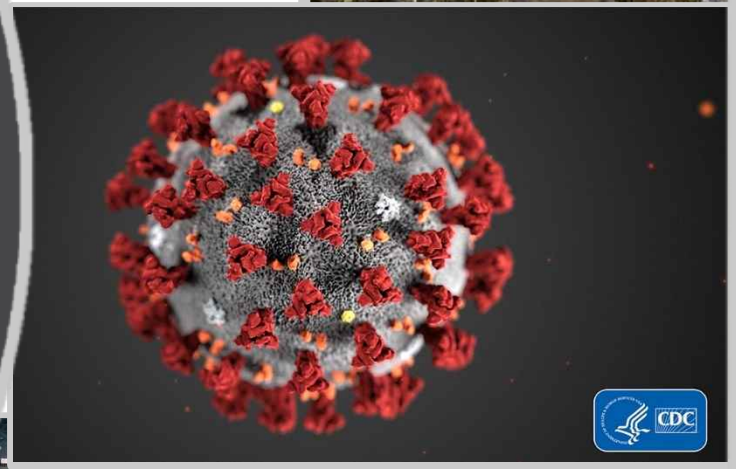
Resilience Analytics for Infrastructure under Compounding Threats: Methodology and Case Studies





Emily Wells, PhD and Igor Linkov, PhD
Engineer Research and Development Center
Risk and Decision Science Team

Battelle Innovations for Climate Resilience

Resilience of Infrastructure Systems

US Army Corps of Engineers

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

What are compounding threats?

The New York Times https://nyti.ms/3kbuBB

Hurricane, Fire, Covid-19: Disasters Expose the Hard Reality of Climate Change

Twin emergencies on two coasts this week — Hurricane Isaias and the Apple Fire — offer a preview of life in a warming world and the steady danger of overlapping disasters.

By Christopher Flavelle and Henry Fountain

Aug. 4, 2020 Updated 1:47 p.m. ET

npr 90.5 WESA DONATE

CLIMATE

Our Future On A Hotter Planet Means More Climate Disasters Happening Simultaneously

September 2, 2021 · 5:12 AM ET

DAN CHARLES

Compound threats pose multiplicative risks and are projected to increase in frequency, severity, and complexity

- When two or more threats interact, potential collective losses can be greater than the sum of its parts (Resilient Cities Network; IPCC, 2022)
- Risks posed by and to physical-cyber-social systems (IPCC, 2022)
  - Rare, even novel
  - Uncertainty
  - Complexity
- Expected to increase in frequency, severity, and complexity with climate change and interdependencies between critical infrastructure systems (Zscheischler et al., 2018; Kruczkiewicz et al., 2021)

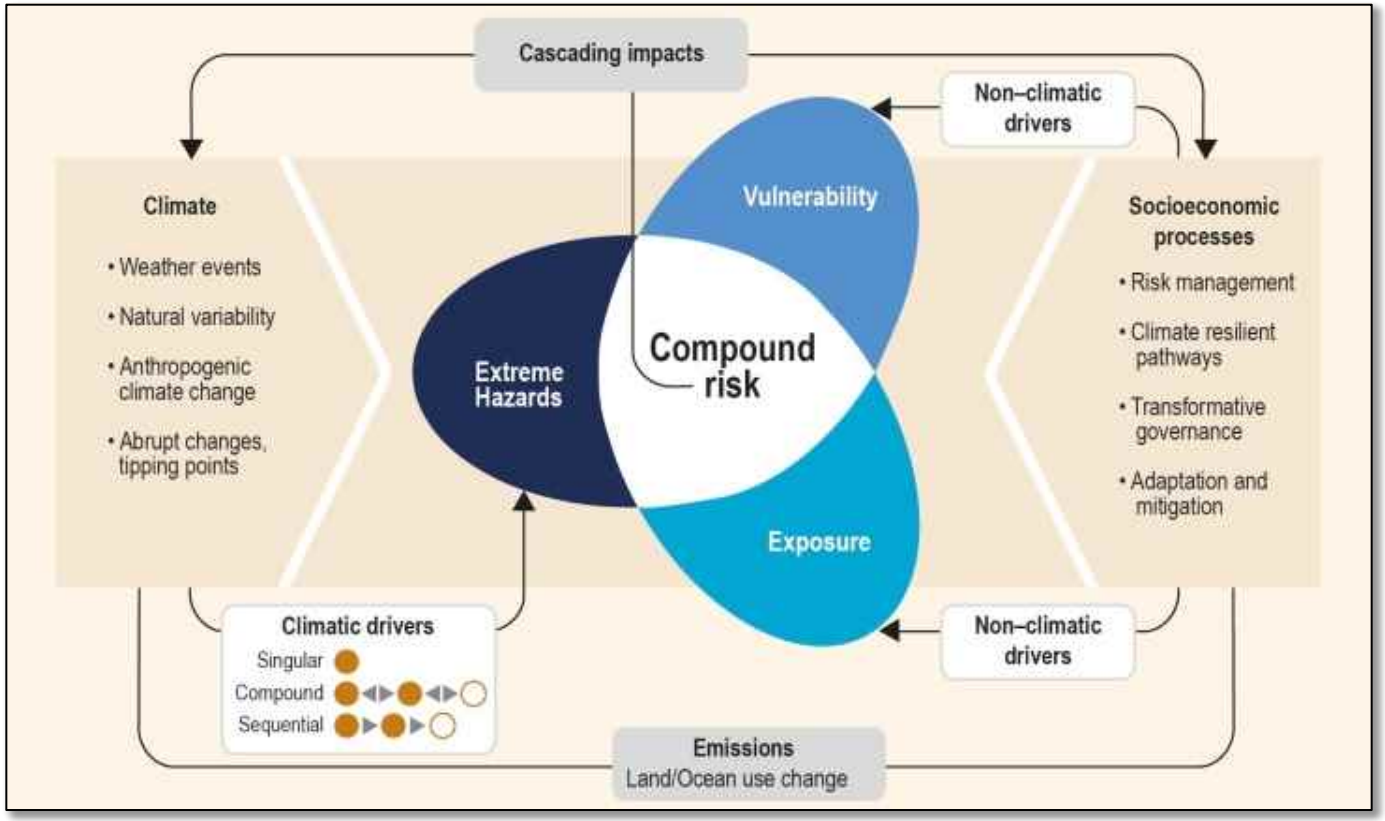
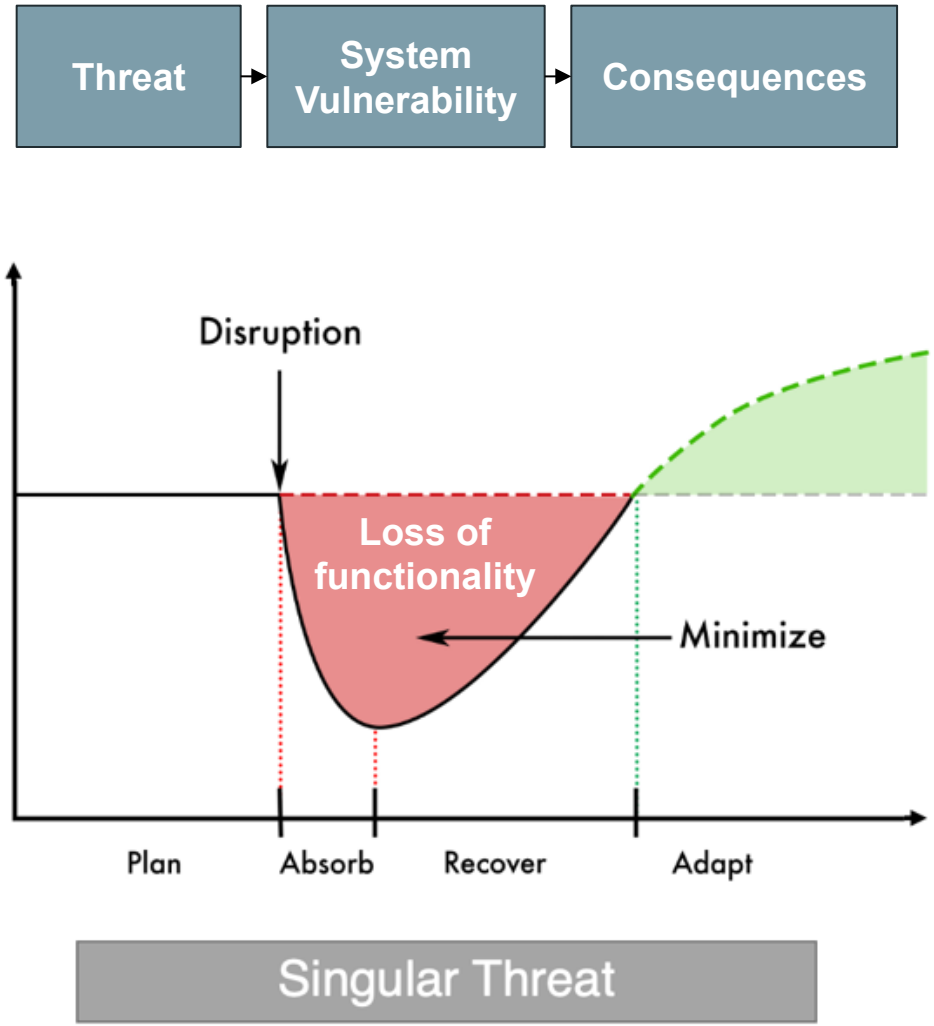


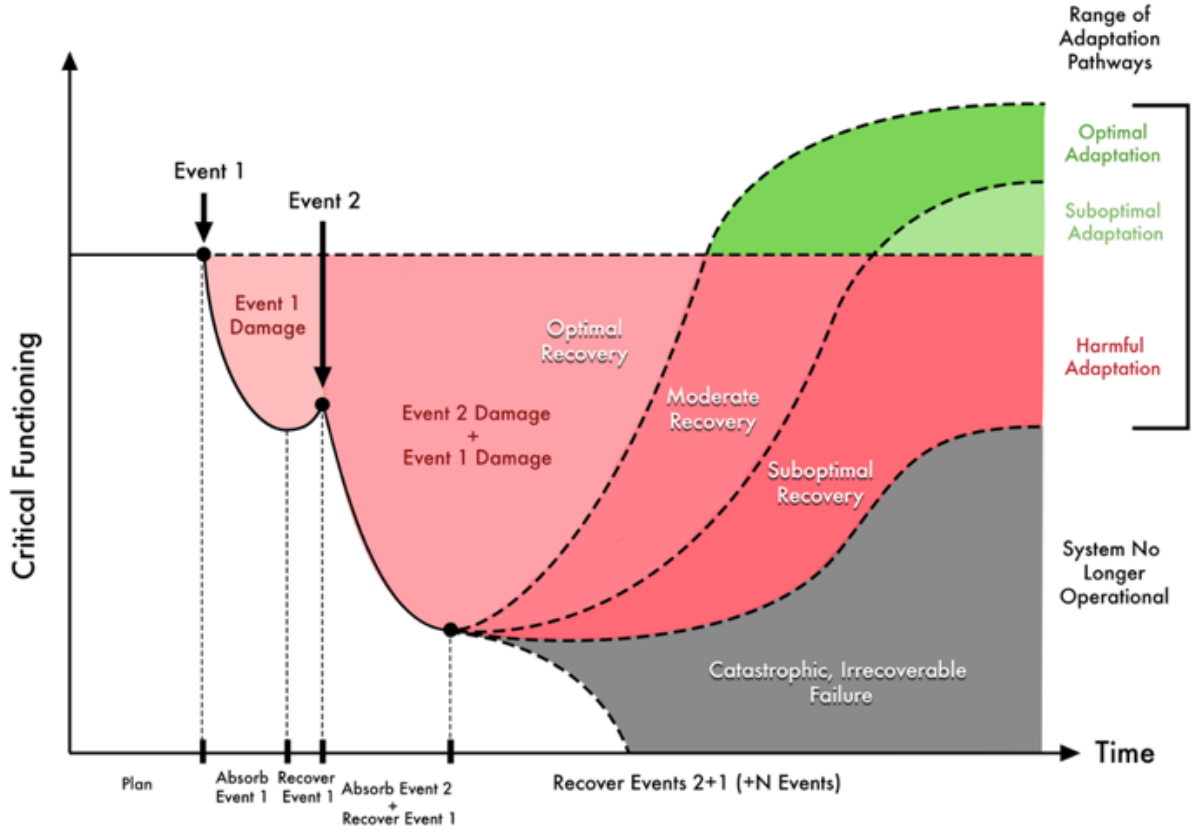
Figure source: Intergovernmental Panel on Climate Change (2022)

Systems resilience of critical infrastructure



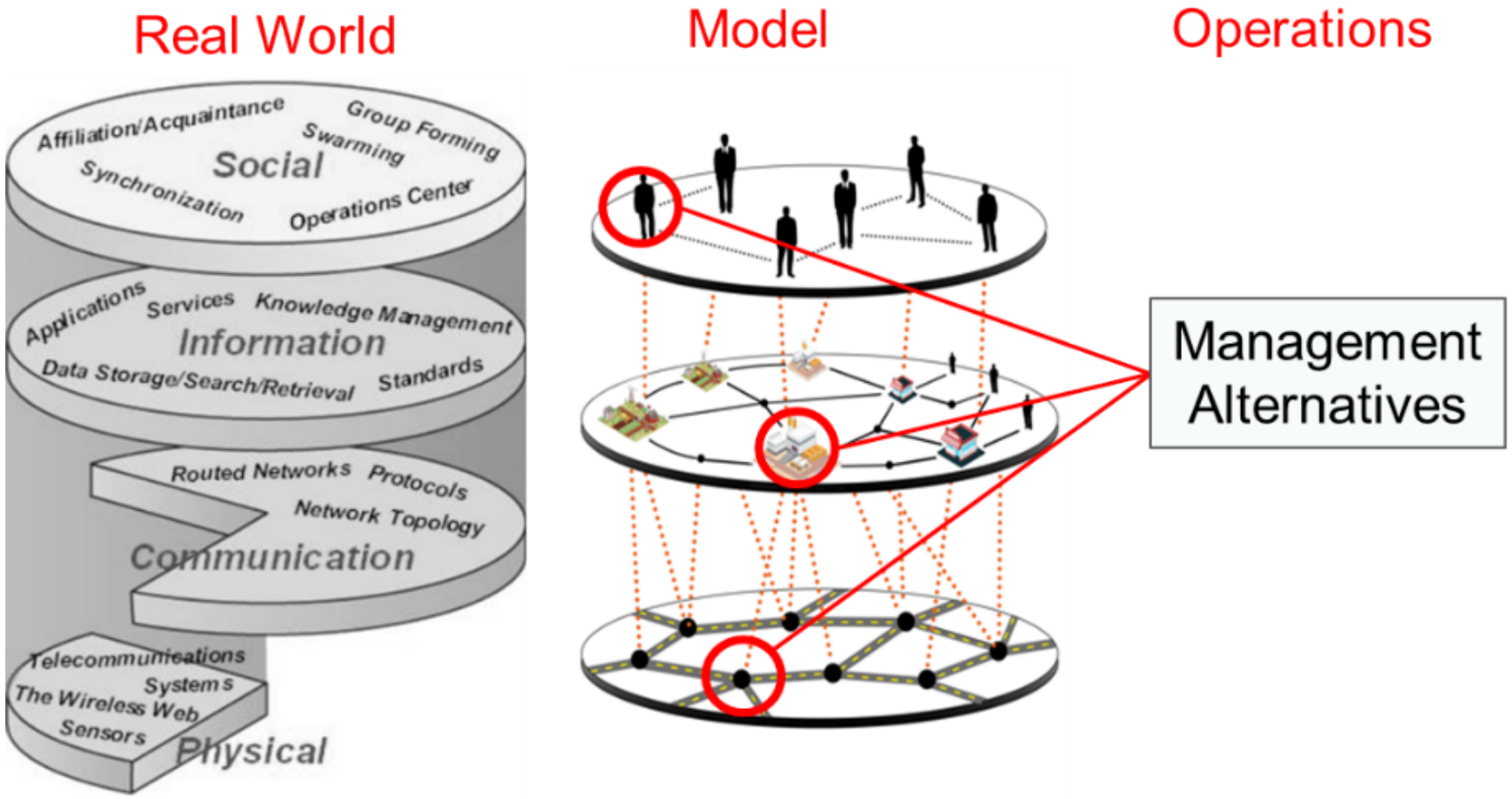
Systems resilience further complicated by compound threats

Threat 1	System Vulnerability	Threat 2	Compounding System Vulnerabilities	Consequences



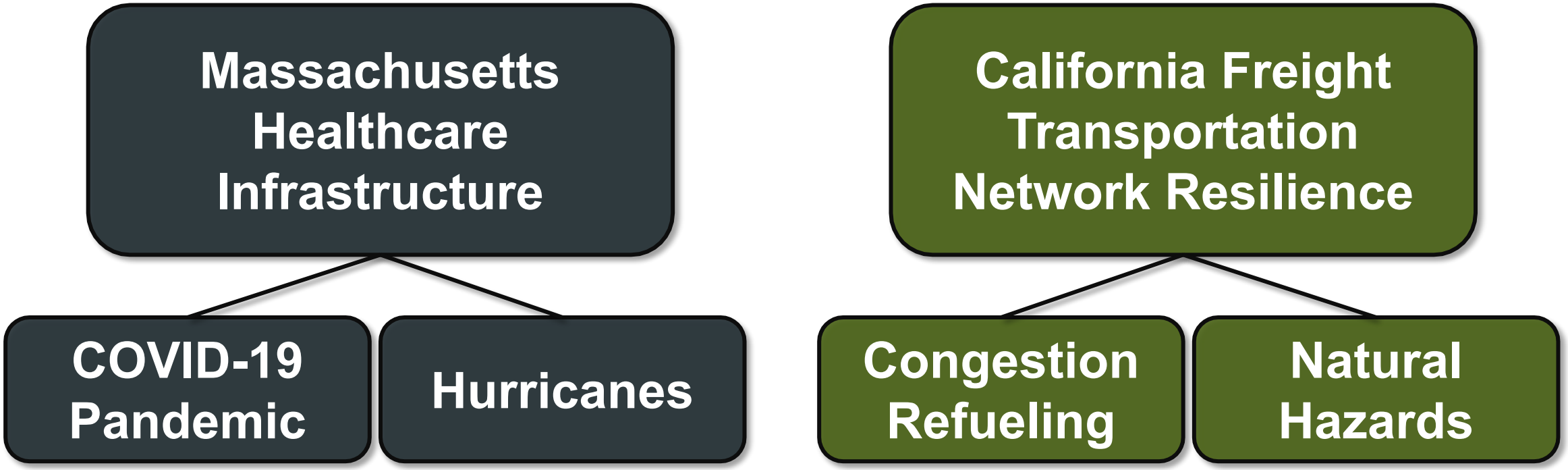
Compound Threat

Critical infrastructure systems resilience: Integrate multiple domains to inform model and operational decision-making

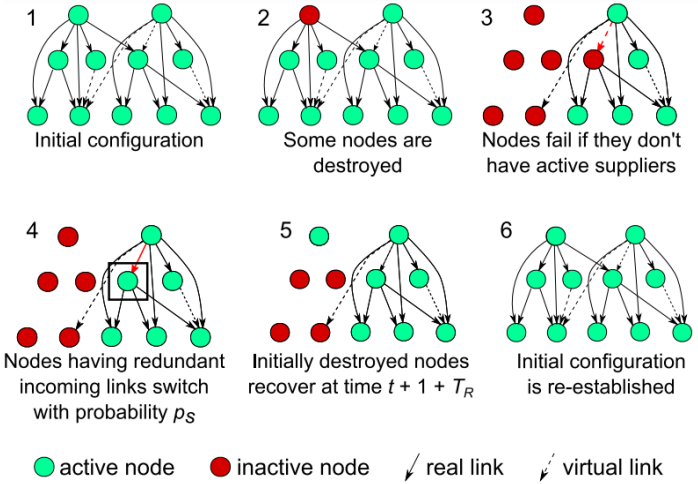


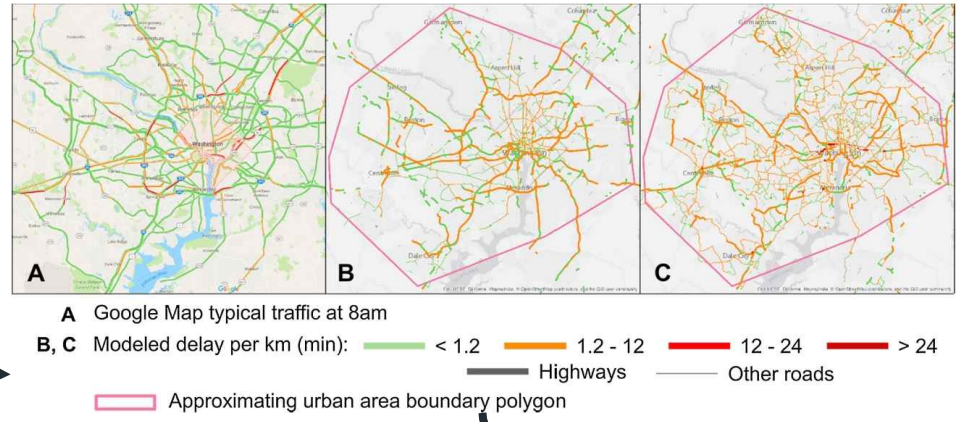
Source: Linkov, I., Carluccio, S., Pritchard, O., Ní Bhreasail, Á., Galaitsi, S., Sarkis, J., & Keisler, J. M. (2020). The case for value chain resilience. *Management Research Review*, *43*(12).

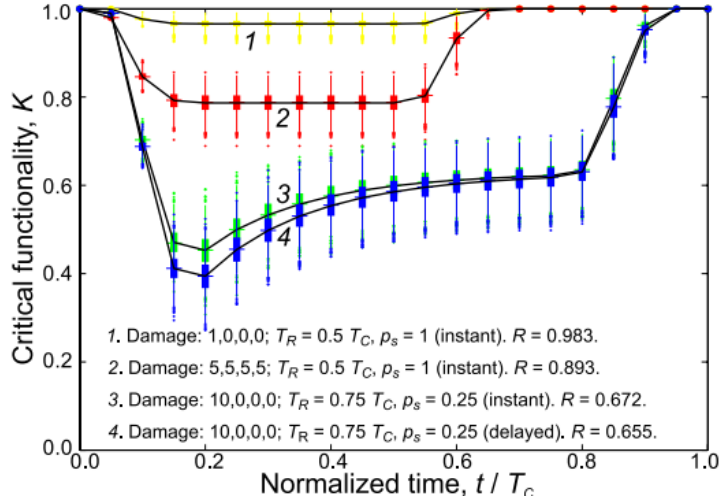
Case studies on critical infrastructure resilience under compounding threats



Network Science: Dynamic modeling of complex, interconnected critical infrastructure systems







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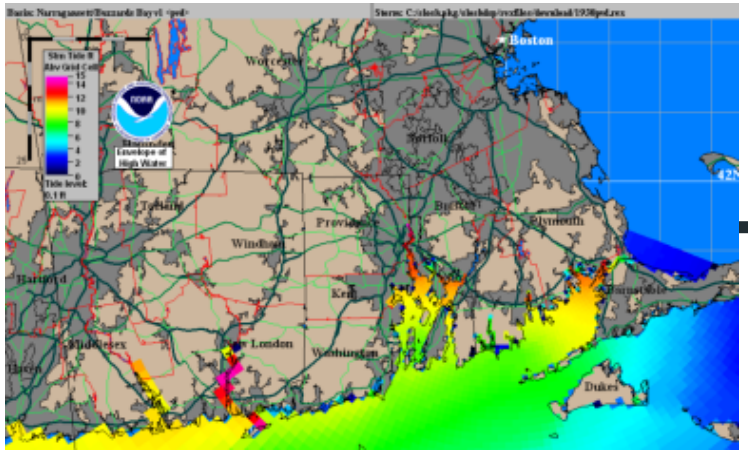
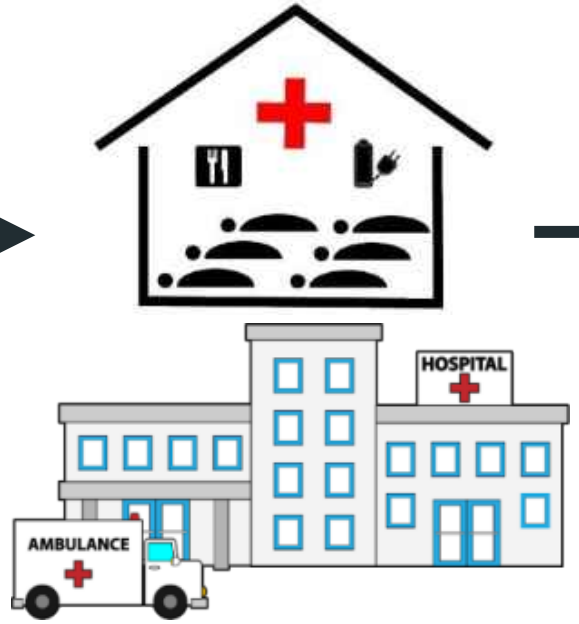
Case Study 1: Modeling the healthcare infrastructure needs during the compounding threats of the COVID-19 pandemic & hurricanes

Flood Inundation Modeling



Data: NOAA storm surge inundation using P-Surge

Modeling of Pandemic Consequences

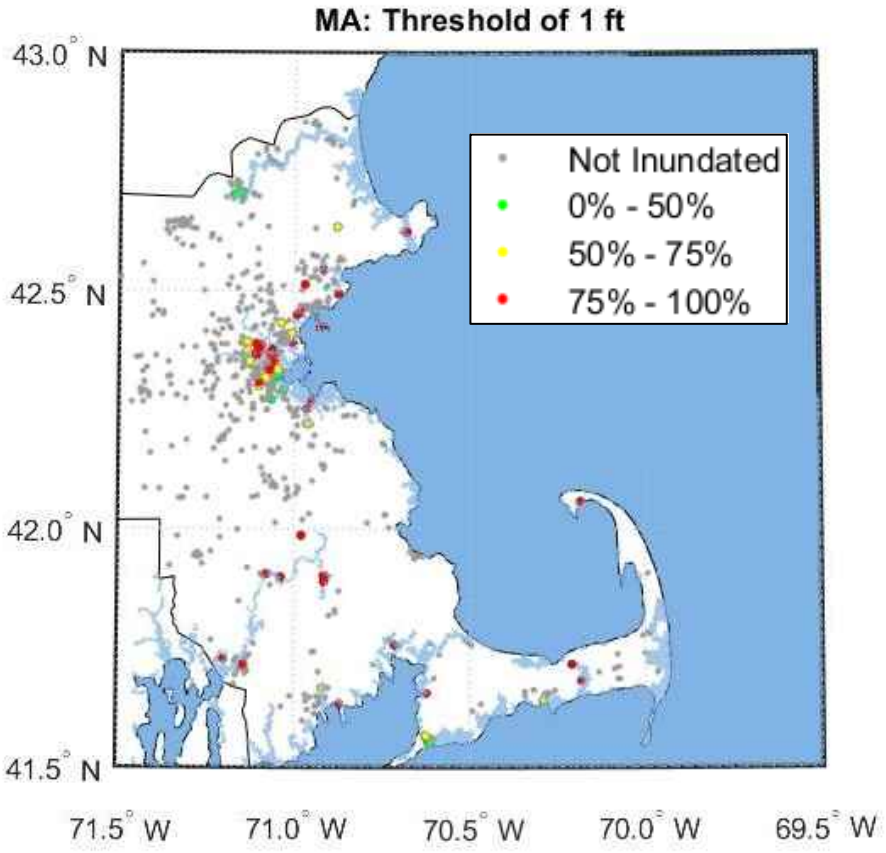


Data: Critical facility locations, capacities

Outcomes

- PPE needs for shelter workers and emergency management personnel
- Additional shelters to maintain social distancing
- Resource needs to maintain functionality of critical healthcare facilities
- Vulnerable community impacts (e.g. elderly)

Evacuation support tool: Critical facilities at risk of inundation



Probability of exceedance given inundation depth = 1 ft

Inundated Facilities

Prob. of Exc. (%)	Facility Type	Facility Name	Street	City	State	Zip
74	Hospital	Mount Auburn Hospital	330 Mount Auburn St 02138	Cambridge	MA	02138
74	Hospital	Lawrence General Hospital	One General St 01842	Lawrence	MA	01842
79	Hospital	Boston Med Ctr - East Newton Campus	88 East Newton St	Boston	MA	02118
80	Hospital	Boston Med Ctr - Harrison Ave. Campus	818 Harrison Ave	Boston	MA	02118
100	Hospital	Somerville Hospital	230 Highland Ave 02143	Somerville	MA	02143
100	Hospital	Tobey Hospital	43 High St	Wareham	MA	02571
100	Hospital	Addison Gilbert Hospital	298 Washington St 01930	Gloucester	MA	01930
100	Hospital	Mass. Eye & Ear Infirmary	243 Charles St	Boston	MA	02114
100	Hospital	Mass. General Hospital	55 Fruit St	Boston	MA	02114
100	Hospital	Cambridge Hospital	1493 Cambridge St 02139	Cambridge	MA	02139
100	Hospital	Tufts Medical Center	800 Washington St	Boston	MA	02111

Evacuation support tool: Displaced persons at the county-level to estimate shelter demand

- Data: *Hurricane Evacuation Studies (HES)*, developed by USACE under the National Hurricane Program (NHP) with FEMA.
- HESs provide results of socioeconomic and behavioral analyses to estimate ***shelter demand*** given storm intensity in terms of displaced persons.

	Evacuation Order Extent	Location	Displaced Persons	Percent Disabled		
				Hearing	Vision	Ambulatory
MEMA Region	*Zone B & C*	Region 1	55029	2.4%	2.6%	7.1%
		Region 2		3.5%	1.6%	5.6%
County	*Zone A*	Barnstable	7372	4.2%	2.2%	6.0%
	Zone B	Bristol	6991	4.2%	2.0%	7.6%
		Dukes		NA	NA	NA
	Zone A	Essex	6017	2.8%	1.8%	6.0%
	Zone B & C	Middlesex	17826	2.8%	1.7%	4.6%
	Zone B	Nantucket	863	NA	NA	NA
		Norfolk		2.7%	1.6%	4.7%
		Plymouth		3.5%	1.6%	5.6%
	Zone B & C	Suffolk	27305	2.4%	2.6%	7.1%
City Town Community		Acushnet		4.2%	2.0%	7.6%
	Zone B	Aquinnah	39	NA	NA	NA
	Zone A	Arlington	581	2.8%	1.7%	4.6%
		Barnstable		4.2%	2.2%	6.0%
	Zone B	Belmont	484	2.8%	1.7%	4.6%
	Zone B	Berkley	106	4.2%	2.0%	7.6%
	Zone B	Beverly	755	2.8%	1.8%	6.0%
	Zone C	Boston	23169	2.4%	2.6%	7.1%

Evacuation support tool: Displaced persons with disabilities at the county-level to estimate shelter demand

- Critical to ensure that those who are deaf, vision-impaired, or have other functional or access needs are accommodated.
- Data: 2018 American Community Survey data on the percentage of population within each New England county with a given disability.

	Evacuation Order Extent	Location	Displaced Persons	Percent Disabled		
				Hearing	Vision	Ambulatory
MEMA Region	*Zone B & C*	Region 1	55029	2.4%	2.6%	7.1%
		Region 2		3.5%	1.6%	5.6%
County	*Zone A*	Barnstable	7372	4.2%	2.2%	6.0%
	Zone B	Bristol	6991	4.2%	2.0%	7.6%
		Dukes		NA	NA	NA
	Zone A	Essex	6017	2.8%	1.8%	6.0%
	Zone B & C	Middlesex	17826	2.8%	1.7%	4.6%
	Zone B	Nantucket	863	NA	NA	NA
		Norfolk		2.7%	1.6%	4.7%
		Plymouth		3.5%	1.6%	5.6%
	Zone B & C	Suffolk	27305	2.4%	2.6%	7.1%
City Town Community		Acushnet		4.2%	2.0%	7.6%
	Zone B	Aquinnah	39	NA	NA	NA
	Zone A	Arlington	581	2.8%	1.7%	4.6%
		Barnstable		4.2%	2.2%	6.0%
	Zone B	Belmont	484	2.8%	1.7%	4.6%
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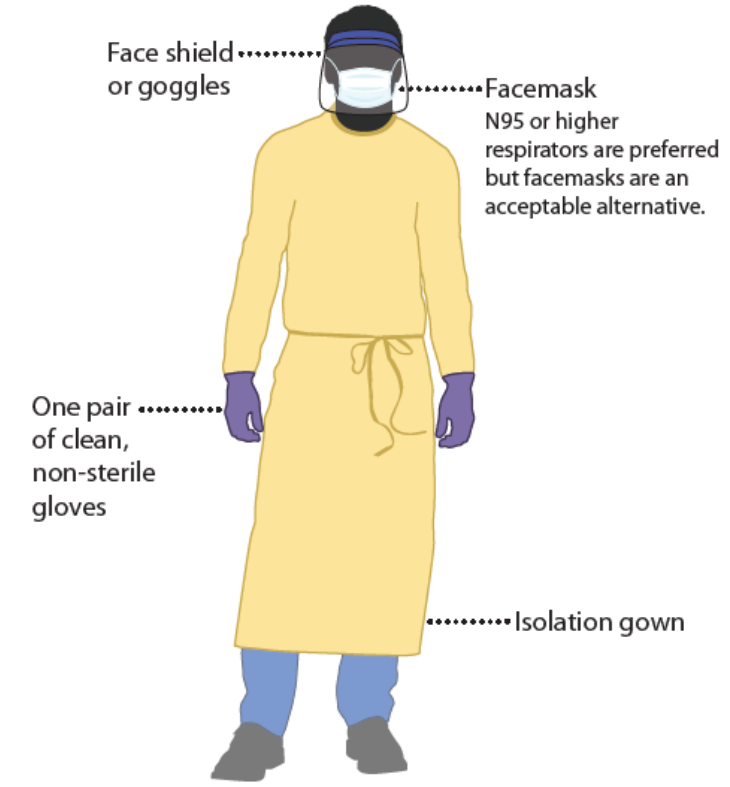
	Zone B	Beverly	755	2.8%	1.8%	6.0%
	Zone C	Boston	23169	2.4%	2.6%	7.1%
		Bourne		4.2%	2.2%	6.0%

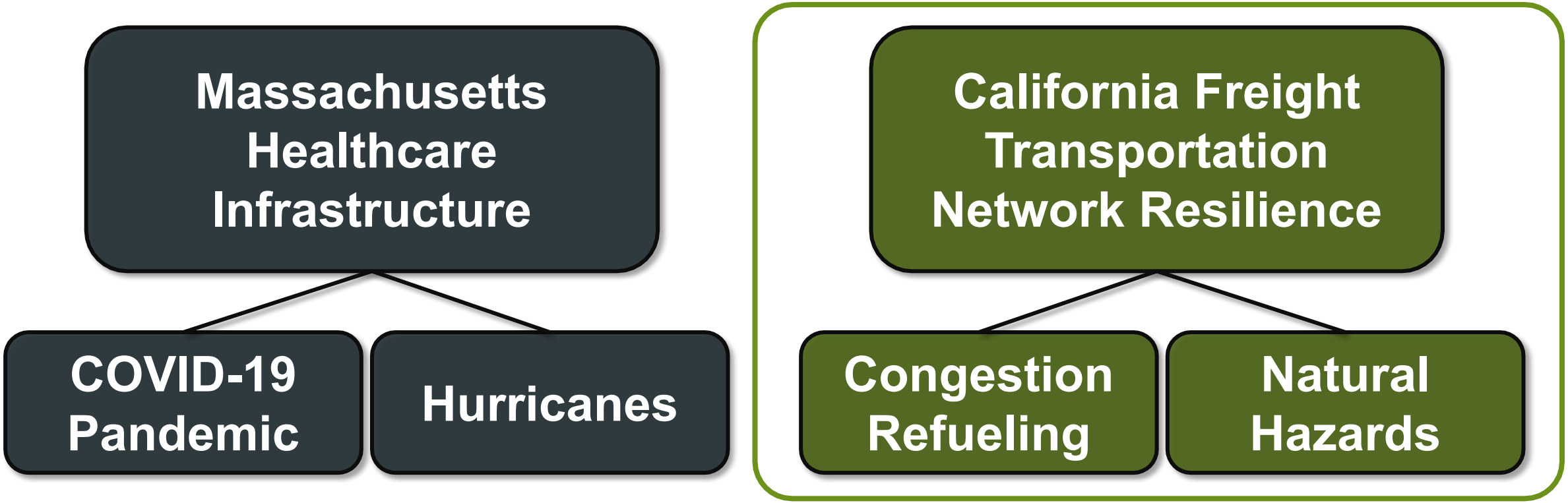
Evacuation support tool: PPE needs for shelter and emergency management personnel

	COVID Scenario - Reuse						
	Pre-Storm			Post-Storm			
	PPE / Client	PPE / Staff	Total PPE	PPE / Client	PPE / Staff	Total PPE	Total PPE
N95 Respirators	NA	1,175	1,175	NA	548	548	1,723
Face Masks	2,447	979	3,426	NA	NA	NA	3,426
Eye Protection	NA	1,175	1,175	NA	548	548	1,723
Gowns/Coveralls	NA	1,175	1,175	NA	548	548	1,723
Gloves (singular)	NA	77,521	77,521	NA	36,176	36,176	113,697
Liquid-Gel Thermometers	2,447	NA	2,447	NA	NA	NA	2,447

	COVID Scenario - No Reuse						
	Pre-Storm			Post-Storm			
	PPE / Client	PPE / Staff	Total PPE	PPE / Client	PPE / Staff	Total PPE	Total PPE
N95 Respirators	NA	7,047	7,047	NA	3,289	3,289	10,336
Face Masks	7,341	2,936	10,277	3,426	1,370	4,796	15,074
Eye Protection	NA	7,047	7,047	NA	3,289	3,289	10,336
Gowns/Coveralls	NA	7,047	7,047	NA	3,289	3,289	10,336
Gloves (singular)	NA	77,521	77,521	NA	36,176	36,176	113,697
Liquid-Gel Thermometers	2,447	NA	2,447	NA	NA	NA	2,447



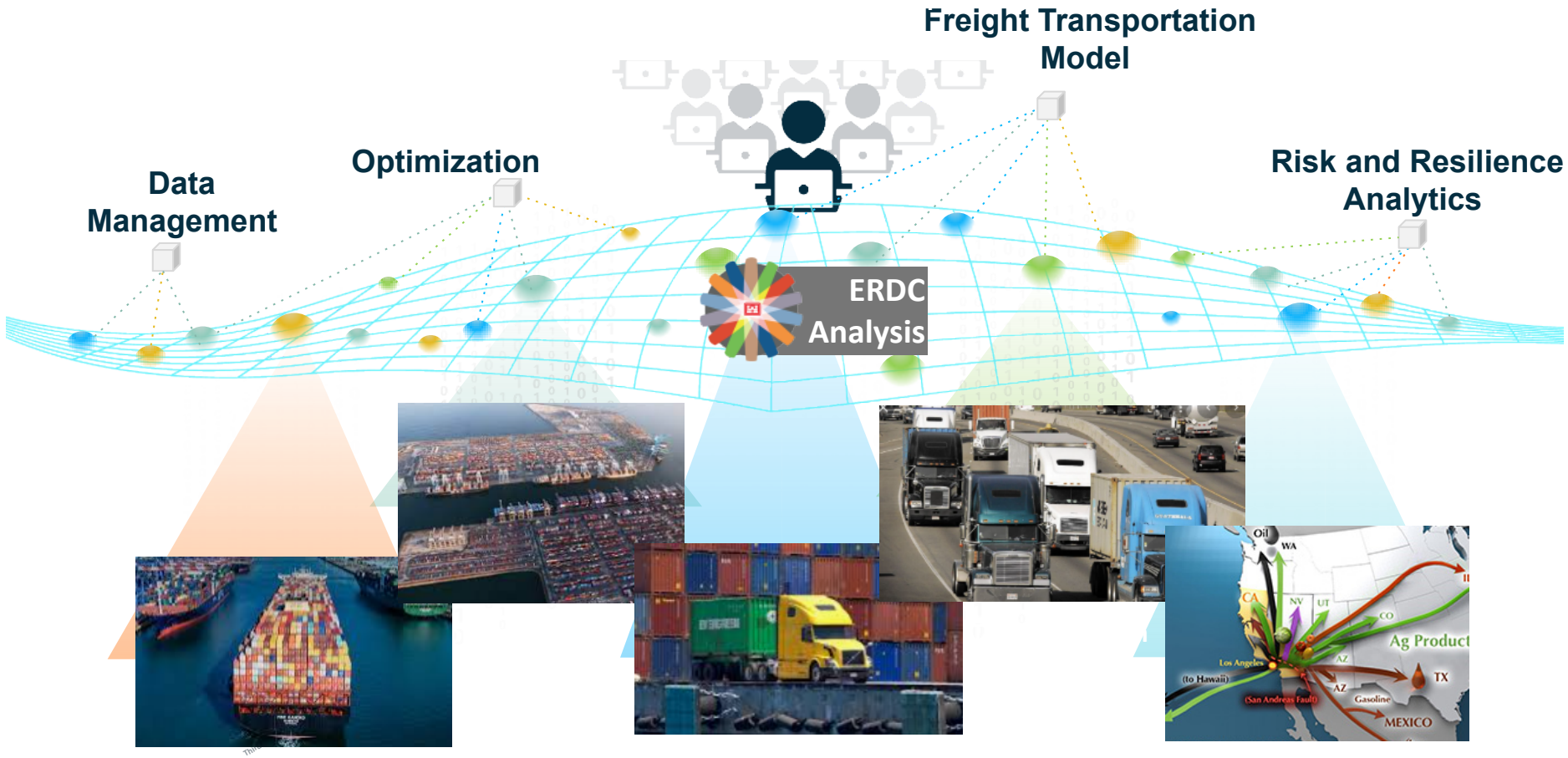
Case studies on critical infrastructure resilience under compounding threats



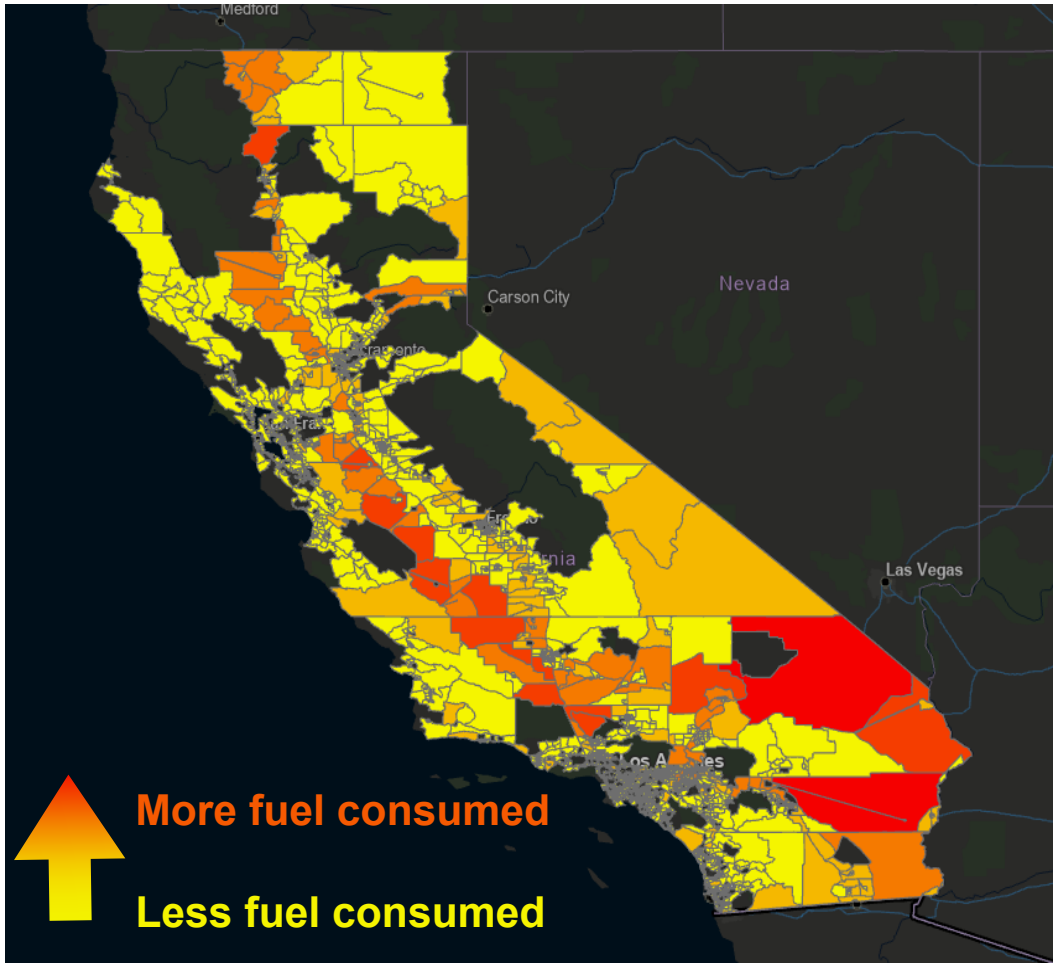
Case Study 2: Resilience-By-Design Approach to Minimizing Freight Disruption – Identifying Zero-Emission Refueling Stations in California

Identify gas stations that could be converted to dispensing stations:

- minimize freight displacement
- scalable
- considering natural hazard disruptions



Freight network demand – traffic congestion and fuel consumption



Compounding threat of wildland fires to identify system vulnerabilities

- Freight volumes with climate change vulnerabilities:
  - Wildland fire risk through early 2045
- **Result:**
  - Network disruption near Stockton, CA
  - N/S freight corridors are close
  - Near-term wildland fire risk
  - Potential post-fire flood risk

Volume of Long-Haul Freight within CA

Overlayed with Caltrans Fire Vulnerability

What is needed to further develop our understanding, modeling, and decision-making towards compound threat resilience?

- Current state of the literature focuses primarily on multi-hazard risk assessments
- Need for resilience-based, dynamical complex systems modeling
  - Discover and include non-obvious real-world relationships resulting from unknown behavior

Preparation	Response	Recovery	Adaptation
• Compound hazard likelihood and types • Critical infrastructure and population vulnerabilities • System interdependencies	• Strains on first response and hazard management community • Operations and management decisions • Coordination and governance approaches	• Identify systems vulnerabilities, critical functions, and interdependencies • Predict recovery trajectories by integrate big data that monitors social systems during and after compound events • Develop and stress test recovery and adaptation pathways	

Thank you!

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BACKUP SLIDES

Need for strategic stress testing of critical infrastructure systems to move beyond multi-hazard risk assessments to resilience assessments

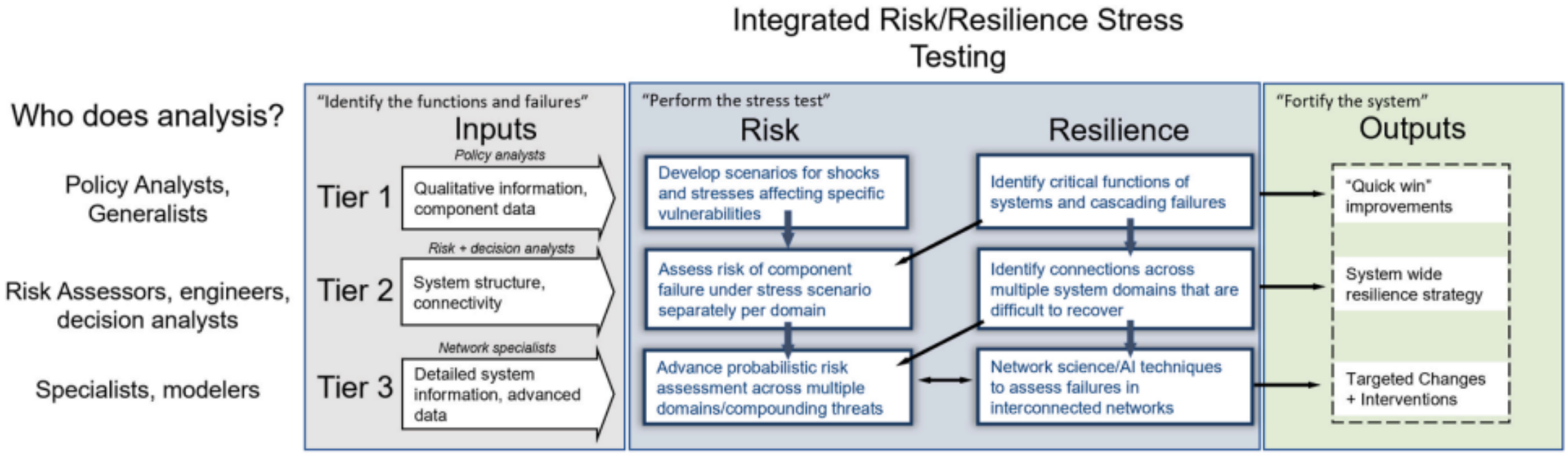
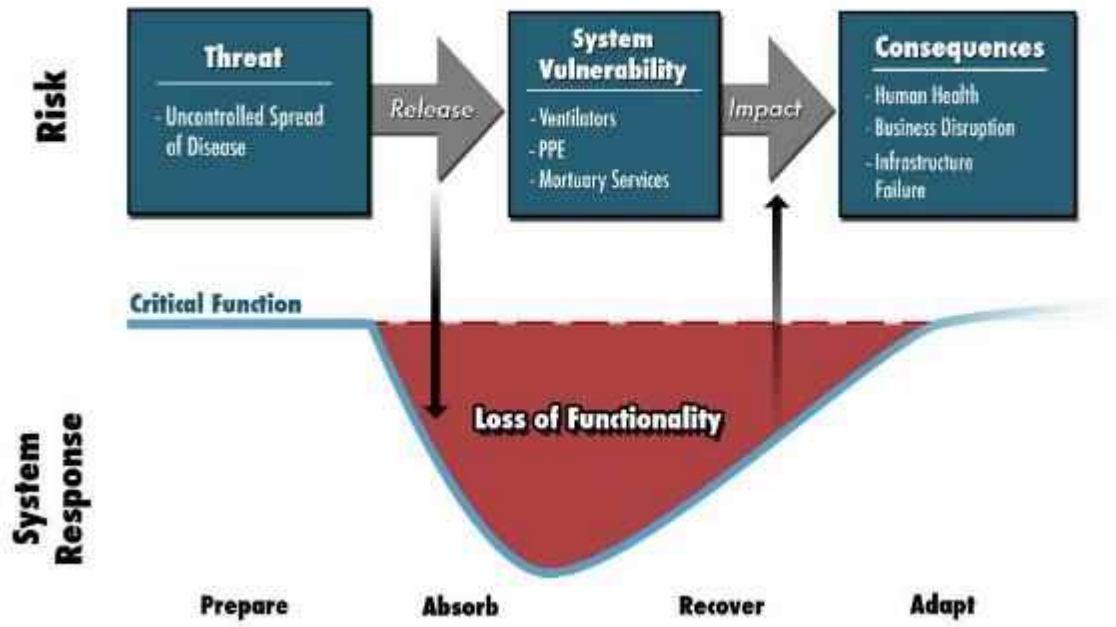
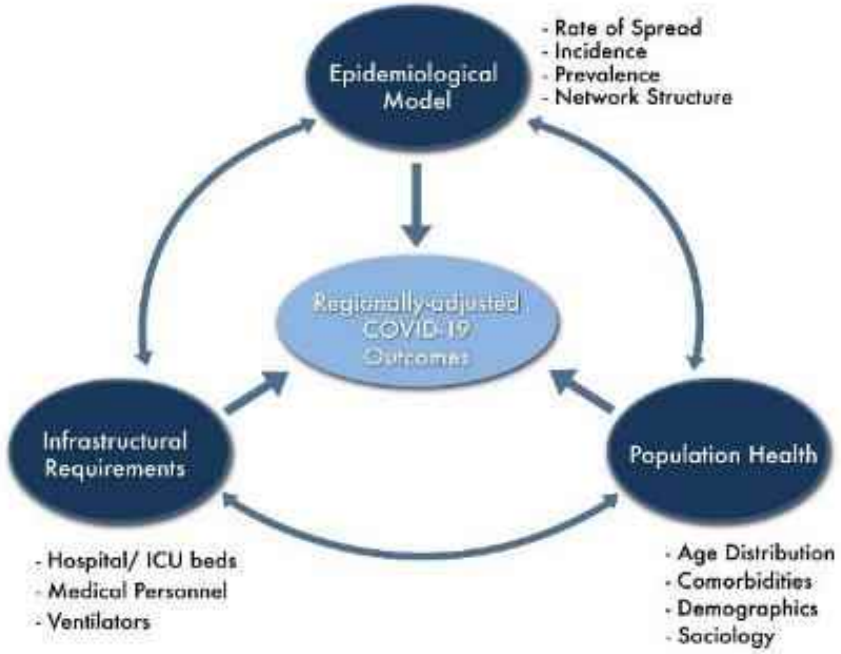


Fig. 1. Tiered approach to integrated risk and resilience stress testing for critical infrastructure.

Source: Linkov, I., Trump, B. D., Trump, J., Pescaroli, G., Hynes, W., Mavrodieva, A., & Panda, A. (2022). Resilience stress testing for critical infrastructure. *International Journal of Disaster Risk Reduction*, 103323.

- Transition from risk- to resilience-based analytics
- Systems Approach to systemic risks combining epidemiological, infrastructure and public health models and evaluation

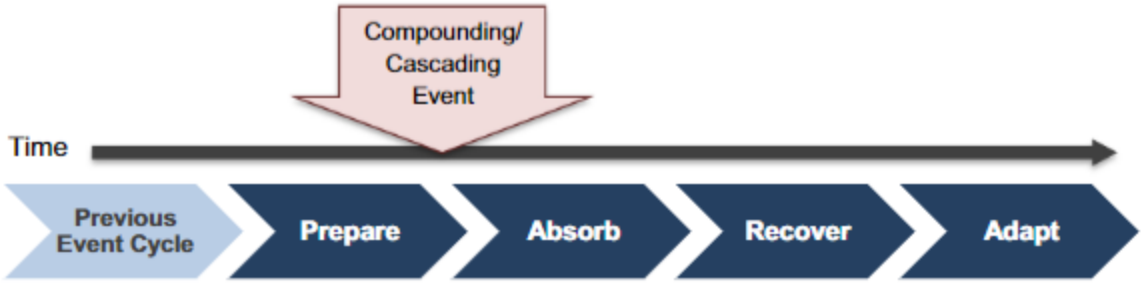




Trump, B. D., Bridges, T. S., Cegan, J. C., Cibulsky, S. M., Greer, S. L., Jarman, H., ... & Linkov, I. An analytical perspective on pandemic recovery. *Health security*.

Coding Scheme – Summary of Key Parameters Collected for Each Article

- Methodology: Novel modeling approa Case study? Lit review?
- Data type: Simulated, Empirical, Both
- Critical infrastructure type(s)
- Event type(s)
  - Compound threat, Cascading failu Both
- Modeling approach
  - Sources of uncertainty
- Direct measure of resilience?
  - If so, name of approach
- Coverage of Resilience Matrix
- Results presentation (i.e., geospatial, scenario analyses, time series analys etc.)



Resilience Domains	Prepare	Absorb	Recover	Adapt
Physical	State and capability of equipment and personnel, network structure	Event recognition and system performance to maintain function	System changes to recover previous functionality	Changes to improve system resilience
Information	Data preparation, presentation, analysis, and storage	Real-time assessment of functionality, anticipation of cascading losses, and event closure	Data used to track recovery progress and anticipate recovery scenarios	Creation and improvement of data storage and use protocols
Cognitive	System design and operation decisions, with anticipation of adverse events	Contingency protocols and proactive event management	Recovery decision-making and communication	Design of the new system configurations, objectives, and decision criteria
Social	Social network, social capital, institutional and cultural norms, and training	Resourceful and accessible personnel and social institutions for event response	Teamwork and knowledge sharing to enhance system recovery	Addition of or changes to institutions, policies, training programs, and culture

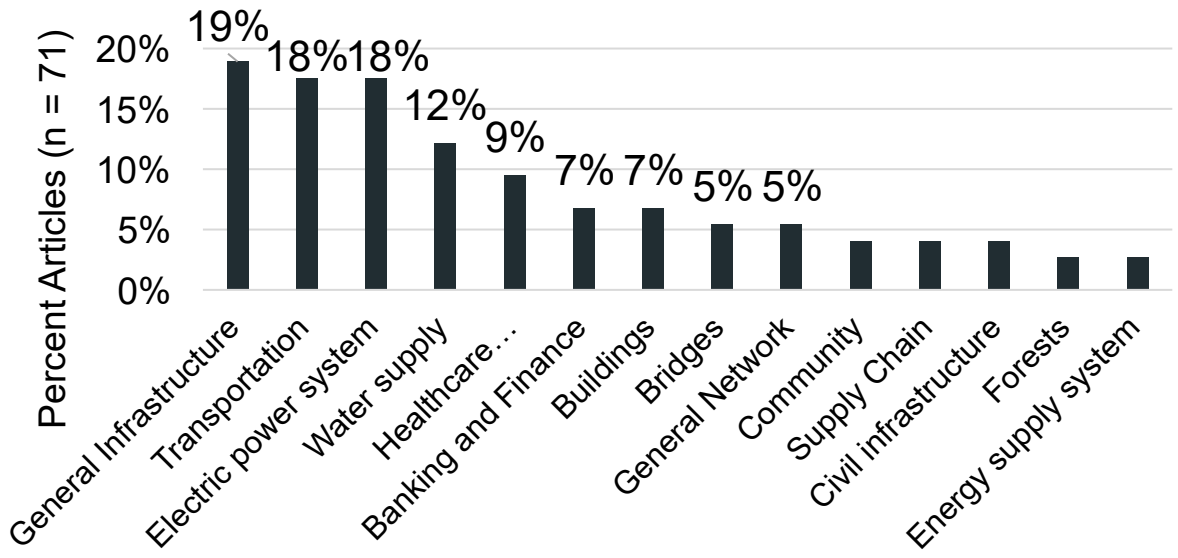
Fig. 1. The Resilience Matrix definitions of the phases and domains of critical infrastructure resilience used to code the literature, as adapted from Linkov et al. [39]. This figure shows the general progression of resilience phases over time following an adverse event (i.e., a threat or hazard).

US Army Corps

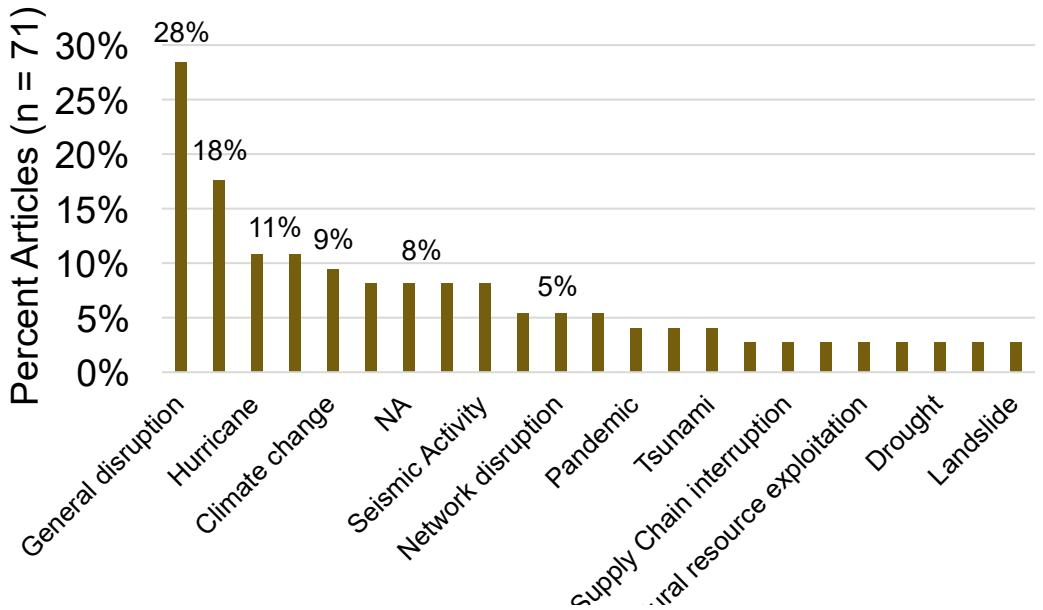
Literature review

- How has the network science literature modeled and assessed critical infrastructure resilience under compounding threat spaces?
- What types of such threats and critical infrastructure systems have been studied in recent years? How have they been studied?
- How does this body of literature relate to overall systems resilience of critical infrastructure?

A.) Critical Infrastructure Type



B.) Threat Type



Systematic literature review: Network science approaches (n = 71) focused on physical and information absorption…

RESILIENCE DOMAINS	RESILIENCE PHASES: Prepare	**Absorb**	Recover	Adapt
Physical	58%	85%	63%	39%
Information	59%	79%	59%	42%
Cognitive	45%	48%	39%	31%
Social	25%	30%	28%	20%

Source: Wells, E. M., Boden, M., Tseytlin, I., & Linkov, I. (2022). Modeling critical infrastructure resilience under compounding threats: a systematic literature review. Progress in Disaster Science, 100244.

Systematic literature review:
…but needed focus for other phases and the cognitive and social domains

RESILIENCE DOMAINS	RESILIENCE PHASES			
	Prepare	Absorb	Recover	**Adapt**
Physical	58%	85%	63%	39%
Information	59%	79%	59%	42%
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Source: Wells, E. M., Boden, M., Tseytlin, I., & Linkov, I. (2022). Modeling critical infrastructure resilience under compounding threats: a systematic literature review. Progress in Disaster Science, 100244.

Systematic literature review: Resilience Matrix results by critical infrastructure type

A.) General Infrastructure

	Prepare	Absorb	Recover	Adapt
Physical	56%	100%	56%	44%
Information	56%	100%	75%	56%
Cognitive	19%	0%	0%	0%
Social	19%	19%	19%	19%

B.) Transportation Systems

	Prepare	Absorb	Recover	Adapt
Physical	43%	100%	57%	64%
Information	43%	100%	57%	79%
Cognitive	21%	57%	36%	57%
Social	21%	100%	57%	36%

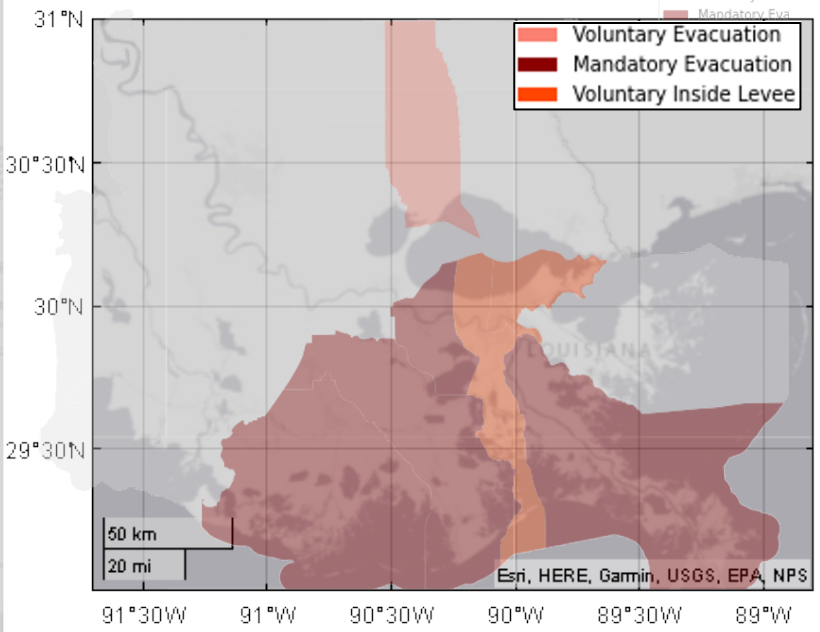
C.) Electric Systems

	Prepare	Absorb	Recover	Adapt
Physical	47%	87%	87%	53%
Information	47%	87%	87%	27%
Cognitive	47%	47%	27%	27%
Social	27%	20%	20%	20%

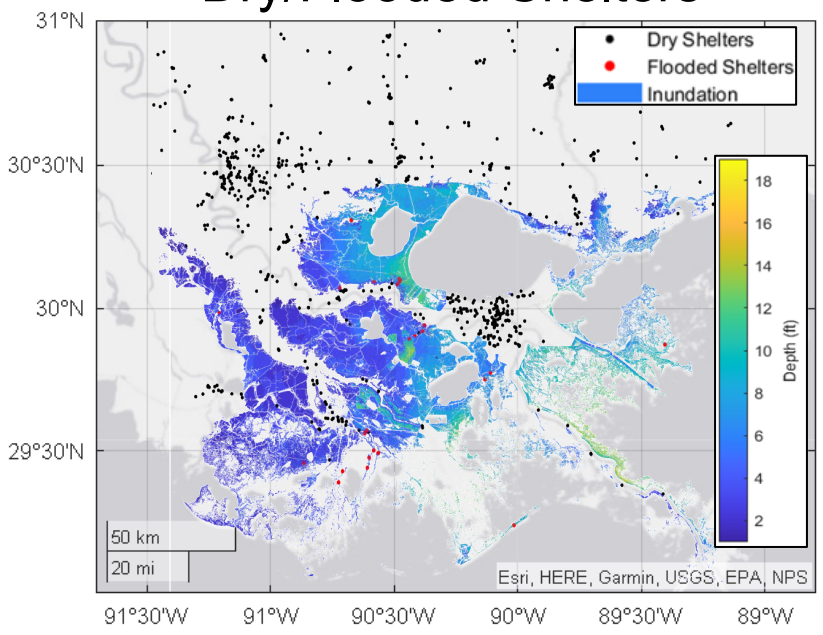
US A

Modeling hurricane evacuations during compounding threats: Case Study on Hurricane Ida, Southeast Louisiana

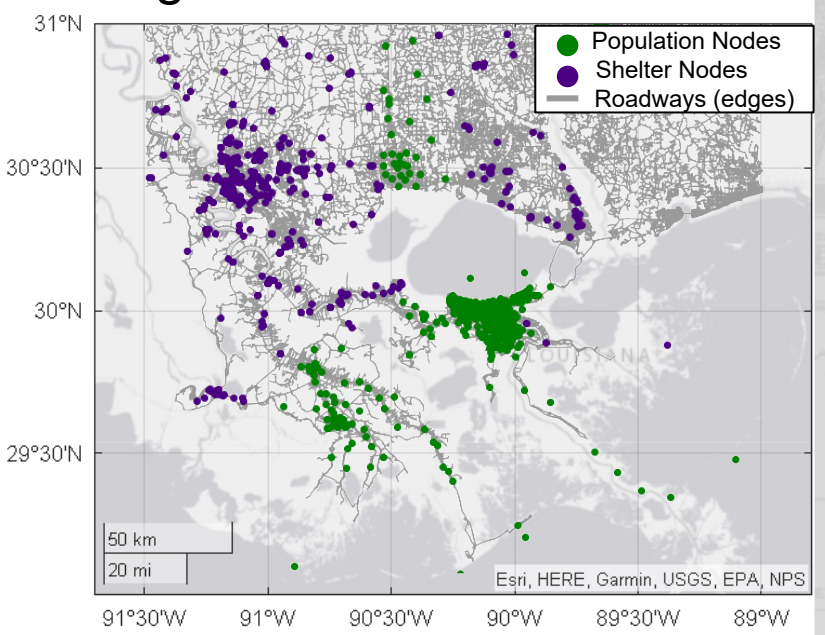
Shelter Demand:
Evacuation Orders



Shelter Capacity:
Dry/Flooded Shelters

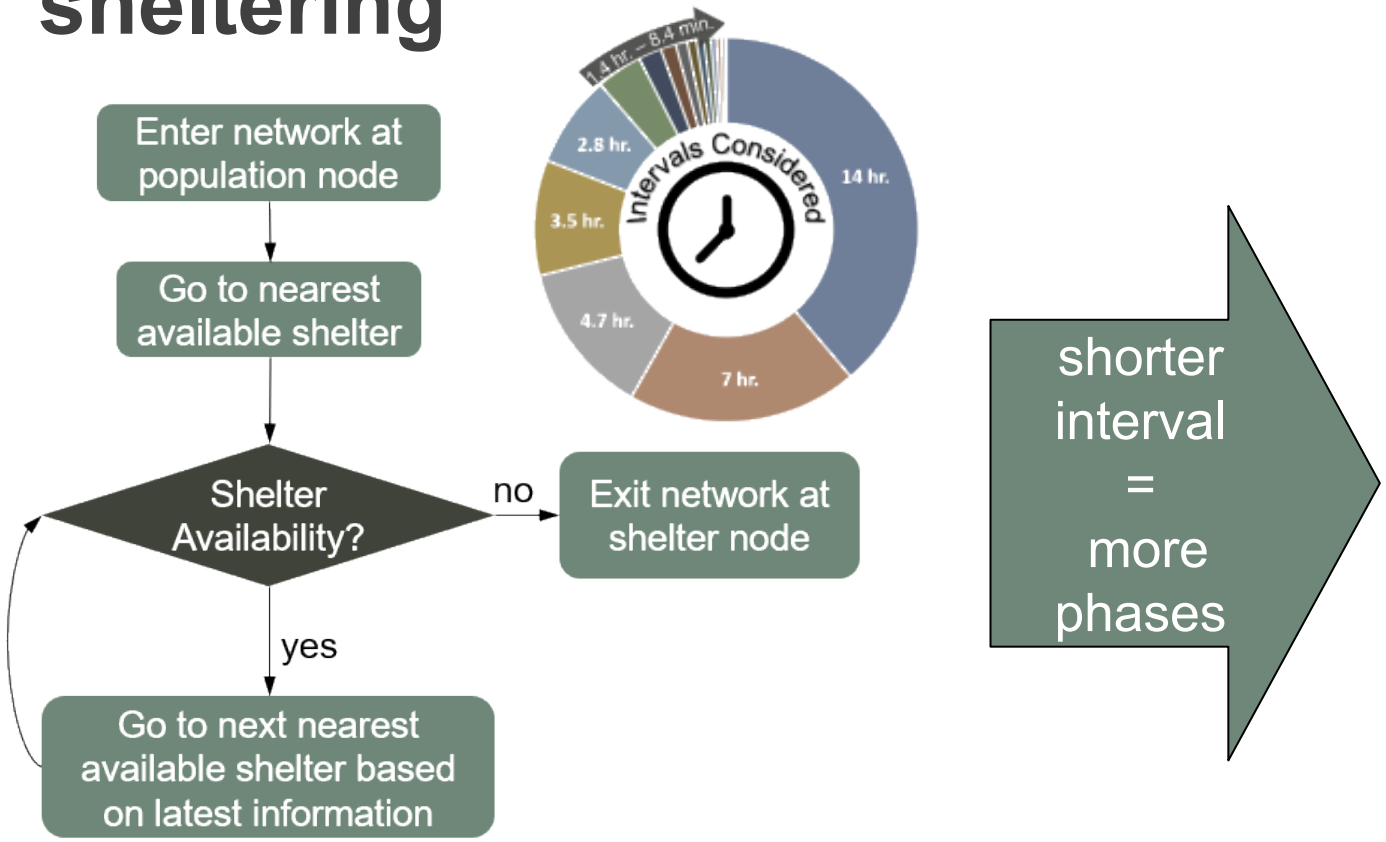


Evacuee Distribution:
Agent-based network model

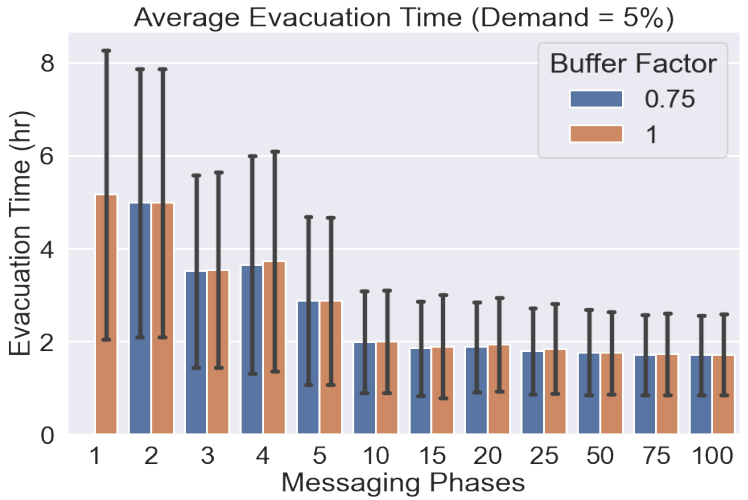


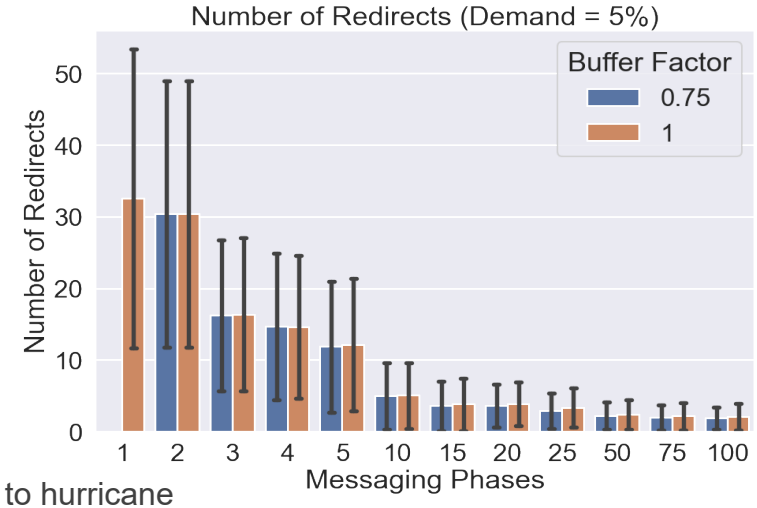
Source: Cegan, J. C., Golan, M. S., Joyner, M. D., & Linkov, I. (2022). The importance of compounding threats to hurricane evacuation modeling. npj Urban Sustainability, 2(1), 2.

Use of agent-based modeling to assess systems-level vulnerabilities, risk, resilience for evacuation and sheltering



shorter interval = more phases



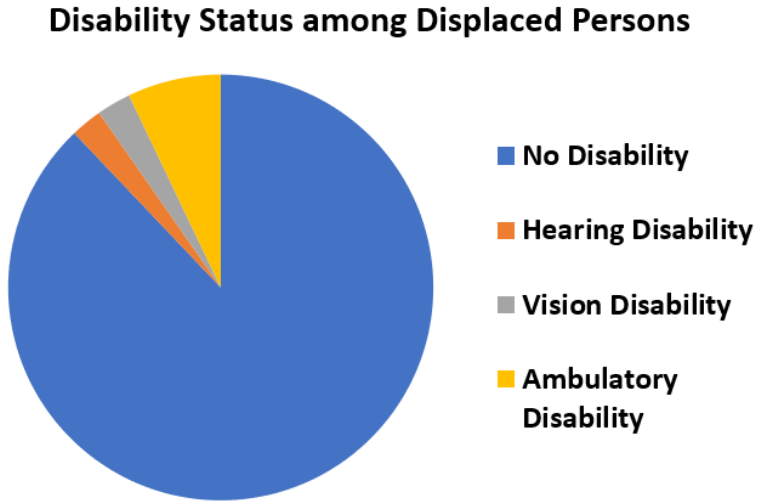


Source: Cegan, J. C., Golan, M. S., Joyner, M. D., & Linkov, I. (2022). The importance of compounding threats to hurricane evacuation modeling. npj Urban Sustainability, 2(1), 2.

Disability accommodation in shelters

- During an emergency, it is critical to ensure that those who are deaf, vision-impaired, or have other functional or access needs are accommodated.
- The model addresses these concerns by using census data from the 2018 American Community Survey on the percentage of population within each New England county with a given disability.

Disability Status	Displaced Persons
No Disability	48,370
Hearing Disability	1,321
Vision Disability	1,431
Ambulatory Disability	3,907
Total	55,029



Breakdown of displaced persons by disability status - Massachusetts