Multi-Hazard Vulnerability and Impact Intensification in Coastal Communities: A Methodological Approach for Assessing Interactive Hazard Compounding

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Abstract

Coastlines in tropical and subtropical regions are becoming increasingly vulnerable to coastal hazards (e.g., hurricanes, sea level rise) due to increasing population, fragile coastal ecosystems, aging infrastructure, presence of offshore facilities (e.g., oil rigs and pipelines), increasing activities at ports, valuable coastal resources for local and regional economies. Multi-hazard vulnerability assessment involves identifying and analyzing the interactions between different hazards and their combined effects on the exposed populations, infrastructure, economies, and ecosystems. The cascading effects can occur within a single domain (e.g., environment), or across multiple domains (e.g., drinking water infrastructure and public health), creating complex challenges that amplify the impacts. The objective of this study was to develop a simple methodology multi-hazard vulnerability ranking method to assess the capacity of communities to prepare for, respond to, and recover from hazard events that can occur simultaneously. The numerical comparison of the multi-hazard vulnerability of the exposed systems can be used for decision-making purposes to allocate resources for improving reliance and hazard readiness. A simple ranking methodology was developed to rank and compare the potential impacts of multiple hazards. The multi-hazard vulnerability was illustrated in the case of cascading risks for four hazard factors (for the Gulf of Mexico): hurricane/flooding, flooding (not hurricane related), oil rig spill, and pipeline accident. The vulnerability of the three exposed systems (people, port services, and ecosystem) were estimated and compared. were ranked for three exposed systems.

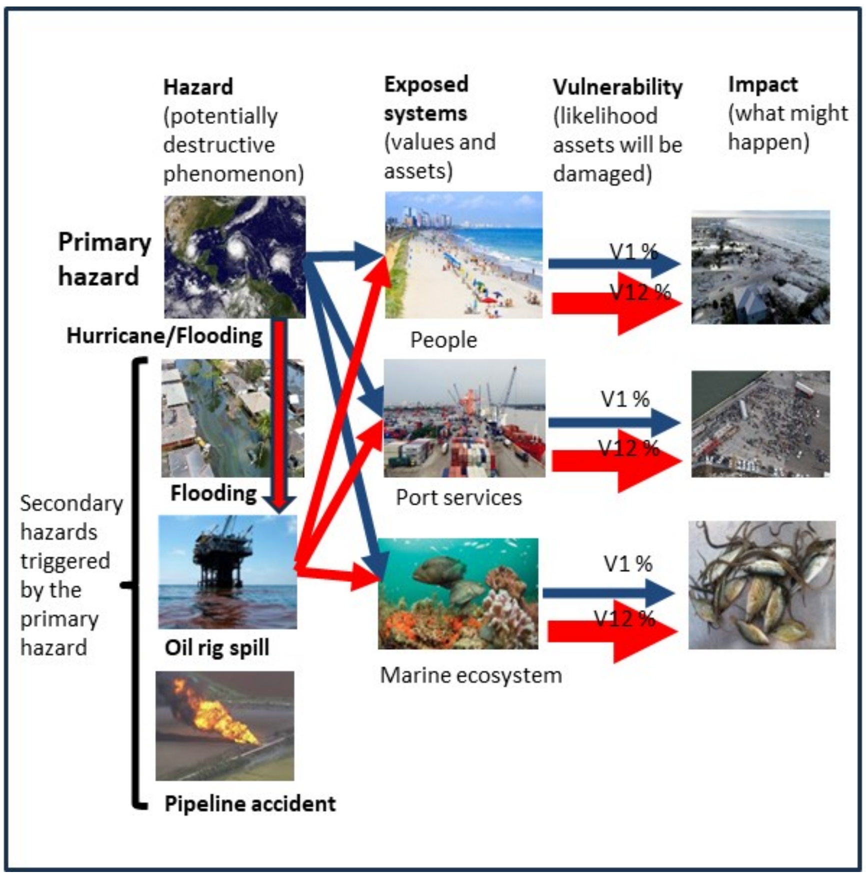
Keywords

Multi-hazards, vulnerability, hazard intensification, cascading risks, coastal communities

Highlights

- Coastal areas are facing growing vulnerability to the occurrence of multiple hazards.
- Increasing population, aging infrastructure, and offshore facilities increase vulnerability.
- Cascading risks can impact multiple sectors.
- Multi-hazards interact and amplify impacts on different multiple systems.
- A numerical ranking framework was developed for comparing multi-hazard impacts on exposed systems.
- Dynamic interactions of exposed systems amplify overall impact.

Graphical abstract



1. Introduction

Increasing land development and population in coastal areas have created highly vulnerable communities that are challenged by the frequency and magnitude of coastal hazards (e.g., hurricanes, king tides, coastal flooding). A hazard is an event that may cause losses or disruptions in the functioning of a system (e.g., loss of life, injury or other health impacts, property damage, social and economic disruption, environmental degradation) (UNISDR, 2016). Exposure is the presence of people, infrastructure, man-made structures, production capacities, tangible resources (e.g., cultural and historical landmarks), and natural resources in hazard-prone areas. The extent to which people or economic assets are at risk is determined by how vulnerable they are (UNISDR, 2009). It is possible to be exposed to a hazard but not be vulnerable (e.g., underground structures may not be affected by wind damage). Vulnerability is the characteristics that are determined by physical, social, economic, and environmental factors or processes that make the communities, assets, or systems susceptible to the impacts of hazards (UNISDR, 2017).

Assessing potential risks due to coastal hazards is complicated due to the interactive characteristics of hazards, exposure elements, and vulnerability (Fig. 1). In addition, in coastal areas, one hazard can trigger additional hazards. For example, a severe hurricane can result in flooding and chemical spills. Exposure elements and vulnerability of the exposed elements also have interactive effects that can amplify the risks.

The vulnerability of a region depends on the characteristics of hazards and exposed systems. Although hazards exist on an individual basis, some hazards result in multi-hazard conditions due to the interaction of the exposed systems. For example, depending on the intensity and precipitation characteristics, hurricanes can result in flooding and oil spills due to damage to oil platforms and pipelines. When two hazards interact (e.g., hurricane/flooding, and oil spills), both the exposure level and vulnerability of the exposed systems would be intensified.

Multi-hazard vulnerability refers to the susceptibility of a system, community, or environment to adverse effects from multiple hazards occurring either simultaneously, sequentially, or as compounding (simple compounding and interactive compounding) events. The objective of this study was to develop a simple methodology multi-hazard vulnerability ranking method to assess the capacity of communities to prepare for, respond to, and recover from hazard events that can occur simultaneously. The numerical comparison of the multi-hazard vulnerability of different vulnerable systems can be used for decision-making purposes to allocate resources for improving reliance and hazard readiness.

2. Multi-hazard vulnerability

The concept of multi-hazard vulnerability recognizes that the presence of multiple hazards can amplify the vulnerability of a system, leading to intensified consequences than the occurrence of each hazard element separately. Addressing multi-hazard vulnerability requires a holistic approach by considering the interplay between different hazards and the combined effects on vulnerable systems. Such models are usually complex and require extensive modeling effort (Ming et al., 2022; Hochrainer-Stigler et al., 2023).

Multi-hazard events can affect exposed systems in different ways. The effect can be simultaneous (i.e., one system exposed to multiple events at the same time), sequential (multiple events occurring in close succession), compounding (one system affected can affect other systems within the same domain), and interactive compounding (i.e., affects can extend beyond system boundaries) manners as shown in Fig. 1.

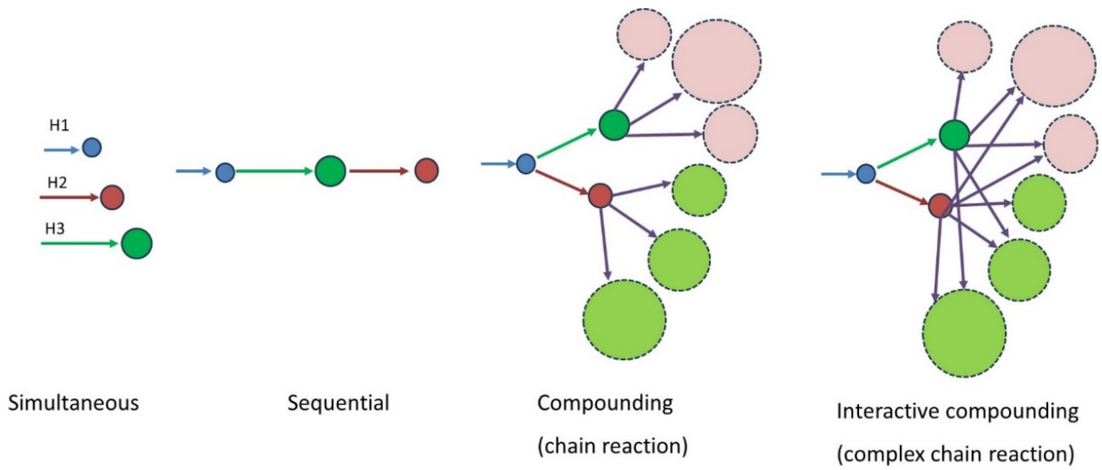


Fig. 1. Multi-hazard vulnerability scenarios for simultaneous, sequential, compounding, and interactively compounding hazard events.

Multi-hazard vulnerability assessment takes into account various factors that contribute to a system's overall vulnerability, including social, economic, environmental, and infrastructural aspects. These systems can interact in complex ways, making some populations or ecosystems particularly susceptible to multiple hazards.

Assessment of multi-hazard vulnerability involves:

1. **Interconnected risks**: Different hazards, such as earthquakes, floods, and storms, may be interconnected, as the occurrence of one hazard increases the likelihood or severity of the impacts of other hazards. For example, a hurricane can lead to infrastructure damage, which in turn can result in increased economic losses and social instability.
2. **Cascading effects**: Cascading effects refer to a chain of events where an initial event or disruption triggers leads to a series of subsequent events, often leading to more significant and widespread consequences. These effects can be particularly challenging to manage because they can amplify the impact of a single risk, affecting various systems

and sectors in unpredictable ways. For example, a hurricane might damage transportation infrastructure, cause loss of power, and/or oil spills due to damage to storage tanks.

3. **Compounding impacts**: Multiple hazards occur simultaneously or in close succession, the overall impact can be intensified, making it harder for communities to recover. For example, a community struggling with drought might be more vulnerable to wildfires.

2.1. Interconnected risks

Risks do not exist in isolation but interact with each other, creating a web of vulnerabilities that can amplify the overall impact of a particular hazard. Interconnected risks are linked in such a way that the occurrence of one risk can influence or amplify the likelihood or severity of other risks (i.e., cascading and compounding effects) (Gill et al., 2022). Interconnected risks are often characterized by high levels of complexity and uncertainty, making them difficult to predict and manage. Understanding these risks requires a holistic approach that considers the interactions between different factors and potential ripple effects. For example, the possibility of an oil spill in a coastal area can lead to other (interconnected) risks, such as the destruction of marine habitats, loss of biodiversity, and contamination of drinking water supplies. These environmental impacts can then lead to economic risks (e.g., loss of tourism, effects on fishing industries) and social risks (e.g., displacement of communities). Managing interconnected risks involves identifying and understanding the linkages between different systems and their associated risks, assessing the potential combined impact, and developing integrated strategies to mitigate or adapt to them.

Interconnected risks often cross the boundaries of systems, affecting multiple areas of society (e.g., economy, transportation, water supply, public health). The interconnected risks exist due to the following factors:

1. **Causal relationships**: Risks can be connected through direct or indirect causal links. For example, climate change can increase the frequency and intensity of extreme weather events, which in turn can lead to flooding, landslides, and infrastructure damage. Each of these outcomes can trigger additional impacts such as public health crises or economic disruptions.
2. **Feedback loops**: Some risks are interconnected through feedback mechanisms, where the outcome of one event feeds back into the system, intensifying the initial effect or creating new ones. For example, deforestation can lead to soil erosion, which reduces aagricultural productivity and increases the likelihood of food insecurity, which can drive further deforestation as people seek new agricultural lands.
3. **Compounding interactions**: Interconnected components can combine to produce effects that are greater than the sum of their parts. For example, during a natural disaster such as a hurricane, the simultaneous impact of strong winds, heavy rainfall, and storm surges can cause widespread destruction, with each element reinforcing the impact of others.

2.2. Cascading effects

Risk propagation refers to the process by which risks spread from one area, system, or entity to another, often intensifying the initial threat and potentially leading to large-scale impacts. This concept is closely related to cascading effects but with a focus on how the initial risk expands and transfers through interconnected systems or networks. Risk propagation and amplification can occur by different mechanisms (Fig. 2).

Cascading effects relate to how an initial event or disruption triggers a series of subsequent events, leading to a chain reaction that can amplify the overall impact. These effects occur when the outcome of one event causes or intensifies another, creating a domino effect where the consequences extend far beyond the initial cause. Systems that are tightly interconnected or have limited redundancy are particularly vulnerable to cascading effects. For example, in a highly interconnected global supply chain, disruption in one part of the world can lead to widespread shortages and economic impacts elsewhere. Systemic vulnerabilities (i.e., weaknesses or vulnerabilities) in a system can facilitate the propagation of risks. For example, poor infrastructure can accelerate the spread of damage during a natural disaster, while inadequate cybersecurity can allow a localized cyberattack to escalate into a widespread data breach. Key factors for cascading effects include:

1. **Sequential triggers**: Cascading effects often unfold in a sequence, where the impact of one event sets off another, which in turn leads to further events. For example, an earthquake might damage a dam, leading to flooding, which then causes landslides and destruction of infrastructure.
2. **Systemic vulnerabilities:** Weaknesses or vulnerabilities in a system can facilitate the propagation of risks. For example, poor infrastructure can accelerate the spread of damage during a natural disaster, while inadequate cybersecurity can allow a localized cyberattack to escalate into a widespread data breach.
3. **Amplification of impacts**: As the effects cascade between interdependent systems, the overall impact can be magnified. For instance, a power outage caused by a storm might lead to failures in communication systems, disrupting emergency responses and worsening the situation.
4. **Cross-domain spread**: Cascading effects often spread across different domains, such as from environmental to social or economic impacts. For example, a natural disaster like a hurricane can not only cause physical damage but also lead to economic losses, public health crises, and long-term social disruption.
5. **Feedback loops**: In some cases, cascading effects can create feedback loops, where the effects of the chain reaction feedback into the system, potentially leading to further destabilization. For example, climate change can cause more frequent and severe wildfires, which in turn release more carbon dioxide, further accelerating climate change.

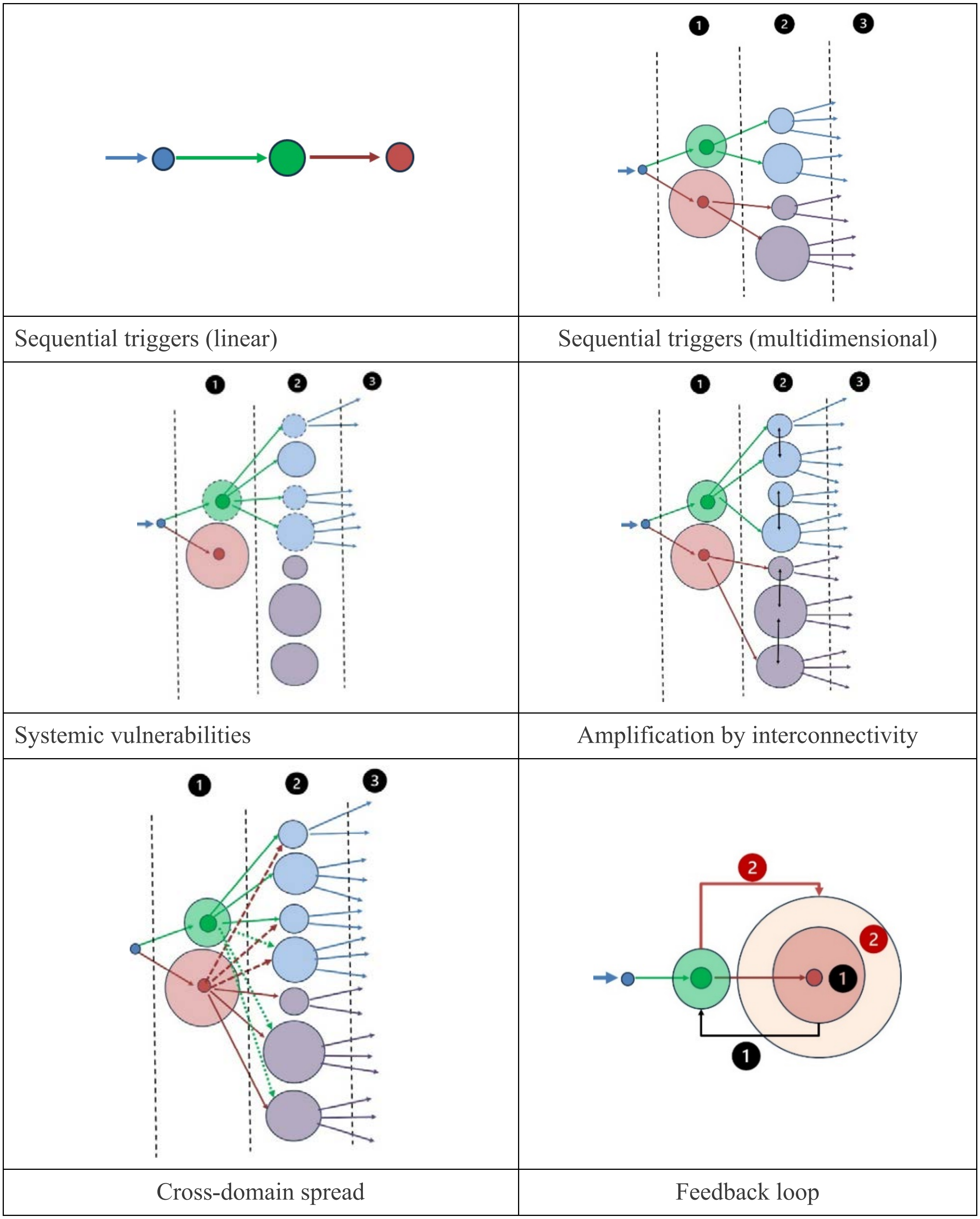


Fig. 2. Risk propagation and amplification and cascading effects.

2.3. Compounding impacts

Compounding impacts refer to situations where multiple risks exist simultaneously or in close succession, resulting in combined effects that are greater than the sum of the individual impacts. The compounded impacts can amplify the overall impacts (i.e., damage) and stress systems beyond their capacity, and make recovery more difficult. The impacts on each affected system can have different intensification profiles across multiple systems and/or with the progression of time (Fig. 3). Therefore, multi-hazard risk assessment requires the consideration of complex, multifaceted, dynamic interactions. In interconnected systems, compounding impacts can lead to systemic failures (i.e., failure of one component of the system spreads, potentially leading to widespread collapse or crisis). Key factors for compounding impacts include:

1. **Simultaneous or sequential events**: Compounding impacts often arise when different events occur at the same time or in quick succession, creating a situation where the effects of one event intensify or worsen the impact of another. For example, a hurricane followed by an infectious disease outbreak can overwhelm healthcare systems and disaster response resources.
2. **Amplified consequences**: The interaction of multiple events can lead to outcomes that are more severe than if each event had occurred independently. For instance, a heatwave during a drought can increase the risk of wildfires, which can degrade air quality and amplify public health impacts.
3. **Cross-domain interactions**: Compounding impacts often involve different sectors, such as the environment, economy, and public health. For example, an economic crisis can reduce the resources available for disaster preparedness, which can worsen the impact of a subsequent natural disaster, which may affect any or all domains.
4. **Nonlinear effects**: The effects of compounding impacts are often nonlinear, meaning that the damage or disruption caused is not directly proportional to the intensity of the events. Small increases in severity or frequency of occurrence can lead to disproportionately large impacts due to the type of interactions between the affected systems.

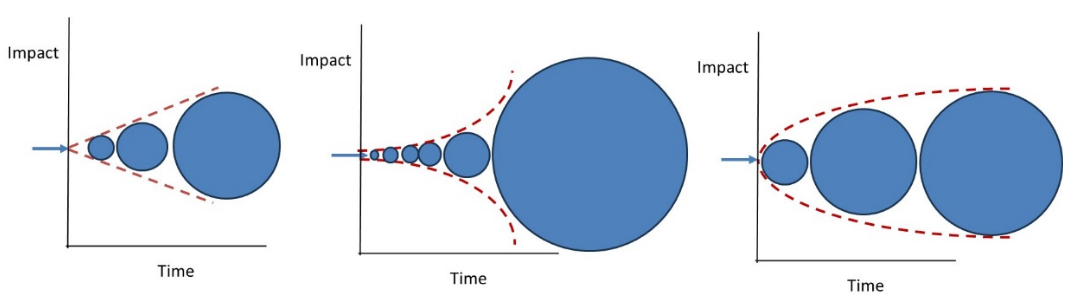


Fig. 3. Examples of hazard impact intensification profiles over time.

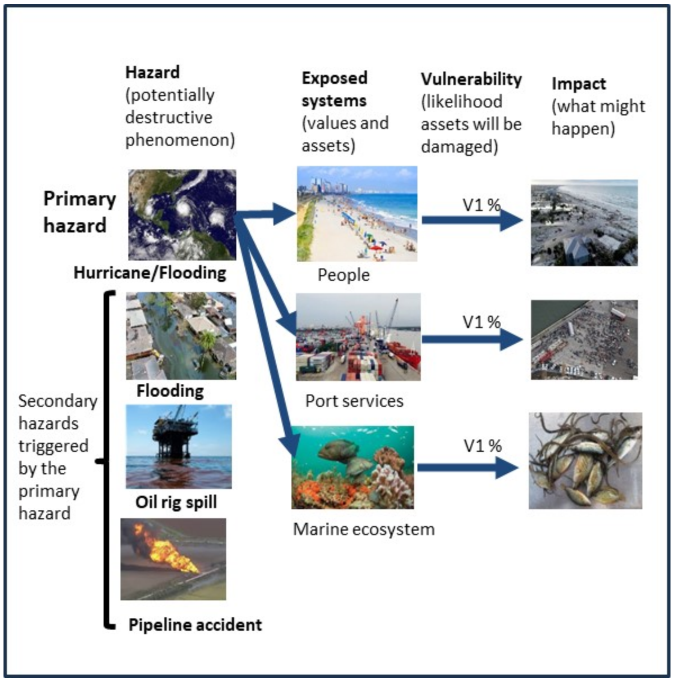
2.4. Complex vulnerabilities

The interrelated elements of complex systems contribute to the overall vulnerability of a system as they interact in intricate ways, often intensifying each other and making the assessment and management of vulnerability more challenging. Complex vulnerabilities can exist due to characteristics of the system, such as:

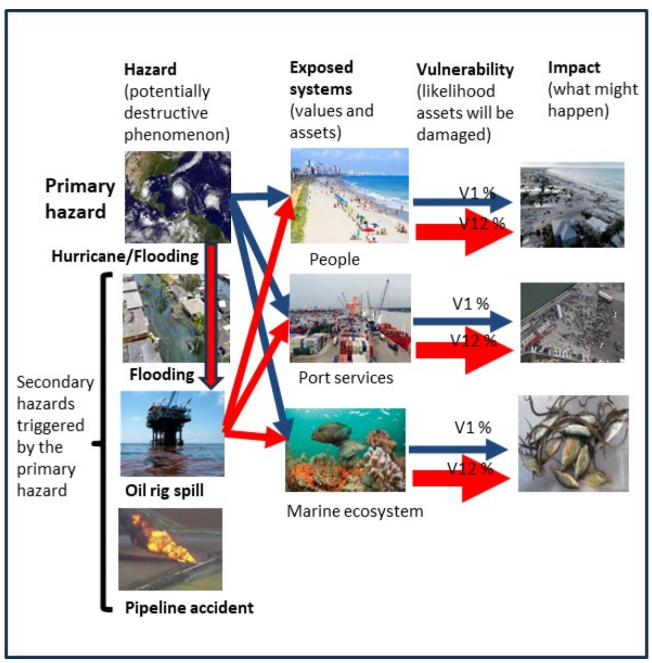
1. **Multidimensional factors**: Vulnerability is not determined by a single factor but by a combination of factors across different dimensions—social, economic, environmental, political, and infrastructural. For example, a community's vulnerability to a natural disaster may be influenced by its economic status, access to healthcare, and local governance.
2. **Interconnectedness**: Complex systems have components that are interlinked, meaning that a change or weakness in one component can impact others. For instance, economic poverty can limit access to education and healthcare, which in turn can reduce a community's capacity to prepare for and respond to hazards.
3. **Dynamic interactions**: The vulnerability of systems is dynamic and changes over time due to external influences such as policy changes, economic shifts, or environmental degradation. For example, urbanization might increase vulnerability to flooding by altering natural drainage patterns and increasing population density in flood-prone areas.
4. **Compounding vulnerabilities**: Multiple vulnerability factors can amplify each other, leading to heightened overall vulnerabilities. For instance, communities in remote locations with economic disadvantages may have limited or no access to information and resources, making them more vulnerable to disasters and less able to recover.
5. **Context-specificity**: The importance and impact of different vulnerability factors can vary depending on the specific context, such as geographic location, cultural background, and the type of hazard involved. For example, the vulnerability factors relevant in a coastal community facing sea-level rise might differ significantly from those in a mountainous area that is prone to landslides.
6. **Systemic vulnerability**: Inherent conditions of a system (e.g., age, maintenance frequency, operational procedures, governance) can affect the vulnerability of other systems. For example, a poorly maintained infrastructure system (e.g., water distribution, wastewater collection, transportation, electric power network) is more vulnerable to disruption during a disaster, which can lead to widespread consequences across society.

3. Vulnerability assessment

Vulnerability of a region depends on the characteristics of hazards and exposed systems. Although hazards exist on an individual basis (Fig. 1), one hazard can trigger other hazard elements, resulting in multi-hazard conditions for the exposed systems. For example, depending on the intensity and precipitation characteristics, hurricanes can result in oil rig spills due to damage to oil platforms. When two hazards interact (e.g., hurricane/flooding with oil spill), both the exposure level and vulnerability of the exposed systems could be intensified significantly.



a. Primary hazard (hurricane) and vulnerable exposed systems.



b. Multi-hazard impacts triggered by primary hazard.

Fig. 4. Primary hazard, hurricane (hurricane/flooding) triggering a secondary hazard (flooding) increasing the overall impact on the vulnerable systems.

4. Methodology

The vulnerability assessment process is essential in risk management, disaster preparedness, and resilience planning as it helps to identify where the greatest risks of damage or loss would occur and where mitigation efforts should be focused. A vulnerability scoring process can be used to assess and rank the susceptibility of systems (e.g., communities, infrastructure) for possible impacts when exposed to specific hazards. Vulnerability scores make it easier to communicate risks to the public and stakeholders, fostering a shared understanding of where and how to focus preparedness efforts.

A simple methodology was developed for estimating cascading risks for a primary hazard, potential secondary hazards, and how the hazards interact and propagate. The occurrence of a primary hazard can trigger secondary hazard factors; thus, the overall impact of a primary hazard can be amplified.

The impact score of the systems (a, b, c) exposed to a hazard (hazard 1) can be expressed as:

$$I_{1a} = E_{1a} \times V_{1a} \quad (1)$$

$$I_{1b} = E_{1b} \times V_{1b} \quad (2)$$

$$I_{1c} = E_{1c} \times V_{1c} \quad (3)$$

Where V_{1a}, V_{1b}, and V_{1c} vulnerability scores and E_{1a}, E_{1b}, and E_{1c} are the exposure scores for systems a, b, and c for hazard 1, respectively. Similarly, the impact vulnerability scores of systems a, b, and c which are exposed to a second hazard (hazard 2), can be written as:

$$I_{2a} = E_{2a} \times V_{2a} \quad (4)$$

$$I_{2b} = E_{2b} \times V_{2b} \quad (5)$$

$$I_{2c} = E_{2c} \times V_{2c} \quad (6)$$

When the primary hazard triggers a secondary hazard, then the overall impact score of the exposed systems a, b, and c for hazard one and the triggered hazard two can be written as:

$$I_{12a} = E_{1a} \times V_{1a} + N_{12a} \times [(E_{12a} \times V_{2a})] \quad (7)$$

$$I_{12b} = E_{1b} \times V_{1b} + N_{12b} \times [(E_{12b} \times V_{2b}) \quad (8)$$

$$I_{12c} = E_{1c} \times V_{1c} + N_{12c} \times [(E_{12c} \times V_{2c})] \quad (9)$$

Where N_{12a}, N_{12b}, and N_{12c} are the intensification factors of each system due to interaction between hazards 1 and 2 for the exposed systems a, b, and c, respectively.

Exposure scoring is used to evaluate and quantify the degree to which people, assets, or systems are exposed to potential hazards. Exposure scoring includes considerations of proximity to hazards, density of exposed assets (e.g., number of homes), duration and frequency of exposure, geographic characteristics (i.e., elevation, topography), and socio-economic factors (i.e., land use patterns, population growth, urbanization). Exposure scoring can be complex, particularly when considering multiple hazards and/or when data are scarce or inconsistent.

Vulnerable systems can have different levels of exposure to specific hazards. An exposure score can be assigned between 0 and 1 depending on the level of exposure. For example, if all systems are exposed to the hazard, then exposure would be 1, and if not exposed to the hazard, then exposure level would be zero. For the case of total exposure:

$$E_{1a} = 1 \quad (10)$$

$$E_{1b} = 1 \quad (11)$$

$$E_{1c} = 1 \quad (12)$$

Then, the overall impact score of the exposed systems a, b, and c for hazard one that will occur simultaneously with hazard two can be written as:

$$I_{12a} = V_{1a} + N_{12a} \times V_{2a} \quad (13)$$

$$I_{12b} = V_{1b} + N_{12b} \times V_{2b} \quad (14)$$

$$I_{12c} = V_{1c} + N_{12c} \times V_{2c} \quad (15)$$

And for three hazards are happening simultaneously (or triggered within a short time of each other):

$$I_{132a} = V_{1a} + N_{12a} \times V_{2a} + N_{13a} \times V_{3a} \quad (16)$$

$$I_{123b} = V_{1b} + N_{12b} \times V_{2b} + N_{13b} \times V_{3b} \quad (17)$$

$$I_{123c} = V_{1c} + N_{12c} \times V_{2c} + N_{13c} \times V_{3c} \quad (18)$$

Hazard scoring methodology was used to assess and rank the severity, likelihood, and potential impact of the multiple hazards considered. This approach helps prioritize risks, guide decision-making, and allocate resources effectively for disaster preparedness, response, and mitigation. By assigning scores to different hazards, organizations, governments, and communities can identify which threats pose the greatest risks and require the most attention.

A scoring rubric was developed to evaluate the relative system vulnerability scores of the selected systems for individual hazards on a scale of 0 (no effect) to 10 (maximum vulnerability). Exposure factors of the systems (evaluated) for individual hazards were scored on a scale of 0 (no exposure) to 1 (maximum exposure). Hazard interaction scores (N) were based on the individual score being one and depending on the potential intensification level due to the interaction of the two hazards on a particular exposed system. For example, if the interaction of two hazards would amplify the impact by 50%, then the interaction score would be 1.50.

5. Numerical example

Gulf of Mexico is one of the most rapidly growing and developed areas in the US. The region is known for its rich energy resources, abundant marine resources, beautiful beaches, and a rich cultural heritage with coastlines from five states, as shown in Fig. 4. The extensive and complex coastline offers a large range of resources and manmade assets that are important for the economic vitality of the region (NOAA, 2011). The Gulf of Mexico coastline is vulnerable to natural disasters (e.g., hurricanes and coastal flooding). The area also has major oil and gas infrastructure (EIA, 2017). However, each segment of the coastline in the Gulf of Mexico does not have the same risks and vulnerabilities. Therefore, vulnerability assessments need to be conducted based on the conditions of the coastal segments.

Relative vulnerabilities of specific coastal segments for specific potential hazards can be quantified based on the characteristics of the vulnerable systems present in the area. The hazards and exposed systems considered for the numerical analysis are presented in Table 1.

Table 1. Factors considered in the impact assessment framework.

<table>
<tr><th>Hazards</th><th>Exposed systems</th><th>Vulnerability factors</th></tr>
<tr><td rowspan="3">Primary hazards
1. Hurricane/Flooding
2. Flooding
3. Oil rig spill
4. Pipeline accident

Interactive hazards (2 hazards)
5. Hurricane/Flooding + Flooding
6. Hurricane + Oil rig spill
7. Hurricane + Pipeline accident

Interactive hazards (3 hazards)
8. Hurricane/Flooding + Flooding + Oil rig spill
9. Hurricane + Flooding + Pipeline accident

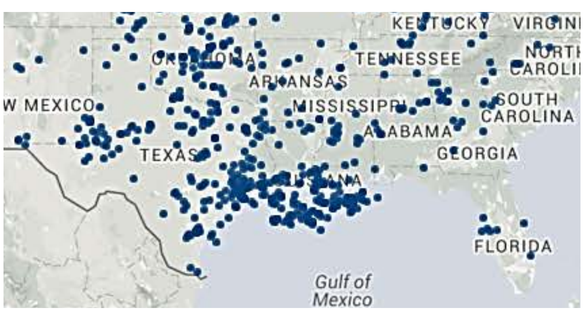
Interactive hazards (4 hazards)
10. Hurricane/Flooding + Flooding + Oil rig spill + Pipeline accident</td><td>a. People</td><td>• Population density
• Economic index
• Dependency on coastal resources</td></tr>
<tr><td>b. Port services</td><td>• Types of services
• Volume of services
• Economic value</td></tr>
<tr><td>c. Coastal ecosystem</td><td>• Diversity of species
• Productivity
• Population of species
• Economic value</td></tr>
</table>

State	Coastline (mi)
Texas	3,359
Louisiana	7,721
Mississippi	359
Alabama	607
Florida	5095 (Gulf), 3331 (Atlantic)

a. States with coastlines in the Gulf of Mexico (left) and the length of coastlines (right).

State	Population in Special Flood Hazard Area
Texas	1,072,642
Louisiana	1,290,051
Mississippi	129,265
Alabama	83,881
Florida	1,645,514

b. The Gulf Coast Special Flood Hazard Area and the inland boundary of counties containing FEMA V-Zones (NOAA, 2011).



State	Incidents	Fatalities	Injuries	Property damage
Texas	1,669	78	371	$668M
Louisiana	590	20	96	$1.42B
Mississippi	114	20	54	$33.4M
Alabama	97	15	42	$29.1M
Florida	56	6	23	$40.6M

c. Significant incidents during 1986-2012 (PST, 2018).

Fig. 4. Coastline and important coastal hazards in the Gulf of Mexico.

5.1. Hazards

The coastal hazards evaluated are: 1. hurricane/flooding, 2. flooding, 3. oil rig spills, and 4. pipeline accidents.

5.1.1. Hurricane/Flooding

For hurricane/flooding hazards, both with and with water damage associated with the hurricane are considered. The Gulf of Mexico is in the path of tropical storms and hurricanes that form in the Atlantic Ocean. Historical storm tracking data show numerous storms have passed through the Gulf of Mexico.

5.1.2. Flooding

For the flooding hazard, the flooding event that is not associated with the hurricane is considered. The flooding event may have occurred before the hurricane event. The Special Flood Hazard Area (SFHA) is defined by the National Flood Insurance Program's (NFIP) floodplain management regulations. For these areas, the purchase of flood insurance is mandatory.

5.1.3. Oil rig spill

Oil rig spills can result from various factors, including extreme weather events like hurricanes, equipment malfunctions, human errors, or structural failures. While hurricanes can damage offshore drilling infrastructure, leading to significant oil spills, other causes such as blowouts, pipeline leaks, and mechanical breakdowns can also contribute to severe environmental disasters.

Some of the largest oil spills that have affected US coastal waters occurred in the Gulf of Mexico (CBD, 2018; NOAA, 2018). Among the numerous oil spills in the past several decades, seven incidents in the Gulf of Mexico are especially notable for the amount of oil spilled, duration of the spill response, and/or resulting environmental impacts (Table 2).

5.1.4. Pipeline accident

Pipelines are the primary mode of transport for crude oil, refined petroleum-based fuels, and processed materials. Spill risk during pipeline transportation is about 4 times higher in comparison to transportation by barges and about 7 times higher in comparison to transport by rail.

Coastal regions are particularly critical in the distribution network of liquid and gas transmission lines, serving as key points for handling and distributing products such as fuel oil. These areas often feature extensive infrastructure to facilitate the transfer and storage of petroleum products, supporting both domestic consumption and international shipping needs. The Gulf of Mexico has been the site of some of the largest and most impactful oil spills in U.S. history, with several incidents causing widespread environmental damage, economic losses, and long-term ecological consequences. According to sources such as the Center for Biological Diversity (CBD, 2018) and the National Oceanic and Atmospheric Administration (NOAA, 2018), seven major oil spills stand out due to the sheer volume of oil released, the prolonged duration of spill response efforts, and the severe effects on marine and coastal ecosystems (Table 2).

Table 2. Most damaging oil spill incidents in the Gulf of Mexico (NOAA, 2018).

Year and name	Spill quantity (million gallons)	Description
1979– Ixtoc	0.4 – 1.2	Exploratory well IXTOC 1 (600 miles south of Texas in the Bay of Campeche, Mexico) blew out. Oil reached Texas beaches.
1979- Burmah Agate	2.6	M/V Burmah Agate collided with the freighter Mimosa southeast of Galveston, causing an explosion and fire.
1984-Alvenus	2.7	T/V Alvenus was grounded in the Calcasieu River Bar Channel southeast of Cameron, Louisiana spilling oil. Oil reached over 100 miles to the west.
1990– Megaborg	5.1	The Mega Borg spilled oil 57 miles south-southeast of Galveston, Texas, following an explosion and fire.
1993- Ocean	0. 336	Three ships collided in Tampa Bay, Florida: the Bouchard B155 barge, the freight ship Balsa 37, and the barge Ocean 255. Nearby beaches, mangrove islands, oyster and seagrass beds, tidal mudflats, jetties, seawalls, and riprap were oiled.
2005–Hurricane Katrina	8	Over 250 oil-related pollution incidents were reported due to Hurricane Katrina. Shallow nearshore areas, coastal and inland wetlands, and sand beaches were impacted.
2010– Deepwater Horizon	200+	The drilling rig Deepwater Horizon explosion released oil for over 87 days, causing damage to marine and wildlife habitats and fishing and tourism industries.

5.2. Vulnerable systems

The vulnerable systems selected for the analyses included: 1. people, 2. port services, and 3. marine ecosystem.

5.2.1. People

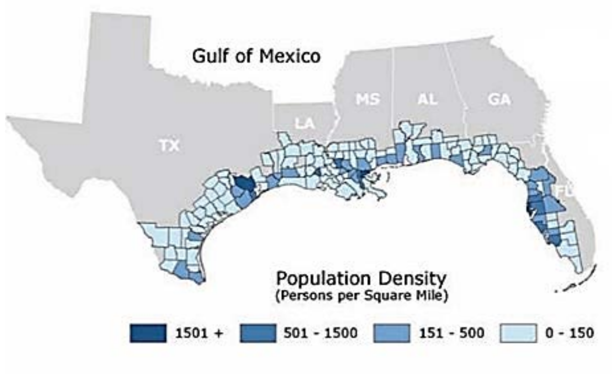
The population of counties on the coastline in the Gulf of Mexico region increased by more than 3 million people (24.5 percent) between 2000 and 2016. By comparison, the United States as a whole increased by 14.8 percent over the same period (Cohen, 2018). Some of the highly populated areas correspond to the major ports.

5.2.2. Port services

Thirteen of the 20 leading ports in the US for tonnage are located in the Gulf of Mexico (NOAA, 2011) (Fig. 3b). Hence, the region plays an important role in the US economy for the import and export of foreign and domestic goods. The Gulf of Mexico is also critical for the Commercial Fishing industry with 10 of the leading 30 most productive commercial fishing ports by value. The top five species landings by poundage in the Gulf of Mexico region using a three-year average from 2004 to 2006 are menhaden (913.4 million pounds), brown shrimp (117.8 million pounds), white shrimp (114.6 million pounds), blue crab (58.9 million pounds), and eastern oyster (21.6 million pounds) (NOAA, 2011; NOAA, 2008).

5.2.3. Marine ecosystem

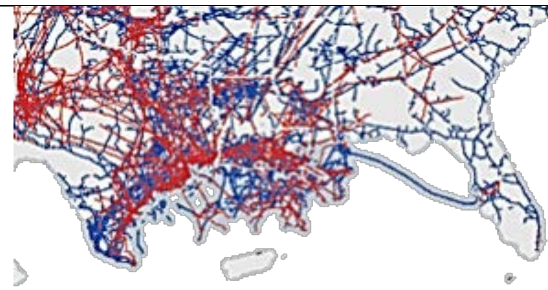
The Gulf of Mexico has very productive ecosystems both in shallow areas and deep waters. Salt marshes and mangrove forests in near-shore areas as well as highly productive deep waters provide rich resources for diverse marine life (e.g., shrimp, crab, fish, migratory birds, reptiles, marine mammals, shallow-water and deep-water corals) and some species have high economic importance. For example, the Gulf region produces about 85% of Eastern oysters (NMFS, 2012) with Louisiana accounting for over 50 percent of the annual oyster fishery (LDWF, 2011). Brown shrimp are an abundant species in estuarine habitats and are also offshore when spawning. Brown shrimp is an important component of the Gulf food web, serving as a food source for many animals. White shrimps are abundant in estuarine marshes and the Mississippi River Delta of Louisiana. Seagrasses, marshes, and mangroves serve as feeding and nursery habitats for post-larval white shrimp (NOAA, 2011). Common shallow-water corals in the Gulf include soft corals, sea whips, sea fans, star corals, and boulder brain corals. Deep-water corals include stony corals, black corals, lace corals, gorgonians, sea pens, and soft corals (NOAA, 2008). Louisiana is a major blue crab production area (GSMFC, 2001). Red snapper supports an active commercial and recreational fishing industry in the Gulf (SEDAR, 2005). Atlantic Bluefin tuna spawns exclusively in the Gulf of Mexico.



a. Population density of coastal counties 2003 (Ocean Services, 2018).

b. Top ports by tonnage in 2009 (NOAA, 2011).

c. Oil and gas platforms (gray) (Fractracker, 2018).



d. Major natural gas and oil pipelines (red: hazardous liquid lines, blue: gas transmission lines) (Groeger, 2012).

Fig. 5. Selected vulnerable systems in coastal areas in the Gulf of Mexico.

5.3. Vulnerability assessment-Numerical example

For the analysis, the vulnerabilities of each exposed system (people, ports, marine ecosystems) were scored from 1 to 10 depending on the potential impact of the hazard on the exposed system. For scoring, the hazard distance can be considered as at or within proximity to the selected segment (e.g., for a hurricane at Category 1, hurricane track passing within 58 miles of the selected coastal segment). The vulnerability rankings for the exposed systems for each hazard occurring individually are presented in Table 2.

Similarly, hazard interaction scores were assigned from 0 to 1 depending on how each hazard may amplify the impact on the exposed systems and added to the main hazard being the base as

1. For example, if the interaction score is 0.50 (i.e., the impact would be increased by 50%), then the overall interaction score would be:

Overall interaction factor = Primary hazard (base case=1) + Intensification score (from 0 to 1)

Overall interaction factor = 1.00 + 0.50 = 1.50.

Table 3 presents the intensification factors for exposed systems when multiple hazards exist. An example set of calculations for estimating the vulnerability scores for individual hazard events when two hazard events occur simultaneously in case of a hurricane/flooding and oil rig spill are presented in Table 4.

Table 2. Vulnerability rankings for hazards occurring individually.

Hazards	Vulnerability (single hazard event)			
	People	Port services	Ecosystem	Overall score
Hurricane/Flooding	7	8	3	18
Flooding	2	1	1	9
Oil rig spill	3	1	5	9
Pipeline accident	1	1	2	4

Table 3. Hazard interaction factors for selected vulnerable systems.

Exposed system - People				
	Hurricane/Flooding	Flooding	Oil rig spill	Pipeline accident
Hurricane/Flooding	1.00			
Flooding	1.20	1.00		
Oil rig spill	1.40	1.10	1.00	
Pipeline accident	1.10	1.10	1.10	1.00
Exposed system – Port services				
Hazards	Hurricane/Flooding	Flooding	Oil rig spill	Pipeline accident
Hurricane/Flooding	1.00			
Flooding	1.10	1.00		
Oil rig spill	1.10	1.10	1.00	
Pipeline accident	1.10	1.20	1.10	1.00
Exposed system - Ecosystem				
Hazards	Hurricane/Flooding	Flooding	Oil rig spill	Pipeline accident
Hurricane/Flooding	1.00			
Flooding	1.05	1.00		
Oil rig spill	1.40	1.20	1.00	
Pipeline accident	1.20	1.20	1.50	1.00

Table 4. Example calculations for the vulnerability of exposed systems (people, port services, ecosystem) for the case of a hurricane/flooding and oil rig spill occurring simultaneously.

Hazards	Vulnerability (interactive hazard event)			
	People	Port services	Ecosystem	Overall
Hurricane/Flooding	V_{1a} = 7.00	V_{1b} = 8.00	V_{1c} = 3.00	18.00
Oil rig spill	V_{2a} = 3.00	V_{2b} = 1.00	V_{2c} = 5.00	9.00
Interaction factor	N_{12a} = 1.40	N_{12b} = 1.10	N_{12c} = 1.40	
Equation	$I_{12a} = V_{1a} + N_{12a} \times V_{2a}$	$I_{12b} = V_{1b} + N_{12b} \times V_{2b}$	$I_{12c} = V_{1c} + N_{12c} \times V_{2c}$	
Hurricane/Flooding + Oil rig spill	7.00 + 1.40 (3.00) = 11.20	8 .00+ 1.10 (1.00) = 9.10	3.00 + 1.40 (5.00) = 10.0	30.30

6. Results

Vulnerability scores for the exposed systems and overall vulnerability for single and multi-hazard scenarios are presented in Table 5. The analyses showed that the overall impact of a hurricane would be intensified significantly when the winds and flooding due to a hurricane trigger other hazard events (i.e., oil rig spill, pipeline accident).

Fig. 6 compares the relative vulnerability scores of exposed systems (people, post services, and ecosystem) for single and multi-hazard scenarios. Higher impact scores for multi-hazard scenarios indicate that systems are more vulnerable to cascading failures and prolonged disruptions. A hurricane/flooding event (considered as both a wind and flooding event) if it triggers additional hazards (e.g., impact in an already flooded area, oil rig spill, pipeline accident), the exposed systems would be impacted at a significantly higher level. For example, a hurricane/flooding event may not alone affect the ecosystem significantly. However, the occurrence of an oil rig spill during such a hurricane can lead to significant damage to the ecosystem (Table 4 and Fig. 6).

Comparing impact scores across different systems helps prioritize resilience measures, such as strengthening emergency response for people, enhancing port infrastructure to withstand multiple threats, and implementing conservation strategies to protect ecosystems. By systematically comparing the overall impact scores for single and multiple hazards, stakeholders can develop comprehensive risk reduction strategies, allocate resources effectively, and enhance the resilience of exposed systems.

Table 4. Vulnerability scores for the exposed systems and overall vulnerability for single and multi-hazard scenarios.

Hazards	**Vulnerability (interactive hazard event)**			
	People	**Port services**	**Ecosystem**	**Overall**
Hurricane/Flooding	7.00	8.00	3.00	18.00
Flooding	2.00	1.00	1.00	4.00
Oil rig spill	3.00	1.00	5.00	9.00
Pipeline accident	1.00	1.00	2.00	4.00
Hurricane/Flooding + Flooding	9.40	9.10	4.05	22.55
Hurricane/Flooding + Oil rig spill	11.20	9.10	10.00	30.30
Hurricane/Flooding + Pipeline accident	8.10	9.10	5.40	22.60
Hurricane/Flooding + Flooding + Oil rig spill	13.60	10.20	11.05	34.85
Hurricane/Flooding + Flooding + Pipeline accident	10.50	10.20	6.45	27.15
Hurricane/Flooding + Flooding + Oil rig spill + Pipeline accident	14.70	11.30	13.45	39.45
Flooding + Oil rig spill	6.20	2.10	8.00	16.30
Flooding + Pipeline accident	3.10	2.10	3.40	8.60
Flooding + Oil rig spill + Pipeline accident	7.30	3.20	10.40	20.90

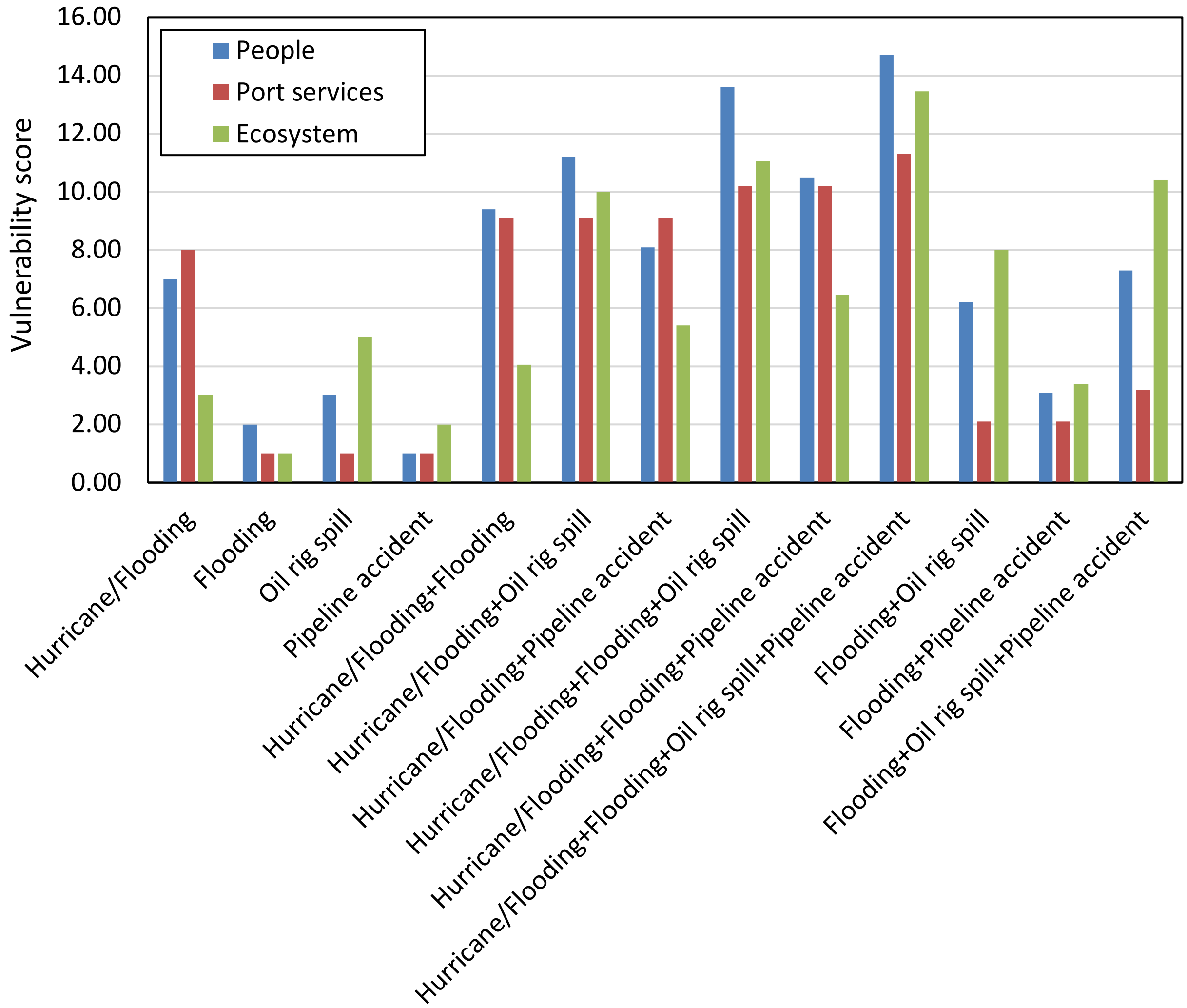


Fig. 6. Comparison of the impact scores of the exposed systems for single and multiple hazards.

The overall impact scores for single and multiple hazards for the exposed systems considered (people, port services, ecosystem) are compared in Fig. 7. By evaluating how each system is affected under various hazard conditions, decision-makers can develop targeted strategies to mitigate damage and enhance adaptive capacity.

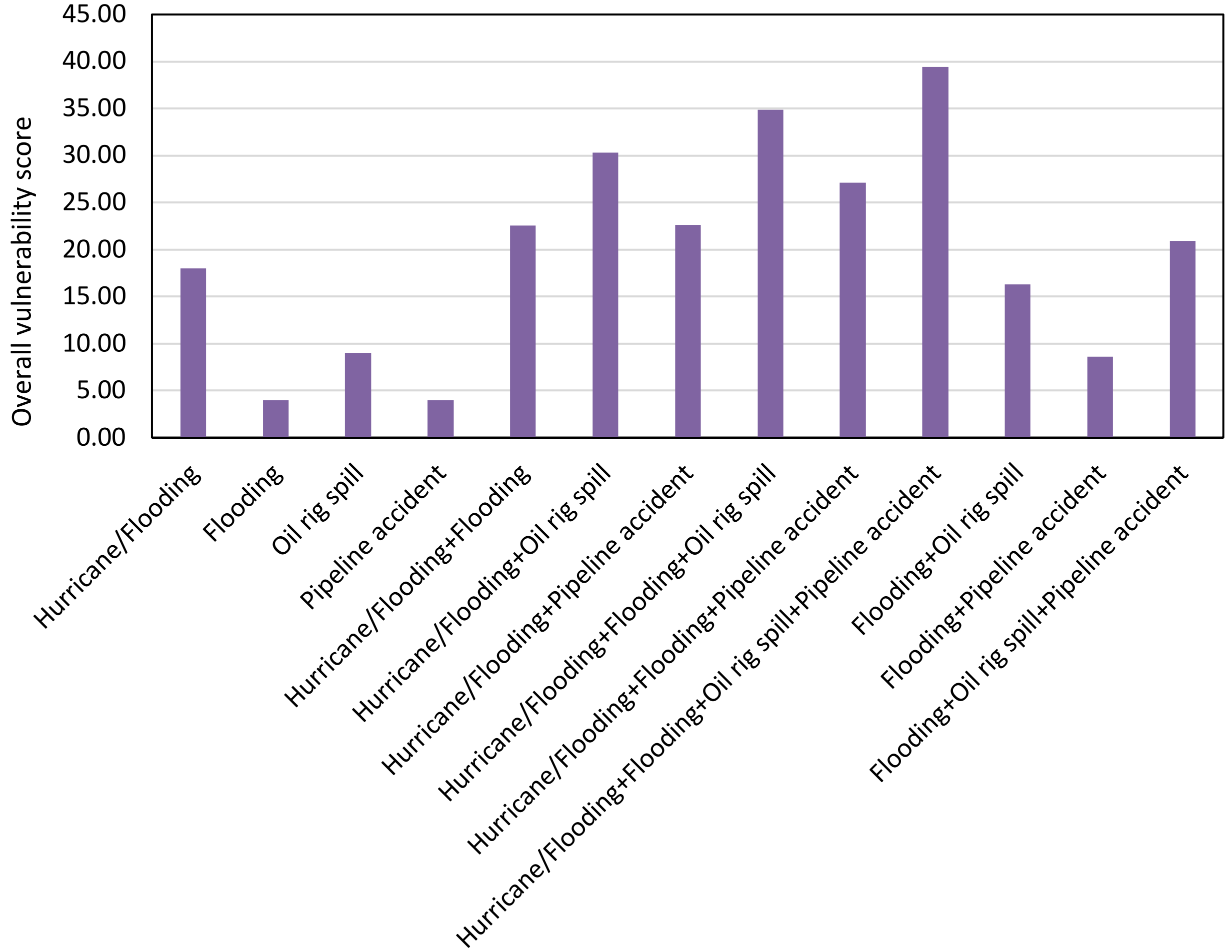


Fig. 7. Comparison of the overall impact scores for single and multiple hazards for the exposed systems considered (people, port services, ecosystem).

7. Conclusions

Coastal vulnerability is increasing with increasing in the size of the exposed elements and level of exposure which increases the vulnerability of coastal areas to natural and manmade hazards. However, understanding the complex interactions between different hazard factors and the exposed systems during a major disaster remains a significant challenge. Comparison of the vulnerability scores for the individual and multi-hazard scenarios allows to identify the most vulnerable systems and allocate resources accordingly to improve the resilience of the exposed systems. Comparing vulnerability scores helps prioritize mitigation and adaptation measures for the most at-risk systems. Limited resources can be directed toward infrastructure retrofitting, emergency preparedness initiatives, and policy interventions where they are needed most.

A predictive methodology was developed to compare the relative vulnerabilities of coastal areas for individual hazards and the interactive effects of multiple hazards in view of the vulnerable elements present in individual coastal segments. The approach relies on an expert opinion-based and/or survey-based scoring system to systematically quantify the vulnerabilities of exposed systems (e.g., people, port services, and marine ecosystems) for individual hazards as well as for scenarios where two or more hazards occur simultaneously.

The impact quantification methodology developed in this study serves as a simple and practcal tool for disaster planning and risk assessment, enabling the identification of the most vulnerable systems and the comparative analysis of exposure across different coastal regions. By capturing the amplification of vulnerability that develops when multiple hazards interact, the methodology highlights how the combined effects of two hazards can lead to significantly greater impacts than when each hazard event occurs individually.

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