Developing an Analytical Framework for Optimizing Disaster Relief Preparedness to Coastal Hazards

A Preliminary Investigation of Factors Affecting Supply Chain Resilience in Hawai'i

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16. Abstract
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The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education, and technology transfer to improve *people's mobility and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment, and 4) managing mobility in high growth areas.

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Disclosure

Principal Investigator, Co-Principal Investigators, others conducted this research titled, "Developing an Analytical Framework for Optimizing Disaster Relief Preparedness to Coastal Hazards: A Preliminary Investigation of Factors Affecting Supply Chain Resilience in Hawai'i" in the Department of Urban and Regional Planning at the University of Hawai'i at Manoa. The research took place from August 2019 to September 2020 and was funded by a grant from the Pacific Southwest Region University Transportation Center in the amount of $ $24,636. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Abstract

With more recognition of climate change's advent and seriousness, it is widely recognized that there could be more severe and frequent disruptions with the existing transportation infrastructure system. When the current infrastructure systems are overwhelmed and disrupted, communities depend on disaster relief supply chains to maintain the community's lifeline and improve disaster assistance response. In particular, the disaster relief supply chain is vital to Hawai’i's communities, given Hawai’i's susceptibility to coastal hazards, sea-level rise, remoteness, and heavy dependence (over 90 percent) on imported goods and fuel. The project conducted stakeholder interviews to investigate the key factors that influence Hawai’i's disaster relief preparedness to coastal hazards and improve Hawai’i's disaster relief supply chain's resilience. The information collected was used to understand the status quo, identify the gaps in preparedness, and develop an analytical framework for optimizing disaster relief supply allocation. By interviewing the key stakeholders involved in the local disaster relief preparedness process, this project was able better identify the primary coastal hazard scenarios of concern, the significant concerns in preparing for disasters, the challenges in the planning process, and decision constraints. To overcome the barriers, we propose to develop and apply more resilient strategies such as establishing warehouses, stock more materials as a backup plan, optimize the location and allocation of redundant supply, and include more E.M. stakeholders (e.g., private sectors and non-profit organizations) into the disaster planning processes as well as invite them to the routine disaster exercises. Finally, the information collected was refined and abstracted to develop a simplified two-stage optimization model for warehouse selection and stock allocation to illustrate the analytical framework.

Developing an Analytical Framework for Optimizing Disaster Relief Preparedness to Coastal Hazards

-- A Preliminary Investigation of Factors Affecting Supply Chain Resilience in Hawai'i

Executive Summary

The archipelago of Hawai'i is one of nine regions that compose the FEMA Region 9 area of operations. About the Pacific Basin regions, FEMA states,

> *"The Region faces complex logistical challenges in preparing for and executing recovery operations … particularly due to the "tyranny of distance"… Due to their geographic isolation and concentration of population … the pacific jurisdictions face … a "perfect storm" of vulnerability" (1).*

With these unique challenges, it is critical that the State of Hawai'i plan for logistical resilience. Unlike other regions, Hawai'i will be mainly left to rely on its resources following a disaster(*1*). In tandem with these geographic challenges, Hawai'i also experiences impact from multiple weather-related events such as hurricanes, tsunamis, tropical storms, high tides, king tides, and sea-level rise. These events' impact creates flooding that can hinder people and supplies around the islands, as many critical roads hug the coastline.

This report details our study's findings that work within the nexus of disaster relief supply chain resilience and transportation vulnerability to flooding on O'ahu's island. The project focused on qualitative interviews with stakeholders to build a preliminary analytical framework to identify factors that influence disaster relief supply chain resilience on O'ahu. Qualitative interviews provided a good overview of the status quo of disaster relief planning and preparedness on O'ahu and the challenges and constraints faced by stakeholders involved. In particular, the research team has identified the following obstacles for Hawai'i Emergency Management regarding disaster relief preparedness.

- Spatially, many communities and infrastructure are along the shoreline, such as ports, airports, and major roadways, making the communities and infrastructure physically exposed to coastal hazards. Vulnerability is exacerbated by a high dependence on Honolulu Harbor and the airport, which requires considerable time and resources to recover if damaged. On the other hand, there is no emergency warehouse for backup supply. Most suppliers on the island (e.g., grocery stores) depend on "just in time" inventory, which might lead to empty shelves before and immediately after the disaster if the supply chain is interrupted.
- As a result, disaster relief supplies on O'ahu are limited and may not support O'ahu's population if a coastal hazard critically impacts Honolulu Harbor. Currently, responsibility for provisioning of disaster relief supplies is primarily placed on the public of O'ahu through the state recommended 14-day household provision of supplies.

- There is a wide acknowledgment of the disaster relief supply chain's vulnerability across sectors due to the Hawaiian Islands' geographic location. Yet, the degree to which the vulnerability is given weight differs. Some organizations see such vulnerability as a pressing obstacle that must be addressed. In contrast, others see the supply chain as secondary to other life-saving services or day-to-day operations.
- There are currently efforts trying to break silos and collaborate across jurisdictions and sectors to address such vulnerability, but much needs to be done to strengthen such collaboration. We found that stakeholders might have inaccurate assumptions about other organizations' responsibilities and missions and incorrectly assume what other organizations would do during disasters.

Given these obstacles and constraints, we suggest the following to strengthen the disaster relief supply chain resilience on O'ahu: 1) Create more opportunities for various stakeholders to know each other's roles and responsibilities. 2) Facilitate more collaboration and coordination between multiple stakeholders (e.g., federal and state agencies and between governments and private sectors). 3) Include more stakeholders (e.g., private and non-profit organizations) into the disaster planning process and invite them to the regular disaster exercises. 4) Create backup plans and increase the relief supply redundancy to complement the "just in time" inventory for worst-case scenarios. 5) Develop plans to optimize the preposition of relief supply inventory to facilitate timely distribution to various communities after a disaster.

Coupled with the interviews' findings, GIS-based vulnerability analysis was performed to better understand which transportation road networks, alternative warehouse locations, and the potential distribution centers will be affected by the various flooding scenarios. The information was used to develop a simplified two-stage optimization model to optimize relief supplies' location and allocation under different coastal flooding scenarios.

1. Introduction

Coastal zones worldwide host the majority of the earth's population and economic activities (2). Within the United States, coastal counties make up approximately 10% of the landmass but contain 39% of the population. The population density of American coasts is four times higher than inland counterparts (3). Due to people's concentration and economic activities, it is imperative to manage and prepare for the hazards that threaten coastal areas.

With more recognition of climate change's advent and seriousness, it is widely acknowledged that coastal areas' existing infrastructure system could be disrupted more severely and frequently. The more frequent and intense flooding from rising sea levels and storm surges has increased the risk of delays, disruptions, and damage across the transportation systems (*4*). Recurrent flooding and inundation already significantly burdened major roads in low-lying areas in Washington, D.C, Maryland, Virginia, New Jersey, San Francisco, and South Florida (*5*). Coastal communities have also been overwhelmed by major storms such as Hurricane Katrina (2005), Ike (2008), Irene (2011), and Sandy (2012), Harvey (2017), and Irma (2017). The frequency and magnitude of such climatic hazards are projected to increase with climate change. The damage to critical infrastructures and emergency facilities could become significantly more destructive than before.

The disaster relief supply chain provides essential goods to support the economy and community when the existing infrastructure system's ability to cope with the impacts is disrupted and overwhelmed (*6*). Its resilience becomes more prominent with the threats of climate change. The disaster relief supply chain's resilience could mean the difference between life and death (*6*). With Hawai'i's susceptibility to coastal hazards, the islands' topographic characteristics, rising sea-levels, geographical remoteness, and heavy dependence (over 90 percent) on imported goods and fuel (*7*), the disaster relief supply chain is of vital importance to communities in Hawai'i.

This project uses mixed methods to investigate the key factors influencing Hawai'i's disaster relief preparedness to coastal hazards to improve Hawai'i's disaster relief supply chain's resilience. Combined with vulnerability analysis, this project uses information collected from stakeholder interviews to identify gaps and challenges in current preparedness, understand the decision factors and constraints, identify the possible alternatives, and develop an analytical framework for optimizing the supply allocation. The study area is the island of O'ahu. It includes considerations of both long-term coastal hazards (i.e., sea-level rise, erosion) and extreme scenarios (e.g., hurricane, tsunami, storm surge, wave action). In particular, it intends to achieve the following objectives:

- Identify the key stakeholders for Hawai'i disaster relief preparedness, their responsibilities, and current preparedness.
- Through key stakeholder interviews, identify the primary coastal hazard and climate change scenarios of concern, preparation capacity in typical and extreme scenarios such as storage and warehouse capacity, existing plan and decision-

making concerns and constraints, information sharing and coordination among stakeholders, and gaps to address in plans.

- Refine and abstract information to extract critical factors for developing an analytical framework using a simplified two-stage optimization model.

1.1 Report Layout

This report presents the research findings in the following chapters to achieve the study objectives.

Chapter 1 presents the introduction and objectives of the study.

Chapter 2 provides a review of related concepts and knowledge from the literature.

Chapter 3 introduces the case study area and hazards scenarios of concern.

Chapter 4 describes the study design and methods.

Chapter 5 summarizes the findings from stakeholder interviews and identifies analytical gaps.

Chapter 6 proposes an analytical model for warehouse location optimization.

Chapter 7 shares conclusions and recommendations.

2. Literature Review

2.1 Overview

Supply chains can be complex and multilayered systems. Depending on the product or service distributed, the suppliers and consumers, and the regulatory frameworks with which a supply chain may reside, a supply chain can have various characteristics and shapes. A disaster relief/humanitarian supply chain adds another layer of complexity. This section will outline some different ways to conceptualize supply chains and disaster relief supply chains.

Disaster relief supply chain management finds its roots in private sector supply chain management. However, while a significant portion of the literature has come from the private sector and their need to procure and ship products logistically, the scope of this study, and disaster relief in general, extend beyond the requirements of corporate supply-chain management and focus more on what the public sector could do to improve its resilience. Supply chains consist of supply nodes, demand nodes, links, and tiers at its most elemental level. These are defined by the (*8*) (pg. 2-3) as:

- Supply Nodes – Entities that manufacture, process, store, and/or ship goods and services. For example, harbor, airport, or warehouses are examples of supply nodes.
- Demand Nodes – Entities that purchase and/or signal for goods and services from supply nodes. They generally include individuals, families, businesses, and governments. Examples include stores, businesses that purchase products, and the consumers on O'ahu (i.e., the population in need of disaster relief).
- Links – The physical and functional connections between nodes, such as communication, transport, or transaction connections. In this study, we consider links as the transportation connectivity between supply and demand nodes.
- Tiers – A common way to group nodes and identify upstream and downstream relationships within the supply chain. Tier 1 suppliers provide products or services to the producer/processor; Tier 2 suppliers provide products or services to Tier 1 suppliers; Tier 3 suppliers provide products or services to Tier 2 suppliers. As the Tier numbers get higher, the further that supplier is from the finished product's producer/processor. This study only focuses on the downstream supply chain with suppliers directly providing products to supply nodes and excluding the upstream supply chain discussion.

For this study, we are primarily interested in the supply/demand nodes and links and how coastal hazards impact these parts. Note that we are not dealing with the entirety of the supply chain, stretching to each piece from production, packaging, processing, and labeling that may extend across the globe. Instead, our study focuses on those nodes and links of the supply chain, forming the disaster relief distribution network on the Island of Oahu.

This has implications for the scope of decision-making dealing with risks. Given the unique geography of Hawai'i, most products consumed on the island are imported. The links import products from off-island origins that are particularly vulnerable to disruption in the event of severe weather. When severe weather disrupts this link, what is harmed is the relationship between the focal firm and the market (between the firm and downstream actors). What is not affected is the relationship between the focal firm and its upstream suppliers, which amounts to the difference between demand risk and supply risk.

Supply chain management may have similar characteristics in everyday operations and during a disaster, but their purpose is very different between scenarios. During normal operations, the end goal is to gain a monetary exchange for a product. In contrast, in the disaster relief context, the end consumer does not offer a monetary exchange, nor do consumers choose the goods they receive. Therefore, disaster relief actors must efficiently supply impacted communities' needs while under various constraints (*9*). These humanitarian aspects lay outside of traditional logistic services. While disruptions to supply chains negatively affect revenue and costs, these disruptions affect people's lives in circumstances with an added humanitarian element.

2.2 Terminology

It is essential to define the terminology of disaster relief supply chains. Throughout the literature, various terms are used. For example, humanitarian aid can also be referred to as humanitarian assistance; disaster relief can also be humanitarian relief. Additionally, these terms are often married together, such as humanitarian aid and disaster relief (HADR) (*10*). Within Honolulu, the disaster organization developed in 1994 also matches the terminology together, referred to as the Center for Excellence in Disaster Management and Humanitarian Assistance (CFE-DMHA) (*11*).

The term relief first put forward by Long & Wood (1995), later echoed by (*12*), is described as "a foreign intervention into a society to help local citizens" (pg.101). Kovács and Spens (*12)* distinguish between two types of humanitarian logistics: continuous aid work and the second disaster relief. For disaster relief is aimed at dealing with sudden catastrophes, both natural and manmade, yet primarily natural disasters. For this study, we will adhere like Day et al. (2012, pg. 24) to the broader definition of disaster put forth by the International Strategy for Disaster (2004 pg.3) as,

> *A serious disruption of society's function, posing a significant, widespread threat to human life, health, property, or the environment, whether caused by accident, nature or human activity, and whether developing suddenly or as a result of complex, long term processes.*

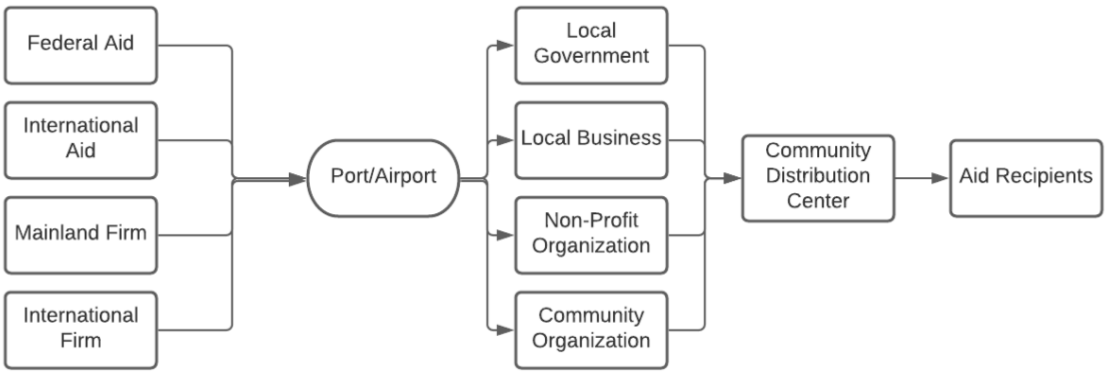
Beyond reconciling humanitarian aid and disaster relief, there is an added layer of comparison between logistics and supply chain management (SCM). Day et al. (*6)* address the relationship between humanitarian/disaster relief logistics and humanitarian/disaster relief supply chain resilience. Although these two fields are differentiated, their arena of research is similar and overlapping. There is yet to be a distinct demarcation between what falls within the realm of humanitarian/disaster relief logistics vs. humanitarian/disaster relief supply chain management. Larson and Halldorsson (*13)* discuss SCM's evolution and the understanding of SCM about the traditional understanding of business. They denoted four different perspectives of SCM and purchasing (Logistics as a subset of purchasing): traditionalist (where purchasing subsumes SCM); relabeling (purchasing becomes SCM); unionist (SCM subsumes purchasing); intersectionist (purchasing and SCM are related and overlapping but different. Day et al. (*6)* adhere to the unionist perspective, whereby SCM subsumes purchasing and logistics. For this research, humanitarian/disaster relief logistics will be considered a subset of humanitarian/disaster relief supply chain management.

To clarify, disaster relief is a subset of humanitarian efforts focused on sudden catastrophes, both manmade and naturally occurring. Logistics is a subset of purchasing, which is a part of the broader practice of SCM. Disaster relief supply chain management is the management of all aspects of a supply chain, including logistics. In this report, some of the terms might be used interchangeably due to different scholars' various terminology on the subject to clarify the terminology. More specifically, Day et al. (*6)* define disaster relief supply chain management as:

> *"The system that is responsible for designing, deploying, and managing the processes necessary for dealing with not only current but also future humanitarian/disaster events and for managing the coordination and interaction of its processes with those of supply chains that may be competitive/complementary. It is also responsible for identifying, implementing, and monitoring the achievement of the desired outcomes that its processes are intended to achieve. Finally, it is responsible for evaluating, integrating, and coordinating the activities of the various parties that emerge to deal with these events." (pg. 28)*

A humanitarian supply chain can be conceptualized in multiple ways due to the multifaceted character of supply chains. The DHS offers two ways to conceptualize disaster relief supply chains as complex, multifaceted systems across large geographic areas (*8*). One method called the "Community Lifeline Framework" outlines the critical areas for jurisdictions to focus on during a disaster event. The Community Lifeline Framework focus areas include Safety and Security, Food, Water, Shelter, Health and Medical, Energy (Power & Fuel), Communications, Transportation, and Hazardous materials are meant to facilitate unity among the entirety of an affected community, including the various levels of government, private sector, and non-governmental organizations (*8*). Another method of conceptualizing a disaster relief supply chain offered by the DHS is based on a more logistics planning approach with the following considerations: Supply Source, Distribution Points, Inventory, Access and Re-entry, Routes, Fuel, Transportation Operators (*8*). Oloruntoba and Gray (*14)* depict a multilateral basis of a typical humanitarian supply chain with international agencies and NGOs. We adapted the concept and described the local humanitarian supply chain in Hawai'i as below in Figure 2.1.

Figure 2.1 Local Humanitarian Supply Chain (adapted from (*14*))



This study only focuses on disaster relief related transportation and logistics problems within the definition of disaster relief supply chain management set forth by (*6*) to more efficiently offer relief to people dealing with sudden catastrophes caused by coastal hazards. More specifically, the study's focus is narrowed to emergency food supply considering potential disruption to the transportation network, shelters, and community distribution centers by coastal hazards.

2.3 Disaster Relief Supply Chain Resilience

While originating in ecosystems research, the concept of resilience has been employed by multiple disciplines, such as engineering, organizational research, and urban system. This conceptual background provides the framework from which supply chain resilience was developed (*15*), (p. 3). A supply chain's resilience affects disaster relief and humanitarian situations because it constitutes the chain's engineered and managerial strength vis-à-vis shocks. In O'ahu, this means that the continued supply of necessities to communities during a crisis is partially dependent on supply systems' resiliency.

As initially defined in the 1973 article, resilient systems had two distinct properties; first, they possessed the ability to absorb changes; and second, they could return to an equilibrium state after a temporary disturbance (*16*). The faster a system returns to normalcy after a disturbance, the greater its resilience (*17*), (p. 125). The concept has been clarified since this original article to mean "the capacity of a system to undergo disturbance and maintain its functions and controls" (*18*), (p. 765). Applied to supply chains, the concept of resilience builds upon the previous literature by combining them with managerial studies of risk and vulnerability. Both supply chain managers and stakeholders utilize techniques to maintain controls over supply chain functioning so that it continues to persist. At their disposal are such measures and tools as flexibility, agility, adaptability, and visibility that form managerial capabilities by which supply chains can increase in their resilience (*15*), (p. 6).

From this multidisciplinary perspective, Ponomarov and Holcomb developed the following definition of supply chain resilience: "The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (*17*). A similar definition is presented by Ponis: "the ability to proactively plan and design the Supply Chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post-event robust state of operations, if possible, more favorable than the one before the event, thus gaining competitive advantage" (*19*), (p. 921). Both of these definitions contain three stages: a proactive stage or preparedness for a shock, a reactive stage or a response to a shock when it occurs, and a transition stage or the recovery from the response state to a new state altogether.

These three stages inherent in the definition of resilience are easily adapted to disaster management situations. The proactive stage includes hazard mitigation and disaster preparedness. The reactive stage includes an emergency response. Finally, the transition stage includes disaster recovery (*17*), (p. 129). On this last note, the question remains whether a supply chain should return to its previous equilibrium state after an initial disruption (*15*), (p. 4). Given disruptions, the opportunity exists to be seized such that the supply chain is built back better than before (*20*), (p. 36). Knowing the definition of resiliency is necessary for determining measurements and knowing what the resiliency returns to. This study mainly focuses on developing effective long-term planning strategies in the proactive stage to prepare for an efficient reactive stage.

2.4 Stakeholders and Actors

As highlighted before, a supply chain is a culmination of various entities and actors, and a humanitarian supply chain will have added actors. Kovács and Spens *(12)* groups humanitarian supply chain actors into seven different groups: Aid agencies, NGOs; Logistics Service Providers; Military; Governments; Suppliers, and Donors. This list of actors has been criticized for omitting the beneficiaries of supplies during a disaster. Some see the beneficiaries as customers influencing the demand of a supply chain (*14*), and others see aid agencies as determining demand through a needs assessment (*21*). Another interesting stakeholder that could be considered is the media. Van Wassenhove *(22)* highlights the impact that media can have on soliciting donors for a disaster. Kovács and Spens *(12)* argue that the media does not have a true role in disaster relief supply chain distribution and should not be considered a stakeholder.

Schiffling and Piecyk *(23)* could list the largest number of stakeholders in humanitarian supply chain management. Through a systematic literature review and considering the salience of stakeholders in humanitarian supply chains, they found 11 key types of stakeholders to consider when looking at the roles of stakeholders in humanitarian supply chain management, and those are as follows: beneficiaries; suppliers; governments; donors; field staff; Other NGOs; Logistics Providers; Military; headquarters; media and volunteers.

When considering the stakeholders and actors involved in a disaster relief supply chain, the list can be expansive and may come together differently in different areas. The critical thing to keep in mind is that a supply chain for disaster relief is a complicated network of different actors, including at the very minimum government actors, private actors, non-government aid groups, as well as the beneficiaries of aid or relief, and sometimes depends on the type of disaster that happens. This study identified the key stakeholders and actors through preliminary interviews with emergency management experts in the case study. We took a snowball sampling method to expand the interviewees' list.

3. Study Area

Due to the Pacific Ocean's remote location, the Hawaiian Islands face unique disaster relief supply chain resilience challenges. Unlike the continental United States, options for prepositioning disaster relief goods in adjacent states are limited or non-existent. This creates challenges in delivering relief and supporting recovery if impacted by a large weather event.

Within the Hawaiian context, due to the remote location, and the fact that Hawai'i is an archipelago, the harbors play an imperative role in its supply chain. There are ten commercial harbors on six islands of Hawai'i (O'ahu, Molokai, Hawai'i, Kaua'i, Maui, and Lāna'i), where Honolulu harbor on the island of Oahu acts as the hub for inter-island cargo, as well as cargo coming to Hawai'i from the mainland United States (*24*). The role that Honolulu harbor plays in receiving goods and supplies from elsewhere cannot be stressed enough. The capacity that Honolulu harbor has, no other harbor in the Hawaiian island, can match. Therefore, the functioning of the Honolulu harbor is essential to the supply chain for Hawai'i.

In addition to having the largest port and main airport, the island of Oahu is the third-largest Hawaiian Islands by area and home to roughly one million people, two-thirds of the population in Hawai'i. Oahu is the center for commercial, economic activities, social, educational, health, and other services in Hawai'i. It also hosts, on average, over 4.5 million tourists every year (*25*). City and County of Honolulu have jurisdiction over Oahu's entire island and the state capital, Honolulu, locates on Oahu's southeast coast. However, dominated by two large mountain ranges, the island's highways and development are primarily located in low lying coastal areas, making it particularly vulnerable to flooding caused by coastal hazards such as hurricane and tsunami. With the projected sea-level rise, the situation is going to get worse. The observed water levels are already 3–6 inches above predicted tidal heights since 2016 (*26*). In late April 2017, levels peaked at more than 9 inches above predicted tides at the Honolulu Harbor tide gauge, resulting in the highest daily mean water level observed over the 112-year record (*26*). Rotzoll and Fletcher (*27)* project that 0.6 meters of potential sea-level rise would cause substantial coastal flooding and a 1-meter sea-level rise would inundate 10% of a 1-km wide heavily urbanized coastal zone in Honolulu. Furthermore, the rising sea level will provide a higher water base from which storm surges can sweep inland, leading to a rapid increase in frequency and magnitude of extreme coastal flooding events (*28*) and even more than double the frequency of extreme water-level events in the Tropics (*29*).

Given its large population, social and economic importance, and high exposure, Oahu's island is selected as the case study area. Located near the middle of the Pacific Ocean, the land is limited and expensive on O'ahu, which restricts warehouse goods' ability. As a result, goods that come to O'ahu and subsequently the rest of the Hawaiian Islands operate on a "just in time" basis. In the face of these challenges, the disaster relief supply chain stakeholders on O'ahu must work together to address these issues; to foster the delivery of disaster relief goods to O'ahu people, and a speedy recovery process. This research tries to understand the factors and constraints that influence disaster relief preparedness to coastal flooding hazards. Through interviews, working with stakeholders aims to identify the current disaster relief supply chain system's strengths and weaknesses to develop a preliminary analytical framework for further research.

4. Methodology

4.1 Research Design

This research was conducted through qualitative, in-depth interviews with emergency management stakeholders to gather information for a simplified quantitative warehouse location optimization model. Open-ended questions were selected to allow unexpected information to surface in the largely unknown territory of disaster relief supply chain resilience in the Hawaiian context. Participants in this research were identified through preliminary interviews with emergency management experts from the Hawai'i Emergency Management Agency. Through this process, we sought to understand the factors that influence disaster relief supply chain resilience and how that could further be impacted by coastal hazards (e.g., sea-level rise, storm surge, hurricane, and tsunami) in Hawai'i. Key characteristics of the supply chain that we sought to identify included crucial stakeholders; their primary concerns; organizational capacity and constraints (in both blue and grey sky); plans and challenges for responding to coastal hazards.

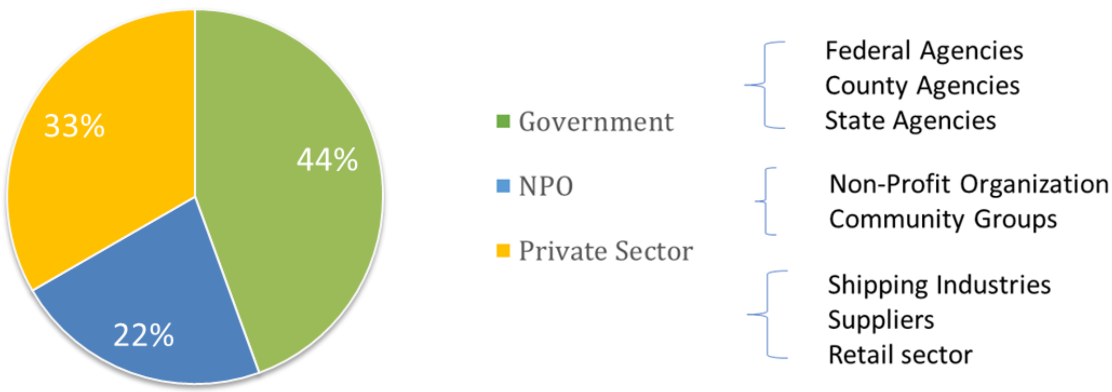
The typical case sampling and snowball sampling method (*30*) were utilized to engage key stakeholders in various backgrounds, such as Federal, State, and City and County Emergency Management agencies, transportation planning and operation agencies; non-profit organizations; and private sector suppliers. Through an analysis of interview responses, this research contributes to further understanding the current gaps in disaster relief preparedness, identifying possible strategies to cope with coastal hazards, and providing recommendations to bridge the gaps.

With the refinement of information from stakeholder interview, a simplified two-stage optimization model (*31*) is built to search for the optimal location and inventory allocation for warehouse beforehand to minimize potential disconnection and comply with the transportation network connectivity constraints, warehouse capacity constraints, and distribution center exposure constraints under various disaster scenarios.

4.2 Sampling Methods

The authors utilized purposive sampling methods to select the interviewees in this research. A typical case sampling method was utilized to identify those critical stakeholders in coastal hazard preparedness. To use the typical case sampling method, as Patton (*30)* said, researchers worked with informants in Hawai'i Emergency Management Agency to identify those key emergency management stakeholders. At the end of every interview, researchers asked the interviewees to recommend the next interviewees who understood those questions to continue this research. It results in a total of 18 interviews with stakeholders from state and city government, non-profit organizations, private companies, academia, and across different sectors such as emergency management, supplier, shipping industry, food industry, energy sector, environmental service, and infrastructure/facility management. 44% of the interviewees come from government agencies, 33% comes from the private sector, and 22% come from non-profit organizations and community groups. Among all government agencies, half of them come from the state, and another half comes from the city and County. Overall it has a diverse representation of various stakeholders involved.

Figure 4.1 Interviewee background



4.3 Interview Design and Analysis

Wording for the interview was thoughtfully put together in advance and paired with follow-up questions to probe for additional information. The information collection was based on grounded theory, which aims to understand the small-scale environment and micro-activities, where little previous research has occurred(*32*). All interview questions were reviewed and approved by the Internal Review Board (IRB) before researchers collect qualitative data.

All interviews are transcribed into texts for further analysis. After that, one researcher read all transcriptions to develop the coding scheme. To test the coding scheme, two researchers then utilized the coding scheme to individually analyze the same five transcriptions and then compare the consistency of their results. During this process, the research team has discussed and resolved the definitions of categories and coding rules. Until sufficient consistency has been achieved, the transcripts are then analyzed using computer software (i.e., QDA Miner Lite and Atlas. ti) to analyze the rest of the interview transcriptions to identify the prevalent themes for each of the following focus areas using the data-driven code (Table 4.1):

- Existing plans and challenges
    - Strategies
    - challenges
- Major concerns and gaps
    - Status quo
    - Causes of challenges
    - Decision-making constraints
- Key factors and constraints in decision making
    - Normal and extreme capacity

- Scenarios and impact

Table 4.1 Data-driven Codes

Theme	Codes		
1. Existing challenges			Major Challenges on transporting resources and materials to those area impacted by disasters
	1-a		Strategies for overcoming the difficulties
	1-b		Do not implement the current plan
	1-c		Do not have backup plans
2. Major concerns			Major concerns to prepare for disasters
	2-a		Do not understand the current situations, so cannot plan for disasters
		2-a-a	Suggest to contact other organizations for further information
		2-a-b	The only plan for those possible hazards
		2-a-c	Misunderstand the meaning of the all-hazard approach
		2-a-d	Lack of Information
	2-b		Responsibilities are from different departments, so cannot plan for disasters in a holistic way
	2-c		Assumptions
		2-c-a	Believe another organization will help
		2-c-b	Believe situation would not get worse/can be controlled quickly
		2-c-c	Believe internal resources/mechanisms are established if the worst case happens
	2-d		The worst scenario
Key factors			Key factors and weights for the development of an analytical framework
	3-a		Resources (The type, amount, and location of resources if existing)
	3-b		Impact (The type and location of vulnerable infrastructure)
	3-c		Scenarios (Scenarios that the interviewees are concerned about or planning for)
	3-d		Process (Planning process including the data source, method, timeline)
Suggestions			Suggestions on better preparing for disasters in the future

5. Findings

After completing and analyzing 18 qualitative in-depth interviews, the research team understands the stakeholder's identified risk and significant concerns, the status quo of preparedness, and the challenges and gaps in existing plans. The following sections summarize the main findings from the interviews.

5.1 Risk Concerns

Throughout the interviews, some common themes surfaced regarding the perceived risk of the disaster relief supply chain. The concept of being cut off both in the context of the entirety of the Hawaiian Islands and smaller enclave communities on O'ahu is highlighted. Such concerns are strongly tied to the Honolulu harbor's vulnerabilities and the coastal roads at risk due to erosion and/or flooding.

The vulnerability of the Honolulu harbor is not necessarily tied to the infrastructure of the port itself. However, that was a concern, but more so tied to the importance of the harbor. The Honolulu harbor is the center node of the supply chain for the State of Hawai'i. If the harbor were impacted to necessitate long-term repairs, it would severely hinder importing necessary goods and materials to the islands. The degree to which interviewees were concerned over the port varies. To some, it represented a severe vulnerability with catastrophic consequences. To others, it was essential but not a top priority when dealing with disasters, and for the rest, the port's vulnerability was just another challenge in daily operations.

Also, currently, no backup harbor exists that has the capacity to move goods as efficiently as the Honolulu harbor. Pearl harbor has been designated as the backup harbor, but one interviewee highlights the limitations of that plan, including:

- From the physical and spatial dynamic perspective, there is the necessity to move essential gantry cranes to Pearl harbor to lift shipping containers
- From a social dynamic perspective, Pearl harbor has never actually acted as a port for the greater Hawaiian public
- Most important, due to its proximity to Honolulu harbor, in the situation that the Honolulu harbor was impacted by an extreme weather event, Pearl Harbor would most likely also be impacted.

When it comes to being cut off from communities' perspective, it is related to roads' characteristics on O'ahu where they tend to be along the coast, and many communities depend on one road for access. Once the access road to these communities is cut off, the ability to get essential supplies to these communities is greatly restricted.

The importance and vulnerability of the transportation systems on O'ahu are magnified by another concern highlighted by the interviewees, which is related to the lack of storage or warehousing facilities on O'ahu. This topic was highlighted and referred to as the "just in time" arrival of goods and supplies or as the "warehouse on the water concept." Both are signaling the mechanism that the supply chain for O'ahu and, subsequently, the Hawaiian Islands operates under, which is the immediate sale and distribution of goods as soon as it gets out of Honolulu harbor—leading one participant to say that "essentially what we have is what we go to battle with" when it comes to a disastrous event.

The type of incidents that interviewees are most concerned about include tsunamis and hurricanes, acknowledging the role of sea-level rise in magnifying the impacts. Some agencies pointed out that they plan for the magnitude of a category four hurricane, but that benchmark is limited. It does not detail at what point critical systems or infrastructure will be impacted. One participant pointed out that they believed it would only take a magnitude 1 or 2 hurricanes impacting directly on the south shore of O'ahu to impact the Honolulu harbor and the supply chain. In almost every interview, and to varying degrees, the concept of debris was discussed including, the potential impact of debris, whose responsibility it might be to remove it, and where to store it after that. Plans for debris removal were referred to and highlighted. However, the majority of the interviewees also acknowledge that it is hard to estimate the speed of debris removal for the disaster scenarios of concern given the high uncertainty in the amount and location of debris as well as the lack of information regarding the estimation of internal and external contractors' capacity under extreme scenarios.

5.2 Existing Plan

Planning for disasters by disaster relief emergency organizations and agencies follow suit with what has been outlined by the Federal Emergency Management Agency. When planning for disaster relief supply chain resilience on Oahu, most organizations have taken an all-hazards approach, highlighting that the response will be similar in most events. In general, it involves steps such as watching for the potential impacts of an event, identifying a specific location that will be impacted, and planning accordingly. As one interviewee said,

> *"We try to make an all-hazards approach. It doesn't mean we look at every possible scenario that could affect us, but what that means is we look at the common elements that we would need in any kind of scenario. And try to build up those systems and capabilities so that we have a way to organize ourselves so that we can solve the problem."*

The federal government does have a Supply Chain Resilience Guide (*8*), in which they suggest a 6-step planning process as follows:

- Form a collaborative Planning Team
- Understand the Situation
- Determine Goals and Objectives
- Plan Development
- Plan Preparation Review & Approval
- Plan Implementation and Maintenance.

Creating a supply chain resilience plan necessitates a cross-industry collaboration and collaboration between public emergency management and private supply chain owners/managers. The creation of a statewide collaborative supply chain resilience plan, at this point, seems to be an immense challenge.

As it stands now, there is a collection of various plans from various organizations that may or may not bet integrated, overlap, or create unnecessary redundancies. It has proven challenging to review and coordinate many existing plans because they are not publicly available or are considered proprietary information. Therefore, we have a series of all-hazards plans in silos. Another aspect of existing plans prevalent in most organizations we spoke with included an organization-specific contingency plan or continuity of operations plan. As described, these plans are meant to keep organizations functioning as much as possible during a disaster. When it comes to coordination with external agencies or estimation of capacities, challenges in information sharing, uncertainty, and assumptions are mentioned.

Some communities have plans but are limited in implementing such plans, either due to regulatory hurdles or lack of community involvement. Other communities have preparedness plans but nothing in the realm of response. Also, there are limited requirements or guidelines for these groups to prepare for the community group disaster. Therefore, you have a series of organizations with varying objectives and abilities. One community might focus on evacuation routes, one on food and water, one on search and rescue, another on communication and education, etc. Due to the varying objectives of the community organizations, the plans will look very different.

5.2.1 Objectives

Throughout the interviews, it became clear that an organization's objective during a disaster is closely tied to the overall mission statement or prerogative of any particular agency or organization. More specifically, it is the continuity of their everyday operations.

One commonality for all organizations' plans was the protection of personnel and equipment as the primary goal. This is sensible because, without the human and technical means to continue operations, other relief efforts are impossible. While this could be considered the top common objectives among all plans, other objectives differ based on agencies. For example, the primary role of emergency management agencies is to act as a coordinating agency. As one interviewee used the metaphor, during the disaster, emergency management agencies are the brain. However, there is limited or none beyond what is enough to support their personnel during an emergency regarding relief supplies. Either the state or city and County have a warehouse to store relief supply for the general public. As a result, the emergency management agencies depend on the other agencies as the limbs that get their plan implemented. For the other government agencies, they have specific roles related to their specific sector that they cover. This could be protecting or rebuilding roads, ensuring the energy sector's continuity, or removing debris and refuse. For non-profit organizations, their plan objectives are more closely tied with the delivery of services and aid—either sheltering people who have lost their homes or mass feeding. For the private sector, such as shipping companies, during the onset of a disaster, the main objectives would fall within the realm of continuing to bring goods into

Hawai'i as much as possible before an event, such as a hurricane, reached the Hawaiian Islands. Some companies might make arrangements at departure ports to ensure the efficient delivery of cargo to Hawai'i. One company mentioned prepositioning relief goods on the water as close as possible to an island that might be impacted. Once the immediate danger has passed, the next step is to resume normal operations after assessing the Honolulu harbor's damage.

It is important to note that one of the essential characteristics of any harbor's response to an incoming extreme weather event includes removing vessels from the port out to sea to avoid any possible collisions on land. Therefore, the time frame to get supplies into the islands is limited by this necessity. The time frame that it takes to remove vessels from the port is related to the number of vessels in the harbor. In addition to that, there would be at least 2-3 days to close the port during the event, and a period of recovery time depending on the damage levels to the port and adjacent roads and how many and how quickly recovery personnel could reach the site. On the other hand, there are many hurricanes in pacific each year. It needs to monitor the trajectory and magnitude of hurricanes until about 3-5 days before the event to judge whether it may become a severe risk to the island. Therefore, only limited actions could be taken during this 3-5 days’ time window for preparedness even with the "warehouse on the water concept."

When it comes to all of the varying organizations' objectives and roles, the lines between responsibilities seem clear and hard. Sometimes the most common sentiment highlighted was jurisdictional finger-pointing, common utterances of "that is not our responsibility that is theirs." This implies that various organizations' collaboration for relief efforts is assumed, but there is a lack of shared responsibility. One can speculate that it is the result of limited funding for organizations. Regardless, this is not conducive to collaboration in a time of disaster.

5.2.2 Strategies

Strategies for creating supply chain resilience during a disaster are varied depending on the type of organization we discussed with and their objectives. Other factors that influence an organizations' strategy include their administrative capability (lack of power, lack of funding, lack of staff), and awareness of this issue.

When it comes to supply chain resilience as it stands now, there is a heavy reliance on the state recommended 14-day supply of food and water for households. This is the backbone of disaster relief as it stands now in Hawai'i. Although it has been acknowledged that this can and will be a challenge for some households, the primary goal is to get those who can purchase their emergency supplies to do so. This sentiment is common both in government agencies and community organizations. As it stands now, the State of Hawai'i relies on the initiative of individuals to sustain themselves if there was a disruption to the supply chain.

What happens if the communities or households do not have the capability to purchase and store 14 days' worth of supplies due to lack of funds or lack of storage space in small houses? From our conversations, the only organization with a backup supply of goods beyond the initial needs to operate is a non-profit organization. Suppose non-profits run out of the little supplies that they have, in that case, they can turn to donations from the greater community locally, nationally, and sometimes internationally, depending on the size of the non-profit. Some communities have to store meals ready to eat (MREs). But again, these backup supplies represent a fraction of the population for a short period. Therefore, some community organizations would turn to emergency management organizations for support.

5.2.3 Stakeholder Collaboration

Stakeholder collaboration is another essential disaster response element, especially with the disaster response center, where multiple agencies and organizations gather during an event. Stakeholder collaboration can be identified in various areas in disaster relief supply chain preparedness. Perhaps that strongest example of collaboration is within the Port of Honolulu itself in preparation for a potential disaster situation. Multiple players are involved with protecting the port and the vessels within the ports and collaborating to resume business as usual after a hazardous event such as a hurricane or a tsunami. This involved multiple organizations' coordination, including but not limited to the private shipping companies, shipping support companies, the coast guard, and the Department of Transportation Harbors. As soon as a potentially disastrous or impactful weather event is detected, all of the organizations involved with the harbor participate in update calls twice a day, referred to as "MITSU" calls. The efficiency of these responses to hazardous events is tested a couple of times a year through practice runs.

Outside of Honolulu harbor, various organization representatives will converge at the Emergency operations center to manage an oncoming disaster in preparation for an emergency. This includes states, County, federal emergency management, non-profits, various County, and state agencies. Beyond these significant response realms of coordination, there is also a collaboration of voluntary organizations called Voluntary Organizations Active in Disasters (VOAD). This is a U.S. National organization. The Hawai'i members of these organizations coordinate to know the needs of different communities during a disaster and how to service them with each organization's resources or donations.

The importance of community organizations' role has been identified as a critical facet of disaster relief in Hawai'i. Therefore, emergency management agencies have worked to coordinate with community-based emergency preparedness organizations. The Hawai'i Emergency Management agency engages various community-based organizations through the Hawai'i Hazards Awareness and Resilience Program (HARPP), which is meant to support communities in being self-reliant and reducing the negative impacts of a disaster(*33*).

5.2.4 Plan Evaluations

Humanitarian relief organizations have proposed ways to evaluate disaster relief supply chains, creating several different evaluating disaster relief supply chains' efficiency and effectiveness. For example, some methods to evaluate supply chains in preparation for a potential disaster are Supply Chain Operations Reference (SCOR) Model (*34*), Mission Maps. (*35; 36*), Balanced Score Card (*36; 37*). However, these evaluation methods are for organization-specific supply chains and are limited in their ability to evaluate larger cross-sector or cross-organization supply chain resilience(*35*).

Throughout the interviews, there was little to no mention of a systematic method of measuring existing plans' performance. The closest way organizations and agencies might have measured their plans' performance included a yearly review, or a periodical update, mainly citing a need to change the point of contact information. It is difficult to measure the performance of a plan constructed for worst-case scenarios that we hope will never occur. From our interviews, the trend of response plans being all-hazard scalable plans becomes evident. The focus of response plans was centered on a hurricane, tsunami, tropical storms, wildfires, lava eruptions, etc. The focus on events such as these is essential and characteristic of disaster relief plans. Still, there is no representation of the potential impacts of a disruption of the supply chain or how to mitigate losses from a supply chain disruption.

5.3 Challenges and Gaps

One gap that has been highlighted through multiple interviews is the quantity of different "non-mutually supporting plans." Almost all of the organizations interviewed have some plans for dealing with a disaster, but most of these plans are not done in collaboration with other organizations. The result is a series of emergency plans created through the silo of each organization.

The Emergency Management Agency acts as a coordinating agency during emergency events, yet the coordination of emergency plans remains tested for implementation. Some organizations had stated that they did work in coordination with emergency management agencies, while others created agency or company-specific plans on their own. In some ways, this can lead to cognitive gaps in various organizations' roles, responsibilities, and capacity. One clear gap that was illuminated through these interviews was the false assumption that County and State Emergency management agencies have backup emergency supply storage; this assumption had surfaced multiple times. From our interviews with these organizations, we had learned that it is not valid. This was further exemplified by one interviewee highlighting the need for a clear understanding of each organization's capacity to more effectively recover from a disastrous event, for which more information gathering and sharing is needed.

Additionally, the gap extends beyond organizational capacity to the need for a broader unified understanding of O'ahu's vulnerabilities, including but not limited to infrastructure vulnerabilities, identification of vulnerable populations, vulnerabilities of ports, supply nodes, and distribution centers. It is necessary to fill the gap in understanding island-wide preparation capacity, which leads to our analysis in Chapter 5.

Another gap/tradeoff is the limitation of jurisdictional segregation when it comes to planning for resilience and mitigation. This was exemplified by the infrastructure overlaps between the Honolulu harbor and the roads that connect it to the rest of the island. The Department of Transportation: Harbors is developing a plan to raise harbors' elevation to deal with sea-level rise. Yet the harbor can only be raised so high to ensure that vehicles transporting goods out of the harbor can access the city roads. This is one area where the management of infrastructure for resilience must be done in collaboration. A similar issue highlighted was the challenge of debris clearance of roads if electrical lines are down. This poses a danger to workers essential to roads' clearance, which is essential for distributing goods and supplies. To prepare for it, it requires collaboration between the department of transportation, environment service, and Hawaiian Electric Company to prioritize clearance routes beforehand. Other gaps like these could be bridged with long-term cross-jurisdictional guidance, supported by a statewide resilience plan that creates goals and standards for developing critical infrastructure in Hawai'i moving forward.

As highlighted before, the supply chain's resilience on O'ahu and the neighbor islands is a complicated and overlapping process with multiple factors at play. Add on the impact of an unknown disaster further complicates planning. It is difficult to predict where collaboration might be needed, but a lack of collaboration on a breadth of potential issues can lead to redundancies and excess expenditure (*38*).

Earlier in this report, the port's collaboration in responding to and returning from an impactful event was highlighted. Collaboration such as this could be extended further beyond the port. Based on interview findings, it seems that freight companies are, to some degree, overlooked when it comes to collaboration for disaster planning.

Another opportunity for more collaboration that surfaced both through interviews and this project's process is the limited connection between the agencies who owns the land or equipment. One emergency management agency personnel highlighted that creating connections with private companies responsible for importing goods and supplies is vital but challenging. As the already established infrastructure and skilled personnel of such companies would help create resilience, emergency management agencies, or non-profits manage warehouses or supplies even though it is not their expertise. This gap also manifested itself in this project as our sampling method was based on referrals; therefore, our ability to interview companies that own the supply chain was hindered. It is difficult to know if these connections exist but were not shared with the project or there is, in fact, a greater collaboration that should take place. Either way, there is a need for an open dialogue with private companies with the skills and existing infrastructure to support disaster relief supply chain resilience.

The analysis and stakeholder interviews show that coastal flooding's current preparation capacity is limited, especially to extreme scenarios.

- Options for prepositioning of disaster relief goods is limited;
- The land is limited and expensive on O'ahu, which limits the ability to have warehouses with relief goods;
- The importation of goods to O'ahu operates on a 'just in time' basis leaving the supply chain vulnerable to the smallest disruption;
- Given the widespread, large scale impact, the distribution network is almost impossible to strengthen through hard structure protection in extreme scenarios;
- Many communities are vulnerable to exclusion from the supply network due to limited access and roads vulnerable to inundations.

6. Warehouse Location Optimization Model

To overcome the identified gaps, we propose establishing warehouses and stock backup materials to prepare for the hazard scenarios of concern. One interviewee suggests considering freeze-dried or dehydrated foods with a shelf life of 25+ years to save the storage space and inventory life-cycle cost. Taking this as an assumption, we developed a warehouse location and inventory allocation optimization model in a hypothesized numeric example with consideration of all six hazard scenarios as a demonstration of the methodology. More accurate information regarding capacity and demand could help develop more realistic backup plans using similar future studies methods.

Based on the interviews, we consider six flooding scenarios caused by SLR and other coastal hazards. These scenarios include:

1. Hurricane Category 1 storm surge
2. Hurricane Category 2 storm surge
3. Hurricane Category 3 storm surge
4. Hurricane Category 4 storm surge
5. 3.2 feet of sea-level rise
6. Tsunami inundation

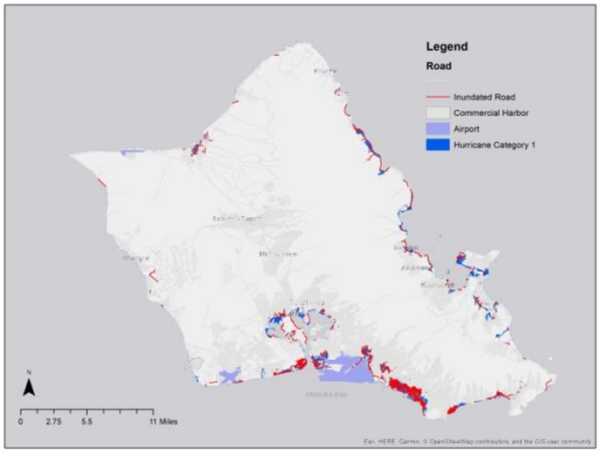
The data sources used to develop these hazard scenarios are summarized in Table 6.1. National Storm Surge Hazard Maps are used to estimate the potential inundation for hurricane category 1 to 4. The hazard maps are created by National Hurricane Center (NHC) using a representative sample of hypothetical storms and the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to estimate the near worst–case scenario of flooding for each hurricane category. For tsunami inundation, Tsunami Evacuation Zone is used as the approximate inundation zone for most tsunami warnings. This zone is produced by FEMA based on the historical tsunami impacts on the State of Hawaii and Island of Oahu over the past 100 years. With regards to sea level rise, based on an upper-end projection of 3.2 feet of sea level rise by 2100 in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), 3.2ft is commonly used by the state infrastructure planning agencies. Sea level rise inundation area estimated by University of Hawaii Coastal Geology Group is used for this study. The exposure area combines three chronic flooding hazards, i.e. passive flooding, annual high wave flooding, and coastal erosion to define the projected extent of long-term, chronic flooding hazards punctuated by annual or more frequent flooding events due to sea level rise.

GIS analysis is performed to identify the vulnerable roads, commercial harbors, airports, and emergency shelters that are within the inundation zone under each scenario. The flooding maps and vulnerable infrastructures under each scenario are mapped in Figure 6.1. Street centerlines, commercial harbor, airport, and emergency shelter location data are all obtained from the Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/. Table 6.2 summarizes the percentage of roads in miles, the percentage of commercial harbor space, airport, and emergency shelters located within the flood zones under each scenario. The results show that the exposure of transportation infrastructures and emergency shelters increases with the severity of the hazards. Under all six hazard scenarios, 100% of Oahu's commercial harbor and airport are within the flooding zone. While the percentage of roads and emergency shelters affected is relatively small for both 3.2 ft SLR and Hurricane Category 1 scenarios, the total length of roads that could be affected doubles in the Hurricane Category 3 scenario and nearly doubles again with Hurricane category 4. The extreme tsunami would result in the largest percentage of roads and shelters inundated. Table 6.3 shows that city and County owns the largest proportion under all scenarios (i.e., over 30%) among all roads that would potentially be affected. There is also 14% to 19% of the roads have multiple owners, which requires coordination among stakeholders.

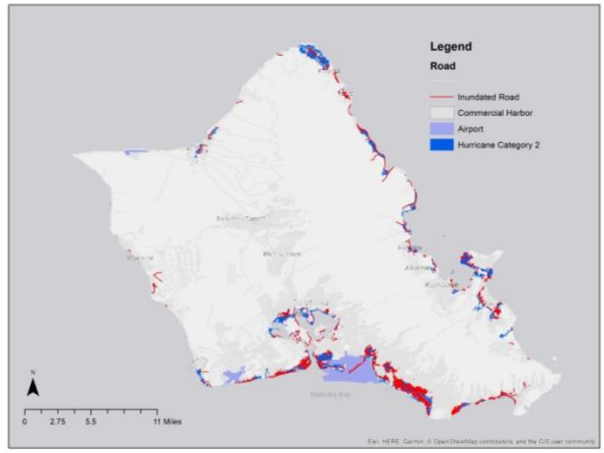
Table 6.1 Hazard Data Sources

Hazard	Descriptions	Data Source
Hurricane Category 1 storm surge	Storm surge inundation under Hurricane Category 1 scenario created by the National Hurricane Center (NHC) Storm Surge Unit with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model	Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. Weather, Climate, and Society, 7(2), 109–117. DOI: https://www.nhc.noaa.gov/nationalsurge/
Hurricane Category 2 storm surge	Storm surge inundation under Hurricane Category 2 scenario created by the National Hurricane Center (NHC) Storm Surge Unit with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model	Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. Weather, Climate, and Society, 7(2), 109–117. DOI: https://www.nhc.noaa.gov/nationalsurge/
Hurricane Category 3 storm surge	Storm surge inundation under Hurricane Category 3 scenario created by the National Hurricane Center (NHC) Storm Surge Unit with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model	Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. Weather, Climate, and Society, 7(2), 109–117. DOI: https://www.nhc.noaa.gov/nationalsurge/
Hurricane Category 4 storm surge	Storm surge inundation under Hurricane Category 4 scenario created by the National Hurricane Center (NHC) Storm Surge Unit with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model	Zachry, B. C., W. J. Booth, J. R. Rhome, and T. M. Sharon, 2015: A National View of Storm Surge Risk and Inundation. Weather, Climate, and Society, 7(2), 109–117. DOI: https://www.nhc.noaa.gov/nationalsurge/
3.2 ft of Sea Level Rise	Three chronic flooding hazards modeled with 3.2 feet SLR: passive "bathtub" flooding, annual high wave flooding, and coastal erosion based on the upper end of the IPCC AR5 RCP8.5 GMSL rise scenario.	Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report & PacIOOS https://www.pacioos.hawaii.edu/shoreline/slr-hawaii/
Tsunami Inundation	Tsunami inundation model using FEMA tsunami evacuation zones	Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/

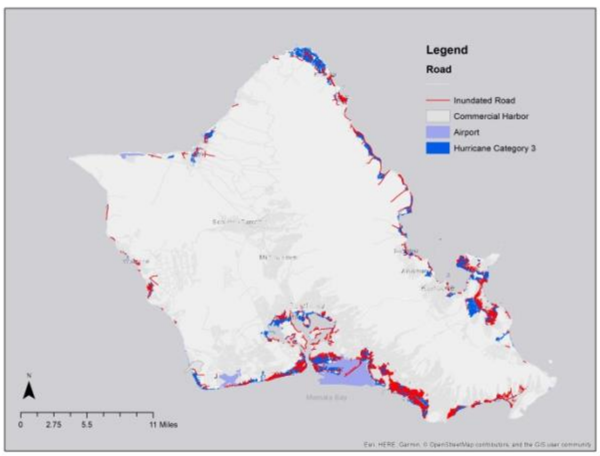
Figure 6.1. Flooding and Vulnerable Infrastructures



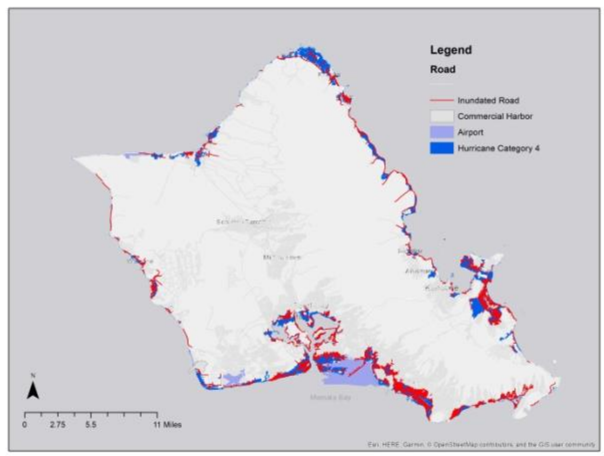
a) Hurricane Category 1



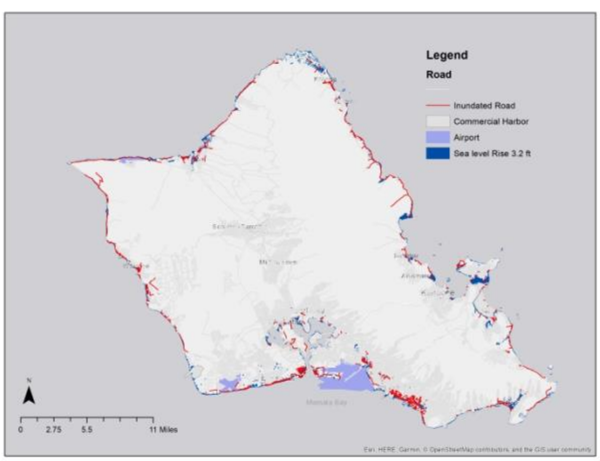
b) Hurricane Category 2



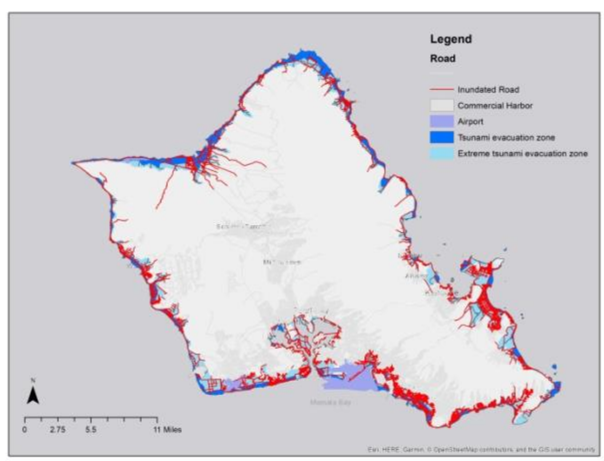
c) Hurricane Category 3



d) Hurricane Category 4



e) Sea Level Rise 3.2 ft



f) Tsunami

Table 6.2 Percentage of Infrastructures within Flooding Zones under Each Scenario

	SLR 3.2ft	Hurricane Category 1	Hurricane Category 2	Hurricane Category 3	Hurricane Category 4	Tsunami
Road	7%	7%	10%	14%	18%	30%
Commercial Harbor	100%	100%	100%	100%	100%	100%
Airport	100%	100%	100%	100%	100%	100%
Emergency Shelter	0%	1%	1%	2%	4%	18%

Table 6.3 Percentage of Vulnerable Infrastructures by Owners

	SLR 3.2ft	Hurricane Category 1	Hurricane Category 2	Hurricane Category 3	Hurricane Category 4	Tsunami
City/County	24%	32%	35%	36%	35%	35%
State	31%	21%	19%	17%	18%	19%
Federal	17%	22%	22%	25%	24%	16%
Multiple Owner	18%	19%	15%	14%	14%	16%
Private	6%	4%	5%	6%	6%	8%
Unknown	5%	2%	3%	3%	3%	6%

Given the above exposures, a suitability analysis is performed to screen and rank the most suitable government-owned land that could serve as a backup warehouse for emergency food supply. Government-owned land is defined as any parcel owned by the city and County, State, or federal government. First, flooding maps under all six scenarios screen out government-owned parcels located within the flooding zones. Second, exiting zoning map is used to select candidate parcels that allow warehousing, which are Industrial Limited (I-1), Intensive (I-2), Waterfront (I-3), and Industrial-Commercial Mixed Use (IMX-1). Digital Elevation Model is used to select the parcels with a maximum slope of fewer than 15 degrees for easy truck access. Easy accessibility in terms of distance to the nearest highway, affordability in land prices, and the maximum slope in degree are used to rank the candidate parcels' suitability for warehousing. Equal weight is given to both criteria.

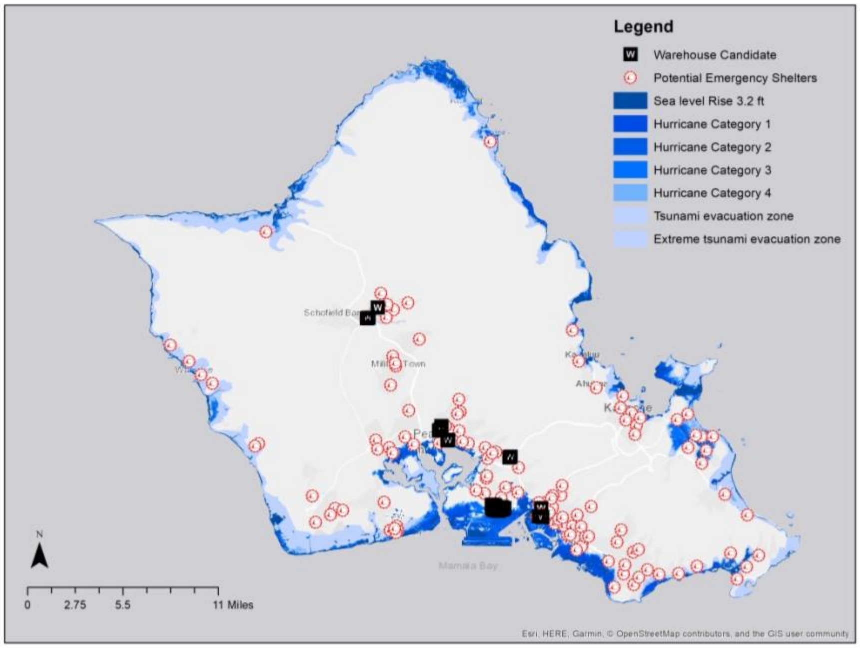
Table 6.4 summarizes the data sources used for the suitability analysis. Out of 99 eligible parcels, we select the top-ranked 32 parcels as a candidate for warehouses based on the Jenks Natural Breaks classification (*39*). A total of 122 emergency shelters exist in the case study area. Table 6.2 shows the percentage of shelters that will be affected by each scenario. Except for the extreme tsunami scenario, in general, the percentage of shelters to be affected is relatively small (less than 4%). The emergency shelters are considered a potential distribution center to receive emergency food from the warehouse and distribute it to the population in its service area. Census block data from the Hawai'i Statewide GIS Program is used to calculate the population that each shelter serves based on the shortest distance from the census block centroid to the nearest shelter. The location of the warehouse candidates and emergency shelters are shown in Figure 6.2. It shows the northern part of the island would have the risk of being cut off under multiple hazard scenarios. However, there is no government-owned land suitable for a backup warehouse in these areas. It would depend on the collaboration with a community organization or private sector to seek storage place for emergency supply in case of isolation during disasters.

Table 6.4 Data Source for Warehouse Suitability Analysis

Criteria	Description	Source Dataset
Outside flood zones	Outside all flooding zones	Refer to Table 6.1 for flooding data
Easy Access	Adjacent to high capacity road/arterial roads	Highway Performance Monitoring System Roads for Hawai'i (HPMS) from Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/
Government-owned land	City and County, State or federal owned land	Parcel data from Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/
Zoning	Permitted land use type I-1, I-2, I-3, IMX-1	Zoning data from Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/
Slope	Less than 15-degree slope	Oahu Digital Elevation Model from University of Hawai'i at Manoa Coastal Geology Group http://www.soest.hawaii.edu/coasts/data/
Land price	Land value per sqft	Real Property Assessment Tax Class (Pitt) Code Table from Hawai'i Statewide GIS Program https://geoportal.hawaii.gov/

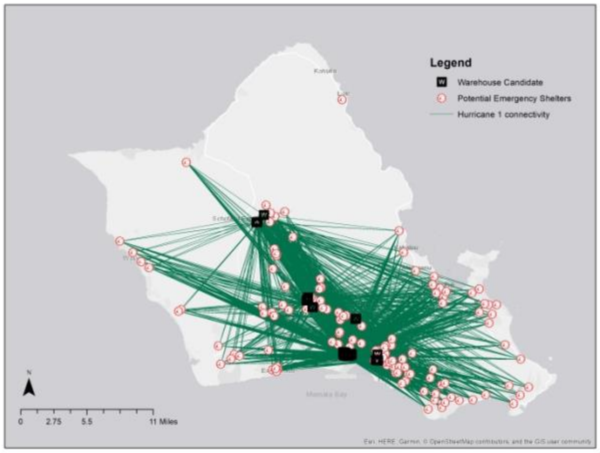
Network analysis is performed in ArcGIS 10.2 to get the connectivity matrix between warehouse candidate locations and potential emergency shelters. The connectivity is represented as a line between warehouse candidate locations and emergency shelters if they remain connected with flooding in Figure 6.3. The results confirm that the northern part of the island, such as Kahuku and Laie, would be cut off under almost all scenarios from the warehouse candidate location. As a result, they would need to collaborate with the community and private sectors to find suitable areas to store backup supply. As hurricane intensity increases, places such as Kahaluu and Waianae would depend more on locally stored emergency food. Under the 3.2 feet, SLR, and extreme tsunami scenarios, most places across the island would be cut off. Surprisingly, 3.2 feet sea level rise, despite the minimal length of roads it affects, it has the most significant connectivity reduction, possibly due to ground inundation on inland roads, and ground inundation on inland roads despite the minimal length of roads it affects.

Figure 6.2 Warehouse Location Candidates and Distribution Centers (Emergency Shelter)

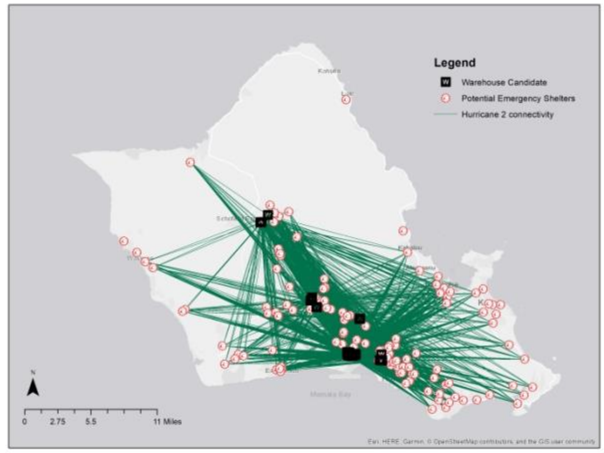


Pacific Southwest Region UTC
University Transportation Center

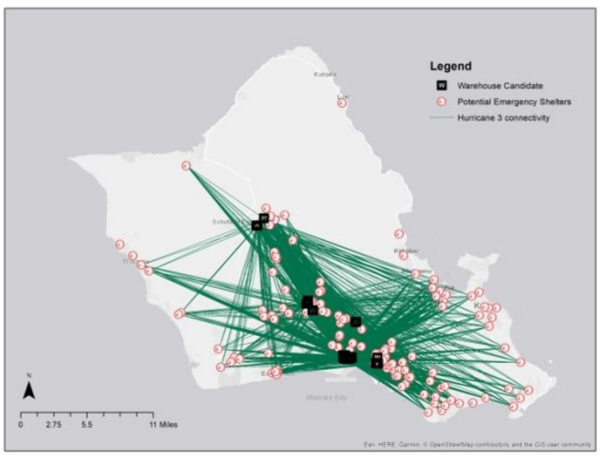
Figure 6.3 Connectivity between Warehouse and Shelters under Different Scenarios



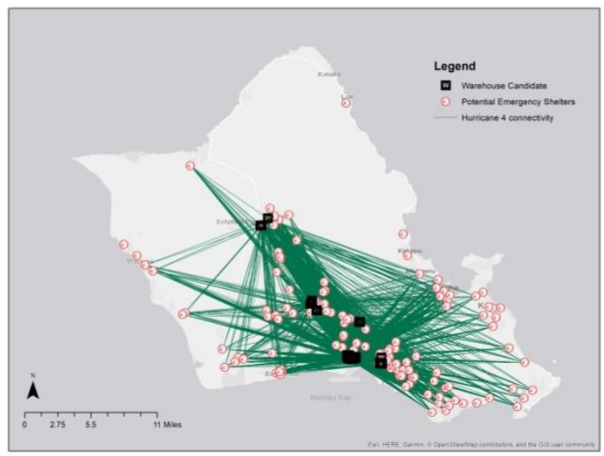
a) Hurricane Category 1



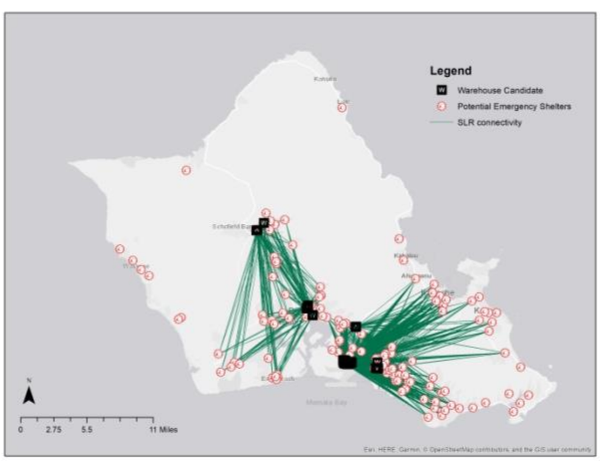
b) Hurricane Category 2



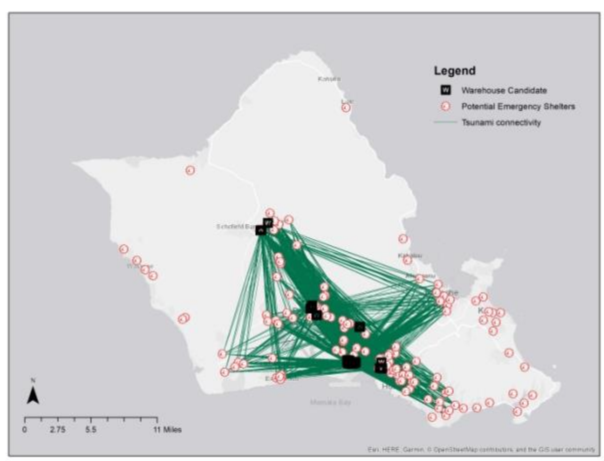
c) Hurricane Category 3



d) Hurricane Category 4



e) Sea Level Rise 3.2 ft



f) Tsunami

The warehouse candidate location, shelter location, and connectivity matrix between warehouse candidates and shelters are used to develop the warehouse location and inventory optimization model. The study of facility location-allocation problems can trackback to the 1960s. The fundamental facility location-allocation problem is presented by Cooper (*40)*, where the formulations are both static and deterministic. Since then, the problem draws extensive attention that many extensions to the facility location-allocation problem were studied, including dynamic location problems that consider some aspects of future uncertainty (*41; 42*), stochastic location problems that capture more complexity of real-world problem where the input parameters are stochastic or assumed to be dramatically changed over time (*43-45*), scenario planning where decision-makers specify the uncertainty by developing multiple disaster scenarios (*46; 47*).

An emergency food supply network consists of warehouses, distribution centers, and connecting links. The warehouse selection decision y_i and the allocation decision x_i are made before a disaster event happens. Once the decisions are made, they cannot be changed because the decisions are capital intense.

In this study, scenarios are defined as different disaster events, like hurricanes, sea-level rise, or extreme tsunami, where connectivity in the road network will differ. Let ξ describe a scenario with the probability p^{ξ}. Let Ξ denotes the set of disaster events, with $\xi \in \Xi$. Each scenario is associated with a road network that some network links will be unusable in an event. Let a_{ij}^{ξ} denotes the road connectivity from warehouse location i to distribution center j in scenario ξ, where $a_{ij}^{\xi} = 1$ means the road is connected such that the emergency food relief supply can be shipped from warehouse location i to distribution center j in scenario ξ, and 0 means disconnected.

The following are the sets, parameters, and variables used in the warehouse location problem.

Sets:

I Set of potential warehouse locations

J Set of potential distribution centers

Ξ Set of disaster scenarios

Parameters:

p^{ξ} Probability of scenario ξ happens

c_i Fixed cost for opening warehouse i

s_i The capacity of warehouse i

d_j^{ξ} Demand at distribution center j

a_{ij}^{ξ} Road connectivity from warehouse location i to distribution center j in scenario ξ. $a_{ij}^{\xi} = 1$ if it is connected, 0 otherwise. We assume that road connectivity is subject to change for different disaster scenarios.

M Big M, it is a large number

γ Tradeoff coefficient between the first stage cost and second stage cost

Variables:

x_i Continuous variable. Units of emergency food relief supply assigned to warehouse location i.

y_i Binary variable. $y_i = 1$ means warehouse location i is selected, 0 otherwise

z_{ij}^{ξ} Continuous variable. Units of emergency food relief supply shipped from warehouse i to distribution center j in scenario ξ.

Two-stage stochastic programming formulation:

$$\min c^T y - \gamma E_{\xi}[Q(x, y, \xi)]$$

where $Q(x, y, \xi)$ is the optimal value of the second stage problem

$$\max \sum_i \sum_j z_{ij}^{\xi}$$

subject to

$$x_i \leq s_i y_i, \forall i \in I \quad (1)$$

$$\sum_j z_{ij}^{\xi} \leq x_i, \forall i \in I, \xi \in \Xi \quad (2)$$

$$\sum_i z_{ij}^{\xi} \leq d_j^{\xi} \ , \forall j \in J, \xi \in \Xi \quad (3)$$

$$z_{ij}^{\xi} \leq M a_{ij}^{\xi}, \forall i \in I, j \in J, \xi \in \Xi \quad (4)$$

$$x_i \geq 0, \forall i \in I \quad (5)$$

$$z_{ij}^{\xi} \geq 0, \forall i \in I, j \in J \quad (6)$$

$$y_i \in \{0,1\}, \forall i \in I \quad (7)$$

The above formulation can be written as

$$\min c^T y - \gamma \sum_{\xi} p^{\xi} \sum_i \sum_j z_{ij}^{\xi}$$

subject to

(1)-(7)

The objective aims to minimize the total fixed cost for opening warehouses and the second-stage optimal value's negative expectation. The second stage optimal value is the maximum expectation of an emergency food supply delivered to the distribution centers under different scenarios. We take the negative sign because the second stage is a maximum problem. Constraint set (1) ensures that emergency food supply allocation can only be made to open warehouses. Constraint set (2) ensures that the total shipment emits from a single warehouse under any scenario cannot be greater than its allocated units before a disaster event. Constraint set (3) ensures that we cannot ship more units than a distribution center's demand. Constraint set (4) enforces the road network's connectivity, where the shipment from a warehouse to a distribution center cannot be made if the roads between them are not connected. Constraint set (5) and (6) states the non-negativity of the variables. Constraint set (7) denotes that the warehouse location decision variables are binary.

Numerical example

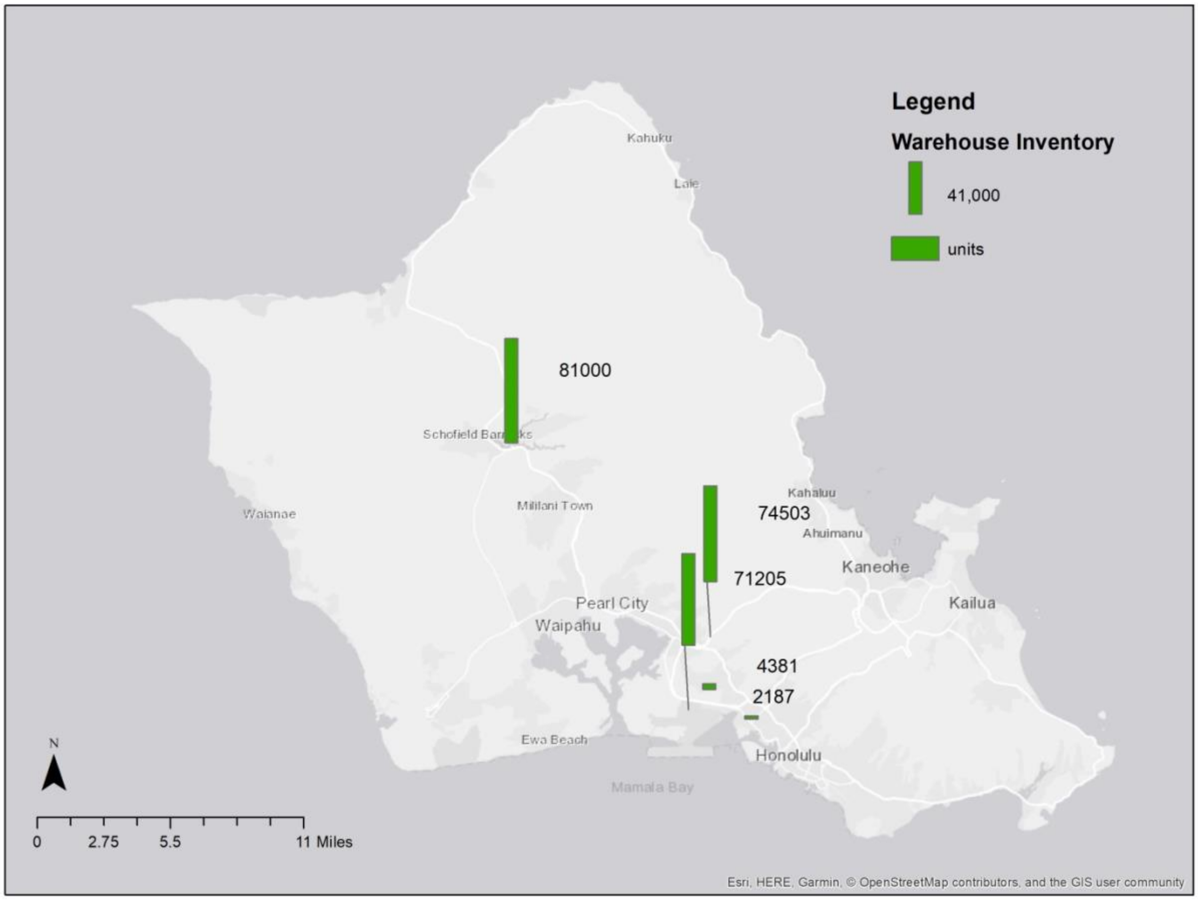
A hypothetical numerical example is developed to test the model. In this example, we are looking for warehouse locations that would provide storage for emergency food supply in the form of dry freeze food to supply Oahu's entire population for 4-6 days. Suppose with a standard U.S. pallet size (48" x 40"); the stack could be ten pallets high in the warehouse. Given the emergency, the food bucket is quite similar to no date codes considering its long shelf life (e.g., 25 years), the product could stack neatly and tight with an assumed 80% warehouse utilization rate. That would allow a warehouse to store roughly five times the sqft buckets of food. Each bucket would roughly supply four persons for the duration planned. There would be a total of 243,641 buckets of emergency dry freeze food that needs to be stored and allocated.

We consider 32 potential warehouses, 122 distribution centers, and six disaster scenarios, as mentioned above. For each lot, we take the minimum of actual land size and 50,000 sq ft as the warehouse-size for that lot as its size, given 50,000 sqft, could already accommodate a regional center. An estimated unit building cost of 20$/sq ft is used to calculate each warehouse location's fixed cost. The fixed cost for each location is warehouse-size times unit building cost. The warehouse capacity is the warehouse-size times the storage ratio (e.g., five units per sq ft). The problem is a mixed-integer programming problem. We used SCIP Optimization Suite 6.0 (*48*) to solve it. The warehouse locations selected and inventory allocation is shown in Figure 6.4. Five out of 32 locations are selected. A small portion of the inventory is located on relatively high land near Kalihi, and most of the inventory near the airport, H3 highway, central Oahu near Wahiawa. The results do not change whether all scenarios are given equal weight (16.7%) or sea-level rise scenario is given dominant (50%) weight, and the rest is 10% weight each. Table 6.5 summarizes the proportion of people being served under each hazard scenarios. It shows that at least 80% of the population could be served with the selected location and inventory plan under all scenarios.

Table 6.5 Percentage of Population Served under Different Scenarios

	Hurricane 1	Hurricane 2	Hurricane 3	Hurricane 4	SLR 3.2 ft	Tsunami
Population served (%)	95.7%	94.3%	88.3%	89.8%	80.8%	81.4%

Figure 6.4 Warehouse Selected and Inventory Allocation



7. Conclusion and Recommendation

After completing and analyzing 18 qualitative in-depth interviews, the research team identified three major obstacles for Hawai'i Emergency Management (E.M.), they are: 1) many communities live along the shoreline, and thus the majority of the infrastructures are vulnerable to coastal hazards, 2) there is a need for better coordination between various organizations (e.g., between federal and state agencies and between government and private sectors), and 3) The "just in time" economy might not benefit from the response to and recovery from disasters.

Since all communities were built along the shoreline, transportation to these communities would be difficult once a coastal disaster strikes, if not impossible. As a result, we suggest that Hawai'i EM stakeholders consider and apply more resilient strategies for managing disasters. These strategies include establishing warehouses and stock more materials for those disasters that would interrupt the maritime transportation from the mainland. We also suggest considering and identifying those alternative routes (detours) for Hawai'i citizens and E.M. organizations to avoid possible interruption and congestion after disasters. To enhance disaster resilience in local communities, the research team suggests cooperating with residents and organizations to better deal with the consequences after disasters. Using community colleges' kitchens to prepare meals, for example, would assist local communities in surviving after disasters. Encouraging citizens to prepare meals and emergency kits at their homes is also a good strategy to enhance disaster resilience in local communities.

Second, we suggest including more E.M. stakeholders (e.g., private and non-profit organizations) into the disaster planning processes and invite them to the regular disaster drills. We found many E.M. organizations might have inaccurate assumptions on what other organizations would do during disasters during this research. The Hawai'i Department of Transportation (DOT) in the Harbor area, for instance, was repeatedly mentioned in the interviews; the interviewees believe Harbor DOT would be able to assist some disaster recovery affairs (such as closing the adjacent roads to the harbor and prevent further injuries). After we interviewed the Harbor DOT and read their missions on the website, this organization does not in charge of such missions. Consequently, the research team suggests creating more opportunities for these E.M. stakeholders to know each other's roles and responsibilities and then test those E.M. plans regularly before disasters. A better understanding of different organizations' roles and responsibilities will facilitate the future implementation of E.M. plans and improve disaster management in Hawai'i.

Finally, due to the high price and limited spaces in the islands, governments, and private sectors do not store Hawai'i materials and goods. This "just in time" economy model does not facilitate the disaster response and recovery in the island. Therefore, the research team suggests to estimate and reconsider the alternative sites to store backup supply on existing government lands and utilize scientific models to select locations of the warehouse and distribution centers that would be able to minimize the numbers of warehouses and maximize the expected number of the population served under six hazard scenarios (i.e., hurricane category 1 -4, 3.2 ft sea level rise, and tsunami). A numeric example was used to demonstrate the methodology, while the model assumptions could be better adjusted with more accurate data and information in future studies. The best warehouse locations and inventory allocation plan are identified as a demo under all scenarios with both equal probability and SLR dominant probability assumptions. Similar methods could be applied to develop more realistic plans with more accurate assumptions and capacity/demand estimations in future studies.

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Data Management Plan

This project collected semi-structured interviews to understand stakeholders' concerns regarding disaster relief preparedness in case study, and utilizes publicly accessible digital elevation models, spatial data related to transportation infrastructure and land use to assess the physical exposure so as to develop a simplified optimization model for disaster relief warehouse location and inventory optimization.

During the stakeholder interviews, the participant background information (e.g., socio-demographic) was collected but processed anonymously. The research proposal and interview data collection plan has been submitted to the University of Hawaiʻi Human Studies Program for Institutional Review Board (IRB) review. The information related to personal identity is collected with participants consent as approved by the IRB. The interview transcripts were uploaded into the qualitative data analysis software, QDA Miner Lite for coding. The transcript will not be shared with the public to protect the participants' background information.

All of the spatial data used are publicly available data. Most of the data is obtained from Hawai’i Statewide GIS Program Geospatial Portal https://geoportal.hawaii.gov/. The spatial data collected through the GIS portal are available for download from the above website in standard spatial data format (e.g., shapefile, geodatabase) and metadata. Other data sources are also listed in Table 6.1 and Table 6.4, which is available for downloading.

Appendix Interview Questions

1. Could you describe the types of Disaster Relief your agency is primarily concerned with?
    a. What role and responsibilities does your agency play in maintaining the supply chain after a disaster strikes?
    b. Based on the local conditions, what are the primary challenges to maintain disaster relief supply chain in coastal flooding events?
2. Would you please describe one past coastal flooding hazard that affected the supply chain of the previous disaster relief works in your organization?
    a. In this event, how flooding affected the needs for disaster relief goods?
    b. What infrastructure and resources (e.g. warehouse inventory, key route or node in the supply chain network, and distribution shelter) were needed to perform the previously mentioned responsibilities?
    c. How these infrastructures/resources were affected?
        - In this event, how flooding affected the costs of preparedness and response?
    d. In this event, how flooding affected the distribution of disaster relief?
    e. What lessons were learned from this hazardous event?
        - Lessons on making decisions
        - Lessons relate to operation
    f. If you have chance to respond to this event again, what operational and decision-making components/processes you will change?
3. How many relief goods does your agency store in your warehouse/distribution center in normal time?
    a. What is the budget (in a rough number) does your agency spend on keeping the previously mentioned inventory levels (e.g. for a week, or a month)? Any justification for the budget/costs?
        - type of data
        - standard or methods
4. How would you assess whether the relief goods are enough after disaster?
        - type of data
        - standard or methods
5. If the amount of relief goods is not enough during disaster, what are the consequences?
    a. What is the backup plan if the relief goods are short?
6. Could you describe your primary concerns (e.g. time, resource constraints, and uncertainty) and decision-making process in responding to coastal hazards?
    a. In planning for such coastal hazards, what scenarios/maps/data does your agency utilized?

- Why do you select and use these scenarios, maps, and collected data?
- What are the priorities on planning for coastal hazards?
- Any scenarios/factors/constraints you consider more important than the others, [If yes,] why?

7. What is the future plan in your organization regarding to coastal hazards response?
    a. [If the interviewee mentioned there is a future plan in her/his organization,]
        - How do you implement the previous plan you mentioned?
        - Any difficulties on implementing the plan?
        - Any further analysis you think would benefit the development and implementation of the future plan(s)?
    b. [If the interviewee mentioned there is no such plan in her/his organization,]
        - Any further analysis you think would benefit the development and implementation of the future plan(s)?
8. Are there any questions that you think we should ask but we did not?
9. Would you please recommend the next interviewees for us, who you think will help this research?
10. Could we follow up with you if we want to clarify any information?