International Journal of Disaster Risk Reduction 28 (2018) 271–283

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Pedestrian evacuation modeling to reduce vehicle use for distant tsunami evacuations in Hawai‘i

Nathan Wood[a,*], Jamie Jones[b], Jeff Peters[b], Kevin Richards[c]

[a] Western Geographic Science Center, United States Geological Survey, 2130 SW 5th Avenue, Portland, OR 97201, USA
[b] Western Geographic Science Center, United States Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, USA
[c] Hawaii Emergency Management Agency, 3949 Diamond Head Road, Honolulu, HI 96816, USA

ARTICLE INFO

Keywords:
Tsunami
Evacuation
Pedestrian
Vehicles
Modeling
Hawai‘i

ABSTRACT

Tsunami waves that arrive hours after generation elsewhere pose logistical challenges to emergency managers due to the perceived abundance of time and inclination of evacuees to use vehicles. We use coastal communities on the island of O‘ahu (Hawai‘i, USA) to demonstrate regional evacuation modeling that can identify where successful pedestrian-based evacuations are plausible and where vehicle use could be discouraged. The island of O‘ahu has two tsunami-evacuation zones (standard and extreme), which provides the opportunity to examine if recommended travel modes vary based on zone. Geospatial path distance models are applied to estimate population exposure as a function of pedestrian travel time and speed out of evacuation zones. The use of the extreme zone triples the number of residents, employees, and facilities serving at-risk populations that would be encouraged to evacuate and slightly reduces the percentage of residents (98–76%) that could evacuate in less than 15 min at a plausible speed (with similar percentages for employees). Areas with lengthy evacuations are concentrated in the North Shore region for the standard zone but found all around the O‘ahu coastline for the extreme zone. The use of the extreme zone results in a 26% increase in the number of hotel visitors that would be encouraged to evacuate, and a 76% increase in the number of them that may require more than 15 min. Modeling can identify where pedestrian evacuations are plausible; however, there are logistical and behavioral issues that warrant attention before localized evacuation procedures may be realistic.

1. Introduction

Evacuations, either self-initiated by individuals or managed by public officials, are critical for saving lives from extreme, sudden-onset events. There has been considerable research to determine what demographic, contextual, and warning-messaging factors influence and motivate individuals to evacuate. For example, demographic attributes related to gender, ethnicity, household size, caregiver status, education level, and age have been documented to predict evacuation behavior, as have other factors such as risk perception, length of residence in an area, previous disaster experience, and trust in warning sources [33,54,6,60].

One area of evacuation behavior that has received scant attention in the literature is the set of factors that influence the decision on mode of travel, such as walking, driving personal vehicles, or using public transportation. For hazards with large geographic extents and evacuation windows measured in days (e.g., hurricanes), personal vehicles have been the primary evacuation mode. As such, evacuation behavior research related to these types of extreme events has focused largely on issues related to departure delays, traffic congestion, the number of vehicles used per household, destinations, and trust in warning sources [17,37,60]. Pedestrian-based evacuations are also possible, especially for extreme events with no or little advance notice and where safety may be relatively close. Pedestrian evacuations in these situations often are motivated by self-preservation in reaction to observable physical cues (e.g., ground shaking, building damage, and unusual noises or smells). A review of the evacuation literature summarized by Bolton [3] however suggests a dearth of evacuation studies prior to 2001 that explicitly mention pedestrians. The rise in studies after 2001 was attributed to an appreciation of large-scale pedestrian evacuations in the aftermath of the U.S. terrorist attacks of September 11, 2001. As a result, research in subsequent years has devoted more attention to best practices for pedestrian mass evacuations (e.g., [18]).

One possible explanation for the dearth of studies on evacuation modes is that most sudden-onset hazards are fairly consistent in terms of available time for warning and their duration, which allows for consistency in mode choice. For example, extreme events that provide little to no warning, last for seconds to minutes, and have relatively

* Corresponding author.
E-mail addresses: nwood@usgs.gov (N. Wood), jamiejones@usgs.gov (J. Jones), jpeters@usgs.gov (J. Peters), kevin.j.richards@hawaii.gov (K. Richards).

https://doi.org/10.1016/j.ijdrr.2018.03.009
Received 29 November 2017; Received in revised form 2 March 2018; Accepted 3 March 2018
Available online 07 March 2018
2212-4209/ Published by Elsevier Ltd.

small distances to reach safety (e.g., tornadoes, flash floods, explosions, and volcanic lahars) lead emergency managers to emphasize pedestrian-based evacuations in outreach efforts. In contrast, extreme events that provide days of warning, persist for several days, and have longer distances to reach safety (e.g., hurricanes) likely condition at-risk individuals to use (and emergency managers to promote) vehicles. Limited studies involving multimodal evacuations (e.g., pedestrians and vehicles operating simultaneously) typically have focused on urban evacuations related to terrorism or technological hazards [69,75,39].

Tsunamis present interesting challenges to evacuation planners due to the range in evacuation characteristics. Local earthquakes can create tsunami waves that arrive within tens of minutes of their generation, are preceded by significant ground shaking that alters the evacuation landscape, and represent significant threats to life safety. As a result, emergency managers typically emphasize self-initiated, pedestrian-based evacuations [44], although studies have shown that at-risk individuals have used vehicles to evacuate during local tsunami disasters [38,49]. Waves generated by earthquakes not only create threats to life safety in the immediate area of their generation, but they also travel across ocean basins and strike other coastal communities several hours later, referred to as distant tsunamis. Because of the larger evacuation window and intact infrastructure, at-risk individuals may be more inclined to use vehicles when threatened by distant tsunami sources.

The use of vehicles instead of walking out of tsunami-hazard zones complicates an evacuation due to congestion [42,49,55] and previous studies have demonstrated how tsunami evacuations on foot move people faster out of an area than those using vehicles [15,27]. Ercolano [18] notes that transit gridlock is likely for evacuations with 24 h or less of warning, which is the case for local or distant tsunamis. This is especially a concern for coastal communities that already have a high amount of traffic during normal non-emergency times, referred to as background traffic [27]. For example, an evacuation in the coastal community of Half Moon Bay, California, in response to local waves generated by the 2011 Tohoku earthquake in Japan created large-scale traffic standstills on one of the two key roads into the area and ultimately required food and water to be transported to the congested area [22].

The use of vehicles during tsunami evacuations is an active topic of research and discussion [55]. However, lacking from these discussions is the ability of transportation and emergency planners to systematically determine across a region where successful pedestrian evacuations may be likely and therefore vehicle use could be discouraged. This information could then serve as the basis in evacuation outreach efforts to promote pedestrian evacuations, which could minimize unnecessary congestion from vehicle use that could ultimately endanger the lives of evacuees.

The objective of this paper is to present a regional evacuation modeling approach to help emergency managers and transportation planners identify areas where pedestrian evacuations for distant tsunamis may be successful. To demonstrate this approach, we focus on the coastal communities in the City and County of Honolulu on the island of Oʻahu, Hawaiʻi (Fig. 1). Oʻahu represents an ideal case study because the island is considered to have significant traffic congestion during non-emergency conditions, is threatened by distant tsunamis from earthquakes sources from around the Pacific Ocean basin, and has been shown to have thousands of residents, employee, and visitors in tsunami-hazard zones [31]. Oʻahu also has two tsunami-evacuation zones (a standard and an extreme zone), which provides an opportunity to determine if recommended evacuation mode in a community may vary depending on tsunami threat. First, we estimate the number of residents, employees, hotel visitors, and facilities that provide services to at-risk populations (e.g., schools, medical clinics) in the two tsunami-evacuation zones. Second, we use geospatial models to estimate and map pedestrian travel times out of these zones and then summarize population exposure by a community as a function of travel time and travel speed. Third, we discuss the implications and challenges of our results for tsunami-evacuation planning. Methods discussed in this paper have direct relevance to evacuation planning in Oʻahu but will also inform planning in other coastal regions throughout the world that are faced with similar evacuation challenges associated with distant tsunamis.

2. Study Region

Situated in the seismically active Pacific Ocean basin, the State of Hawaiʻi has experienced extensive damage from several distant tsunamis in the past century, including the 1946 Aleutian, 1952 Kamchatka, 1957 Aleutian, 1960 Chile, and 1964 Aleutian events [16,34,4]. The most recent tsunami-related damage in Hawaiʻi was the more than $30 million (2011 U.S. dollars) in damages resulting from the tsunami generated by the 2011 Tohoku earthquake in Japan [63]. Research on distant tsunami potential suggests that wave run-up is fairly focused and, given a detailed tsunami warning, limited evacuations of specific areas may be more appropriate than statewide evacuations [70].

The City and County of Honolulu (which covers the entire island of Oʻahu) has two published tsunami-evacuation zones [8], referred to as a standard zone and an extreme zone (Fig. 1). The standard tsunami-evacuation zone was developed based on historic data from past tsunami events (1946 Aleutian, 1952 Kamchatka, 1957 Aleutian, 1960 Chile, and 1964 Aleutian) and two-dimensional numerical models that incorporate bathymetric variations [7]. The extreme evacuation zone is considered to be the probable maximum tsunami scenario and is a composite of potential tsunami inundation associated with M_w 9.3 and M_w 9.6 great Aleutian earthquake scenarios with estimated recurrence intervals of 1000 years [2,31,5,7]. Full discussion of the seismic parameters for each earthquake scenario and inundation modeling considerations can be found in Cheung [7]. Both the standard and extreme evacuation zones represent distant tsunami threats and estimated wave arrival to the Hawaiian coastline ranges from approximately 4 h for tsunami waves generated by an Aleutian earthquake [5] to 15 h for a Chilean earthquake [45]. Evacuation zones reflect the maximum areas of inundation from various historical events (standard zone) or two different Aleutian scenarios (extreme zone) plus some buffering so that evacuation boundaries align with street networks. Therefore, our evacuation-modeling results should be interpreted in the context of general evacuation planning and not as mortality estimates from any specific tsunami in the future. Local tsunamis have been rare in Hawaiʻi but are possible, as evidenced by the 1975 tsunami on the Island of Hawaiʻi that was generated by a M_w 7.7 earthquake and large-scale slumping on the southern flank of Kilauea volcano [40]. However, evacuation zones and planning focus on distant tsunami sources due to the perceived higher likelihood of distant tsunamis affecting Hawaiian coastal communities.

Both the standard and extreme evacuation zones are publicly available [9] and information included with the maps encourage at-risk individuals to evacuate inland out of evacuation zones to higher ground on foot if possible [13]. Vertical evacuation is mentioned as an option, but only if individuals can evacuate to the fourth floor or greater in a reinforced concrete building or to the tenth floor or greater in a steel building [13]. During an actual tsunami that threatens the Oah'u coast, the NOAA Pacific Tsunami Warning Center releases a series of public statements on the level of risk over time and determines whether evacuations are necessary [48]. Evacuations are coordinated by state and county emergency management agencies and the State of Hawaii further notifies the public via a statewide outdoor warning siren system, emergency alert broadcasts for radio and television, and sound-and-text alerts sent to mobile devices [26]. Evacuation drills are not mandated but are often conducted by schools and other community groups at the same time as monthly tests of the statewide siren system (e.g., [24]).

Although evacuation information encourages people to evacuate on foot if possible, the potential for vehicle-based evacuations for distant tsunamis is high on Oʻahu, given the several hours available for

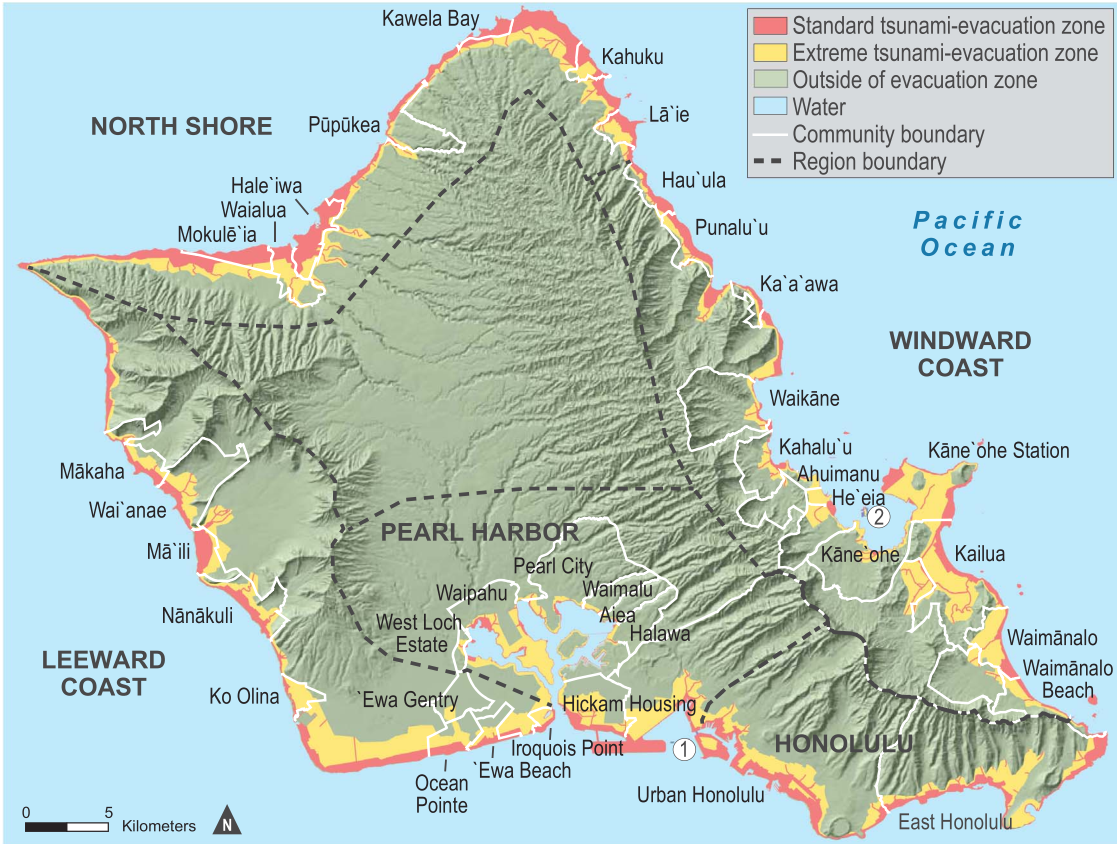

Fig. 1. Study area map of Oʻahu Island, Hawaiʻi, including all communities with land in either the standard or extreme tsunami-evacuation zones [8]. Regional delineations are subjective based on common usage in Oʻahu and are included to organize evacuation-modeling results for discussion purposes only. Sites numbered 1 and 2 refer to developed islands with no ability to evacuate by foot out of certain evacuation zones.

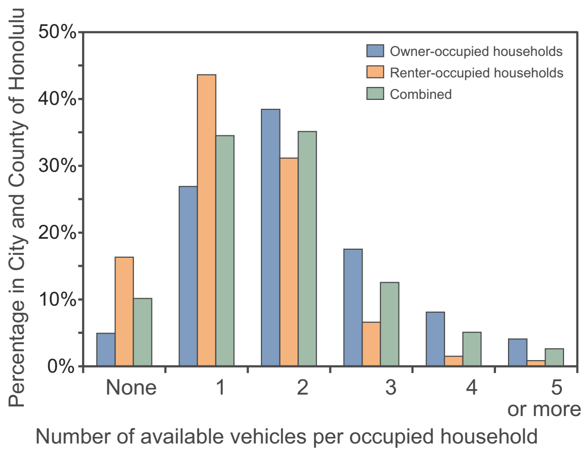

Fig. 2. Percentage of occupied households in the City and County of Honolulu in terms of available vehicles and based on 2011–2015 American Community Survey 5-Year Estimates [65].

evacuations before wave arrival and the high number of registered passenger vehicles and trucks in personal use (753,898) in the City and County of Honolulu [56]. Five-year estimates (2011–2015) from the American Community Survey (ACS) of the U.S. Census indicate that 309,602 of these vehicles are related to owner- or renter-occupied households. This suggests the remaining 444,296 vehicles (59% of the county totals) are non-residential, such as commercial use or rental cars for tourists. The 2011–2015 ACS data also indicate that 95% of owner-occupied households and 84% of renter-occupied households have at least one vehicle. The potential for traffic congestion may be exacerbated by the 68% of owner-occupied households and 40% of renter-occupied households that have two or more vehicles (resulting in a combined percentage of 55% of all occupied households) (Fig. 2), including approximately 8085 households that have 5 or more vehicles. The use of several vehicles from the same household has been observed in hurricane evacuations and has been cited as a contributor to traffic congestion during evacuations [17,37].

Aside from the incorporated City of Honolulu, the remainder of Oʻahu Island does not contain incorporated cities; therefore, 2015 census-designated place (CDP) boundaries from the U.S. Census Bureau were used to differentiate and delineate communities [25,65]. Based on a spatial overlay of CDP boundaries and tsunami evacuation zones, there are 37 CDPs (hereafter called communities) on Oʻahu Island that contain tsunami-prone land. For discussion purposes, communities are organized into five regions commonly understood on the island of Oʻahu, including Honolulu, Pearl Harbor, Leeward Coast, North Shore and Windward Coast (Fig. 1). Evacuation-modeling results for any land in evacuation zones not included in the 37 communities are referred to as "remaining land" of a specific region. Official names and spellings of geographic features and communities follow recommendations of the Hawaiʻi Board on Geographic Names [23].

3. Methods

Our analysis focuses on estimating travel times for various populations out of the standard and extreme tsunami-evacuation zones on Oʻahu Island. The objective is to identify areas where pedestrian travel times to safety may be considered too high and individuals may instead choose to use vehicles to evacuate. Vehicular use introduces complexity to an evacuation or can even cause one to fail due to gridlock; therefore, emergency managers were interested in knowing and communicating

to the public where pedestrian evacuations could be reasonably accomplished. We discuss here the various input data and geospatial analytical methods related to geospatial, pedestrian-evacuation modeling to characterize the evacuation landscape and to estimate population exposure as a function of travel time to safety.

3.1. Tsunami evacuation zones

Geospatial data characterizing the standard and extreme tsunami-evacuation zones were provided by the City and County of Honolulu [8]. Wave arrival time for distant tsunamis that would warrant evacuations out of these zones is approximately 4 h or greater [5]. Given the many hours before wave arrival, we assume that all individuals can reach safety on foot. Therefore, pedestrian evacuation modeling is not done to identify direct threats to life safety, but instead to determine where individuals may choose to drive instead of walk. For this study, fifteen minutes of pedestrian travel time out of an evacuation zone is chosen as the point at which vehicle use may be considered. Due to the lack of available walking-distance data from the tsunami-evacuation literature, we relied on transportation studies that indicate that 0.5 miles (~805 m) is the maximum distance that people will walk to access transit [62]. This translates to 15 min of travel time if we assume individuals move at 0.89 m/s, which is a conservative walking speed and associated with the travel speed of an impaired adult [30]. The use of 15 min was supported by input from county and state emergency managers on Oʻahu, who felt pedestrian travel times to safety of 15 min or greater would likely lead individuals to drive, instead of walk, to safety. Although the 15 min walking threshold provides some insight on evacuation behavior, it is not definitive threshold for action, as many evacuees in areas with low walking times may still decide to drive to minimize physical exertion and/or protect their vehicles and any moveable belongings.

3.2. Distribution of populations within tsunami-evacuation zones

Residential and nonresidential population locations were estimated using various data sources. Residential sites (i.e., geospatial points) were identified within all census blocks that had any land in either tsunami-evacuation zone and were determined using 2009 building footprint data [10]; 2016 tax parcel data [11,12]; block-level 2010 Census boundaries and household counts [64]; and manual interpretation of 2015 1-m resolution, red-green-blue (RGB)-band orthorectified imagery [66] and Google Street View. The total number of households in each census block was matched to the household count in census data, parcel land use data were used to identify residential and non-residential buildings, and satellite imagery was manually interpreted to further differentiate residential housing units from non-residential structures (e.g., backyard sheds, businesses). Once residential sites were identified, residential-population counts at each residence were determined by disaggregating the block-level Census data to all sites within that block. Population was differentially assigned to sites based on the number of housing units at a building (e.g., an apartment building was assigned a higher total population than a single-family home).

The location and size of nonresidential populations are based on the 2012 Infogroup Employer Database, which is a proprietary database comprised of georeferenced point files representing businesses, each with attributes of employee counts and North American Industry Classification System (NAICS) codes [28]. Business NAICS codes were used to identify businesses that may contain individuals considered to be “at-risk populations,” which are defined as individuals who may have additional functional needs and unique evacuation procedures related to communication, medical care, supervision, or transportation. Examples of at-risk populations include children, senior citizens, and pregnant women, as well as individuals who have disabilities, live in institutional settings, lack transportation options, have chronic medical disorders, or have pharmacological dependencies [67]. NAICS codes were used to identify businesses that provide adult assistance services (e.g., adult-care facilities, hospices, nursing homes, retirement communities); child services (e.g., group homes, foster care, child-care centers, preschools and nursery schools, and after-school programs); correctional facilities; public and private schools; medical centers (e.g., general, psychiatric, and substance abuse hospitals); and medical and health services (e.g., clinics).

The Island of Oahu has a substantial visitor population, demonstrated by the approximately 5.4 million visitors in 2016 [57]. On average, there are 101,006 visitors on the island per day, ranging throughout the year from approximately 90,000 (April and October) to 114,000 (June, July, and December). Accounting for the exact number and location of all visitors is beyond the scope of this study given the high number of accommodation options (e.g., hotels, condominiums, timeshare apartments, bed and breakfast homes, rental homes, hostels, campsites, and private homes). Therefore, we focus on hotel visitors, for which there is available geospatial data on hotels and the number of units within each hotel (although limited to hotels with 10 or more units) [58]. We assume that visitors staying at hotels in tsunami-evacuation zones would be affected by an evacuation, as they are likely to be going to beaches and businesses closest to their hotels. Hotel visitors accounted for approximately 74% of 2016 visitors on Oahu Island [57]; therefore, estimates of visitors in tsunami-evacuation zones based on hotel locations provides some insight but not a complete picture. The number of hotel visitors in tsunami-evacuation zones is based on the number of hotel units at a location multiplied by 2.25, which is the 2016 average party size for hotel-only visitors [57]. Estimates are then multiplied by 0.884, which is the highest monthly average occupancy rate for Oahu hotels in 2016 (found in July). Occupancy rates for Oahu hotels range from 82% to 88.4% and we use the highest rate to provide a worst-case scenario for hotel visitors [57]. Estimating the number of customers at other types of businesses (e.g., restaurants and retail stores) or other visitors to natural areas (e.g., beaches and parks) in tsunami-evacuation zones is beyond the scope of this study; however, their presence should be considered in local evacuation planning for individual businesses or locations.

3.3. Anisotropic path distance modeling

Pedestrian travel times out of evacuation zones are based on a least-cost-distance (LCD) model implemented in ESRI's ArcMap 10.5 geographic information system (GIS) software that takes into account the slope and land cover of an area to calculate the most efficient (i.e., least cost) paths on foot to safety from every location in a hazard zone [30,72,73]. Pedestrian travel times out of the standard and extreme tsunami-evacuation zones were estimated using an anisotropic, path distance model where the difficulty of traveling through each location is represented as a cost in terms of increased travel time. Anisotropy incorporates direction of travel and path distance calculates distances and slopes between cells of varying elevations.

Agent-based models have been developed for tsunami evacuations (e.g. [41,42,15]); however, we use LCD-based methods in this study because our focus is on the spatial distribution of evacuation times in many communities across a large area (the entire island of Oʻahu) that are not contingent on the initial location and concentration of evacuees. To apply an agent-based approach, many scenarios would be needed to properly characterize the dynamic nature of residents, employees, and tourists on the Oʻahu coastline. County and state emergency managers were primarily interested in spatially explicit maps of travel times for various evacuation-planning needs and not results tied to specific population scenarios. This insight was provided by one co-author (K. Richards), who is a Natural Hazards Officer with the State of Hawaii Emergency Management Agency, as well as through meetings with representatives of the Department of Emergency Management of the City and County of Honolulu.

To estimate travel times out of evacuation zones using a LCD framework, land cover and elevation derived slope data are transformed into speed conservation values (SCVs) that represent the proportion of maximum travel speeds that are expected on areas with given conditions. The modeling then estimates travel directions based on optimal routes of least costs (lowest amount of time in our case), which can be used to estimate overall travel times along an evacuation path for any maximum speed under ideal conditions (which is slightly downhill on paved streets). Slope SCVs are based on Tobler's [61] hiking function and slopes were derived from high-resolution LiDAR-derived elevation data produced by the National Oceanic and Atmospheric Administration (NOAA) [46]. Digital elevation models were created based primarily on 2013 1-meter resolution point cloud data, although 2007 1.3-meter data were used for any gaps in coverage for the evacuation zones. Land cover was characterized using 2.4-meter, 2010–2011 land-cover data produced by NOAA's Coastal Change Analysis Program (C-CAP) [47]. Both the land cover and DEM rasters were converted to a common 2.5-meter resolution for analysis.

Land cover SCVs are based on Soule and Goldman's [59] energy cost terrain coefficients for certain land cover types [73]. Ancillary land cover data included roads, building footprints (described earlier), and fences and were merged on top of the C-CAP land cover raster. Street centerlines were determined using 2012 Navteq road data that are part of the Homeland Infrastructure Foundation-Level (HIFLD) database [68]. Road data were further refined using OpenStreetMap [52] and by manually interpreting the previously described imagery and Google Street View. Fences and other obstructions were identified in this imagery and Google Street View, as well as field verified by limited fieldwork. Artificial driveways that connected building centroids to the nearest road were generated using the ArcMap Near tool [19]. Line segments to allow for travel (roads and driveways) or to block travel (fences) were buffered and then merged on top of the C-CAP data. Based on manual interpretation of satellite imagery, driveways, paths, and fences were buffered 2.5 m, whereas roads were buffered different lengths depending on the number of lanes (e.g, 5 m for 1 or 2 lanes, 6 m for 3 or 4 lanes, 7 m for 5 lanes, and 10 m for 6 lanes).

Once a composite land cover raster was created, five distinct SCV values (in parentheses) were used to estimate evacuation times across various landcover types, including roads (1.0); impervious surfaces and artificial driveways (0.9091), light brush (0.833), unconsolidated shore and beach (0.556), and heavy brush, water, wetlands, buildings, and fences (0.0). Pedestrian travel was restricted to roads, impervious surfaces, light brush, and beaches, which is reflected in the SCV assignment of 0.0 (i.e., a travel barrier) to the other land cover classes. State and county emergency managers requested that pedestrian travel was not modeled through forested areas and wetlands due to the thickness of local vegetation and the likelihood that evacuees would remain on roads. Cost surfaces that integrate land cover and slope variability were converted to maps of pedestrian travel times out of evacuation zones using maximum travel-speed assumptions of an impaired walk, a slow walk, and a fast walk (0.89 m/s, 1.10 m/s and 1.52 m/s, respectively; [30]), which were determined to reasonable speeds based on discussions with local emergency managers. These travel speeds represent the average speed one may move during the duration of an evacuation, recognizing that individuals may move faster at times but also initially may be delayed in their departure or may slow down during an evacuation due to fatigue or navigation delays. Therefore, these average speeds may implicitly account for potential departure delays or other unique behavior of individuals during an evacuation. For example, Fraser et al. [21] document how the use of a fixed evacuation speed to estimate population evacuation potential across a region is consistent with estimates based on variable speeds during an evacuation. Finally, geospatial data that map travel times out of tsunami-evacuation zones were integrated with population and CDP boundaries to yield estimates of population exposure by community as a function of travel time.

Table 1
Estimated number of residents, employees, businesses, and various facilities serving at-risk populations in the standard and extreme tsunami-evacuation zones of Oʻahu Island. Percentages for residents, employees, and businesses in the standard and extreme evacuation zone columns are relative to totals for Oʻahu Island.

	Standard evacuation zone	Extreme evacuation zone	Percentage increase from standard to extreme zone
Residents	80,576 (8%)	242,220 (25%)	201%
Employees	79,188 (19%)	208,858 (51%)	164%
Businesses	5392 (17%)	14,895 (46%)	176%
Hotel visitors	53,253	67,389	27%
Adult assistance services	8	26	225%
Child services	22	77	250%
Correctional facilities	2	2	0%
Medical and health services	363	1469	305%
Medical center	7	30	329%
Schools	29	92	217%

4. Results

The standard and extreme tsunami evacuation zones on Oʻahu Island contain thousands of residents, employees, hotel visitors, and businesses (Table 1). The extreme tsunami-evacuation zone contains approximately three times the number of businesses and facilities serving at-risk individuals that are within the standard zone. Although residents outnumber employees in the standard and extreme evacuation zones, they represent smaller percentages of the two populations for all of Oʻahu Island (8–25% for residents compared to 19–51% for employees). The higher percentage of employee exposure in the evacuation zones is an indication of the high amount of economic activity focused along the Oʻahu coast, such as tourism-related businesses (e.g., restaurants, hotels, and retail). Of the facilities serving at-risk populations, the most common facilities in the standard and extreme evacuation zones are those providing medical and health services, such as clinics and physician offices. The number of most population groups and facilities serving at-risk populations increases by 200% or greater from the standard to the extreme evacuation zone but only by 27% for hotel visitors (Table 1). The smaller increase for hotel-visitor exposure suggests that most high-capacity hotels in Oʻahu are close to the shoreline; therefore, increasing the size of the evacuation zone does not translate to a substantial increase in hotel-visitor exposure. Although beyond the scope of this study, there are likely to be business customers and beachgoers in evacuation zones other than those that live, work, or occupy hotels in the zones and these populations should be considered in local evacuation planning.

4.1. *Population exposure as a function of travel time out of tsunami-evacuation zones*

The potential use of vehicles during a tsunami evacuation varies for the two zones based on pedestrian travel times to safety. For the standard-evacuation zone, results suggest that 99.8% of employees, 98.2% of hotel visitors, and 97.5% of residents are in areas that may require less than 15 min of travel time at a reasonable rate of travel (i.e., a fast walking speed or slower) (Fig. 3). Approximately 98% of the employees in this evacuation zone only would need to move at a speed associated with impaired adults, with the remaining 2% moving at a slow or fast walk. Approximately 89% of the residents in this zone would need to move at this same speed, with the remaining 4% moving at a slow walk and 5% at a fast walk. Minimal travel speed for the majority of hotel visitors (98%) to evacuate in less than 15 min is also that of an impaired walk, with the remaining 2% in an area that would require 15 min at a

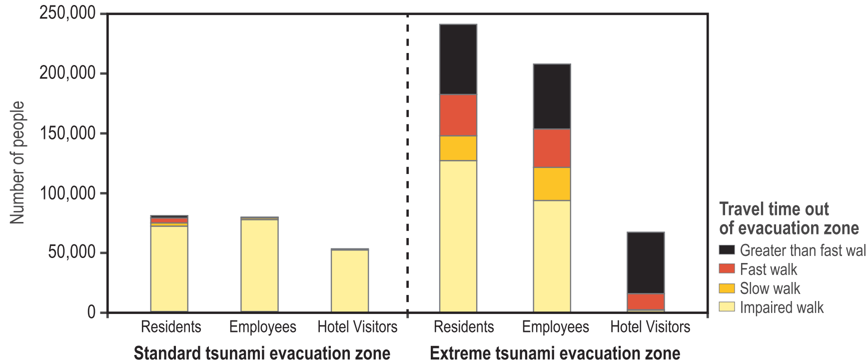

Fig. 3. Graphs of cumulative population exposure to tsunami hazards as a function of travel time out of evacuation zones for residents, employees, and hotel visitors for the standard and extreme evacuation zones on Oʻahu Island, Hawaiʻi.

fast walking speed.

The number of individuals in areas where travel time to safety is greater than 15 min increases substantially for the extreme tsunami-evacuation zone. Approximately 25% of the residents in this zone would need to move at a speed greater than a fast walk to evacuate within 15 min (Fig. 3). Similar results were observed for employees, where approximately 26% of the employees in the extreme evacuation zone would need to move at a speed greater than a fast walk to evacuate within 15 min. These results suggest that tens of thousands of residents and employees may feel the need to use cars to exit the extreme tsunami-evacuation zone, regardless of wave arrival time. Although the overall number of hotel visitors in evacuation zones does not increase substantially, approximately 76% of them in the extreme evacuation zone would need to move faster than a fast walk to evacuate within 15 min. This is a substantial increase from the 2% in the standard evacuation zone and it suggests the possibility of vehicular evacuations of approximately 51,000 hotel visitors. However, vertical evacuation to higher floors in a building may be a more realistic option for many hotel visitors in the extreme-evacuation zone since 95% of them are in Urban Honolulu, which is dominated by high-rise hotel complexes.

4.2. Community-level variations in residential and employee evacuation travel times

Results disaggregated to the community level indicate that the largest percentage of residents in the standard tsunami evacuation zones on Oʻahu Island are in Urban Honolulu (31%), followed by East Honolulu, ʻEwa Beach, Māʻili, Nānākuli, and Kailua (each at 7%). The Urban Honolulu and East Honolulu CDPs comprise the incorporated city of Honolulu. Urban Honolulu continues to have the highest percentage of residents in the extreme evacuation zone (37%), followed by Kailua (11%) and East Honolulu (8%). Urban Honolulu also has the highest percentage of Oʻahu employees in the standard and extreme evacuation zones (82% and 81%, respectively), with all other communities under 5%.

As discussed earlier, the majority of residents and employees will likely require less than 15 min to walk out of the standard evacuation zone, assuming a fast walking speed or slower (Fig. 4). However, we estimate there are 2002 residents with longer evacuation travel times and the majority of them are in the North Shore communities of Mokulēʻia, Haleʻiwa, and Lāʻie (Fig. 4b). All of the estimated 121 employees that may require 15 min or more in travel time also are in North Shore communities, specifically Haleʻiwa and Mokulēʻia (Fig. 4f).

The number of residents and employees with high travel times (i.e., 15 min or greater) increases substantially with the extreme tsunami-evacuation zone (58,930 residents and 54,587 employees, assuming a fast walk). Unlike the standard-evacuation zone, populations with high travel times out of the extreme evacuation zone are found in all Oʻahu regions (Figs. 4c, 4g). Urban Honolulu has the highest number of residents (22,661) and employees (43,313), each representing approximately 25% of these populations in the community's extreme evacuation zone. Several other communities have far fewer residents and employees in the extreme evacuation zone (in the hundreds to thousands, compared to tens of thousands in Urban Honolulu); however, these smaller populations represent substantial percentages of the populations in these communities, ranging from 45% in Haleʻiwa to 99% in Mokulēʻia (Fig. 4d).

Several communities also have high percentages of employees that were in areas with high travel times out of the extreme evacuation zone (Fig. 4h). In four communities, 100% of their employees in the extreme evacuation zone may require high travel times, including Iroquois Point, Kawela Bay, Lāʻie, and Mokulēʻia. Other communities with high percentages of employees that may require high travel times include Hickham Housing, Māʻili, Waialua, and Punaluʻu.

Of the individuals in areas where travel times are greater than 15 min, many of them would not require much more time to reach safety. For the standard evacuation zone and assuming a fast walking speed, 88% of the 1987 residents with travel times greater than 15 min would only need 5 min more to reach safety (Fig. 5). The remaining 240 residents in this group may be able to evacuate in 20–24 min. The majority of the individuals that may require this additional time to evacuate are in Mokulēʻia and Haleʻiwa in the North Shore region (Fig. 5a). Similar results were found for employee numbers in the standard evacuation zone, but with fewer total employees (121) requiring 15–24 min to evacuate (Fig. 5c).

The number of residents and employees that may require greater than 15 min to evacuate rises substantially for the extreme evacuation zone. Approximately 58,909 residents will need more than 15 min to reach safety (also assuming a fast walking speed), indicating an increase by an order of 30 over those in the standard evacuation zone. As was the case with the standard zone, the majority of individuals in this group may be able to reach safety in 15–19 min (52%), 20–24 min (31%), or 25–29 min (13%) and are primarily in Urban Honolulu, Kailua, Lāʻie, Māʻili, and Nānākuli (Fig. 5b). The number of employees requiring greater than 15 min increases from 121 in the standard zone to 54,587 in the extreme evacuation zone. The estimated time to evacuate this group is greater than that for residents, ranging from 15 to 19 min (13,818 employees) to 55–59 min (368 employees), and are located primarily in Urban Honolulu and the Leeward Coast region.

Populations located on two small islands around Oʻahu will need to evacuate by boat because there is no safe area for one or both evacuations zones. The first is Mokauea Island, located between the runways of Honolulu International Airport and Sand Island (site #1 in Fig. 1), where there are 15 residents, according to 2010 U.S. Census Bureau data. There is no safety for either evacuation zone on Mokauea Island. The second is Mokuʻoloʻe Island near Kāneʽohe on the windward coast (site #2 in Fig. 1), which is the site of a marine institute with 10 employees according to 2012 employee data [28] and an unknown

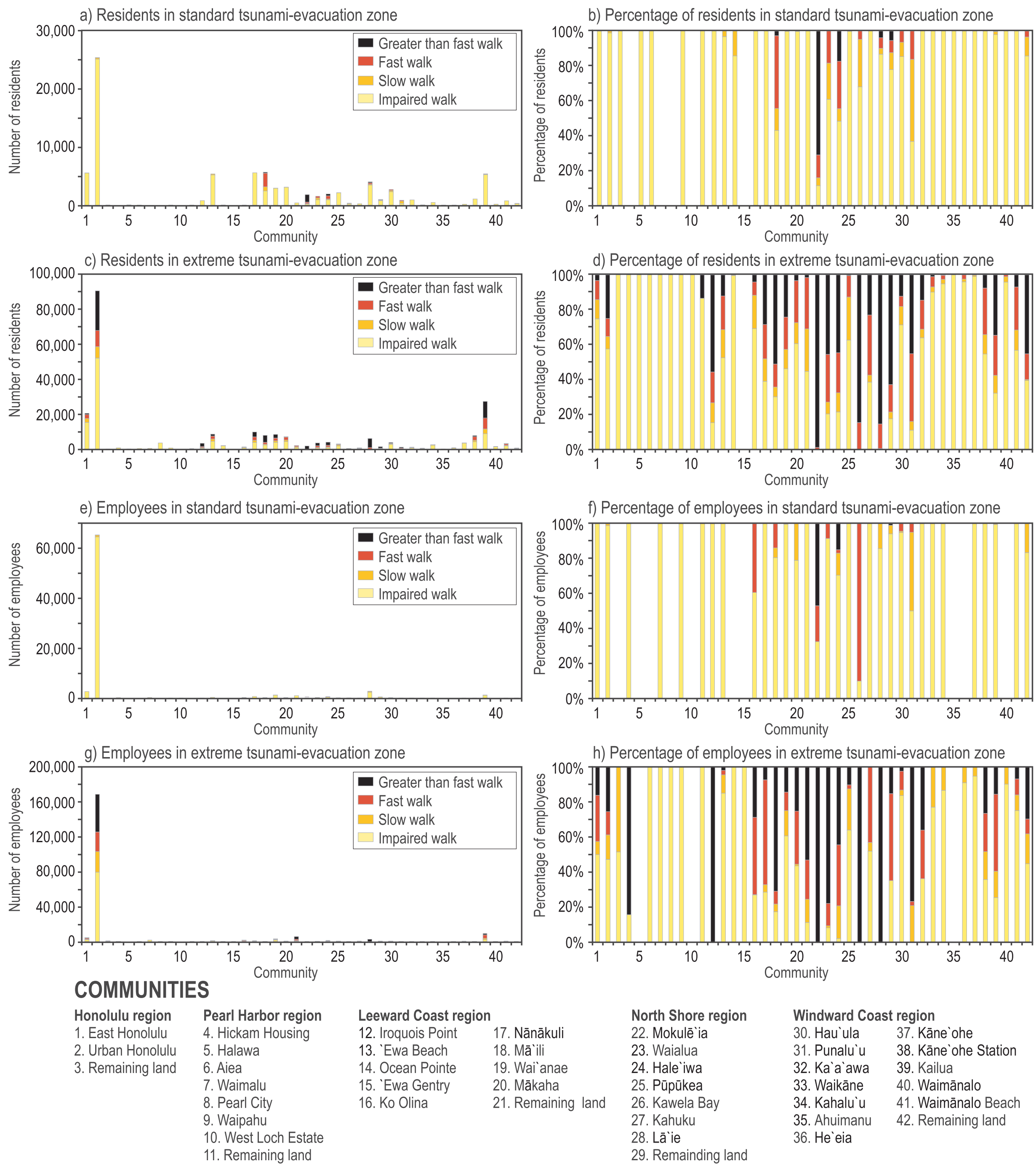

Fig. 4. Graphs of cumulative population exposure to tsunami hazards as a function of travel speed out of evacuation zones for residents (a-d) and employees (e-h) for the standard and extreme evacuation zones on O'ahu Island, Hawai'i. Travel-speed assumptions indicate the estimated pedestrian speed required to exit an evacuation zone in less than 15 min. Communities on the x-axis are organized geographically by region (Fig. 1).

number of visitors. The majority of the island is not in the standard evacuation zone (highest modeled travel times to safety is 6 min); however, the entire island is within the extreme evacuation zone.

4.3. Evacuation travel times for hotel visitors

Tsunami-evacuation zones on O'ahu contain between 53,253 (standard) and 67,389 (extreme) hotel visitors (Table 1). The overwhelming majority of hotel visitors in the standard and extreme evacuation zones are in Urban Honolulu (96% and 89%, respectively). In most communities, there are far fewer hotel visitors than residents in tsunami evacuation zones. Exceptions to this trend include Urban Honolulu (~51,000 hotel visitors and ~25,000 residents in the standard zone), Kawela Bay (~1200 hotel visitors and ~330 residents in both evacuation zones), and Ko Olina (~4300 hotel visitors and ~1200 residents in the extreme zone).

The minimal travel speed to evacuate the standard zone in less than 15 min for most hotel visitors (98%) is that of an impaired adult (Fig. 6a). The only exception is one hotel in Kawela Bay on the north shore of Oahu, where individuals would need to move faster than a fast walk. However, actual evacuation challenges at this hotel may not be daunting as Fig. 6a suggests because modeling results estimate that only 15 min (the cut-off value used in this analysis) are necessary to evacuate at a fast walking speed. In addition, estimated travel times for all hotels

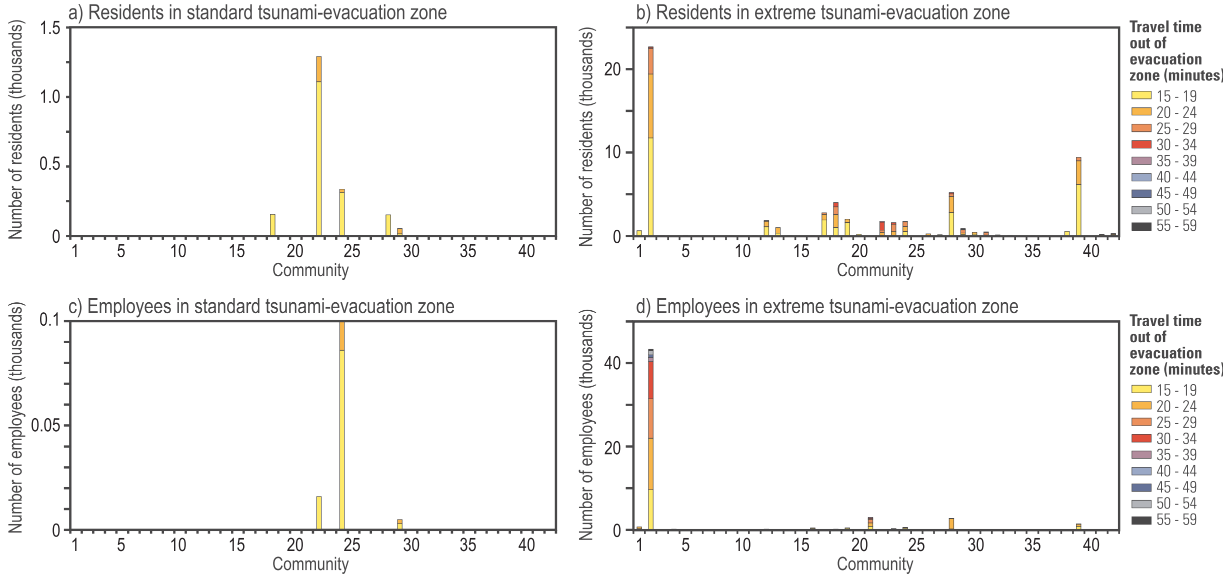

Fig. 5. Graphs of cumulative population exposure to tsunami hazards as a function of travel time out of evacuation zones for residents and employees in the standard and extreme evacuation zones on O'ahu Island, Hawai'i. Travel speed is assumed to be a fast walk (1.52 m/s) and only travel times of 15 min or higher are show here. Communities on the x-axis are organized geographically by region (Fig. 1) and are listed in Fig. 4.

are based on the location of a single, representative geospatial point; therefore, the use of a single point to characterize the substantial footprint of a large resort can be misleading and suggest more issues than may truly exist.

The shift to the extreme evacuation zone instead of the standard zone results in approximately 14,000 more hotel visitors (representing a 26% increase) with most of them estimated to be in Urban Honolulu and Ko Olina (Fig. 6b). The number of hotel visitors does not change between the standard and extreme evacuation zones in several communities. Although the extreme evacuation zone does not result in a substantial number of additional hotel visitors, it does substantially change the evacuation potential for hotel visitors in several communities. The percentage of hotel visitors that can evacuate in less than 15 min at a fast walking speed or slower drops from 100% to 20% in Urban Honolulu and from 100% to 0% in Wai'anae (Fig. 6b). In Urban Honolulu, 18 hotels are not in the standard evacuation zone but they would require more than 20 min at a fast walking speed to evacuate the extreme zone. Six other hotels in this area go from needing less than 7 min to over 30 min to evacuate, assuming a fast walk.

4.4. Evacuation travel times for at-risk populations

Tsunami-evacuation zones on O'ahu contain between 431 (standard) and 1696 (extreme) facilities that provide services to at-risk populations (Table 1). The overwhelming majority of these facilities in the standard and extreme evacuation zones (84% and 87%, respectively) are identified as medical and health services, such as clinics and doctors' offices. Of the 431 facilities in the standard tsunami-evacuation zone, only 8 of them are in areas where estimated travel times to safety are 15 min or greater, assuming the slowest travel speed of 0.89 m/s (Fig. 7a). These facilities are primarily in Lā'ie and Hale'iwa and include medical and health service providers, a school, and a child service provider. These facilities also include 88 employees, who would likely move at the impaired speed as well to help individuals with limited mobility.

Approximately 60% of the facilities serving at-risk populations in the extreme tsunami-evacuation zone are in areas that may require 15 min or more to evacuate. Ninety-two percent of these 1010 businesses provide medical and health services (e.g., physician offices) and

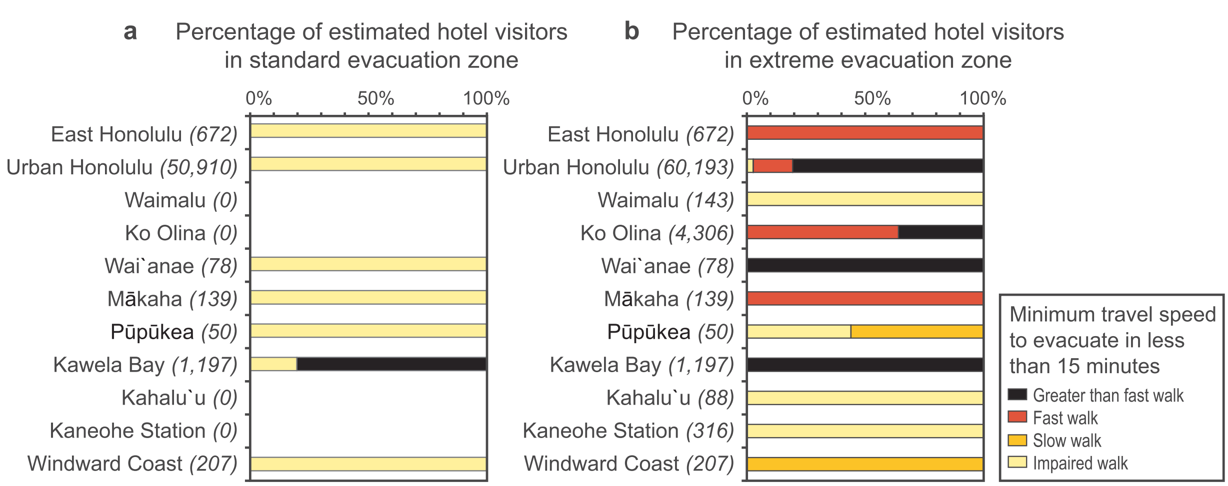

Fig. 6. Graphs of cumulative hotel-visitor exposure to tsunami hazards as a function of travel speed out of evacuation zones for the (a) standard and (b) extreme evacuation zones on O'ahu Island, Hawai'i. Travel-speed assumptions indicate the estimated pedestrian speed required to exit an evacuation zone in less than 15 min. Only communities with estimated visitors at hotels with 10 or more units in either the standard or extreme evacuation zone are shown; therefore, additional hotel visitors at smaller accommodations in the evacuation zones are possible. Italicized numbers in parentheses for each community denote the estimated number of hotel visitors in an evacuation zone.

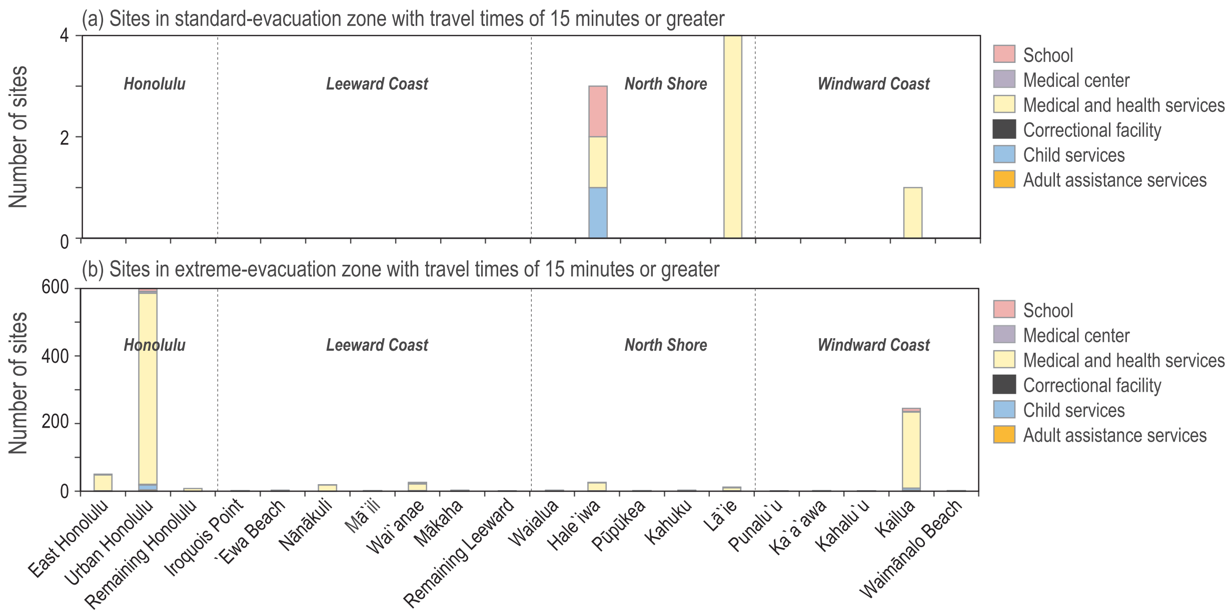

Fig. 7. Cumulative number of facilities serving at-risk populations in areas that may require 15 min or greater out of the (a) standard tsunami-evacuation zone and (b) extreme tsunami-evacuation zone. Travel speed for individuals at these facilities is assumed to be 0.89 m/s, which characterizes the travel speed of an impaired adult. Communities on the x-axis are organized geographically by region (Fig. 1) and only include communities with at least one facility in the extreme tsunami-evacuation zone.

most of these service providers are in Urban Honolulu and Kailua (Fig. 7b). Other facilities with estimated high travel times include 11 adult assistance services, 28 child services, 2 correctional facilities, 10 medical centers (e.g. hospitals, large collections of clinics), and 34 schools. There are an estimated 7522 employees working at the facilities serving at-risk populations that would require more than 15 min to evacuate the extreme zone.

4.5. Sensitivity of population evacuation potential to assumed travel time limit

This study assumes that 15 min of pedestrian travel time out of an evacuation zone is the point at which individuals may consider vehicles to evacuate instead of walking. As discussed earlier, this assumption is based on non-emergency transit research, as well as input from county and state emergency managers in Hawaiʻi. To provide more context to emergency managers, we examined how sensitive results were to changes in this assumption and used residents as an example. Fig. 8 portrays the cumulative percentage of residents in the standard and extreme evacuation zones as a function of estimated travel time out of the zones based on various travel-speed assumptions. Results indicate that the percentage of residents that may decide to use vehicles does not vary substantially for the standard evacuation zone but does for the extreme evacuation zone. Assuming a fast walking speed, the percentage of residents that may decide to use vehicles for the standard-evacuation zone ranges from 8% for a 10-min limit to 0% for a 20-min limit (Fig. 8). Similar trends were observed for the slow walking speed (14–0%, respectively) and the impaired adult speed (21–0%, respectively). Estimated ranges are higher for the extreme-evacuation zone, where the percentage of residents that may decide to use vehicles ranges from 39% for a 10-min limit to 9% for a 20-min limit, assuming a fast walking speed. Differences are similar for the impaired adult and slow walk speeds (59–32% and 52–23%, respectively). These results suggest that estimates of evacuation mode preference are less sensitive to travel-time assumptions for the standard zone than they are for the extreme zone.

5. Discussion

Successful evacuations are critical to saving lives from future tsunamis. Pedestrian-evacuation modeling related to local tsunami threats has primarily focused on life-safety issues by identifying areas and populations where successful evacuations are unlikely before wave arrival. Distant tsunamis provide hours of warning before arrival; therefore, it is often assumed that evacuations will be successful, even those that involve vehicles. However, vehicular evacuations can lead to congestion and create new threats to life safety or at the very least impacts to quality of life. Emergency managers currently lack the ability to identify areas where pedestrian evacuations can be completed in a reasonable amount of time, yet this information could be helpful to

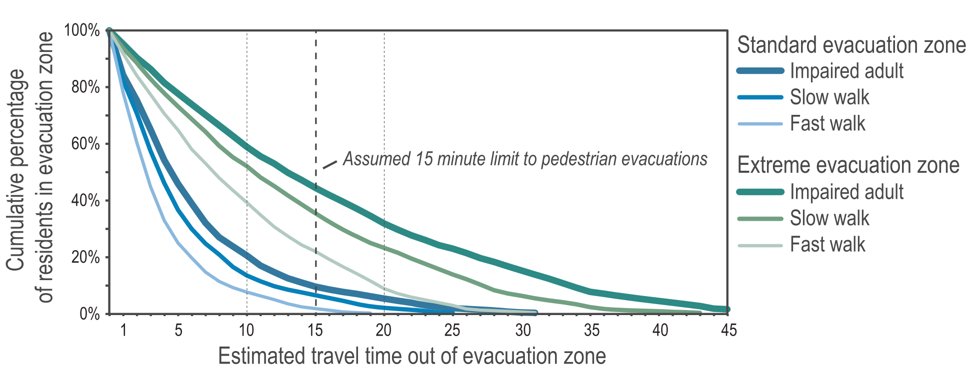

Fig. 8. Cumulative percentage of residents in the standard and extreme evacuation zones as a function of estimated pedestrian travel time out of the zones based on various travel-speed assumptions. The dashed line highlights 15 min, which we consider is the travel time at which individuals may decide to use vehicles during an evacuation instead of walking. The dotted lines shift this assumption to 10 or 20 min.

inform outreach efforts aimed at minimizing and discouraging vehicle use when appropriate. In this section, we discuss the implications of our results on evacuation planning, as well as areas for further research.

5.1. Implications for evacuation planning

Results suggest that use of the extreme evacuation zone instead of the standard zone would have a substantial impact on the number of people encouraged to evacuate. The use of the extreme evacuation zone effectively triples the number of residents, employees, and facilities serving at-risk populations that would be encouraged to evacuate (Table 1). The number of hotel visitors from large hotels in an evacuation zone also increases with the extreme zone but more modestly (26%) than other populations.

The extreme evacuation zone was created to recognize worst-case tsunami exposure from scenarios of earthquakes originating in the Aleutian Islands, based on an improved understanding of subduction-zone earthquakes following the 2011 Tohoku event [5]. Therefore, it is assumed that the use of the extreme evacuation would be rare and not implemented for tsunamis generated elsewhere within the Pacific Ocean basin. If a tsunamigenic earthquake did occur within the Aleutian Islands, then ideally there is time for the U.S. tsunami warning centers in Alaska and Hawaiʻi to evaluate and communicate the size and likely areas of inundation prior to local evacuation decisions being made.

Local officials however do not have a large amount of time to decide between the two evacuations zones. First, threat confirmation and warning dissemination from national tsunami warning centers to county and state emergency managers often can take up to 1.5 h before evacuation orders are issued for distant tsunami events in the Pacific Ocean basin [43]. Second, evacuation behavior in past tsunami disasters suggests that departure delays are common for evacuees [32], ranging from 7 to 38 min in past studies [20,21,29,41]. Third, results in this study indicate that pedestrian travel times are as high as 60 min for some employees in the extreme evacuation zone (Fig. 5d). Therefore, if wave arrival to the Hawaiian coastline is approximately 4 h for an Aleutian event [5], then county and state officials may have at most one hour to decide which evacuation zone to use. Facilities serving at-risk populations, such as assisted living facilities and medical centers, may need even more time to prepare for an evacuation, thereby reducing the decision window [74].

Choice of evacuation zone also determines the extent of evacuation challenges for Oʻahu coastal communities. Assuming a fast walking speed or slower, only 2% of residents and hotel visitors, as well as 0.2% of employees, in the standard evacuation zone are estimated to require more than 15 min to evacuate and of those that do, they may only need up to 10 min of more time to reach safety. Therefore, with proper and sustained outreach on evacuation behavior by county and state emergency management agencies, it may be possible to reduce the number of cars used during an evacuation out of the standard zone. This could reduce the potential for vehicular congestion and provide an unimpeded opportunity for the estimated 121 employees (Fig. 5c), 2002 residents (Fig. 5b), and 8 facilities serving at-risk populations (Fig. 6a) that are in areas that may require 15 min or more to leave the standard evacuation zone. Outreach could also be targeted to the communities with higher travel times (e.g., Mokulēʻia, Haleʻiwa, and Lāʻie in the North Shore region), communities with substantial numbers of residents with functional needs that restrict their ability to evacuate, and to the facilities serving mobility-limited populations (Fig. 6) to determine how to best evacuate these individuals, such as shuttles. Additional outreach that encourages vertical evacuation in appropriate buildings could also help alleviate potential evacuation challenges for the approximately 53,000 hotel visitors in the standard-evacuation zone (Table 1).

Evacuation challenges increase substantially for the extreme evacuation zone, where 24% and 26% of residents and employees, respectively, may require greater than 15 min to evacuate. The increase in the number of individuals requiring more than 15 min to evacuate is greater for employees than it is for residents (Fig. 5). The distribution of individuals requiring more than 15 min to evacuate also varies by type, in that 57% of employees and 84% of residents in these areas may only need an additional 10 min to be successful. Again, in these situations, short-distance shuttles or outreach that encourages individuals to walk for slightly longer durations may decrease vehicle use. While relatively short travel times estimated for a standard evacuation may support outreach that emphasizes pedestrian travel, the longer travel times estimated for the extreme evacuation zone suggest that plans to coordinate vehicular evacuations may be warranted. Regardless of choice of evacuation zone, transportation plans may be warranted to assist special-needs populations (Fig. 6) or those with pre-existing health issues [54] during a distant tsunami evacuation (see [53] for recommended practices). The percentage of hotel visitors that may require more than 15 min to evacuate increases substantially from the standard to the extreme zone (2–76%, respectively) (Table 1; Fig. 6); however, as discussed earlier, vertical evacuations in appropriate buildings may greatly reduce this issue.

The varying evacuation challenges due to the two evacuation zones are best exemplified by communities in the North Shore region. Areas with individuals that would need to move faster than a fast walk to get out of the standard evacuation zone within 15 min are limited to relatively small residential areas near parks (Fig. 9). Short-distance shuttles may be a realistic option given the limited scope and location of the problem areas. There are also several egress routes to reach safety in each of these towns. If the extreme evacuation zone is recommended (Fig. 9b), then the majority, if not all, of the populations in each these communities may be in areas that would take more than 15 min at a reasonable walking speed. The number of egress routes would also decrease; for example, egress options in Lāʻie would be limited to three roads that go into the island uplands.

As briefly discussed earlier, one approach to reduce vehicle use during an extreme evacuation is encouraging vertical evacuations to higher floors, where possible. In official guidance for the extreme evacuation zone, individuals are instructed to evacuate to the fourth floor or above in reinforced concrete or structural steel buildings of ten stories or more [13]. One challenge is that evacuees may not know the structural composition of a nearby building during an evacuation. In addition, this recommendation is not feasible in North Shore communities, as well as many of the other smaller communities around Oʻahu, due to the rarity of high buildings. This recommendation is more feasible and likely to have a substantial positive impact on evacuations in Urban Honolulu, which contains the concentrated hotel and high-rise apartment zone of Waikīkī Beach. Seventy-nine percent of the employees and 38% of the residents that may require more than 15 min to evacuate in the Oʻahu extreme evacuation zone are in Urban Honolulu. In addition, the majority of the hotel visitors in the standard and extreme evacuation zones (96% and 89%, respectively) are in Urban Honolulu, where vertical evacuations are likely. Therefore, a substantial number of individuals with high travel times may be able to evacuate by seeking higher floors in nearby buildings or are already located in high buildings due to the nature of where they live, work, or stay while on vacation.

5.2. Challenges of multi-modal evacuation planning

The ability to identify areas where pedestrian travel speeds and times to evacuate are not plausible provides emergency managers with actionable information for developing effective outreach and procedures. Results of this study demonstrate that the choice of evacuation zone could substantially influence the size and travel modes of a distant tsunami evacuation on Oʻahu. Results that demonstrate that foot-based evacuations can be completed in a reasonable time can be used to increase positive outcome expectancy, which is considered a significant

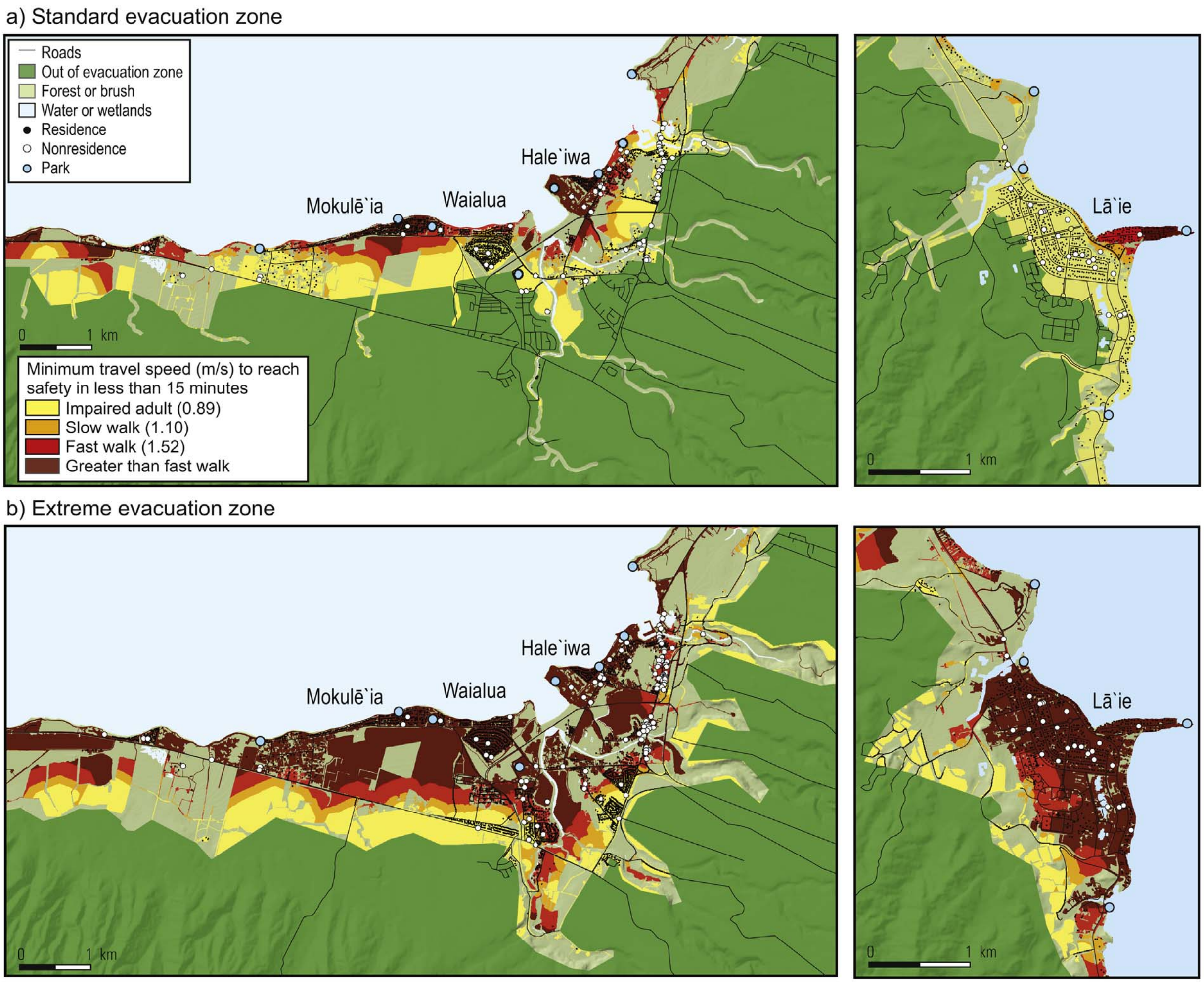

Fig. 9. Maps of minimum travel speed required by pedestrians at residences and nonresidences to exit evacuation zones within 15 min, including (a) the standard evacuation zones and (b) extreme evacuation zones of Mokulēʻia, Waialua, Haleʻiwa, and Lāʻie in the North Shore region of the Island of Oʻahu.

factor in motivating people to prepare for extreme events [50]. An increase in pedestrian evacuations will hopefully decrease concerns about potential traffic, which has been shown to be a significant negative factor in an individual's decision to evacuate hazard zones [17].

Use of these findings to develop multiple evacuation plans is challenging for several reasons and warrant additional research. First, neighborhood-level evacuation plans based on different distant-tsunami scenarios may be difficult to develop for county and state emergency managers, who are responsible for developing plans at much greater scales. Such a local intervention could be implemented with outreach efforts capable of reaching individual households and businesses, such as the tsunami-related Neighborhood Educator Project in Seaside, Oregon [14]. Advances in mass notification systems and other mobile-communication technology also could be harnessed to help communicate local evacuation procedures, such as the use of targeted shuttles for at-risk populations.

An additional challenge in multi-modal evacuation planning is knowing whether or not individuals in evacuation zones would comply with localized evacuation procedures. Results presented here make the geographic case that successful foot-based evacuations in a reasonable amount of time are possible for many individuals; however, it does not address the behavioral and sociological aspects of an evacuation that would influence the decision-making process of evacuees. There is currently a lack of sociological or psychological literature on evacuation behavior during tsunamis, particularly in the United States [36,44]. Two areas of related research are to gauge likely evacuation behavior based on our results and how to incentivize pedestrian evacuations given the multiple hours before wave arrival. Residents may choose to drive because they wish to save their cars and belongings, or may decide to drive if they see other vehicles being used. Another factor favoring car use is the perceived liability by tourists for damages to rental cars, which may be a significant issue on an island where 61% of all vehicles are non-residential [56]. Another aspect of tsunami evacuation behavior is our assumption of a 15-min threshold, which is based on mass transit studies and may vary for evacuations. Our sensitivity analysis of this time threshold indicates that the percentage of residents that may decide to use vehicles does not vary substantially for the standard evacuation zone but does for the extreme evacuation zone (Fig. 8). In addition to incentivizing pedestrian evacuations, more research is warranted on how to enforce localized evacuation procedures, since public-safety officials will have limited resources and managing pedestrian evacuations can be challenging [3].

Another complicating factor in implementing localized evacuation procedures is the role of shadow evacuees, defined as individuals who are outside of an evacuation zone but still decide to leave. In a study of flood evacuations in New Zealand, Lamb et al. [33] document that 33% of study participants outside of an evacuation zone said that they would evacuate, either because they incorrectly included themselves in an evacuation order or did so knowingly because they had high levels of concern about their safety. In our case study, residents and employees that are in the extreme evacuation zone but not the standard zone may feel compelled to evacuate regardless of what is communicated during an event. They also may not understand the distinction between the two zones and to date, we are not aware of any studies to gauge whether or

not individuals in O'ahu (including residents, employees, and tourists) understand the distinction in affected areas or purposes between the two evacuation zones.

From a modeling perspective, more research is warranted on the role of evacuation congestion in rural coastal communities, both in terms of just pedestrians and the interaction of people and vehicles sharing egress routes. Previous work on multimodal evacuation modeling has focused primarily on mid-size to large urban areas. For example, Allan et al. [1] assert that tsunami evacuations were hampered in Concepción, Chile following the 2010 earthquake and tsunami partly due to pedestrian congestion at the junctions between the low-lying plains and the hills out of evacuation zones. Yuan and Puchalsky [69] observed increases in evacuation time due to pedestrian-vehicle interactions in evacuation simulations of Philadelphia, Pennsylvania (USA). Several studies have shown that increased use of vehicles over pedestrian travel during an evacuation decreases the number of individuals that reach safety [15,42,71]. Similar issues may exist in smaller, more rural, coastal communities on O'ahu as at-risk individuals move to high ground on a limited number of small roads or trails. Our results indicate that vehicle use may be warranted in certain neighborhoods of a coastal community; therefore, modeling could examine the effect of localized congestion on the success of the larger system. Because of both a local and regional perspective in the current O'ahu case study, a mixed multimodal, evacuation model that leverages LCD and agent-based analytical approaches may provide multi-scalar perspectives.

In light of the various logistical, behavioral, sociological challenges briefly discussed here, predetermined pedestrian evacuation plans could be developed to implement and communicate targeted evacuation procedures [18,3]. Short-term preparedness elements could include priority routes for buses and shuttles to focus on individuals with limited mobility (e.g., assisted living facilities), shelters to provide pickup points for shuttles, the addition of walking routes on evacuation maps, and educational efforts to encourage vertical evacuation. More long-term solutions may include sidewalk widening and pedestrian bridges over busy roads [18]. In addition, attention to urban design and wayfinding mitigation (e.g., street lighting and signage) in areas with high buildings may improve distant tsunami evacuations [35,51].

6. Conclusions

The objective of this paper is to present a regional evacuation modeling approach to help emergency managers and transportation planners on O'ahu Island identify areas where pedestrian evacuations for distant tsunamis may be successful. This information could then be used in outreach efforts to discourage vehicle use in distant tsunami evacuations. Based on our analysis, we reach several conclusions that bear on future tsunami risk-reduction research and management in at-risk coastal communities.

- Recommendations to use the extreme evacuation zone over the standard zone will have a dramatic impact on the size of an evacuation, since the number of residents, employees, and facilities serving at-risk populations increases by a factor of three between the two zones (e.g., ~80,000 versus ~242,000 residents).
- Recommended travel mode could vary depending on evacuation zone. Pedestrian evacuations at a reasonable speed and within a reasonable amount of time are possible for 98% of the residents in the standard evacuation zone, but only 76% of those in the extreme evacuation zone. This suggests effective education could reduce traffic issues for a standard evacuation, but vehicle use is likely in certain areas during an extreme evacuation.
- Outreach to discourage vehicle use during standard evacuations could be done in all communities except certain neighborhoods in the North Shore region, where populations may have evacuation travel times greater than 15 min. For extreme evacuations, populations with long pedestrian travel times are found in many coastal communities around O'ahu; therefore, plans to coordinate vehicular evacuations may be warranted.
- The number of facilities serving at-risk populations that would require greater than 15 min walking to safety increases by an order of magnitude when comparing the standard and extreme evacuation zones. These facilities are largely in the North Shore region for the standard zone, but in Urban Honolulu for the extreme evacuation zone. Targeted use of shuttles may be warranted to help specific facilities get their patients or students to safety.
- Evacuation modeling can identify where pedestrian evacuations in a reasonable amount of time at a reasonable speed are possible; however, there are significant logistical and behavioral issues that warrant additional research and targeted outreach before localized evacuation procedures may be realistic.

Acknowledgments

This study was supported by the US Geological Survey (USGS) Land Change Science Program, Coastal and Marine Geology Program, and Science Application for Risk Reduction (SAFRR) project. We thank Kevin Henry and Mathew Jamieson for their assistance in data development. We thank Stephanie Ross and anonymous reviewers for their insightful reviews of earlier versions of the article. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government. All results of this study are publicly available at [https://doi.org/10.5066/F7862FNT].

References

[1] P. Allan, M. Bryant, C. Wirsching, D. Garcia, M. Rodriguez, The influence of urban morphology on the resilience of cities following an earthquake, J. Urban Des. 18 (2) (2013) 242–262.
[2] K. Berryman, L. Wallace, G. Hayes, P. Bird, K. Wang, R. Basili, T. Lay, R. Stein, T. Sagiya, C. Rubin, S. Barreintos, C. Kreemer, N. Litchfield, M. Pagani, K. Gledhill, K. Haller, C. Costa The GEM Faulted Earth Subduction Characterization Project [Version 1.0, June 2013, GEM Faulted Earth Project]: 〈http://www.nexus.globalquakemodel.org/gem-faulted-earth/posts〉, (Accessed 13 May 2015).
[3] P. Bolton, Managing pedestrians during evacuation of metropolitan areas. Publication No. FHWA-HOP-07-066. Federal Highway Administration. 71 p, 2007.
[4] R. Butler, D. Burney, D. Walsh, Paleotsunami evidence on Kauai and numerical modeling of a great Aleutian tsunami, Geophys. Res. Lett. 41 (2014) 6795–6802.
[5] R. Butler, D. Walsh, K. Richards, Extreme tsunami inundation in Hawai'i from Aleutian–Alaska subduction zone earthquakes, Nat. Hazards 85 (2017) 1591–1619.
[6] T. Charnkol, Tanaboriboon, Evacuee behaviors and factors affecting the tsunami trip generation model: a case study in phang-nga, Thailand, J. Adv. Transp. 40 (3) (2006) 313–330.
[7] K. Cheung, Hawaii Tsunami Mapping Project: Data Sources, Procedures, and Products for Extreme Aleutian Events. Final Report to Hawaii Emergency Management Agency, University of Hawaii, Honolulu, 2015.
[8] City and County of Honolulu Final_extreme_tsunami_evacuation_2015. Available at 〈http://cchnl.maps.arcgis.com/home/item.html?Id=81423ae459d84188a7def8f357533dd2〉.
[9] City and County of Honolulu, Tsunami evacuation zones. Available at 〈https://www.honolulu.gov/demevacuate/tsunamimaps.html〉, 2018.
[10] City and County of Honolulu Building footprints (CCH). Available at 〈http://honolulu-cchnl.opendata.arcgis.com/datasets/aa444ba7c76e475f8dc54e0fa0913b34_0〉.
[11] City and County of Honolulu Parcels – Tax. Available at 〈http://honolulu-cchnl.opendata.arcgis.com/datasets/3216a20b21fd438495716a78c4642737_1〉.
[12] City and County of Honolulu Honolulu County Tax Office. Available at 〈http://qpublic9.qpublic.net/hi_honolulu_search.php〉.
[13] City and County of Honolulu, New extreme tsunami evacuation zone FAQ. Available at 〈https://www.honolulu.gov/rep/site/dem/XTEZ-FAQs_FINAL_rev_20170616.pdf〉, 2017d.
[14] D. Connor, The City of Seaside's tsunami awareness program outreach assessment—how to implement an effective tsunami preparedness outreach program. Open File Report O-05-10, Oregon Department of Geology and Mineral Industries, 78 p, 2005.
[15] M. Di Mauro, K. Megawati, V. Cedillos, B. Tucker, Tsunami risk reduction for densely populated Southeast Asian cities: analysis of vehicular and pedestrian evacuation for the city of Padang, Indonesia, and assessment of interventions, Nat. Hazards 68 (2) (2013) 373–404.
[16] W. Dudley, The Pacific Tsunami Museum–a memorial to those lost to tsunamis, and an education center to prevent further casualties, Sci. Tsunami Hazards 17 (2) (1999) 127–134.
[17] K. Dow, S. Cutter, Emerging hurricane evacuation issues– Hurricane Floyd and South Carolina, Nat. Hazards Rev. 3 (1) (2002) 12–18.

[18] J. Ercolano, Pedestrian disaster preparedness and emergency management of mass evacuations on foot: state-of-the-art and best practices, J. Appl. Secur. Res. 3 (3/4) (2007) 389–405.
[19] ESRI ArcGISResources – Near (Analysis). Available at 〈http://resources.arcgis.com/EN/HELP/MAIN/10.2/index.html#/Near/00080000001q000000/〉, (Accessed 24 September 2015).
[20] S. Fraser, D. Johnston, G. Leonard, Intended evacuation behaviour in a local earthquake and tsunami at Napier, New Zealand, Science Report 2013/26, GNS Science, Lower Hutt, New Zealand, 2013.
[21] S. Fraser, N. Wood, D. Johnston, G. Leonard, P. Greening, T. Rossetto, Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling, Nat. Hazards Earth Syst. Sci. 14 (2014) 2975–2991.
[22] M. Foyer Tsunami scare sends locals to the hills, Half Moon Bay Review, March 16, 2011, 〈http://www.hmbreview.com/tsunami-scare-sends-locals-to-the-hills/article_3d16f6b4-4ff7-11e0-9fac-001cc4c002e0.html〉, last referenced 9/21/2017.
[23] Hawai'i Board on Geographic Names Board on Geographic Names: 〈[http://planning.hawaii.gov/gis/hbgn/〉, last (accessed 26 February 2015).
[24] Hawaii State Department of Education Haleiwa El marks Tsunami Awareness Month with evacuation drill. 〈http://www.hawaiipublicschools.org/ConnectWithUs/MediaRoom/PressReleases/Pages/Haleiwa-El-Tsunami-Evacuation-Drill.aspx〉, last (accessed 9 January 2018).
[25] Hawai'i Office of Planning Hawai'i Statewide GIS Program: 〈[http://planning.hawaii.gov/gis/〉, (Accessed 9 April 2015).
[26] Hawaii Emergency Management Agency, Siren and emergency alert system test. Available at 〈https://dod.hawaii.gov/hiema/files/2018/01/20180102-Monthly-Siren-Test-NR.pdf〉, 2018.
[27] K. Henry, N. Wood, T. Frazier, Influence of road network and population demand assumptions in evacuation modeling for distant tsunamis, Nat. Hazards 85 (2017) 1665–1687.
[28] Infogroup Employer database: Infogroup online dataset. 〈http://referenceusagov.com/Static/Home〉. (Accessed 27 October 2014).
[29] F. Imamura, A. Muhari, E. Mas, M. Pradono, J. Post, Sugimoto, Tsunami disaster mitigation by integrating comprehensive countermeasures in Padang City, Indonesia, Disaster Res. 7 (2012) 48–64.
[30] J. Jones, P. Ng, N. Wood The pedestrian evacuation analyst—geographic information systems software for modeling hazard evacuation potential. U.S. Geological Survey Techniques and Methods, book 11, chap. C9. Retrieved from 〈http://dx.doi.org/10.3133/tm11C9〉. ISSN: 2328–7055.
[31] J. Jones, M. Jamieson, N. Wood Community Exposure to Tsunami Hazards in Hawai'i. U.S. Geological Survey Scientific Investigation Report 2016–5053, 32 p., http://dx.doi.org/10.3133/sir20165053.
[32] R. Lachman, M. Tatsuoka, W. Bonk, Human behavior during the tsunami of May 1960, Science 133 (3462) (1961) 1405–1409.
[33] S. Lamb, D. Walton, K. Mora, J. Thomas, Effect of authoritative information and message characteristics on evacuation and shadow evacuation in a simulated flood event, Nat. Hazards Rev. 13 (4) (2012) 272–282.
[34] J. Lander, P. Lockridge, United States tsunamis (including United States possessions), 1690–1988: Boulder, Colo., U.S. Department of Commerce, National Geophysical Data Center, Publication 41-42, 1989.
[35] J. Leon, A. March, An urban form response to disaster vulnerability–improving tsunami evacuation in Iquique, Chile, Environ. Plan. B—Urban Anal. City Sci. 43 (5) (2016) 826–847.
[36] M. Lindell, C. Prater, Tsunami preparedness on the Oregon and Washington coast–recommendations for future research, Nat. Hazards Rev. 11 (2) (2010) 69–81.
[37] M. Lindell, J. Kang, C. Prater, The logistics of household hurricane evacuation, Nat. Hazards 58 (2011) 1093–1109.
[38] M. Lindell, C. Prater, C. Gregg, E. Apatu, S. Huang, H. Wu, Households' immediate responses to the 2009 American Samoa earthquake and tsunami, Int. J. Disaster Risk Reduct. 12 (2015) 328–340.
[39] Y. Liu, G. Chang, Y. Liu, X. Liu, Corridor-Based Emergency Evacuation System for Washington, D.C.: System Development and Case Study, In Transportation Research Record: Journal of the Transportation Research Board, No.2041, Transportation Research Board of the National Academies, Washington, D.C. 58-67, 2008.
[40] K.-F. Ma, H. Kanamori, K. Satake, Mechanism of the 1975 Kalapana, Hawaii, earthquake inferred from tsunami data, J. Geophys. Res. 104 (B6) (1999) 13153–13167.
[41] E. Mas, A. Suppasri, F. Imamura, S. Koshimura, Agent-based simulation of the 2011 great east Japan earthquake/tsunami evacuation– an integrated model of tsunami inundation and evacuation, J. Nat. Disaster Sci. 34 (2012) 41–57.
[42] E. Mas, B. Adriano, S. Koshimura, An integrated simulation of tsunami hazard and human evacuation in La Punta, Peru, J. Disaster Res. 8 (2) (2013) 285–295.
[43] K. Miller, K. Long, Emergency management response to a warning-level Alaska-source tsunami impacting California. in: Ross S.L., Jones L.M. Ross (eds.) The SAFRR (science application for risk reduction) tsunami scenario: US Geological Survey Open-File Report 2013–1170, p 245, 2013.
[44] National Research Council, Tsunami Warning and Preparedness—an Assessment of the U.S. Tsunami Program and the Nation's Preparedness Efforts, Committee on the Review of the Tsunami Warning and Forecast System and Overview of the Nation's Tsunami Preparedness, Ocean Studies Board, National Research Council, 2011.
[45] NOAA NCEI, Tsunami travel time maps—tsunami sources: [〈https://ngdc.noaa.gov/hazard/tsu_travel_time_events.shtml〉, (Accessed January 8, 2018), 2018.
[46] NOAA OCM, NOAA—Data Access Viewer: 〈https://coast.noaa.gov/dataviewer/#/〉, (Accessed 4 October 2017), 2017.
[47] NOAA OCM C-CAP – NOAA Office for Coastal Management: 〈[http://coast.noaa.gov/ccapftp/〉, (Accessed 11 May 2015).
[48] National Weather Service Pacific Tsunami Warning Center Frequently Asked Questions: 〈http://ptwc.weather.gov/ptwc/faq.php〉, (Accessed 9 January 2018).
[49] M. Okushima, H. Yamanaka, Traffic simulation of evacuation by vehicle at the outbreak of tsunami in the coastal plain area of the local city. Paper B5-3, Proceedings of the 2012 annual conference of the International Institute for Infrastructure Resilience and Reconstructions, Kumamoto, Japan, 10 p, 2012.
[50] D. Paton, B. Houghton, C. Gregg, D. Gill, L. Ritchie, D. McIvor, P. Larin, S. Meinhold, J. Horan, D. Johnston, Managing tsunami risk in coastal communities—identifying predictors of preparedness, Aust. J. Emerg. Manag. 23 (1) (2008) 4–9.
[51] Portland Urban Architecture Research Lab Oregon tsunami wayfinding research project–a study in Seaside and Warrenton. Report prepared for the Oregon Office of Emergency Management. Available at 〈http://www.oregon.gov/oem/Documents/Up_And_Out_Phase2.pdf〉.
[52] F. Ramm, J. Topf, S. Chilton, OpenStreetMap: Using and Enhancing the Free Map of the World, 1st ed., UIT Cambridge, Cambridge, 2010.
[53] J. Renne, T. Sanchez, T. Litman National study on carless and special needs evacuation planning–a literature review. Unpublished report prepared for the U.S. Federal Transit Administration. 110 p. Available at 〈www.planning.uno.edu/docs/CarlessEvacuationPlanning.pdf〉.
[54] M. Rosenkoetter, E. Covan, B. Cobb, S. Bunting, M. Weinrich, Perceptions of older adults regarding evacuation in the event of a natural disaster, Public Health Nurs. 24 (2) (2007) 160–168.
[55] H. Shimamoto, J.-D. Scmocker, N. Bunpei, T. Nakamura, N. Uno, H. Yamazaki, Evaluation of tsunami evacuation planning considering vehicle usage and start timing of evacuation, Transp. A: Transp. Sci. (2017) 1–16, http://dx.doi.org/10.1080/23249935.2017.1290708.
[56] State of Hawaii Section 18, 2015 Data Book, prepared by the Department of Business, Economic Development and Tourism. Available at 〈http://dbedt.hawaii.gov/economic/databook/db2015/〉.
[57] State of Hawaii, Visitor Statistics, Prepared by the Department of Business, Economic Development and Tourism, 2016, 〈http://dbedt.hawaii.gov/visitor/visitor-research/〉.
[58] State of Hawaii Hotel geospatial data. Available at 〈http://planning.hawaii.gov/gis/download-gis-data/〉.
[59] R. Soule, R. Goldman, Terrain coefficients for energy cost prediction, J. Appl. Physiol. 32 (1972) 706–708.
[60] R. Thompson, D. Garfin, R. Silver, Evacuation from natural disasters: a systematic review of the literature, Risk Anal. 37 (4) (2017) 812–839.
[61] W. Tobler Three presentations on geographical analysis and modeling—non-isotropic geographic modeling. Speculations on the geometry of geography; and global spatial analysis. UCSB. National Center for Geographic Information and Analysis Technical Report 93-1. 〈http://www.ncgia.ucsb.edu/Publications/Tech_Reports/93/93-1.PDF〉. (Accessed 19 July 2010).
[62] Transportation Research Board Transit capacity and quality of service manual, 3rd edition, Transit Cooperative Research Program Report 165, 685 p. http://dx.doi.org/10.17226/24766.
[63] F. Trusdell, A. Chadderton, G. Hinchliffe, A. Hara, B. Patenge, T. Weber Tohoku-Oki earthquake tsunami runup and inundation data for sites around the Island of Hawai'i. U.S. Geological Survey Open-File Report 2012–1229, 36 p., 〈http://pubs.usgs.gov/of/2012/1229/〉.
[64] U.S. Census Bureau United States Census 2010—It's in our hands: U.S. Census Bureau Web page, (Accessed 27 February 2015), at 〈http://www.census.gov/2010census/〉.
[65] U.S. Census Bureau Cartographic boundary files: 〈http://www.census.gov/geo/maps-data/data/tiger-cart-boundary.html〉, (Accessed 27 February 2015).
[66] U.S. Department of Agriculture Geospatial Data Gateway. Available at 〈http://datagateway.nrcs.usda.gov/〉, (Accessed 1 February 2017).
[67] U.S. Department of Health and Human Services At-risk, behavioral health and community resilience (ABC): Office of the Assistant Secretary for Preparedness and Response, available at 〈http://www.phe.gov/Preparedness/planning/abc/Pages/default.aspx〉.
[68] U.S. Department of Homeland Security, Homeland Infrastructure Foundation-Level Data (HIFLD). Available at 〈https://gii.dhs.gov/HIFLD/〉, 2015.
[69] F. Yuan, C. Puchalsky, Multimodal evacuation simulation and scenario analysis in dense urban area–Philadelphia, Pennsylvania, case study, Transp. Res. Rec.: J. Transp. Res. Board. 2532 (2015) 91–98.
[70] D. Walker, Regional tsunami evacuations for the state of Hawaii–a feasibility study based on historical runup data, Sci. Tsunami Hazards 22 (1) (2004) 3–22.
[71] H. Wang, A. Mostafizi, L. Cramer, D. Cox, H. Park, An agent-based model of a multimodal near-field tsunami evacuation– decision-making and life safety, Transp. Res. Part C: Emerg. Technol. 64 (2016) 86–100.
[72] N. Wood, M. Schmidtlein, Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest, Nat. Hazards 62 (2) (2012) 275–300.
[73] N. Wood, M. Schmidtlein, Community variations in population exposure to near-field tsunami hazards as a function of pedestrian travel time to safety, Nat. Hazards 65 (3) (2013) 1603–1628.
[74] N. Wood, J. Ratliff, J. Peters, K. Shoaf Population vulnerability and evacuation challenges in California for the SAFRR tsunami scenario, chap, in: Ross S. and Jones L., eds., The SAFRR (Science Application for Risk Reduction) Tsunami Scenario: U. S. Geological Survey Open-File Report 2013–1170, 53 p.
[75] X. Zhang, G. Chang, A dynamic evacuation model for pedestrian–vehicle mixed-flow networks, Transp. Res. Part C 40 (2014) 75–92.