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Households' Intended Evacuation Transportation Behavior in Response to Earthquake and Tsunami Hazard in a Cascadia Subduction Zone City

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Abstract

Earthquakes along the Cascadia subduction zone would generate a local tsunami that could arrive at coastlines within minutes. Few studies provide empirical evidence to understand the potential behaviors of local residents during this emergency. To fill this knowledge gap, this study examines residents' perceptions and intended evacuation behaviors in response to an earthquake and tsunami, utilizing a survey sent to households in Seaside, OR. The results show that the majority of respondents can correctly identify whether their house is inside or outside a tsunami inundation zone. Older respondents are more likely to identify this correctly regardless of any previous disaster evacuation experience or community tenure. The majority of respondents (69%) say they would evacuate in the event of a tsunami. Factors influencing this choice include age, motor ability, access to transportation, and trust in infrastructure resiliency or traffic conditions. While the City of Seaside actively promotes evacuation by foot, 38% of respondents still state they would use a motor vehicle to evacuate. Females and older respondents are more likely to evacuate by foot. Respondents with both higher confidence in their knowledge of disaster evacuation and higher income are more likely to indicate less time needed to evacuate than others. Generally, respondents are more likely to lead rather than follow during an evacuation, especially respondents who report being more prepared for an evacuation and who have a higher perceived risk. This study showcases a unique effort at empirically analyzing human tsunami evacuation lead or follow choice behavior.

Earthquakes along the Cascadia Subduction Zone (CSZ) would generate a local tsunami that could arrive at coastlines within 15–30 min of the earthquake's start (*1*). With minimal evacuation time, mortality rates could reach 60% depending on the speed of evacuation, available evacuation routes, evacuation mode of choice, terrain, and other factors (*2*). It is critical for local authorities to determine whether the Oregon Coast is prepared for a tsunami hazard. From a transportation engineering and social science perspective, this study examines residents' intended evacuation perceptions and behaviors in response to a magnitude 9 (M9) CSZ earthquake and tsunami.

A generally accepted assumption in evacuation analysis is that households will evacuate as soon as physically possible. To add conservatism to evacuation time estimate analyses, researchers also assume that 100% of participants will evacuate if told to do so by authorities (*3*). Interestingly, these assumptions are not supported by the outcomes of the survey analyzed in this study or by other empirical studies (*4*). The decision to evacuate is triggered and influenced by environmental and social cues (*5*), and varies between individuals (*6*). Therefore, it is important to understand the characteristics of the individuals at risk and the reasons they may choose to evacuate or stay.

Evacuation mode of choice and lead or follow behavior could play a crucial role in evacuation efficiency. While there have been numerous studies evaluating people's choice of evacuation mode during tsunamis (*7–11*), there is little examination of why people choose certain modes and how those decisions vary within populations.

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While there have been multiple efforts to simulate and understand variations in behavior (e.g., lead or follow, delay start, search for family) in disaster evacuations (*12–14*), few studies have empirically analyzed human lead or follow choice behavior. This study examines five research questions and the factors that influence them. The answers to these questions are important to understand when developing policy and disaster evacuation plans for communities at risk of rapid-onset disasters:

Q1. Can respondents correctly identify whether their house is located inside or outside a tsunami inundation zone?
Q2. Who chooses to evacuate and who chooses to stay?
Q3. What are the respondents' intended evacuation modes?
Q4. How much time do respondents think is needed to evacuate from their homes to tsunami safe zones?
Q5. Do respondents choose to lead or follow during a tsunami evacuation?

Literature Review

Recent and devastating events such as the earthquakes and tsunamis in the Indian Ocean in 2004, American Samoa in 2009, Chile in 2010, Tohoku (Japan) in 2011, and Sulawesi in 2018 have highlighted a need to understand and mitigate the impacts of these events. Existing research has examined elements of the five abovementioned research questions as they pertain to recent earthquake and tsunami events.

According to the protective action decision model (PADM), the decision to evacuate can be influenced by environmental cues, social cues, warnings, and other human characteristics (5). When evacuation is the most important and effective method to save human lives during a tsunami (*15*), the factors that influence evacuation decisions show significant variations in different contexts. Jon et al. compared respondents' actions in the first 30 min after the earthquake in Christchurch and Wellington, New Zealand, and Hitachi, Japan (*16*). The authors concluded that actions taken were weakly related to demographic variables, earthquake experience, contextual variables, and actions taken during the shaking. However, actions taken were significantly related to perceived shaking intensity, risk perception and affective responses to the shaking, and damage or disruption to infrastructure (*16*). In contrast, another research that studied the tsunami response behavior of two local earthquakes in New Zealand found that evacuation decisions are unrelated to ground shaking intensity and duration (*17*). Households in Hitachi had a higher level of tsunami risk perception and were more likely to evacuate than Christchurch households (*18*). Many respondents in the 2016 New Zealand earthquake event stated they were confused directly after the earthquake and waited for official sources to inform them of a potential tsunami evacuation (*19*). Within those 69% evaluated respondents, only 11% evacuated because of the environmental cue. There are similar patterns as well as significant differences between tsunami threats in relation to household reactions (*16*, *18*). More empirical evidence is needed to illustrate the impact variables on the evacuation decision and evacuation process (*18*).

Risk perception includes the judgment of perceived probability and consequence (financial loss, property damage, injury, death, disruption to daily life, etc.). The impact of risk perception on reaction has been studied in different earthquake and tsunami settings (*8, 10, 17, 18, 20, 21*). Some of these studies show that people with higher risk perception are more likely to evacuate (*18*, *22*); whereas some show the opposite, such as in the 2009 American Samoa event (*8*). Previous education had little influence on tsunami impact perception in the two 2013 New Zealand earthquake events, but being a resident in the inundation zone has a significant impact on the expectation of a tsunami occurring (*17*).

Relatively little research has been done to examine the accuracy of perceptions within the tsunami inundation zone. Respondents had accurate perceptions of safety in relation to the tsunami hazard zone in the 2013 New Zealand event. Furthermore, being within the tsunami inundation zone significantly affected respondents' evacuation decisions (*17*). However, the research did not deeply analyze people's perceptions of whether or not they were in the evacuation zone. One study conducted interviews in the Chicago metropolitan area to analyze how people would respond to no-notice emergency evacuation orders, including child pick-up and family gathering behavior (*23*). This study provides empirical evidence of human behavior associated with location perception (i.e., whether children or parents were within disaster impact zones). To date, there have been very limited in-depth research attempts to understand the location perception of the tsunami threat globally, especially in the CSZ.

Recent studies have documented evacuation mode choice and its potential impact in tsunami events (*7–11*, *24*). Patterns show that local residents' evacuation mode choices are highly local and case dependent. For instance, in the tsunami that struck American Samoa in 2009, the majority of residents of the capital city, Pago Pago, evacuated by foot (*7*); whereas an overwhelming number of residents in the other five villages on the western side of the island evacuated by motorized vehicle (*8*). Most respondents in the 2004 Thailand earthquake and tsunami event evacuated by foot, and the same was observed with tourists in Kamakura City, Japan, in 2011 (*9*). However, only about half of the respondents intended to evacuate by foot in a local earthquake and tsunami study for Napier, New Zealand (*10*). A majority of respondents evacuated by foot in the 2018 Sulawesi earthquake tsunami (*25*). Therefore, the evacuation mode distribution seems to be location and scenario dependent. Because of the relatively low frequency of devastating earthquake and tsunamis compared with other frequently occurring disasters such as hurricanes, there are limited case studies to examine tsunami evacuation behavior. This knowledge gap is especially large for CSZ earthquake and tsunami events. Wood et al. used least-cost-distance with consideration to critical retrofit bridges after an earthquake to create a beat-the-wave (BTW) map illustrating the minimum pedestrian travel speed to evacuate safely for each census cell (*26*). This analysis, with its applied approach, can help locals to identify effective evacuation strategies. The evacuation of Seaside faces difficulty from the problematic seaward off-shore-parallel waterways, especially for those with mobility issue. However, the authors mentioned that this method is based on case scenarios, so there is no universal answer for all communities (*26*).

Methods

To answer the research questions for the CSZ, a household survey was conducted in the coastal town of Seaside, OR. The population of Seaside is 6,457 residents, according to the 2010 U.S. Census. The town has a fairly flat topography. Tsunami shelter areas are located approximately 1.5 km east from any shoreline, and the city's transportation system is heavily dependent on a network of bridges. All of these factors contribute to Seaside's high vulnerability to earthquake and tsunami events (*24*, *27*).

The survey data was collected between October and December 2017. Following the tailored design method (*28*), surveys were mailed to a random sample of 1,000 households. Participants were given an option to mail their responses or complete the questionnaire online; 211 completed surveys were returned (Figure 1), resulting in a 22.2% response rate. The study sample is representative of Seaside's population, except that residents with a bachelor's degree or higher and residents over 65 years of age were slightly over-represented in the study sample.

In addition to using a bivariate chart to understand and describe respondents' choices from their survey responses, an inter-correlation table and a linear regression analysis are used to evaluate factors that answer the five research questions. The results are evaluated to explore differences in choices and intentions across demographic groups.

Instrument

The questionnaire (see Supplemental Material) sent to participants was composed of three sections. Section 1 asked participants about their knowledge, perceptions, and preparation for a M9 CSZ earthquake and tsunami; Section 2 asked participants about their potential behavior and the factors related to how they would respond in the event; and Section 3 collected background and demographic information.

Factor Analysis. Factor analysis was applied to reduce multiple-item survey questions into indexes and construct indexes, creating the following variables: risk perception to self, risk perception to others, self-preparation, community preparation, and knowledge perception. Varimax rotation was used to extract factor loadings during the factor analysis. Only items with factor loadings above 0.5 were used in the analysis. Indexes were created by multiplying factor loadings with item values and dividing their sum by the sum of factor loadings for each factor, respectively. A Cronbach alpha measure was used to check scale reliability. For example, risk perception was measured by asking respondents the likelihood (1 = very unlikely, 5 = very likely) of a M9 CSZ earthquake and tsunami causing:

1. Injuries to you or your family
2. A life-threatening situation for you or your family
3. Severe damage or destruction of your home
4. Severe financial burden for you or your family
5. Severe damage or destruction of roads and homes in your town
6. A life-threatening situation for people in your town

The risk perception measure was divided into two components: perception of risk to self and perception of risk to others. The perception of risk to self index consists of items 1–3 with a Cronbach alpha of 0.85, while the perception of risk to others index includes items 4–6 with a Cronbach alpha of 0.77.

Preparation was measured by asking respondents to mark all actions they have undertaken in the past two years. After factor analysis, two indexes were created. The self-preparation index, with a Cronbach alpha of 0.65, includes items: having a communication plan with your family, having an emergency plan with your family, having an emergency supply kit, and having an emergency contact person outside of the Pacific Northwest. The community preparation index, with a Cronbach alpha of 0.61, includes items: attended a meeting about CSZ earthquakes and tsunamis, discussed the topic of tsunami with community members, and attended first aid or CPR training. Preparation indexes are used as

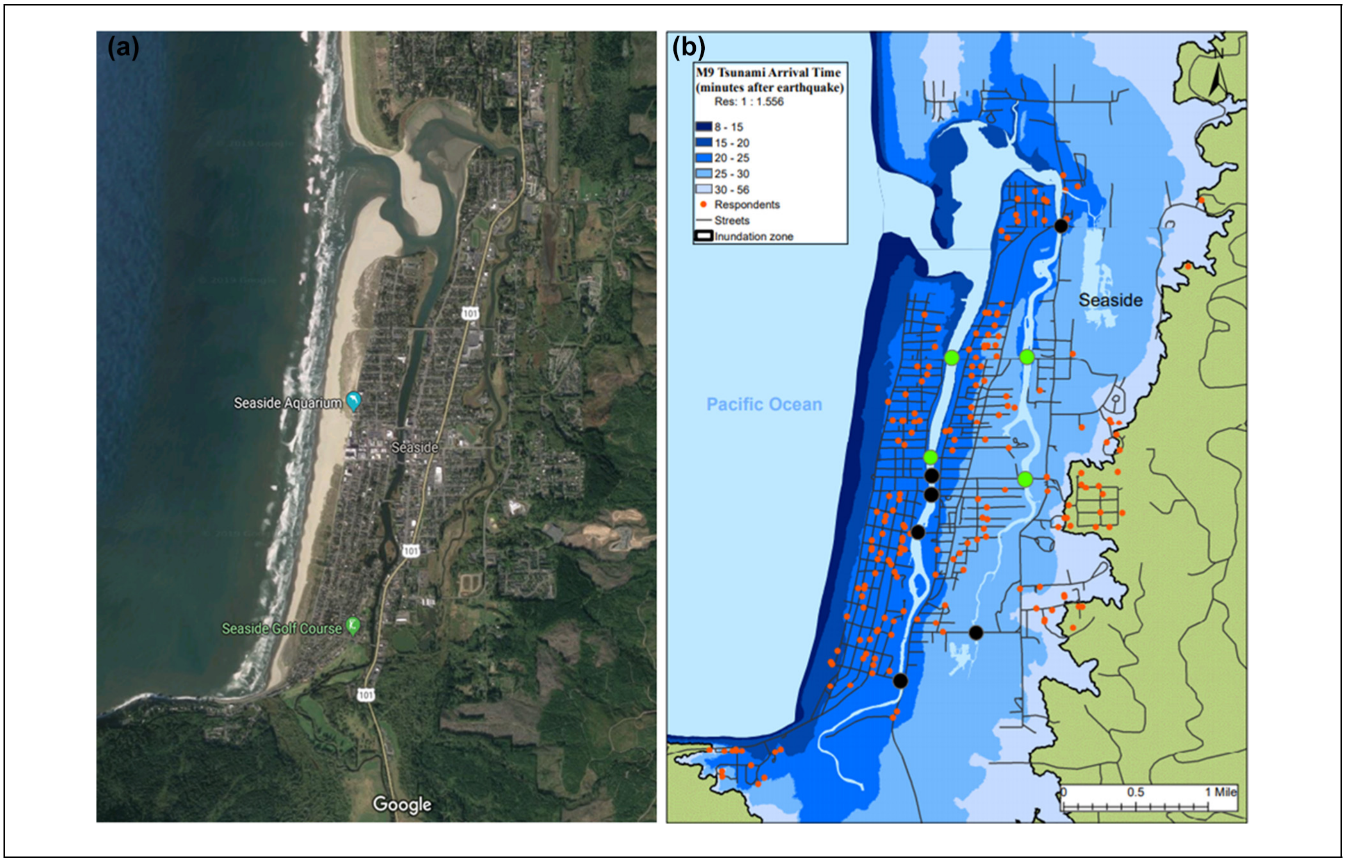

Figure 1. (*a*) Aerial image of Seaside, OR and (*b*) locations of survey respondents.

continuous variables ranging from 0 (no actions taken) to 1 (all survey action items taken) in the analysis.

Knowledge perception index items include: knowing the difference between local and distant tsunamis, understanding natural warning signs of tsunamis, understanding tsunami warning messages, knowing where to get information about tsunami preparation, knowing government recommendations on tsunami preparation, knowing what to do when there is a tsunami warning, knowing tsunami evacuation routes from home, and knowing tsunami safe locations near home. The knowledge perception index has a Cronbach alpha of 0.93.

Variable Descriptions. A hazard can be considered a disaster when human life or property is affected to the point at which society is significantly damaged. During a disaster, people begin protective action and decision-making processes depending on their identification and assessment of risk. Research question 1 evaluates individuals' decisions to take protective action with respect to their individual assessment on location. This is done in five categories:

1. Interpreting their location as exposed to the hazard; the location is exposed to the hazard (true positive);
2. Interpreting their location as exposed to the hazard; the location is not exposed to the hazard (false positive);
3. Interpreting their location as not exposed to the hazard; the location is exposed to the hazard (false negative);
4. Interpreting their location as not exposed to the hazard; the location is not exposed to the hazard (true negative);
5. Cannot decide whether their location is exposed to the hazard; the location is exposed to the hazard (dangerous not sure);
6. Cannot decide whether their location is exposed to the hazard; the location is not exposed to the hazard (safe not sure).

Table 1 displays summary statistics and descriptions for critical independent and dependent variables (n = 206 for all variables).

Results and Discussion

This section discusses the results of the five research questions stated in the introduction. The inter-correlations shown in Table 2 will be compared with a regression analysis to identify influential factors and predictors.

Table 1. Summary Statistics for Dependent and Independent Variables

Variable name	Mean	Standard deviation	Min.	Max.
Perception and behavior variable				
Correctly identify risk zone (1 = can correctly identify house in/out of inundation zone [True positive and true negative]; 0 = otherwise)	0.80	0.404	0	1
Evacuation decision (1 = choose to evacuate, 0 = choose to stay)	0.69	0.464	0	1
Mode: foot (1 = evacuate by foot, 0 = evacuate by other mode)	0.39	0.489	0	1
Mode: drive (1 = evacuate by vehicle, 0 = evacuate by other mode)	0.38	0.486	0	1
Evacuation time (1 = <15 min, 2 = 15–30 min, 3 = 30 + min)	1.52	0.680	1	3
Lead or follow (1 = more likely to lead; 0 = otherwise)	0.67	0.473	0	1
Location perception (whether they think their home is in tsunami inundation area, 1 = Yes, 0 = No)	0.75	0.44	0	1
Risk perception to self (1–5 continues scale, 1 = lowest risk perception to 5 = highest level of risk perception)	4.05	0.89	1	5
Risk perception to others (1–5 continues scale)	4.58	0.61	1	5
Knowledge perception (1–5 continues scale)	3.84	0.97	1.4	5
Self-preparation (0–1 continues scale)	0.36	0.33	0	1
Self-efficacy (confidence in being able to effectively protect themselves, 1 = Not at all confident to 5 = Very confident)	2.83	1.11	1	5
Disaster evacuation experience (whether they have ever experienced a natural disaster where they needed to evacuate, 1 = Yes, 0 = No)	0.23	0.42	0	1
Wave arrival time (time in minutes when tsunami is predicted to arrive at the coastline based on [29])	25.4	4.11	19.3	34
Distance to shore (shortest linear distance in meters between each household and a shoreline)	935.7	584.1	88.9	2,388
Demographics				
Community tenure, years	21.2	19.2	0	99
Gender (1 = female, 0 = male and other)	0.58	0.49	0	1
Income (ranging between 1 = less than \$10,000 to 9 = higher than \$75,000)	6	2.55	1	9
Age, years	60.8	15.2	24	95
Difficulty to walk (1 = Yes, 0 = No)	0.27	0.45	0	1

Note: Min. = minimum; Max. = maximum.

Correctly Identify Location inside or outside the Tsunami Inundation Zone

Identifying whether individuals or households are located within a tsunami inundation zone can define physical exposure and potential risk. While only 14% of residents in Florida coastal counties can specify their home elevation given a five-foot range (*3*, *30*), 80% of respondents in this study correctly identified whether their house is located inside or outside the tsunami inundation zone. Figure 2 shows a complete breakdown of responses to this question.

Individuals or households in categories 1 and 2 are likely to take protective actions. Even though the hazard is no direct threat to people in categories 2, 4, and 6, evacuees in these categories can strain transportation infrastructure. For example, 92% of stay-at-home parents state that they would pick up their children in an inundation zone even if their home is outside the inundation zone (*23*). Individuals or households in categories 3 and 5 may not take appropriate protective action, leading to an unexpected loss of life and property.

A better understanding of residents who can correctly identify whether they are in the inundation zone can help facilitate preparations by local authorities. This study defines category 1 (true positive) and 4 (false negative) as "correct" identifications. The correlation table indicates that distance to shoreline (r = –0.192, $p < 0.01$) and wave arrival time (r = –0.253, $p < 0.01$) are negatively correlated with correct identifications, whereas risk perception to self (r = 0.319, $p < 0.01$) and risk perception to others (r = 0.153, $p < 0.05$) are positively correlated with correct identifications.

The binary logit regression (model 1 in Table 3) shows that an increase of risk perception to self (β = 0.77, $p < 0.01$) and self-preparation level (β = 1.60, $p < 0.05$) increases the likelihood of correctly identifying whether a home is in the inundation zone. Age (β = 0.03, $p < 0.05$) indicates that older people are more likely to correctly identify their location, even when controlling for community tenure (model 2).

Conversely, increase in wave arrival time (which is highly correlated with distance to shore) decreases the likelihood of correctly identifying whether a home is in the inundation zone. The increase in altitude inland could attribute to this significance. Inland residents require detailed understandings of the inundation zone's

Table 2. Inter-Correlation between Variables

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Probability	1	na	na	na	na	na	na	na	na	na	na	na	na
2	Disaster experience	0.062	1	na	na	na	na	na	na	na	na	na	na	na
3	Evacuation experience	–0.102	.240**	1	na	na	na	na	na	na	na	na	na	na
4	Self-efficacy	–0.029	.155*	–0.021	1	na	na	na	na	na	na	na	na	na
5	Evacuation decision	0.095	–0.037	0.047	–0.071	1	na	na	na	na	na	na	na	na
6	Location perception	0.027	0.083	0.082	–0.116	.310**	1	na	na	na	na	na	na	na
7	Correctly identifying location	0.089	0.053	0.079	–0.064	0.129	.760**	1	na	na	na	na	na	na
8	Lead than follow	0.046	0.063	0.021	.184**	.309**	.162*	0.132	1	na	na	na	na	na
9	Mode drive	–.180**	–0.008	.162*	–0.1	0.048	0.131	0.047	–0.048	1	na	na	na	na
10	Mode foot	0.111	–0.014	–0.109	0.056	.191**	0.073	0.008	.178*	–.622**	1	na	na	na
11	Gender	0.087	–0.092	.141*	–0.135	0.07	0.12	0.036	0.097	–0.049	0.129	1	na	na
12	Age	0.087	–0.061	0.001	–.342**	0.01	.180**	0.102	–0.126	0.047	0.039	–0.066	1	na
13	Walking disability	.154*	–0.049	0.05	–.361**	0.08	0.129	0.038	–.151*	0.108	–0.129	0.008	.376**	1
14	Household size	–0.062	–0.032	0.006	.188**	0.046	–.186**	–0.087	0.065	0.04	–0.055	0.045	–.410**	–.151*
15	Ownership	0.029	–0.016	–0.059	.205**	–0.063	–0.093	–0.017	0.064	–.142*	0.085	–0.083	.148*	–0.135
16	Primary residence	0.118	0.076	–0.01	–0.037	0.057	0.046	0.028	0.002	0.066	–0.057	0.084	0.031	0.059
17	Community tenure	0.051	–0.003	0.073	0.039	–0.064	0.07	0.06	–0.051	0.041	–0.01	–0.117	.274**	0.089
18	Education	–0.099	0.11	0	0.01	–0.058	–0.017	0.056	0.021	–0.086	0.013	–0.011	0.02	–0.106
19	Income	–0.084	–0.047	–0.084	.173*	–0.019	–0.112	0.045	.180**	–0.044	–0.064	–0.054	–0.067	–.315**
20	Wave arrival time	0.108	–0.048	–0.107	.273**	–.144*	–.469**	–.253**	–0.073	–.255**	0.061	–0.124	–0.046	–0.005
21	Distance to shore	0.099	–0.047	–0.058	.253**	–0.082	–.344**	–.192**	–0.099	–.138*	0.004	–0.115	0.026	0.089
22	Self-preparation	0.014	.145*	0.085	.431**	–0.052	–0.055	0.082	.258**	–0.126	.143*	0.019	–.169*	–.162*
23	Community preparation	0.117	0.1	0.108	.286**	–0.043	–0.014	–0.007	.188**	–.167*	0.113	.147*	–0.118	–0.108
24	Risk to self	.197**	0.08	0.123	–.287**	.210**	.319**	.319**	.164*	0.037	–0.025	.163*	–0.03	.138*
25	Risk to other	.191**	0.077	0.056	–0.055	0.06	.160*	.153*	.210**	–0.034	–0.011	0.055	–0.107	0.113
26	Knowledge perception	0.018	.150*	–0.037	.534**	0.053	–0.045	0.039	.274**	–0.097	0.08	–0.123	–.165*	–.231**
27	Estimated evacuation time	.143	–.048	–.054	–.297**	–.05	.045	.002	–.077	–.288**	.168*	.14	.20**	.20**

		14	15	16	17	18	19	20	21	22	23	24	25	26
15	Ownership	0.085	1	na	na	na	na	na	na	na	na	na	na	na
16	Primary residence	–0.017	–0.084	1	na	na	na	na	na	na	na	na	na	na
17	Community tenure	0.012	.228**	0.082	1	na	na	na	na	na	na	na	na	na
18	Education	–0.095	.161*	–.145*	–.172*	1	na	na	na	na	na	na	na	na
19	Income	.234**	.356**	–0.042	–0.006	.308**	na	na	na	na	na	na	na	na
20	Wave arrival time	.204**	.172*	–0.054	0.042	–0.004	0.128	1	na	na	na	na	na	na
21	Distance to shore	.150*	.165*	–0.005	0.085	–0.098	0.02	.838**	1	na	na	na	na	na
22	Self-preparation	.201**	.174*	0.026	0.104	0.048	.145*	.215**	.148*	1	na	na	na	na
23	Community preparation	0.063	.216**	0.062	0.128	.141*	0.135	0.093	0.102	.328**	1	na	na	na
24	Risk to self	–0.053	–0.038	.187**	0.042	–0.007	–0.029	–.355**	–.226**	–0.085	0.067	1	na	na
25	Risk to other	0.008	–0.023	0.104	0.134	–0.049	–0.111	–.155*	–0.126	0.102	0.119	.554**	1	na
26	Knowledge perception	.168*	.297**	0.018	.178*	0.039	.209**	.156*	.149*	.487**	.393**	–0.044	0.106	1
27	Estimated evacuation time (n=181)	–0.101	–0.004	0.007	–0.04	0.033	–.193**	–.058	–.068	–.083	–.028	.131	.065	–.281**

Note: na = not applicable.
**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed).

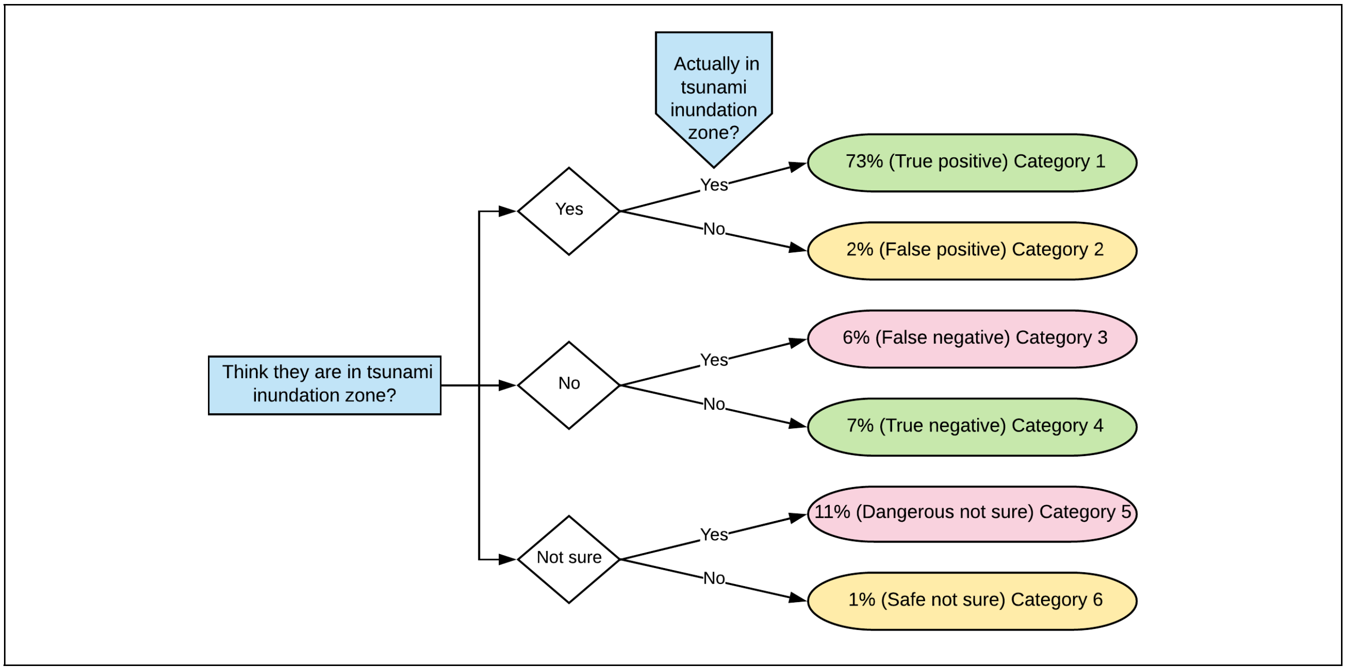

Figure 2. Perception versus actual household location in the tsunami inundation zone.

Table 3. Binary Logit Regression for Q1

Dependent variable = correctly identify in/out of inundation zone (1 = correct; 0 = incorrect)	Model 1	Model 2
Variable	Estimate (standard error)	Estimate (standard error)
Constant	–0.622 (1.86)	–0.795 (2.06)
Risk perception to self (1–5 scale)	0.769 (0.22)***	0.778 (0.22)***
Wave arrival time	–0.118 (0.05)**	–0.122 (0.05)**
Self-preparation (1–5 scale)	1.602 (0.67)**	1.493 (0.73)**
Age	0.026 (0.01)**	0.026 (0.01)*
Community tenure (Years)	na	–0.0001 (0.01)
Gender (1: female; 0: male)	na	–0.129 (0.41)
Knowledge perception (1–5 scale)	na	0.094 (0.24)
Disaster experience (1: experienced disaster; 0: otherwise)	na	–0.014 (0.40)
Likelihood ratio test significance	<0.01	<0.01
AIC	185.57	193.25
BIC	202.21	223.20

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; na = not applicable.
Significance codes: *** = 0.01; ** = 0.05; * = 0.1.

boundary to answer the question correctly, whereas individuals and households in low-lying areas logically understand that they are in the inundation zone. Cities should consider education campaigns in combination with more evident and frequent signs for inundation zone boundaries for residents in higher elevation areas of the inundation zone. Comparing model 1 and model 2 eliminates the endogeneity by showing that community tenure, knowledge perception, and disaster experience cannot change the estimated coefficient and significance of other variables in model 1.

Evacuation Decision

Some of the stated reasons why older respondents intend not to evacuate when they feel the ground shaking:

> "I am getting older and have lived a good life…"—65-year-old male

> "I am not ambulatory - live alone"—76-year-old female with disability, living alone

> "Wheelchair-bound, no transportation"—65-year-old male with disability, living alone

"Escape is not available to me"—81-year-old female with disability, living alone

"My daughter is physically disabled. Evacuating quickly would be difficult if not impossible."—68 year old female living with her 45-year old disabled daughter

Individuals or households may decide against evacuating because of age, motor disabilities, lack of transportation modes, or family members with disabilities. Of those responding either "not sure" or "no" (n = 66) to whether they would evacuate after environment cues, 33% state that their houses are not in the tsunami inundation zone; and 10% mentioned that they are not able to evacuate because of age and disability.

The higher the percentage of elderly and poor within the community, the more likely an individual will not have a car (*31*). Facilitating transportation options to older or walking disabled populations will be a challenge to local authorities. Public transportation can be offered in slow-onset disasters such as a hurricane (1% of households in Hurricane Bret, 1% in Lili, 1% in Ike, and less than 1% in Rita [*3*]), but this option is less feasible in a rapid-onset disaster because of very short preparation times. Locals in Seaside need to generate a more effective transportation solution, such as carpooling with neighbors. Carpooling was found to be common for older unmarried residents, residents with low education and household incomes, and people with limited mobility from coastal cities (*32*). Carpooling can not only reduce the traffic congestion in mass evacuations, but also facilitate transportation for people with mobility issues. While some criticize that carpooling creates more milling time, it is found that carpooling evacuees left no later than those evacuating on their own (*3*, *32*). More people choose carpooling and public transit when the traveling distance is shorter (*3*) (e.g., 13% carpooled in four flood evacuations, versus 7% in Hurricane Bret, 9% in Lili, 7% in Katrina/Rita; 13% took public transit in four floods [*33*], versus 1% in Hurricane Bret, 1% in Lili, 1% in Ike, and less than 1% in Rita [*3*]). In some short-notice cases, authorities have even used aircraft, postal vehicles, and firetrucks to facilitate evacuations (*3*, *33*). Many uncertainties still remain on this topic and more research is needed to explore the willingness and efficiency of using carpooling, public transit, or official transportation services for tsunami evacuation. However, one issue is certain: beyond coastal cities, the problem of limited mobility also exists for people living in suburban areas (*3*). Facilitating transportation is a critical topic transcending disaster types and various locations.

Of those who answered "not sure" or "no" to whether they would try to evacuate, 9% mentioned that they do not believe the infrastructure (especially bridges crossing the Necanicum River in Seaside) could survive a M9 earthquake and that existing transportation facilities cannot support mass evacuations. Of those who answered "not sure" and "no," 28% stated they would collect more information before deciding. Among those who only answered "not sure" (n = 32), 52% would wait for a siren or warning from authorities, and collect more information on the magnitude of the earthquake and its distance before making a decision.

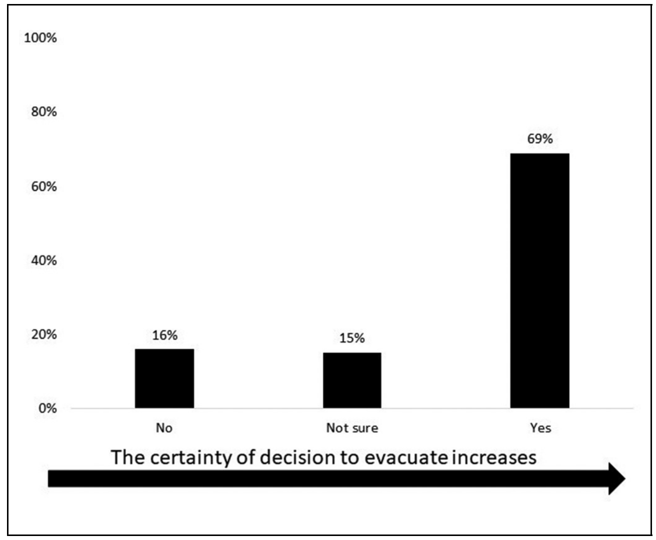

Figure 3. Intended immediate evacuation decision after earthquake (n = 206).

Figure 3 depicts how the certainty of the decision to evacuate from receiving environment cues increases. The inter-correlation table shows that several variables correlate with the evacuation decision. The positive correlation between perception of risk to self with the decision to evacuate (r = 0.319, $p < 0.01$) indicates that the higher the risk perception the more likely it is that individuals or households will choose to evacuate.

The wave arrival time (r = –0.144, $p < 0.05$) is negatively correlated with the evacuation decision. The negative correlation is consistent with previous studies (*7*), which found that increased distance to the shoreline was associated with a slightly lower likelihood of household evacuation. The 2006 study by Charnkol and Tanaboriboon also found that individuals living closer to the shoreline are more likely to evacuate (*34*). Choosing by foot as an evacuation mode (r = 0.191, $p < 0.01$) and location perception (r = 0.31, $p < 0.01$) are also correlated with evacuation decision.

Multiple linear regression results of evacuation decision are shown in Table 4. On average, whether people think they are within the inundation zone (β = 0.54, $p < 0.01$) and risk perception to self (β = 0.13, $p < 0.05$) have a positive impact on evacuation decision. This means that higher perception of being injured in a tsunami is associated with higher likelihood of evacuation

Table 4. Multiple Linear Regression Results for Q2

Dependent variable = evacuation decision (no, not sure, yes)	Model 1	Model 2	Model 3
Variable	Estimate (standard error)	Estimate (standard error)	Estimate (standard error)
Constant	1.602 (0.23)***	1.406 (0.30)***	1.350 (0.30)***
Location perception (1: in inundation zone 0: not in inundation zone)	0.538 (0.12)***	0.534 (0.12)***	0.529 (0.12)***
Mode foot (1: evacuate on foot 0: not evacuate on other mode)	0.309 (0.10)***	0.312 (0.10)***	0.333 (0.33)***
Community tenure (years living in community)	–0.006 (0.00)**	–0.007 (0.00)***	–0.007 (0.01)***
Risk perception to self (1–5 scale)	0.133 (0.06)**	0.129 (0.06)**	0.124 (0.06)**
Difficulty to walk (1: walking disability, 0: able to walk)	na	0.101 (0.11)	0.093 (0.11)
Knowledge perception (1–5 scale)	na	0.051(0.05)	0.098 (0.06)*
Self-preparation (1–5 scale)	na	na	–0.295 (0.17)*
Adjusted R-square	0.200	0.198	0.207
F-statistic significance	<0.001	<0.001	<0.001
AIC	430.59	433.08	431.79
BIC	450.56	459.70	461.74

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; na = not applicable.
Significance codes: *** = 0.01; ** = 0.05; * = 0.1.

intention. Intending to evacuate by foot has a positive impact on evacuation decision (β = 0.3, $p < 0.01$), while community tenure has a negative impact on evacuation decision (β = –0.006, $p < 0.05$), when keeping all other variables constant in model 1.

It may be argued that choosing by foot as an evacuation mode should not be included as an independent variable in the model; however, the assessment of evacuation mode (foot, vehicle, or public transit, etc.) can provide feedback to the previous decision-making process. This has been documented in the PADM model (*5*). Some may also argue that choosing by foot as a mode may not have significant effects as shown in model 1 because of a correlation with (i) walking disability; and (ii) knowledge and preparation. To address this concern, this study compares model 1 with both model 2 (including the walking disability variable) and model 3 (including knowledge and preparation variables). The results indicate none of three variables alter the sign or decrease the significance of the mode by foot variable. Choosing by foot as evacuation mode is a significant predictor for evacuation decision, even when considering disability, preparation, and knowledge level.

Evacuation Mode

Some of the stated reasons why respondents cannot evacuate by themselves:

> "Transport by facility bus."—72-year-old female

> "No option, I am disabled. Someone would have to rescue me."—79-year-old female

> "Need a ride from someone as I do not drive."—80-year-old male with disability

Figure 4*a* depicts the transportation mode choices from the survey results. Individuals or households are most likely to choose to drive (38%) or evacuate by foot (39%), while 6% report that they are likely to evacuate by bicycle. Among the 9% answering "others," 33% state that they need facilitated transportation because of a disability. Unlike mass evacuation in hurricanes, when people need to evacuate long distances, under the threat of a tsunami people are likely to choose by foot as a mode to evacuate to avoid uncertain traffic conditions (if the safe zone is within walkable distance). It is approximately 1–1.5 mi from the shore to a safe zone in Seaside, providing the opportunity for residents to walk or run to evacuate, assuming a speed of 4.5 mph (*2*).

As noted above, in the 2009 earthquake and tsunami, nearly 75% of respondents in Pago Pago chose by foot as an evacuation mode, followed by car (15.9%), carpool (9.7%), public transportation (3.9%), and emergency vehicle (1.9%) (*7*). Conversely, the study by Lindell et al. (2015) shows that in five villages on the island of Tutuila, near Pago Pago, the evacuation mode choices were: car (53.8%), carpool (15.8%), public transportation (9.8%),

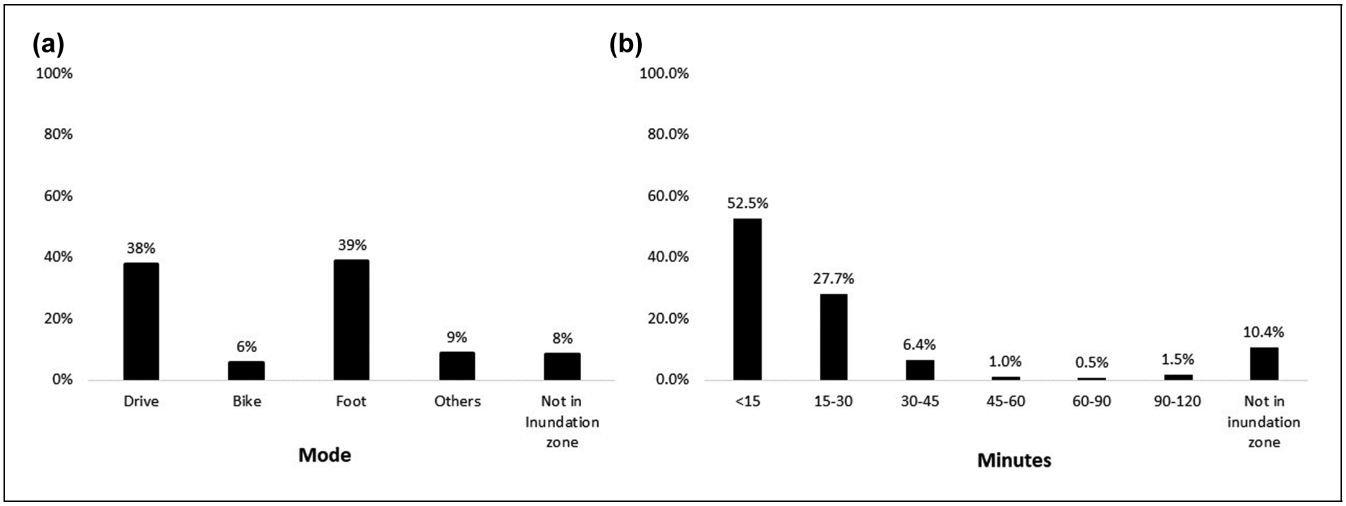

Figure 4. (*a*) Intended evacuation mode choice ($n = 205$) and (*b*) estimated evacuation time ($n = 202$).

Table 5. Binary Logit Regression Results for Q3

Dependent variable = evacuate by foot (1: by foot; 0: by others)	Model 1	Model 2
Variable	Estimate (standard error)	Estimate (standard error)
Constant	–2.251 (0.92)**	–3.500 (1.87)*
Evacuate binary (1: trying to evacuate 0: not trying to evacuate)	1.101 (0.36)***	1.189 (0.38)***
Self-preparation (1–5 scale)	1.290 (0.49)***	1.182 (0.57)**
Difficulty to walk (1: walking disability, 0: able to walk)	–1.135 (0.42)***	–1.220 (0.44)***
Income	–0.134 (0.06)**	–0.145 (0.07)**
Age	0.023 (0.01)**	0.024 (0.01)**
Gender (1: female; 0: male)	0.657 (0.32)**	0.701 (0.33)**
Have evacuation experience in disaster (1: yes; 0: no)	–0.885 (0.39)**	–0.841 (0.39)**
Wave arrival time	na	0.053 (0.04)
Knowledge perception (1–5 scale)	na	–0.017 (0.20)
Risk perception to self (1–5 scale)	na	–0.018 (0.19)
Likelihood ratio test significance	<0.001	<0.001
AIC	259.50	266.47
BIC	286.13	299.75

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; na = not applicable.
Significance codes: *** = 0.01; ** = 0.05; * = 0.1.

and emergency vehicle (2.7%), and with just 17.9% choosing to evacuate on foot (*8*). In Thailand, in the 2004 earthquake and tsunami, 75% of respondents evacuated by foot, and a quarter by motor vehicle. An intended behavior survey of tourists in Kamakura City, Japan, shows that 71% intended to evacuate on foot, but nearly 20% of respondents expected to evacuate by vehicle or combining vehicles with other modes (*9*). In a local earthquake and tsunami study for Napier, New Zealand, nearly 50% of residents intended to evacuate from home on foot or combining by foot with other modes (*10*). An overwhelming majority (90%) of respondents in the 2018 Sulawesi earthquake tsunami evacuated by foot, followed by motorcycle (8%), bicycle, and car (*25*). The evacuation mode distribution is location and scenario dependent, and therefore requires more research exploring factors that explain variation in observations. Nevertheless, high percentages of evacuation by vehicle can cause traffic congestion that would slow down the evacuation process (*11*, *27*).

Shown in Table 2, probability (r = –0.180, $p < 0.01$), wave arrival time (r = –0.255, $p < 0.01$), distance to shore (r = –0.138, $p < 0.05$), and community preparation (r = –0.167, $p < 0.05$) are negatively correlated with individuals or households choosing vehicle as an evacuation mode.

While self-preparation is the only variable correlated with choosing by foot as an evacuation mode, the binary logistic regression (Table 5) depicts a more complex story. It should be noted that model 2 is designed to eliminate the possible endogeneity in model 1. Including

Table 6. Multiple Linear Regression Results for Q4

Dependent variable = evacuation time (1: <15 min, 2: 15–30 min, 3: >30 min)	Model 1	Model 2
Variable	Estimate (standard error)	Estimate (standard error)
Constant	1.675 (0.38)***	1.906 (0.59)***
Mode drive (1: evacuate by vehicle 0: the otherwise)	–0.429 (0.09)***	–0.438 (0.09)***
Knowledge perception (1–5 scale)	–0.176 (0.48)***	–0.174 (0.06)***
Age	0.007 (0.003)**	0.008 (0.003)**
Risk perception to self (1–5 scale)	0.105 (0.04)**	0.102 (0.06)*
Income	–0.034 (0.02)*	–0.034 (0.02)*
Wave arrival time (minutes)	na	–0.007 (0.01)
Location perception (1–5 scale)	na	–0.051 (0.13)
F-statistic significance	<0.01	<0.01
Adjusted R-squared	0.21	0.20
AIC	338.06	341.70
BIC	360.45	370.48

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; na = not applicable.
Significance codes: *** = 0.01; ** = 0.05; * = 0.1.

the extra variables (wave arrival time, knowledge perception, and risk perception to self) did not change the estimated coefficient and significance of the variables shown in model 1.

In model 1, those who said "yes" to evacuation decision are more likely to choose by foot as an evacuation mode (β = 1.10, $p<0.01$). Higher levels of self-preparation have a positive impact on choosing foot (β = 1.29, $p<0.01$), indicating that the more individuals or households prepare for earthquakes and tsunami, the more likely they would choose walking or running to evacuate. Possible reasons for this are that: (i) walking or running is a feasible evacuation mode for Seaside tsunami threats; and (ii) people with higher preparation levels receive more evacuation information from authorities, which educate people to evacuate by foot (*35*). People with previous evacuation experience in disasters are less likely to evacuate on foot (β = –0.89, $p<0.05$). Among them (n = 135), 80% had experienced a tornado, while only 13% experienced a tsunami. Evacuation on foot during a tornado is normally not recommended.

Among demographic variables, having difficulty walking (β = –1.14, $p<0.01$) and higher income (β = –0.13, $p<0.05$) can decrease the likelihood of evacuating on foot while keeping other variables constant. Females are more likely to evacuate on foot (β = 0.66, $p<0.05$), consistent with similar research (*9*). Older respondents, when controlling for difficulty walking, are also more likely to evacuate on foot.

Evacuation Time

Responding to the question on estimated evacuation time using the evacuation mode of choice, 52.5% of respondents think it would take them less than 15 min to evacuate to a safe zone, 27.7% think it would take 15–30 min, and nearly 10% think it would take more than 30 min, as shown in Figure 4*b*. Evacuation mode and travel distance are theoretically direct influencers on the intended evacuation time. The correlation table shows that choice of vehicle (r = –0.28, $p<0.01$) and by foot (r = 0.17, $p<0.05$) as evacuation modes are negatively and positively correlated with the intended evacuation time, respectively. However, location perception, distance to shore, and wave arrival time are not significantly correlated with evacuation time. Age (r = 0.20, $p<0.05$) and difficulty walking (r = 0.20, $p<0.05$) are positively correlated with evacuation time, while income (r = –0.19, $p<0.05$) and knowledge perception (r = –0.28, $p<0.05$) are negatively correlated. To better understand the impact of those variables, multiple linear regression models are fitted. As shown in Table 6, while model 1 is the primary estimated model results, model 2 is compared with model 1 to eliminate the endogeneity by including two theoretically correlated variables (wave arrival time and location perception) in the model.

Choosing to drive as an evacuation mode decreases respondents' estimated evacuation time (β = –0.43, $p<0.01$). It is reasonable for respondents to interpret evacuating by vehicle as faster than walking, running, or bicycling in normal traffic conditions. However, a high percentage of vehicle evacuation can cause traffic congestion that would slow down the evacuation process (*11*, *27*). While local authorities encourage people to evacuate by foot if possible, there are still respondents who believe driving is faster than walking or running. Furthermore, visitors who have little knowledge of where and how to evacuate tend to congregate in the tsunami inundation zone (*36*). Fortunately, only 38% of respondents choose to evacuate by vehicle, which may mitigate the traffic congestion issue during evacuation. Traffic simulation research is needed to test the impact of mode choice (*37*)

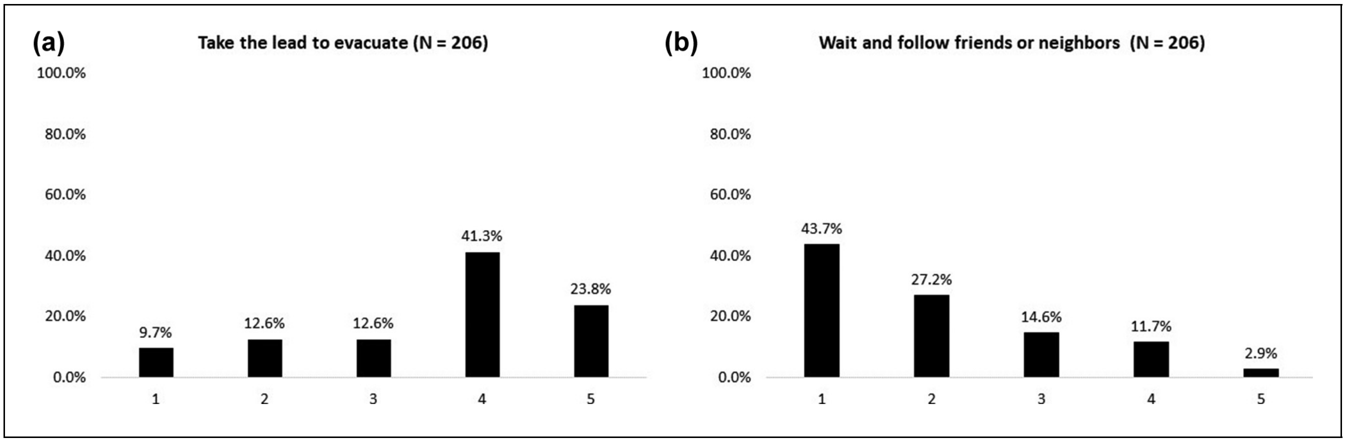

Figure 5. Respondents' attitudes toward (*a*) leading or (*b*) following during evacuation.

Table 7. Binary Logit Regression Results for Q5

Dependent variable = would lead than follow (1: more likely to lead than follow; 0: the otherwise)	Model 1	Model 2
Variable	Estimate (standard error)	Estimate (standard error)
Constant	–6.429 (1.79)***	–6.644 (1.81)***
Evacuate binary (1: trying to evacuate 0: not trying to evacuate)	1.662 (0.38)***	1.626 (0.39)***
Self-preparation (1–5 scale)	1.689 (0.66)**	1.678 (0.66)**
Risk perception to others (1–5 scale)	0.846 (0.32)***	0.717 (0.36)**
Income (USD)	0.192 (0.07)***	0.177 (0.08)**
Evacuate by foot (1: by foot; 0: otherwise)	0.730 (0.39)*	0.682 (0.40)*
Distance to shore (ft)	–0.0007 (0.0003)**	–0.0006 (0.0003)*
Self-efficacy (1–5 scale)	0.341 (0.05)**	0.362 (0.20)*
Gender (1: female; 0: male)	na	0.347 (0.36)
Risk perception to self (1–5 scale)	na	0.167 (0.25)
Difficulty to walk (1: walking disability, 0: able to walk)	na	–0.236 (0.44)
Likelihood ratio test significance	<0.01	<0.01
AIC	216.16	220.34
BIC	242.78	256.95

Note: AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; na = not applicable.
Significance codes: *** = 0.01; ** = 0.05; * = 0.1.

on traffic conditions and evacuation time based on the survey results.

Respondents with higher knowledge perception (β = –0.18, $p < 0.01$) and income (β = –0.03, $p < 0.1$) are more likely to believe they need less time to evacuate than others; whereas increases in age (β = 0.007, $p < 0.05$) and risk perception to self (β = 0.11, $p < 0.05$) can increase the respondent's estimated evacuation time with controlling transportation mode constant.

Lead or Follow

Figure 5 depicts the respondents' attitudes toward lead or follow behavior during evacuation. Nearly 65% of respondents are "likely" or "very likely" to lead and encourage others to evacuate; whereas around 80% stated they are "unlikely" or "very unlikely" to wait and follow friends or neighbors to safe zones. The distribution of respondents' answers shows a trend that people generally prefer to lead rather than follow.

To understand better why people choose to lead or follow, a binary logit regression analyzing variables that may influence people's choices was implemented. A binary dependent variable is created for the two questions in the survey:

1. How likely or unlikely are you to take the lead to evacuate and encourage people to leave with you? (five-point Likert scale: 1 = not at all likely; 5 = extremely likely)

2. How likely or unlikely are you to wait to see if their friends or neighbors are evacuating then follow them? (five-point Likert scale: 1 = not at all likely; 5 = extremely likely)

The lead or follow binary variable = 1 if a respondent chooses a higher number (on the five-point Likert scale) in question 1 than in question 2 (an individual or household is more likely to lead and less likely to follow) (binary variable = 0 otherwise).

The model results in Table 7 show that the evacuation variables: self-preparation level, risk perception to others, income, evacuation on foot, and self-efficacy have positive impacts on the likelihood to lead. Distance to shore has a negative impact. Changing the evacuation decision binary variable (β = 1.66, $p<0.01$) from 0 to 1 has a positive impact on taking the lead to evacuate. It is logical that people who are not evacuating are not leading others. Increases of self-preparation (β = 1.68, $p<0.05$) and self-efficacy (β = 0.634 $p<0.05$) can increase the likelihood of leading behavior. Individuals or households with better preparation and higher confidence levels are more likely to lead or encourage others to evacuate. People with higher income (β = 0.19, $p<0.01$) are more likely to lead, which may be explained by better preparation and education levels. Interestingly, people with higher perception of risk to others (β = 0.84, $p<0.01$) are more likely to lead than follow, even when controlling for perception of risk to self in model 2. This indicates that people with a better understanding of how tsunamis could endanger others in the community are more likely to help or encourage people to evacuate. People further from shore (β = –0.0006, $p<0.05$) are less likely to lead. In Seaside, the majority of the population is concentrated on the flat zone on the west side of the river, leaving them physically isolated from others. This gives those individuals fewer chances to interact with others during evacuation. Even though the influence of distance to shore seems small (β = –0.0006), note that the unit of measurement is by feet.

Managerial Implications and Recommendations

The previous section discusses the logistics behind households' potential evacuation decisions and behaviors in a CSZ event. This was also compared with events in other locations. Even though disaster events are scenario-based and there is no universal solution for coastal residents, some significant patterns can be drawn from this study to inform emergency management for CSZ communities:

1. Tsunami educational programs, especially education programs focused on identifying tsunami inundation zones, should be promoted to younger residents and residents with lower risk perception and lower self-preparation. While residents living close to a shoreline can correctly identify whether or not they are in an inundation zone, those living inland or close to the inundation boundary tend to have more difficulty. Therefore, education programs should also be tailored to households near the inundation boundary.
2. Considering the large population of senior citizens or disabled individuals living in CSZ coastal towns, local authorities should focus on facilitating emergency transportation to these at-risk populations.
3. Based on the evacuation mode choice distribution, emergency managers and cities can create a simulation to analyze the traffic delay in an evacuation, and tailor education programs to inform locals of optimal evacuation mode choices and other logistics. For example, respondents in this study with higher intended self-preparation levels, of older age (controlling for disability), and who are females, are more likely to choose to evacuate by foot. This information can be used to target the demographics the authorities would like to evacuate by foot if simulations show that the current distribution of evacuation modes is not optimal.
4. People choosing to evacuate by car think it will take them less time to evacuate, however, this may be inaccurate. In Oregon, the authorities in coastal cities promote walking to evacuate because of expectations of vehicle congestion, delays, and abandonment of car behaviors that have occurred in other evacuations. Therefore, the authorities should re-evaluate the effectiveness of their educational programs to dissuade residents from choosing to evacuate by car.
5. Authorities should take individuals' evacuation experience into consideration when creating educational programs. For example, people with previous experience of evacuation from tornado events may carry evacuation behaviors they have developed, including evacuation by vehicle, over to rapid-onset disaster evacuations. This means they will likely still intend to choose motorized vehicles as an evacuation mode even if the authorities have been promoting evacuation by foot.
6. Individuals or households with higher intended preparation levels, higher incomes, and higher intended self-efficacy levels are more likely to lead other groups in an evacuation. Authorities should consider potential collaborations with these populations to create local leaders who will aid in evacuation management, including decision to evacuate, mode choices, route choices, and so forth.

Conclusion

Utilizing a survey instrument sent to residents of Seaside, OR, this study examined residents' intended evacuation perceptions and behaviors in response to a M9 CSZ earthquake and tsunami. Bivariate chart, inter-correlation table, and regression analyses were used to examine five research questions: accuracy in identifying if a house is inside the tsunami inundation zone, willingness to evacuate, intended evacuation mode, estimated evacuation time, and lead or follow behavior during a tsunami evacuation. Potential factors that can affect responses to the five research questions were also analyzed.

The results found that 80% of respondents can correctly identify that their houses are located inside the tsunami inundation zone. Older respondents are more likely to identify their location correctly regardless of the number of years they have lived in the community or their previous disaster evacuation experience. While 69% of respondents would evacuate in a tsunami, individuals or households may decide against evacuating because of age, motor disabilities, lack of transportation modes, or family members with disabilities. The City of Seaside has been educating people to evacuate on foot; however, 38% of respondents indicate an intention to evacuate by vehicle. Interestingly, females are more likely to evacuate on foot. Older generations are also more likely to evacuate on foot. While respondents with higher knowledge perception and income are more likely to think they need less time to evacuate than others, nearly 10% of all respondents think they will need more than 30 min to evacuate to the safe zone. Generally, people are likely to lead rather than follow during an evacuation, especially among those with higher preparation levels and higher levels of risk perception to others.

Based on the survey results, this study concludes that: (i) there are considerable proportions of individuals and households that lack knowledge and preparation for a CSZ earthquake and tsunami in the City of Seaside; (ii) local authorities need to extend education programs, specifically on identifying tsunami inundation zones and proper evacuation modes in different areas of the city; (iii) city officials need to facilitate transportation options to assist older people, individuals with motor disability, lack of transportation options, and family members with a disability. More research is needed to assess bicycling as an evacuation mode and feasibility with different age groups. Additional research exploring how people's evacuation behavior impacts transportation efficiency is needed. Traffic simulation research can test the impact of mode choice on traffic conditions and evacuation time by integrating survey results with simulation. Future studies can also examine when people choose to lead or follow during evacuation and develop an algorithm to optimize evacuations considering aspects of volunteer leaders (number of leaders, leader location, etc.). Finally, the results of this study indicate that individuals or households with higher preparation levels or higher evacuation knowledge levels can serve as potential leaders to encourage or help people in their surroundings to evacuate in different scenarios.

Author Contributions

The authors confirm contribution to the study as follows: study conception and design: Chen Chen, Alexandra Buylova, Lori A. Cramer, Haizhong Wang, Daniel T. Cox; data collection: Alexandra Buylova, Lori A. Cramer; analysis and interpretation of results: Chen Chen, Alexandra Buylova, Cadell Chand; draft manuscript preparation: Chen Chen, Alexandra Buylova, Cadell Chand. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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Data Accessibility

The data that support the findings of this study are available from the National Science Foundation: https://www.nsf.gov/statistics/data-tools.cfm with the permission of the National Science Foundation. Restrictions apply to the availability of these original data, because of human subjects and confidentiality, which were used under license for this study.

Supplemental Material

Supplemental material for this article is available online.

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