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Tsunami preparedness and resilience: Evacuation logistics and time estimations

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ABSTRACT

Extensive research has studied the near-field tsunami threat in the Cascadia Subduction Zone (CSZ), but little research has examined the ability to evacuate the inundation zone before the first tsunami wave arrives. To address this gap, this study provides empirical evidence about people's expectations about hazard onset and evacuation logistics when a tsunami threatens. We surveyed households in five CSZ communities to assess residents' expected first wave arrival time, as well as their expectations about evacuation destinations, route choices, preparation times, travel times, and clearance times. Heatmaps are used to summarize residents' evacuation destinations and route choices, and probabilistic functions are used to model evacuation distances and time estimates. The results suggest that respondents have similar patterns of time estimates, but a few plan to evacuate within the inundation zone, and some plan to evacuate on routes that were congested in a previous event and end their evacuations at destinations within the inundation zone.

1. Introduction

In recent decades, tsunamis have caused loss of life and property in many communities throughout the world (Mori et al., 2011; Lindell et al., 2015; Vana et al., 2020; Harnantyari et al., 2020). Fortunately, tsunamis striking the US mainland have been far-field events that provide hours of forewarning and, thus, ample time to evacuate before the first wave strikes. However, the Cascadia Subduction Zone (CSZ) poses a near-field threat that, as yet, exposes research gaps in preparedness and response, especially whether people living in CSZ inundation zones can evacuate successfully before first wave arrival (Lindell and Prater, 2010; National Research Council, 2011; Chen et al., 2020, 2021, 2022b). A significant amount of research has been conducted to understand the physical science and coastal engineering aspects of this threat, but much less research has examined the social science and transportation engineering implications of this tsunami threat — especially household evacuation logistics (Lindell and Prater, 2010; Lindell et al., 2019c). Therefore, studying CSZ households' expected tsunami responses will bridge the research gap and help communities become better prepared for near-field tsunamis.

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2. Recent research on household tsunami evacuation logistics

Most previous reviews of tsunami studies have focused on topics such as tsunami warning systems, infrastructure resilience, structural vulnerability, and, inundation modeling and mapping (National Research Council, 2011; Løvholt et al., 2014). Social scientists examined tsunami preparedness by communities (Lindell and Prater, 2010), as well as household evacuation decisions in actual tsunamis (Lindell et al., 2015; Yun and Hamada, 2015; Apatu et al., 2016; Fraser et al., 2016; Wei et al., 2017; Blake et al., 2018) and expected responses to hypothetical future tsunamis (Lindell et al., 2019c; Buylova et al., 2020; Chen et al., 2020, 2021). These studies have provided a foundation for understanding people's decisions and behaviors when responding to tsunami threats (Makinoshima et al., 2020). In particular, these studies have found that the results from surveys of expected behavior are broadly similar to those from post-event surveys of responses to actual tsunamis, a finding that is consistent with hurricane research (Kang et al., 2007; Huang et al., 2016). However, there are some notable differences between expected and actual behavior, so further research is still needed (Dhellemmes et al., 2016; Blake et al., 2018).

Researchers have long recognized the many commonalities in the response to different types of disasters (Drabek, 1986; Tierney et al., 2001). These commonalities are summarized in the Protective Action Decision Model (PADM) (Lindell and Perry, 2012; Lindell, 2018), which depicts the process by which people respond to an imminent threat by seeking information and making protective action decisions after receiving warning messages and observing environmental cues and social cues — e.g., Lindell et al. (2019a). More recently, studies guided by the PADM and other perspectives have increasingly addressed evacuation logistics, the activities that people perform after they decide to evacuate (Lindell et al., 2011, 2019b). For example, most studies of tsunami response have concentrated on people's risk perceptions, evacuation expectations (for hypothetical events), and evacuation decisions (for actual events). However, only a few studies documented people's expectations of near-field tsunami first wave arrival time or of tsunami evacuation logistics — especially evacuation destinations, routes, distances, and clearance time components such as household preparation time and evacuation travel time. Thus, there is an urgent need to examine these issues.

2.1. Evacuation destinations

The destinations to which people evacuate can impact their life safety, as well as shelter operation and other emergency management issues. In near-field tsunami threats, those in the inundation zone have only a limited time to respond and plan their evacuation routes, destinations and accommodations (Lindell et al., 2019b). In this rapid-onset situation, people can often reach safety by evacuating to nearby high ground rather than traveling to inland locations that are tens or hundreds of kilometers inland, as is typical in hurricane evacuations. For instance, in the 2018 Indonesia earthquake and tsunami, 59% of respondents evacuated to nearby high ground, 26% evacuated to public facilities, and only 15% evacuated to shelters or peers' homes (Harnantyari et al., 2020). In the 2009 American Samoa tsunami, people evacuated to public parks (29%), homes of relatives (31%), and homes of friends (12%) (Lindell et al., 2015). However, not everyone knows where to evacuate because they do not know the boundaries of the inundation zone. People choose different destinations depending on their previous experience and familiarity with local routes and shelters (Lindell et al., 2015). For example, Arce et al. (2017) found that most visitors in Kamakura City, Japan, lacked any knowledge of where and how far to evacuate. Indeed, 76% of them intended to evacuate to a place that is within the inundation zone.

Tsunami evacuation is distinctive because the distance from an evacuee's location to their evacuation destination influences their transportation mode choice. For example, Lindell et al. (2015) found that the evacuation distance of people who drove was about four times longer than the evacuation distance of people who walked in response to the 2009 tsunami in American Samoa. Chen et al. (2022a) analyzed the impact of shelter location on evacuation destination choice, route choice, and *levee effect* caused by shelter placement. Yun and Hamada (2015) analyzed the impact of shelter distance and wave height on evacuation outcomes for 13 cities in the 2011 Tohoku earthquake and tsunami. The average distance to shelters from the risk area varied from 170–708 m among cities due to heterogeneous geographic features. This study found that shelter distance and wave height had a negative impact on survival rate. For cities having shelters closer than 415 m from the center of the risk zone, the fatality rate was lower than 6%, which is much lower than others cities having longer shelter distances.

Previous studies have analyzed what type of accommodations evacuees sought, such as nearby parks that were on high ground or farther inland, as well as public shelters, or peers' homes. However, no previous studies have provided respondents with maps and asked them to mark the specific locations to which they actually evacuated or expected to evacuate.

2.2. Evacuation Time Estimate (ETE) components

The time to clear a risk area (t_T) is a function of authorities' decision time (t_d), warning dissemination time (t_w), evacuation preparation time (t_p), and evacuation travel time (t_t) — see Lindell et al. (2019b) for a review of the past 40 years of research on evacuation time components. For a local tsunami, authorities' decision time and warning dissemination time drop out of the ETE equation (i.e., $t_d + t_w = 0$) if those in the inundation zone recognize that long and strong shaking is their environmental cue to evacuate. This leaves households' evacuation preparation time and evacuation travel time as the only remaining ETE components. Evacuation preparation time include two activities — (1) psychological preparation that involves information seeking and processing for making evacuation decisions ["milling" (Wood et al., 2018)], and (2) logistical preparation during which people perform essential tasks (e.g., collecting documents, packing essential items, and securing the home) before leaving (Lindell et al., 2005, 2019b). However, the preparation tasks people perform, and thus the time it takes them to prepare, are affected by how soon people think a threat will arrive. Consequently, fewer tasks are performed if people think less time is available before the disaster strikes. Moreover, people's expected evacuation travel time is affected by their choices of transportation mode, evacuation route, and evacuation destination. Less obviously, however, actual travel time is affected by evacuation impediments such as road debris from collapsed buildings and bridges, landslides, and liquefaction.

Although most hurricanes provide several days of forewarning before the landfall (Huang et al., 2012; Lindell et al., 2019b), near-field tsunamis allow much less time for people to evacuate (Priest et al., 2013). For example, Priest et al. (2013) reported that the first wave of a CSZ tsunami will arrive at the Coos Bay coast in about 20 min and will inundate almost all the rest of the community within 60 min. Similarly, a tsunami inundation simulation for Crescent City shows that the first wave from a CSZ rupture will arrive 25 min after the earthquake (Uslu et al., 2007).

The time that people take to prepare and travel depends on whether the hazard is a slow-onset or rapid-onset events. Lindell et al. (2020) reported that people actually took up to 7.5 h to finish preparation tasks in hurricane Lili, Katrina, and Rita, whereas the majority of respondents expected to finish evacuation preparations within 2 h for hypothetical events at three nuclear power plants. These nuclear power plant data are consistent with findings from Rogers and Sorensen (1989), who found that the majority of people evacuated within a 2–6 h time period in two hazardous materials transportation incidents. Of course, this is far longer than the first wave arrival time for a near-field CSZ tsunami.

Some studies have documented people's preparation time in responding to actual and hypothetical tsunamis. In 2009 American Samoa tsunami, 61% of respondents reported leaving within 15 min, and 96% of them left within 60 min (Lindell et al., 2015). This finding is similar to the expected preparation times in a 2015 Aotearoa/New Zealand study in which 7% expected to evacuate immediately and 63% expected to evacuate within 10 min (Dhellemmes et al., 2016). Compared this hypothetical study, a post-event study for the 2016 Aotearoa/New Zealand tsunami indicates that people spent longer than expected in response to the real event. Specifically, 7% evacuated without taking any other action, 36% evacuated within 10 min, 52% evacuated within 30 min (Blake et al., 2018). The Arce et al. (2017) study in Japan reported that most visitors expected to evacuate immediately (53%), and the rest would leave within 5 min (29%), 5–15 min (10%), or >20 min (8%). Yun and Hamada (2015) found that 14% of the evacuees from the 2011 Tohoku tsunami evacuated immediately and 66% evacuated within 20 min. Interestingly, this study also examined the milling time of non-survivors by using witness data. The data showed that 48%, 35%, and 10% non-survivors did not evacuate, evacuated within 20 min, or evacuated immediately, respectively.

For evacuation travel time, Arce et al. (2017) reported that expected travel times for visitors in Kamakura City, Japan were <7.5 min (11%), 8–15 min (20%), 16–30 min (22%) >30 min (14%), and do not know (33%). In the 2018 Indonesia earthquake and tsunami, travel time varied from 0–5 min (24%), 5–10 min (36%), 15–30 min (20%) and >30 min (21%) (Harnantyari et al., 2020). The Chen et al. (2022b) study of a walking evacuation drill in Newport OR found that the mean evacuation travel time was 10 min and almost all participants arrived in the safe zone within 25 min, which is close to the 20–40 min that is the scientifically assessed first wave arrival time. Other transportation modelers also simulated the evacuation process (Mas et al., 2012, 2015; Wang et al., 2016; Takabatake et al., 2017; Mostafizi et al., 2017) and concluded that preparation time and travel time could significantly impact evacuation outcomes.

Although previous studies documented the time that people spent during preparation and traveling to safety, this information is lacking for a CSZ earthquake and tsunami. Transportation modelers simulated the tsunami evacuation process for Seaside OR (Wang et al., 2016; Mostafizi et al., 2017, 2019), but their assumptions and distributions of time components are based on data from other communities with possibly significant differences in culture, decision-making, and behaviors. Specifically, the departure time distribution was assumed to follow a Rayleigh distribution proposed for nuclear power plant evacuations (Tweedie et al., 1986) and foot evacuation speeds following a discrete distribution from Knoblauch et al. (1996).

2.3. Research objectives and questions

To bridge the gaps in the literature on tsunami evacuation logistics, this study analyzes residents' expected first wave arrival times, evacuation route choices, evacuation destinations, evacuation preparation times, evacuation travel time, and total clearance times. Statistical functions are evaluated to estimate the parameters of the cumulative distribution functions for expected evacuation distances, expected first wave arrival times, and the ETE components to inform future tsunami evacuation studies. Analyses of expected evacuation destinations and distances are based on two communities (Coos Bay, OR and Crescent City, CA), whereas the ETE component analyses are based on the five communities shown in Fig. 1 (Commencement Bay, WA; Coos Bay, OR; Lincoln City, OR; Crescent City, CA; and Eureka, CA). The studies reviewed in the preceding sections lead to four research questions:

1. To what destinations will CSZ residents evacuate when responding to a tsunami?
2. What are residents' route choices and which routes are likely to be congested?
3. How far would residents evacuate by foot and by car and what statistical distributions can describe the evacuation distance data?
4. What are residents' estimates of first wave arrival time, evacuation preparation time, evacuation travel time, and total clearance time and what statistical distributions can describe the ETE component data?

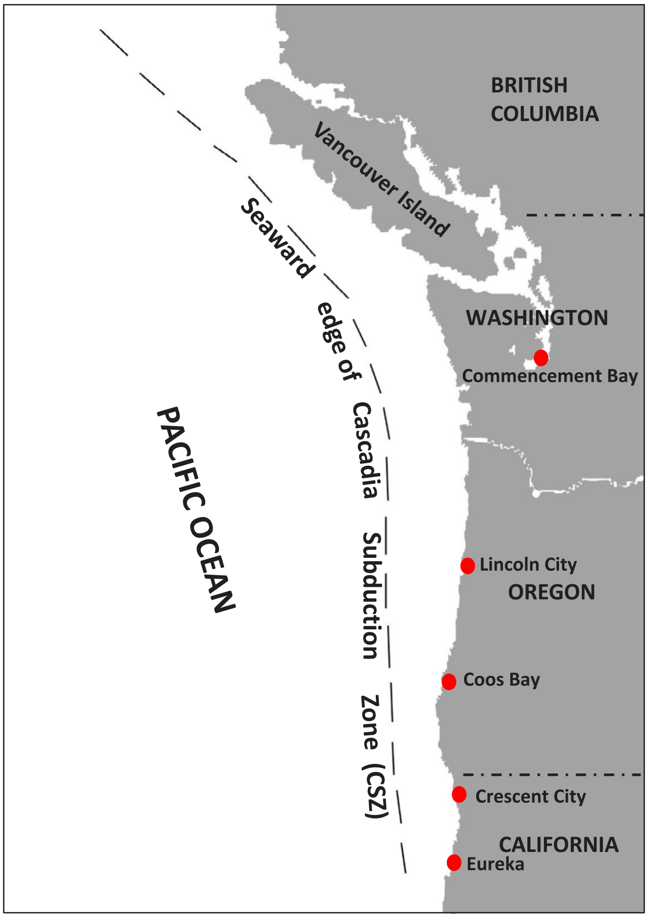

Fig. 1. Primary study sites along the Cascadia Subduction Zone.

3. Method

3.1. Study area

CSZ communities face the threat of tsunamis from the 1000 km dipping fault. An M9 earthquake is expected to trigger a near-field tsunami with waves of more than 10 m that strikes coastal communities within 20–40 min (Uslu et al., 2007; Witter et al., 2011; Priest et al., 2014, 2016). The probability of such an event occurring in the next 50 years is 7%–25% for the entire margin and 85% for the Southern CSZ margin (Goldfinger et al., 2012). Therefore, it is critical to understand household's tsunami evacuation logistics for household emergency preparedness, community emergency planning, and evacuation management purposes. We selected five coastal communities that are in the tsunami inundation zone (completely or partially), as shown in Fig. 1. Due to the higher rupture probability and earlier first wave arrival time in the southern CSZ (Chen et al., 2021; Goldfinger et al., 2012), three (Coos Bay, OR; Crescent City, CA; and Eureka, CA) of those five communities are selected from southern zone.

3.2. Questionnaire survey

We mailed questionnaires to 2007 randomly selected households within each census block group in Coos Bay, OR and Crescent City, CA. There were 483 (258 from Coos Bay and 225 from Crescent City) participants who returned questionnaires and another 380 questionnaire packets that were undeliverable, which produced a 29.7% response rate. The questionnaire provided a local road map for each respondent to mark their household locations, their expected evacuation destinations, and evacuation routes. The questionnaire also asked participants to report their estimates of first wave arrival time, evacuation preparation time, and evacuation travel time to their expected destination in response to a CSZ tsunami. Because of the availability of the same questions in a previous tsunami preparedness survey, we included ETE component data from other three communities in the CSZ: Commencement Bay, Lincoln City, and Eureka (Lindell et al., 2019c). Out of 1200 households who were recruited for that study, 221 provided usable responses which resulted in a 21% response rate. Thus, a total of 704 respondents from five communities in the CSZ are

Table 1
Sample and census demographics of study sites (United State Census Bureau, 2020).

	Coos Bay		Crescent City		Other three cities		Entire U.S.
	Sample	Census	Sample	Census	Sample	Census	Census
Age							
under 6	3.0%	6.4%	4.0%	3.4%			6.0%
6 to 18	12.0%	21.2%	16.0%	13.2%	59.0	44.8	22.3%
19–65	46.0%	50.4%	51.0%	73.9%	(median)	(median)	55.2%
above 65	39.0%	22.0%	29.0%	9.5%			16.5%
Gender (female)	53.0%	54.0%	63.0%	71.0%	52.9%	51.5%	50.8%
Household size (Mean)	2.13	2.36	2.16	2.16	2.31	2.38	2.63
Household monthly income (median)	$3,666	$3,648	$3,432	$2,607	$4,166	$4,322	$5,024
Education							
No high school diploma	4.0%	13.0%	4.0%	33.0%	0.8%	11.6%	22.3%
High school graduate to Bachelor's degree	58.0%	69.0%	58.0%	58.0%	50.2%	59.82%	56.2%
Bachelor's degree or higher	38.0%	19.0%	38.0%	9.0%	44.5%	28.85%	31.5%
Ethnicity (White)	91.0%	83.0%	88.0%	51.0%	82.7%	76.0%	76.3%

used for analyzing participants' estimates of tsunami arrival time, household preparation time, and evacuation travel time. In turn, respondents' estimates of their preparation and travel times were used to compute their implied estimates of clearance time.

Demographic characteristics of the respondents from the five communities are summarized in Table 1. Compared with the overall U.S. population, the five communities have slightly more females, smaller household sizes and lower incomes, but roughly equivalent education levels. Coos Bay has significant higher proportion of Caucasians and larger proportion of seniors than other communities. Crescent City has significantly lower levels of income and education than the other communities. The samples over-represent Caucasians, age > 65, and the highly educated. While this sample bias is consistent with many previous mail surveys of environmental hazards, the impact of this issue is limited as long as it is not so severe that it substantially attenuates the variances of the variables (Lindell and Perry, 2000; Chen et al., 2021).

4. Results and discussion

4.1. Inundation zone location accuracy

Figs. 2 and 3 show that 41% and 17% of respondents in Coos Bay and Crescent City, respectively, are located within tsunami inundation zone. There were 63% of the respondents who could mark their house location on the map within a 100 m error range, as shown in Fig. 4. Given the road network density for the two communities, 100 m roughly represents the length of one city block. The accuracy curve in Fig. 4 indicates a noticeable decrease in slope at 100 m, which means that approximately two-thirds of the respondents can identify their house location within one city block. Conversely, approximately 10% of the respondents would not identify their house location within 400 m. Thus, most respondents in the two communities are reasonably accurate in identifying their house location on the road map. Nonetheless, there is a wide range of hazard map accuracy even on these large-scale maps, which is consistent with previous findings of significant errors in hazard map comprehension — see Lindell (2020). Possible reasons for these location errors include the scale of the map and respondents' misinterpretation of key map feature (such as rivers, roads, and jurisdictional boundaries). However, the most likely explanation for the location errors is that some of the respondents have poor spatial skills. For example, MacPherson-Krutsky et al. (2020) found that some respondents not only had difficulty interpreting map contours but even made errors in using the map compass and scale. These results underscore the need for local emergency managers to supplement hazard maps with readily identifiable markers of tsunami zone boundaries in the "real world" — for example, by striping pavement or color coding street signs at their communities' tsunami zone boundaries.

4.2. Evacuation destination

Figs. 2 and 3 illustrate the respondents' expected evacuation destinations and route choices in response to a CSZ tsunami. Very few of them (5% in Coos Bay; 8% in Crescent City) intended to evacuate to destinations within the inundation zone. On the Coos Bay peninsula, the majority of residents expected to evacuate to churches, high hills, public parks, or schools. Almost all (95%) expected to evacuate to destinations that are outside the inundation zone, but a few respondents in Barview and the downtown areas of Coos Bay and North Bend expected to evacuate to locations within the inundation zone. All roads except one in Coos Bay show light to moderate usage (less than 5% of respondents), which may be because the respondents are distributed over a large area with many alternative routes to safety. Most of the respondents living in Barview expected to use Libby Lane (shown as the red line at southwest base of the peninsula) because this is the only available egress inland from the inundation zone. Since this road has only one lane in each direction, it has the potential to produce a bottleneck during evacuation.

In Crescent City, the majority of people expected to evacuate to local schools, churches, hospitals, or malls. Unfortunately, a few of them (8%) expected to evacuate to Del Norte County Fairgrounds, which is inside the inundation zone. A likely reason for this error is that they lack of knowledge about the inundation zone boundaries. For evacuation route choice, Fig. 3 indicates that

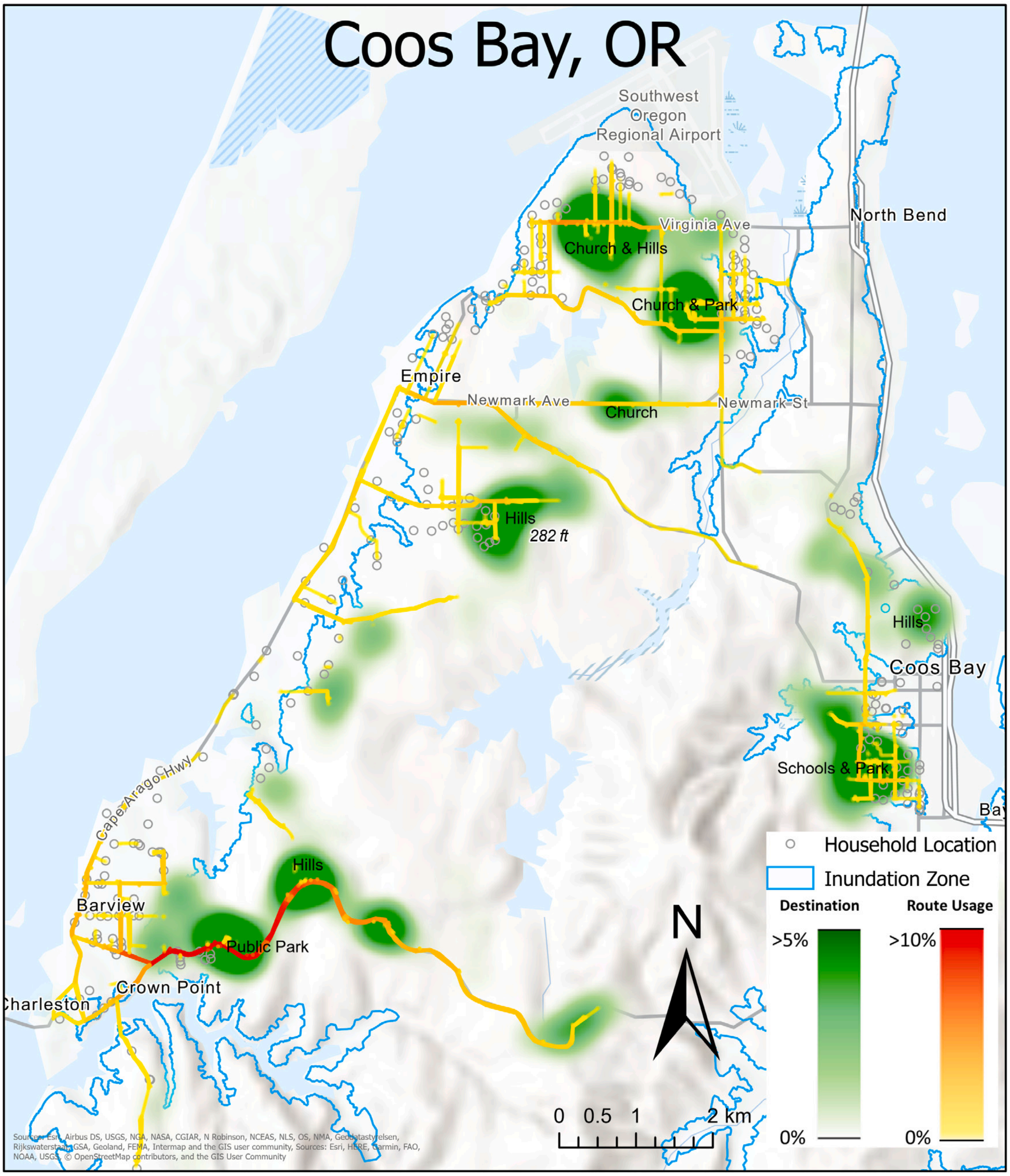

Fig. 2. Evacuation destination and route choice in Coos Bay, OR. Color of the heatmap represents the percent of respondents plan to evacuate to that destination or use that route, shown in the legend. Inundation Zone (blue line); Household location (gray halo dots). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

people in Crescent City expect to use major arterials (such as Highway 101, Washington Blvd., Inyo street, and Northcrest Drive) more than collectors or local roads. This finding is consistent with the tendency for evacuees to overload familiar routes (Lindell et al., 2019b), but different from the pattern of expected evacuation route usage in Coos Bay. The major roads in Crescent City are located outside the inundation zone except for part of Highway 101. Even though some respondents reported that they encountered heavy traffic congestion on this highway during the 2011 tsunami evacuation, more than 10% of respondents would still use this road in future tsunami evacuations.

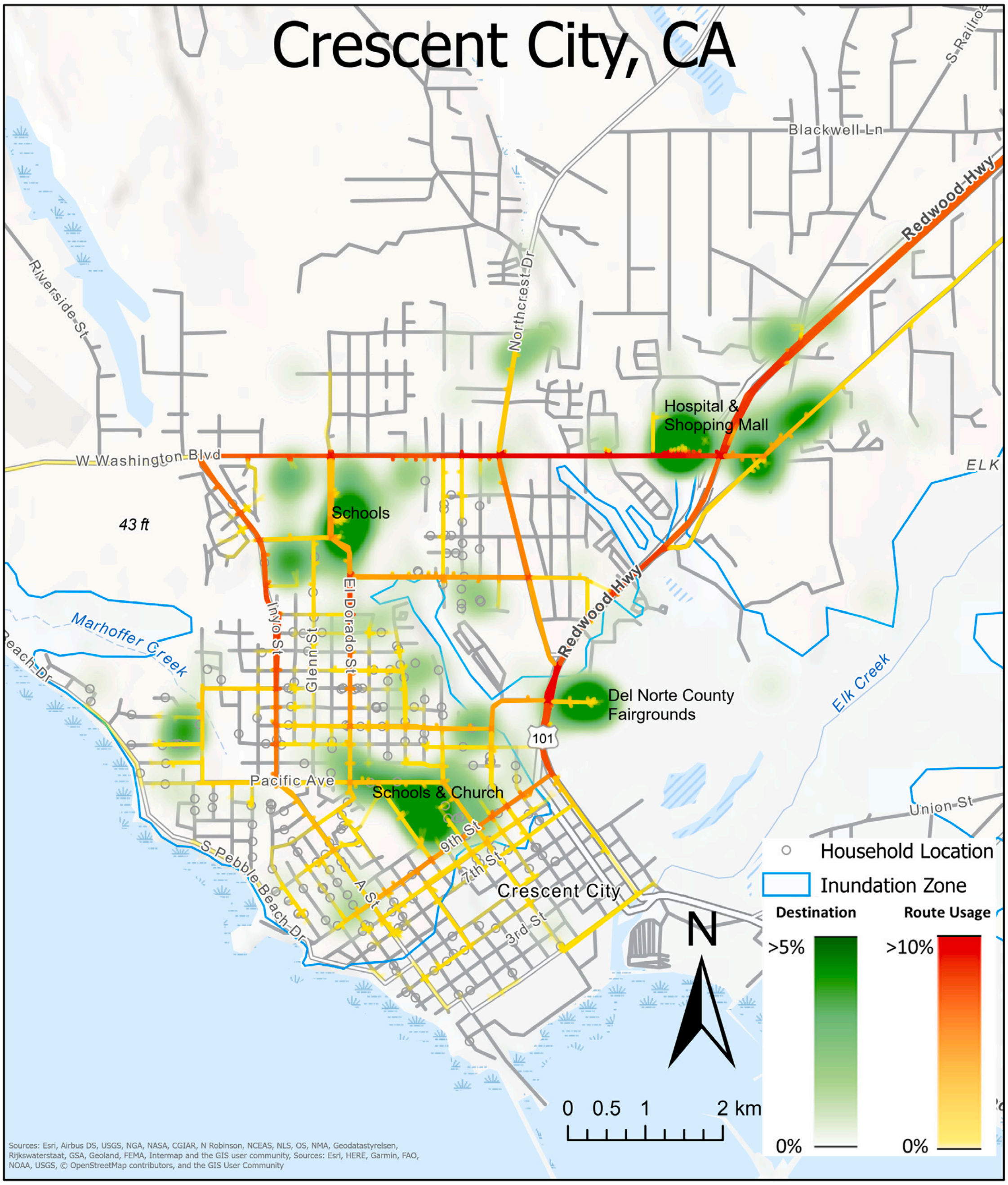

Fig. 3. Evacuation destination and route choice in Crescent City, CA. Color of the heatmap represents the percent of respondents plan to evacuate to that destination or use that route, shown in the legend. Inundation Zone (blue line). Household location (gray halo dots). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3. Evacuation distance

Fig. 5 indicates an obvious difference between evacuation distance by foot and by car. Almost all respondents in both communities who intended to evacuate by foot expected to evacuate less than 3.5 km, whereas one-quarter (Coos Bay) to one-third (Crescent City) of those who expected to drive expected to travel farther than this. There is no significant difference in foot evacuation distance between the two communities (Coos Bay mean (M) = 883 m, Crescent City M = 1170 m, $t_{26} = 2.05, p = .22$), whereas respondents who expect car evacuation for Crescent City expected to go farther than respondents in Coos Bay (Crescent City M = 3.5 km, Coos Bay M = 2.4 km, $t_{232} = 1.97, p < .01$). This difference can be explained by the geographical features of the two communities.

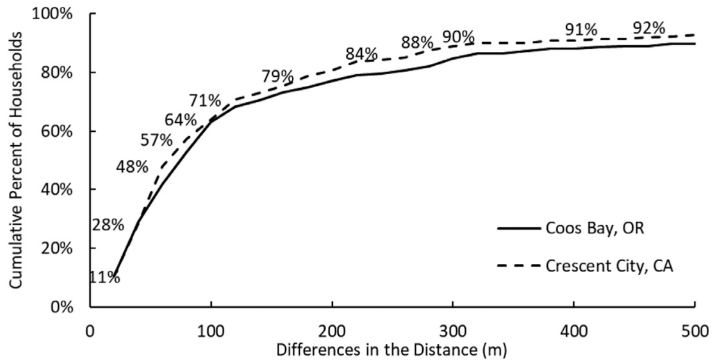

Fig. 4. Distributions of the differences in distances of actual location and perceived household location on Map.

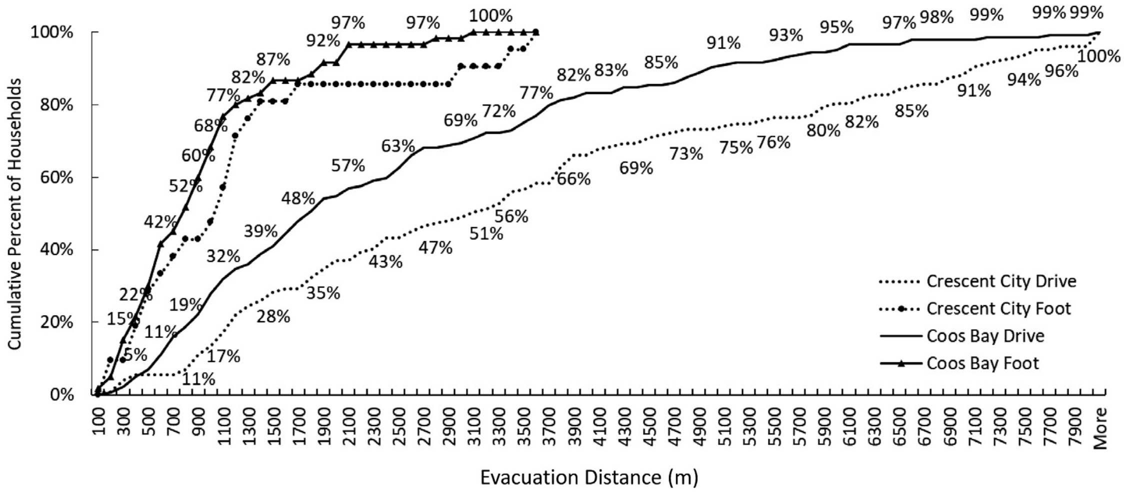

Fig. 5. Evacuation distance by communities and modes.

Specifically, residents in Coos Bay can reach safety in a shorter driving distance because there are hills in the middle part of the Coos Bay peninsula, as shown in Fig. 2. Thus, Coos Bay residents only need to drive a short distance to safety. By contrast, Crescent City residents need to drive a longer distance to safety because there is a large flat area close to the coast, even though most of the flat zone is actually outside the inundation zone (see Fig. 3).

Three probabilistic functions – gamma, log-normal, and Weibull – are suitable to model the distribution of evacuation distances, with separate distributions for each travel mode. Our evaluation of alternative probability distributions considered three key issues: (1) the shape of the function (the distance and time data are right-skewed); (2) the limit of the data (driving distance has a longer tail than walking distance); and (3) the simplicity of use in practice [the three functions proposed are defined by two (shape and scale) parameters and, thus are easy to implement in evacuation simulation models]. The overall similarity in evacuation distance distributions for the two communities indicates that these data can be pooled for a single distance distribution, but the differences between transportation modes indicates that the foot and car distributions should be modeled separately.

Fig. 6 shows the distribution of distances to destinations by foot (Panel a) and the degree of fit for each of three probabilistic models. The quantile–quantile plot in Fig. 6(b), indicates that all three functions provide good fits to the distribution of foot evacuation distances within the range of 0–1500 m, but not beyond that distance. However, around 90% of the residents who choose to evacuate by foot expect to travel distances within that range, so those functions provide reasonable estimates of foot evacuation distances for the vast majority of evacuees. The gamma function yields the best goodness-of-fit statistics among the three density functions, as indicated in Table 2. The gamma probability density function can be written as:

$$f(x) = \frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{\theta}} \quad (1)$$

where k indicates the shape, θ represents the scale, and Γ represents the gamma function. As shown in Table 2, the Maximum Likelihood Estimation package in R (Delignette-Muller and Dutang, 2015) indicates that the best estimate parameters are $k = 1.920$ and $\theta = 0.002$.

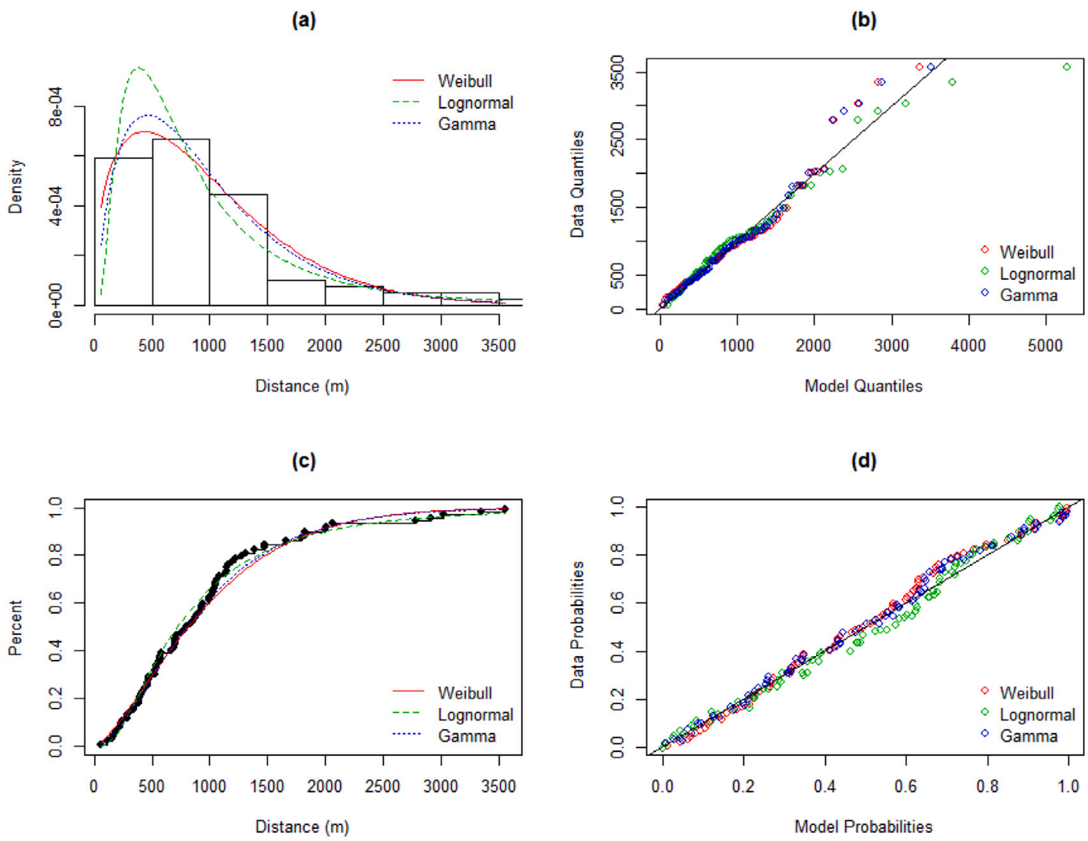

Fig. 6. Distribution of evacuation distance on foot and fitted models.

Table 2
Evacuation distance model goodness-of-fit statistics.

	Walking evacuation distance			Driving evacuation distance		
	Weibull	*Lognormal*	*Gamma*	*Weibull*	*Lognormal*	*Gamma*
Kolmogorov–Smirnov	0.09	0.07	0.07	0.06	0.07	0.05
Cramer–von Mises	0.09	0.07	0.05	0.19	0.24	0.16
Anderson–Darling	0.61	0.41	0.34	1.16	1.71	0.99
AIC	1264	1263	1261	1084	1106	1083
BIC	1269	1268	1266	1091	1113	1090
Parameters			Estimate (Std. error)			Estimate (Std. error)
k			1.920 (0.149)			1.646 (0.130)
θ			0.002 (0.00008)			0.573 (0.053)

AIC: Akaike's Information Criterion. BIC: Bayesian Information Criterion.

Fig. 7(a) depicts the distribution of expected destination distances by car and the three fitted functions. Consistent with foot evacuation distribution, Table 2 indicates that a gamma function has the best fit for the driving evacuation distance distribution. The quantile–quantile plot shown in Fig. 7(b) indicates that all three functions fit the driving evacuation distance distribution well, especially within 8 km, but not beyond that distance. However, around 97% of residents who chose vehicular evacuation expect to evacuate within that distance, so the gamma function provides a good fit for the distribution of driving evacuation distances for the vast majority of evacuees. The best estimate parameters of the gamma function by maximum likelihood estimation are $k = 1.646$ and $\theta = 0.573$.

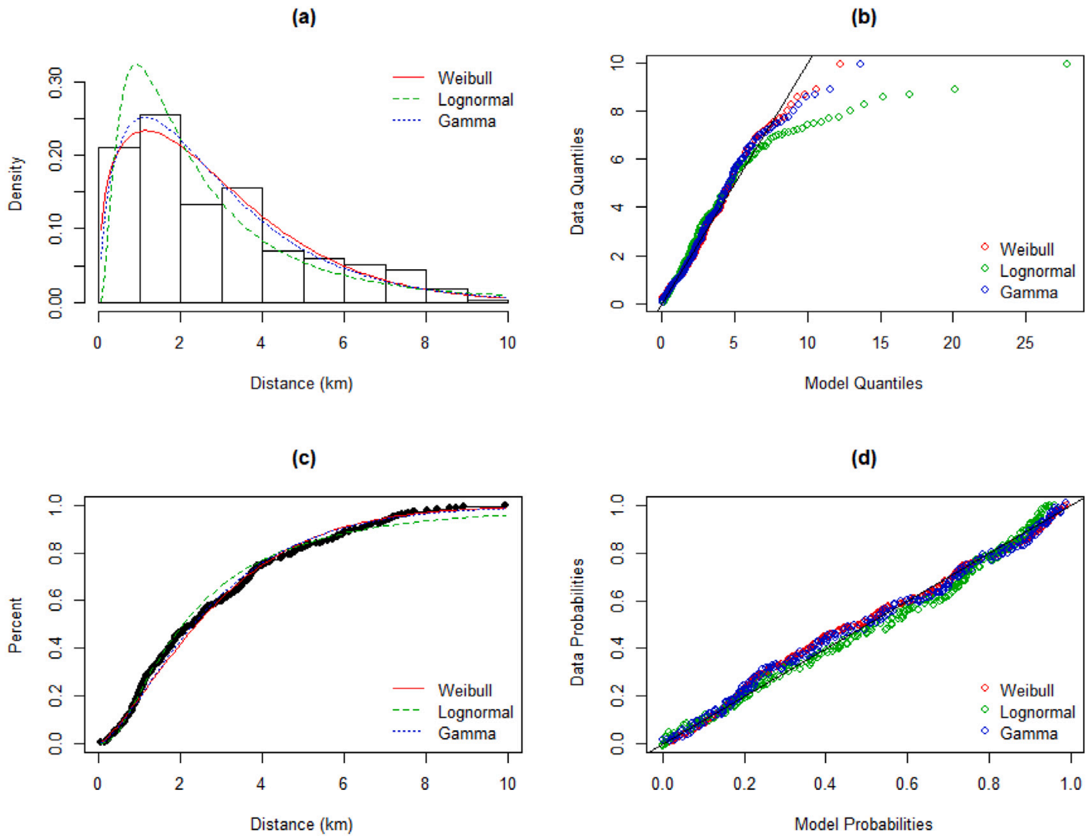

Fig. 7. Distribution of evacuation distance by car and fitted models.

4.4. First wave arrival time and clearance time components

The respondents in Coos Bay and Crescent City were similar in their estimates of tsunami arrival time, as well as household preparation time and evacuation travel time, and thus their implied clearance time. In addition, the Coos Bay and Crescent City data are similar to those from two other CSZ communities: Lincoln City and Eureka (see Fig. 8). However, the four time estimates from Commencement Bay are significantly different from the other four communities, as shown in Table 3. That is probably due to differences in location. Specifically, the Commencement Bay communities are located on the Puyallup River where it discharges into the Puget Sound/Salish Sea, so these residents can expect a much longer tsunami arrival time than the four communities that are located on the Pacific Ocean. Consequently, Commencement Bay residents have lower level of tsunami risk perception, hazard education, and evacuation preparation. Overall, the similarities of the four time estimates for the four Pacific Coast communities (i.e., excluding Commencement Bay) indicate that pooled data are suitable for characterizing the density functions for these distributions.

Fig. 9 indicates a high density near the origin and a sharp decrease in density as time increases for all four time components. Figs. 9 and 10 depict the probability density and cumulative distribution functions, respectively. Although all three functions provide a good fit to the data, the log-normal function has the best fit. Table 4 shows that the log-normal function not only has the best fit statistics for respondents' expectations of first wave arrival time, it also has the best fit for the two ETE components – evacuation preparation time and evacuation travel time – as well as total clearance time.

In a log-normal distribution, the logarithm of X is normally distributed with a mean of μ and a variance of σ^2. The log-normal function, which can be written as $\ln(X) \sim \mathcal{N}(\mu, \sigma^2)$, has a probability density function:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right) \tag{2}$$

where $exp()$ represents the natural exponential function. The fact that the time component distributions are strikingly similar in these four CSZ communities suggests that these parameters will generalize to a wide range of other CSZ communities.

4.4.1. Estimated first wave arrival time

Fig. 8(a) illustrates residents' estimates of first wave arrival time in all five communities. The majority of respondents (65% in Commencement Bay, 91% in Lincoln City, 83% in Coos Bay, 79% in Crescent City, 87% in Eureka) expect a tsunami wave to

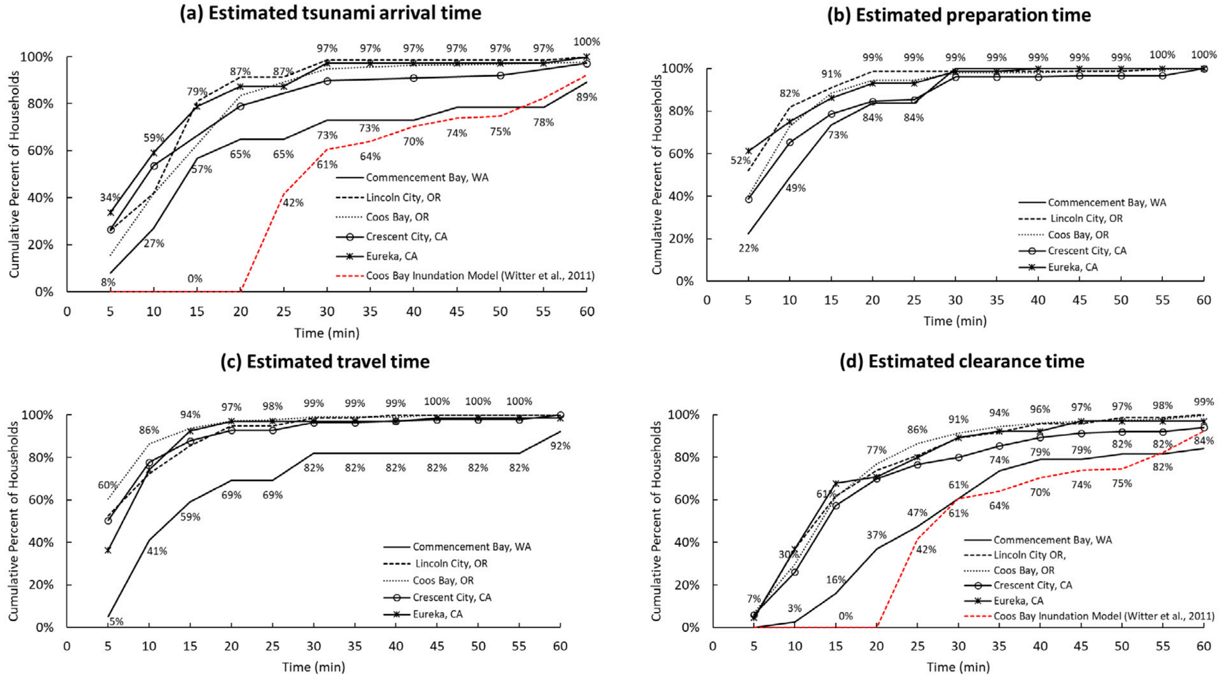

Fig. 8. ETE components for CSZ communities.

Table 3
Differences in ETE components between communities.

	Mean	Std. dev	1	2	3	4
Arrival time						
1. Commencement Bay	32.51	34.97				
2. Lincoln City	13.20	9.46	19.31*			
3. Coos Bay	16.73	18.91	15.78*	−3.53		
4. Crescent City	18.72	19.81	13.79*	−5.52	−1.99	
5. Eureka	12.82	11.46	19.70*	0.39	3.92	5.91
Preparation time						
1. Commencement Bay	14.36	8.30				
2. Lincoln City	8.77	7.33	5.59*			
3. Coos Bay	10.21	8.62	4.16	−1.44		
4. Crescent City	13.02	12.56	1.34	−4.26*	−2.82*	
5. Eureka	8.83	8.23	5.53*	−0.07	1.37	−4.19*
Travel time						
1. Commencement Bay	23.03	18.87				
2. Lincoln City	9.45	7.87	13.58*			
3. Coos Bay	8.72	9.22	14.31*	0.73		
4. Crescent City	8.24	7.30	14.79*	1.21	0.48	
5. Eureka	10.09	9.12	12.93*	−0.65	−1.37	−1.86
Clearance time						
1. Commencement Bay	34.63	21.77				
2. Lincoln City	17.88	11.72	16.75*			
3. Coos Bay	19.56	15.06	15.08*	−1.68		
4. Crescent City	19.57	14.63	15.06*	−1.70	−0.02	
5. Eureka	18.39	15.00	16.24*	−0.51	1.16	1.18

*The mean difference is significant at the 0.05 level.

arrive in <20 min. Although 20–40 min is the scientifically estimated first wave arrival time for a local tsunami in the CSZ, only a few respondents (8% in Commencement Bay, 7% in Lincoln City, 13% in Coos Bay, 12% in Crescent City, 10% in Eureka) provided estimates in this range. A few respondents (27% in Commencement Bay, 1% in Lincoln City, 4% in Coos Bay, 9% in Crescent City, 3% in Eureka) estimated > 40 min, whereas some respondents (8% in Commencement Bay, 26% in Lincoln City, 27% in Coos Bay, 16% in Crescent City, 34% in Eureka) expected the first wave to arrive in <5 min. Overall, Commencement Bay respondents had longer estimates of tsunami arrival time than those in the other communities (Commencement Bay $M = 32.5$ min, Lincoln City $M = 13.2$

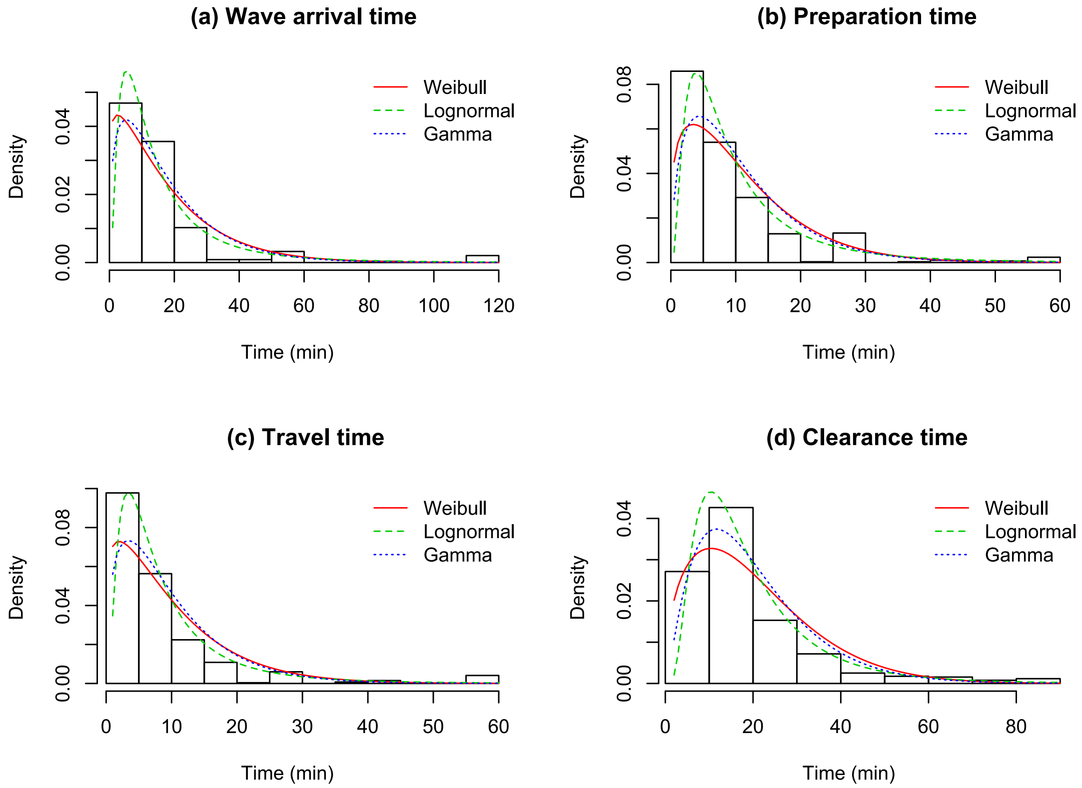

Fig. 9. Probability density function of time components and fitted models.

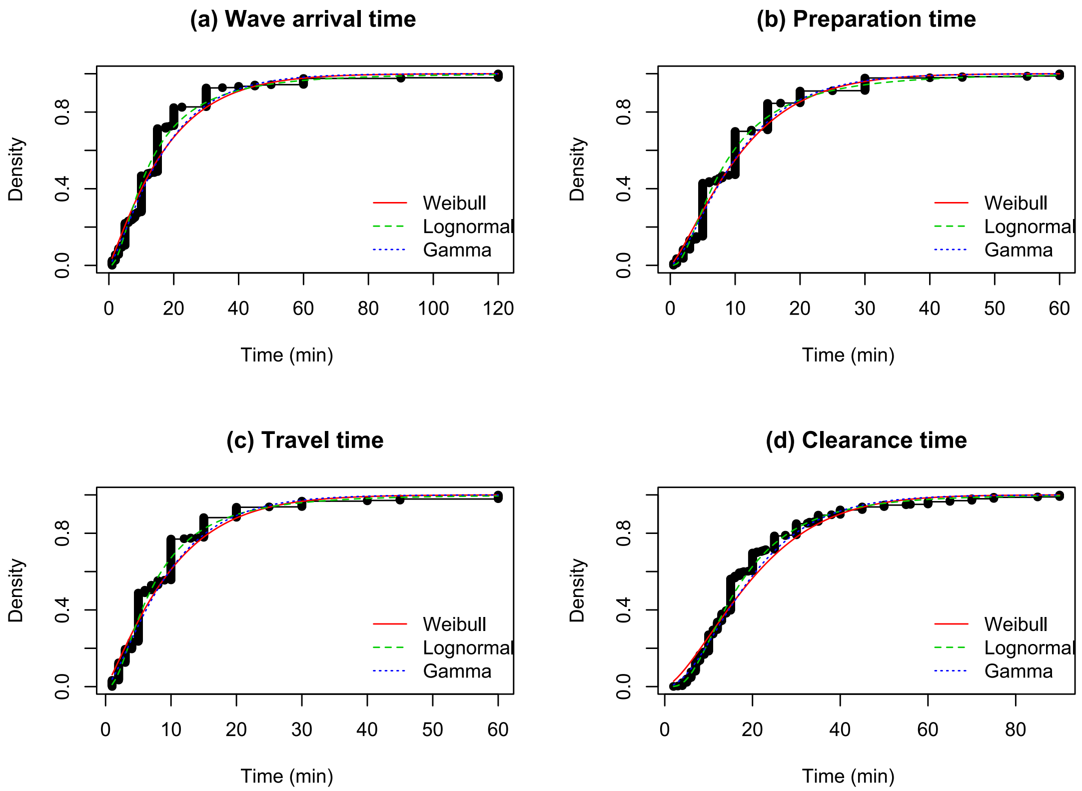

Fig. 10. Cumulative density function of time components and fitted models.

Table 4
Time-related models estimation and goodness-of-fit statistics.

Goodness-of-fit statistics	Wave arrival time			Preparation time			Travel time			Clearance time		
	Weibull	Lognormal	Gamma	Weibull	Lognormal	Gamma	Weibull	Lognormal	Gamma	Weibull	Lognormal	Gamma
Kolmogorov–Smirnov	0.16	0.15	0.16	0.15	0.15	0.17	0.16	0.14	0.17	0.15	0.11	0.15
Cramer-von	2.31	1.69	1.89	2.33	1.85	2.17	2.04	1.43	2.17	1.84	0.49	1.29
Anderson–Darling	13.33	8.79	10.45	12.81	9.55	11.34	11.66	7.24	11.97	11.01	2.40	6.97
AIC	4146.46	4079.47	4120.00	3955.14	3552.72	3573.00	3126.33	3046.83	3481.55	3660.14	3556.81	3609.75
BIC	4155.08	4088.08	4128.62	3963.9	3561.30	3581.57	3134.75	3055.25	3490.12	3668.48	3565.15	3618.09
Parameters		Estimate (std. error)			Estimate (std. error)			Estimate (std. error)			Estimate (std. error)	
μ		2.43 (0.04)			2.03 (0.04)			1.86 (0.04)			2.74 (0.03)	
σ		0.88 (0.03)			0.86 (0.03)			0.81 (0.03)			0.64 (0.02)	

Table 5
Departure time delay comparison between studies.

Study	Type	Departure time delay (min)					
		0	5	10	15	20	60
CSZ	Hypothetical	8%	43%	70%	84%	91%	100%
East Coast New Zealand (Dhellemmes et al., 2016)	Hypothetical	7%		62%			94%
Kamakura City, Japan (Arce et al., 2017)	Hypothetical	53%	82%		92%		
Aotearoa, New Zealand (Blake et al., 2018)	Actual	7%		36%			
American Samoa, U.S.A. (Lindell et al., 2015)	Actual				61%		96%
Tohoku, Japan (Yun and Hamada, 2015)	Actual	14%				66%	
Uttarakhand, India (Lindell et al., 2019a)	Actual				54%		60%

min, Coos Bay M = 16.7 min, Crescent City M = 18.7 min, Eureka M = 12.8 min; $p < 0.01$ between Commencement Bay and any other community). In addition, the correlation between tsunami arrival time and household preparation time ($r = 0.31, p < .01$) supports the proposition that underestimating the arrival time encourages a shorter preparation time. In the 2013 Wellington, New Zealand tsunami, Fraser et al. (2016) found that 56% and 90% of the respondents expected 30 min and 60 min first wave arrival times, respectively. By contrast, more than 93% of the CSZ respondents in our study expected the first wave to arrive in <30 min. The Arce et al. (2017) study in Japan found that tourists expected slightly longer first wave arrival times: <10 min (26%), 30 min (59%), and 60 min (74%).

The expected first wave arrival time histogram in Fig. 9(a) depicts a sharp decrease in density as time increases. A quantile–quantile plot (see supplement material) shows the three functions can accurately model the wave arrival time distribution especially from 0–60 min, but not beyond that range. However, overwhelming majority of respondents (>97%) expect the first wave to arrive <30 min, so the best fit is still the log-normal function with $\mu = 2.43$ and $\sigma = 0.99$ within the range of 0–60 min.

4.4.2. Evacuation preparation time

Fig. 8(b) indicates that Commencement Bay respondents had slightly longer expected preparation times than respondents in the other communities (Commencement Bay M = 14.4 min, Lincoln City M = 8.8 min, Coos Bay M = 10.2 min, Crescent City M = 13.0 min, Eureka M = 8.8 min, differences among communities and the significance of those differences are shown in Table 3). About 40%–50% of the respondents expected to take <5 min to prepare for evacuation in all communities except the Commencement Bay. There is a sharp increase in the percentage of prepared households as time increases from 0–15 min, as shown in Fig. 8(b). The vast majority of residents (84% in Commencement Bay, 99% in Lincoln City, 95% Coos Bay, 85% in Crescent City, 93% in Eureka) estimated <20 min of preparation time. Indeed, most respondents expected to spend 0–10 min on preparation and there is a sharp decrease in density as time increases beyond that, as shown in Fig. 9(b). The quantile–quantile plot (see supplement material) shows the three functions provide a good fit to the preparation time data in the range from 0–30 min, but not beyond that. However, the overwhelming majority (>97%) of respondents expect to evacuate within 30 min, so one can use the log-normal function with $\mu = 2.07$ and $\sigma = 0.86$ to model this preparation time distribution.

The respondents' evacuation preparation time distribution found in this study is, unsurprisingly, much shorter than for hurricanes (Lindell et al., 2020) and even some rapid-onset hazardous material releases (Rogers and Sorensen, 1989). Moreover, when compared with previous local tsunamis, we found two plausible similarities and differences. First, the evacuation preparation time distribution for CSZ communities is similar to the evacuation preparation time distribution for east coast cities of Aotearoa/New Zealand in which 7% of the respondents expected to evacuate immediately (vs. 8% in the CSZ), 62% within 10 min (vs. 70% in the CSZ), and 94% within 60 min (vs. 100% in the CSZ) (Dhellemmes et al., 2016). Second, Table 5 shows that CSZ residents (as well as in hypothetical studies from Aotearoa/New Zealand and Japan) had slightly shorter expected preparation times than the actual preparation times found in events such as the 2009 tsunami in American Samoa (Lindell et al., 2015), 2016 tsunami in Aotearoa/New Zealand (Blake et al., 2018), 2011 Tohoku tsunami (Yun and Hamada, 2015), 2013 Uttarakhand India flash flood (Lindell et al., 2019a). Specifically, Lindell et al. (2015) found that 61% of the American Samoa respondents evacuated in <15 min, and 96% evacuated in <60 min. In the 2016 tsunami in Aotearoa/New Zealand (Blake et al., 2018), 7% of the respondents reported evacuating without taking any other action, 36% evacuated in <10 min, and 52% evacuated in <30 min. The Yun and Hamada (2015) data from the 2011 Tohoku tsunami found 14% evacuated immediately and 66% evacuated in <20 min. The Lindell et al. (2019a) data from the Uttarakhand India flash flood found that 54% evacuated in <15 min and 60% evacuated in <60 min. The (Arce et al., 2017) data for Japanese inundation zone visitors are even more optimistic, with 82% of the respondents expecting to be prepared to leave in <5 min and 92% in <15 min.

In summary, respondents from hypothetical studies seem to be reporting shorter preparation times. This difference can result from the *planning fallacy*, which research indicates is a result of failing to anticipate all of the tasks required to complete a project, failing to accurately estimate how long individual tasks take, and failing to understand interdependence among tasks (i.e., tasks that must be completed serially rather than in parallel), as well as failing to account for interruptions by irrelevant tasks — e.g., Buehler et al. (2010). Indeed, previous research has found that delayed evacuation is prevalent in many evacuations and the reasons for these delays include milling (seeking additional information, relaying warnings to others, discussing evacuation plans, and gathering family members), as well as protecting property, gathering pets, helping others, packing travel kits, purchasing travel supplies (e.g., gasoline), and collecting valuable items (Lindell et al., 2015, 2019a; Blake et al., 2018; Wood et al., 2018). In addition, evacuation preparation after an earthquake could include extricating people from collapsed buildings, so the preparation time delays could be even longer after an M9 CSZ earthquake. The total number of expected preparation tasks is similar between Coos Bay and Crescent City (Coos Bay $M = 3.0$, Crescent City $M = 3.2$, $t_{434} = -0.83, p = 0.41$) and is significantly correlated with estimated preparation time ($r = 0.40, p < 0.01$) for the two communities.

To account for evacuation preparation times, researchers have applied different methods. Mas et al. (2013) used a Rayleigh distribution with a mean departure time of 7 min and 100% departure in <20 min in a tsunami simulation model for La Punta, Peru, which yields somewhat shorter estimates than the CSZ data. In addition, Gabel et al. (2019) input a constant 10 min departure delay for all evacuees as the evacuation preparation time in a Beat-the-Wave (all walking evacuation) model for Coos Bay. A 10 min delay for all evacuees is appropriate for a walking-only evacuation but could be problematic when there is a large percentage of vehicular evacuation because it would load the evacuation route system with all evacuees at the same time rather than distributing them over the 30 min time interval found in the CSZ data.

4.4.3. Evacuation travel time

Fig. 8(c) shows the overall similarity in travel time for the four CSZ communities except Commencement Bay. The overwhelming majority of respondents expected to spend <20 min traveling to their destinations. Consistent with their close proximity to their evacuation destinations, 60% of Coos Bay residents reported 5 min as their estimated travel time, which is greater than in Crescent City (50%) and the other CSZ communities. However, respondents' overall travel time distributions are similar for the four Pacific Coast communities (Lincoln City $M = 9.5$ min, Coos Bay $M = 8.7$ min, Crescent City $M = 8.2$ min, Eureka $M = 10.1$ min, $p > 0.05$ for any pair of communities) but different from Commencement Bay ($M = 23.0$ min, $p < 0.05$ with any other community), as shown in Table 3.

Compared to respondents' reports about the 2018 Indonesia earthquake and tsunami (Harnantyari et al., 2020), those in the CSZ expected shorter travel times. Specifically, 24% of the Indonesian respondents reported taking <5 min of travel time (versus 49% in the CSZ), 36% reported 5–10 min (versus 28% in the CSZ), 20% reported 10–30 min (20% in the CSZ), and 21% reported > 30 min (versus 3% in the CSZ). CSZ respondents also expected shorter travel times than the Arce et al. (2017) Japanese coastal visitors, 11% of whom estimated taking <7.5 min of travel time, 20% estimated 8–15 min, 22% estimated 16–30 min, and 14% estimated > 30 min, (33% could not provide an estimate). Although these comparisons suggest that people in the CSZ may underestimate the delay caused by traffic congestion during evacuation, this is understandable given that they have limited experience with tsunami evacuations (Buylova et al., 2020). Nonetheless, these travel time estimates might indicate that the CSZ data will not generalize to communities outside of the CSZ. If there are no actual evacuation data available, expected travel time can be compared with tsunami evacuation simulations (Mas et al., 2012; Wang et al., 2016; Wang and Jia, 2021; Kim et al., 2022) to assess the accuracy of coastal residents' travel time estimates. For example, the Kim et al. (2022) evacuation simulation shows that the majority of people in Waikiki will arrive at safe areas in <20 min, which is similar to the travel time estimates in the five CSZ communities.

Fig. 9(c) depicts a sharp decrease in probability density as expected travel time increases. The quantile–quantile plot (see supplement material) shows the three functions fit the travel time distribution in the range 0–35 min, but not beyond that. However, the overwhelming majority (>96%) of people expect to arrive at their destination <30 min, so the log-normal function can capture the majority of travel time estimates for CSZ households. One can use the log-normal function with $\mu = 1.86$ and $\sigma = 0.81$ to describe the evacuation travel time distribution in the range 0–35 min.

4.4.4. Inundation zone clearance time

Fig. 8(d) shows the implied clearance time for the CSZ communities that results from combining the respondents' evacuation preparation and evacuation travel times. The cumulative distribution of clearance times has an exponential shape for all communities — the percentage of households expecting to reach safety increases rapidly near the origin and decelerates sharply > 20 min. The majority of respondents reported evacuation preparation times and evacuation travel times that yield implied clearance times <30 min. There are no significant differences in the implied clearance time distributions among four of the CSZ communities (Lincoln City $M = 17.9$ min, Coos Bay $M = 19.6$ min, Crescent City $M = 19.6$ min, Eureka $M = 18.4$ min, $p > .05$ for any pair of communities), but Commencement Bay ($M = 34.6$ min, $p < .05$) is significantly different from the other four communities. This indicates that the pooled data (excluding Commencement Bay) can be used to create a clearance time probability distribution for evacuation analysis and planning.

There is no significant difference between expected first wave arrival time and total clearance time for Commencement Bay (paired $t_{30} = -0.38, p = 0.70$), Coos Bay (paired $t_{175} = -1.88, p = .06$), and Crescent City (paired $t_{127} = -0.21, p = .84$). However, significant differences are found for Lincoln City (paired $t_{59} = -2.65, p < .01$) and Eureka (paired $t_{58} = -2.97, p < .01$). Specifically, the data from these communities indicate that some respondents have expected first wave arrival times that are less than their implied clearance times and, thus, they would be overtaken by the first tsunami wave. This result suggests that some people have not thought through the implications of their individual ETE components. In particular, it suggests that these inundation zone residents need to prepare "Grab and Go" kits before a tsunami strikes to reduce their preparation times when one is imminent.

Respondents' expected first wave tsunami arrival times can impact evacuation decisions, but may not reflect the actual first wave arrival time for each household. The tsunami inundation model from Witter et al. (2011), as shown in the red dashed line in Fig. 8(d), indicates that the first wave arrives in Coos Bay after 20 min and reaches the majority (75%) of 128 respondents who reside in inundation zone in <50 min. Fig. 8(d) indicates that the overwhelming majority of respondents expect to reach safety before the first wave arrives in Coos Bay (expected clearance time $M = 19.6$ min, modeled wave arrival $M = 35.7$ min, paired $t_{127} = 6.48, p < 0.01$). Due to the limited availability of data from the Witter et al. (2011) tsunami inundation model, we could not compare implied clearance times to inundation model results for the other communities. However, it is possible to produce rough estimates of first wave arrival time by the distance between the shore and the edge of CSZ megathrust. This shows that communities at the CSZ's southern margin (i.e. Coos Bay, Crescent City, and Eureka in this study) have similar first wave arrival times (Uslu et al., 2007; Goldfinger et al., 2012). For example, the Uslu et al. (2007) model for Crescent City indicates that the first wave would arrive in 25 min (5 min later than for Coos Bay). That is, the estimated inundation time for respondents in Crescent City would be similar to that for Coos Bay. Furthermore, the scientifically estimated first wave arrival time is longer for communities at the northern margin (Uslu et al., 2007; Goldfinger et al., 2012). Thus, inundation model results for the other communities would generate a similar curve (or slower curve for northern margin) to that in Fig. 8(d), which indicates that the majority of respondents can reach safety before the tsunami's first wave arrives — if their estimates of evacuation preparation and evacuation travel times are correct.

Fig. 9(d) depicts an increase in density from 0–20 min and a sharp decrease in density after that. The quantile–quantile plot shows that the estimated log-normal function fits the clearance time well especially from 0–50 min, but not beyond that (see supplement material). However, the overwhelming majority (>94%) of respondents expect a clearance time <50 min, so the fitted log-normal function can describe the calculated clearance time for the majority of respondents. One can use the log-normal function with $\mu = 2.74$ and $\sigma = 0.64$ to inform the tsunami evacuation clearance time distribution in the range 0–50 min.

5. Conclusion and future research

Although physical scientists have extensively studied the processes of CSZ tsunami generation and transmission, much less research has examined people's expected evacuation logistics in response to that threat (Lindell and Prater, 2010; National Research Council, 2011). To address this gap, the present study modeled questionnaire data from households in five CSZ communities. The questionnaire for Coos Bay and Crescent City provided a local road map to assess residents' expectations of their evacuation destinations and routes, in addition to the estimates of first wave arrival times, evacuation preparation times, and evacuation travel times collected by Lindell et al. (2019c). Respondents' estimates of their evacuation preparation times and evacuation travel times allowed us to calculate implied clearance times for all households in the five CSZ communities.

One product of this study is the pair of heatmaps that depict residents' evacuation destinations and route choices for Coos Bay and Crescent City. Evacuation modelers can use these heatmaps to guide their choice of appropriate shelter locations and potential evacuation issues such as congestion hot spots if their local topography is similar to that of one of these two communities. A gamma function provided the best fit for the foot and car evacuation distance distributions, whereas a log-normal function provided the best fit for the first wave arrival time and ETE components. The similarity of the time distributions across all five CSZ communities suggests that other CSZ communities could use those functions to inform the ETE analyses in their evacuation plans.

This study also made significant contributions on reporting and modeling coastal residents' estimates of first wave arrival time, evacuation preparation time, and evacuation travel time. In turn, the latter two time estimates allowed us to compute implied clearance time estimates for residents from the five CSZ communities. The results suggest that respondents from all five communities have similar patterns of time estimates, and the majority of residents anticipate being able to reach safety before first wave arrival. The log-normal functions, as the best fitted models, were used to describe the probability distributions of four estimated time components.

In summary, results from these five coastal communities provide empirical evidence about people's expected evacuation logistics when responding to an imminent tsunami threat. These results suggest a need for local jurisdictions to address (1) tsunami hazard education, (2) evacuation demand, and (3) evacuation route capacity not only for tsunamis (Chen et al., 2022a), but also for other rapid-onset disasters such as flash floods (Lindell et al., 2019a), and wildfires (Siam et al., 2022).

First, this research can improve tsunami hazard education and household preparedness if emergency managers explain to coastal residents the importance of recognizing long and strong earthquake shaking as an environmental cue to evacuate. During earthquake and tsunami, conventional warning systems will have limited effectiveness for a local CSZ tsunami (Lindell and Prater, 2010). Electronic alerts could be effective, but only 25% of our Commencement Bay/Lincoln City/Eureka sample had involved in the electronic alert system (Lindell et al., 2022). Thus, training people to recognize long and strong shaking remains the primary means of evacuating people out of the tsunami zone before the first wave arrives.

In addition, the results emphasize the need for all coastal residents to understand how soon the tsunami's first wave will arrive, so everyone has an appropriate sense of urgency in their response (see Section 4.4). Moreover, the results suggest that emergency managers need to ensure that residents recognize earthquake shaking as a tsunami cue because that eliminates authorities' decision time (t_d) and warning dissemination time (t_w) from the estimate of clearance time (t_T). Those who wait for an official warning are very likely to be overtaken by the tsunami. Finally, emergency managers need to emphasize the need for coastal residents to prepare "Grab and go" kits before an earthquake strikes so they can reduce their evacuation preparation times.

Second, local jurisdictions can address evacuation demand by helping coastal residents to pick destinations that are outside the inundation zone — marking street signs and designating assembly areas to which people can safely evacuate (see Sections 4.2 and 4.3). Additionally, situational factors can also significantly impact evacuation speed, so it is critical for emergency managers to communicate the risk of environmental hazards and encourage the public to prepare for the adverse conditions they might face during disaster response. For example, night time (probably due to decreased visibility) was found to impede evacuation travel speed in both post event survey (Sun and Sun, 2020) and evacuation drill (Chen et al., 2022b) studies. Thus, emergency managers should encourage residents, via preparedness programs, to pick primary and alternate evacuation routes in advance and practice them so they know those routes and their travel times during the day, night, and inclement weather conditions.

Third, local authorities should understand that the majority of people will attempt to evacuate by car (Chen et al., 2021), so reducing people's preparation and departure time for evacuation could substantially increase the slope of the demand curve, overloading the evacuation routes and causing traffic jams. Thus, local authorities need to encourage people with no mobility limitations to evacuate on foot in order to save road capacity for people with disabilities who can only evacuate by driving out of the inundation zone. Additionally, local jurisdictions should also conduct analyses to assess the capacity of the evacuation route system — especially identifying critical intersections and infrastructures/facilities (see Section 4.2) to increase their capacity.

Moreover, future research needs to develop a more sophisticated understanding of the differences between expected evacuation behaviors in hypothetical events and actual behaviors in real events. Such research should examine the applicability of research on the planning fallacy (Buehler et al., 2010) to achieve this objective. However, due to low probability of the near-field M9 CSZ event and lack of empirical data (the last instance of this magnitude of event was about 300 years ago), studying CSZ residents' expected behavior will remain an important method of conducting tsunami evacuation research.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trd.2022.103324.

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