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Community variations in population exposure to near-field tsunami hazards as a function of pedestrian travel time to safety

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Abstract Efforts to characterize population exposure to near-field tsunami threats typically focus on quantifying the number and type of people in tsunami-hazard zones. To develop and prioritize effective risk-reduction strategies, emergency managers also need information on the potential for successful evacuations and how this evacuation potential varies among communities. To improve efforts to properly characterize and differentiate near-field tsunami threats among multiple communities, we assess community variations in population exposure to tsunamis as a function of pedestrian travel time to safety. We focus our efforts on the multiple coastal communities in Grays Harbor and Pacific Counties (State of Washington, USA), where a substantial resident and visitor population is threatened by near-field tsunamis related to a potential Cascadia subduction zone earthquake. Anisotropic, path distance modeling is conducted to estimate travel times to safety, and results are merged with various population data, including residents, employees, public venues, and dependent-care facilities. Results suggest that there is substantial variability among communities in the number of people that may have insufficient time to evacuate. Successful evacuations may be possible in some communities assuming slow walking speeds, are plausible in others if travel speeds are increased, and are unlikely in another set of communities given the large distances and short time horizon. Emergency managers can use these results to prioritize the location and determine the most appropriate type of tsunami risk-reduction strategies, such as education and training in areas where evacuations are plausible and vertical-evacuation structures in areas where they are not.

Keywords Tsunami · Evacuation · Path distance · Modeling · Pedestrian · Cascadia

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1 Introduction

Tsunamis are significant threats to coastal communities worldwide, as evidenced by the 244,333 lives that collectively were lost in the past decade due to the 2004 Indian Ocean, 2006 Java, 2009 Samoa, 2010 Chile, 2010 Sumatra, and 2011 Tohoku tsunamis (NOAA National Geophysical Data Center/World Data Center 2012). The potential for life loss continues as impacted communities rebuild in place and as development continues to grow in coastal areas throughout the world. As a result of these dramatic events, greater attention is being paid to the societal risks associated with tsunami hazards.

One important tool for understanding societal risks from tsunamis is the vulnerability assessment. Vulnerability as a science involves examining the combination of physical, social, economic, and political components that influence the degree to which an individual, community, or system is threatened by a particular event, as well as that individual's or system's ability to mitigate these threats and recover if the event was to occur (Cutter 2003; Mileti 1999; Hewitt 1997; Wisner et al. 2004). Vulnerability assessments attempt to quantify and qualify the conditions that create an environment in which the potential for societal losses is created or amplified. This information can be used to develop, target, and prioritize actions to reduce or manage these vulnerabilities, such as outreach programs, response planning, and mitigation projects. It can also be used as input to risk assessments, which typically focus on quantifying the joint probability of event occurrence and asset fragility within a specific scenario, timeframe, sector, or potential adaptation strategy.

Vulnerability is often characterized by the exposure, sensitivity, and adaptive capacity of the individual, asset, system, or coupled systems relative to predicted threats (Turner et al. 2003; Polsky et al. 2007). A common approach to characterize population exposure to a given hazard is to use geographic information system (GIS) tools to overlay hazard and demographic data to identify the location and number of people in hazard zones. Population exposure to tsunamis has been communicated through the creation of site-specific maps to identify the location of high population counts or densities in hazard zones (e.g., Morgan 1984; Wood and Good 2004; Papathoma et al. 2003; Dall'Osso et al. 2006; National Research Council 2007; Sumaryono et al. 2008; Taubenbock et al. 2008). To support regional risk-reduction efforts, GIS-based indices have been created to compare community exposure in terms of the number of people in tsunami-prone areas that includes multiple jurisdictions (e.g., Wood and Soulard 2008). Although the scale of analysis and purpose vary in these studies, they share a common goal of identifying the number and geospatial hotspots of populations in tsunami-prone areas.

Although exposure is an important first step in understanding population vulnerability, it fails to take into account the demographic characteristics of at-risk individuals and their ability to receive and understand warning messages (Mileti and Sorenson 1990; Miller et al. 1999; Morrow 1999; Cutter 2003). This sensitivity, the second element of vulnerability, is typically inferred by identifying certain demographic characteristics of exposed populations, such as age, race and ethnicity, education, socioeconomic status, among others (Cutter et al. 2003; Tierney et al. 2001; Wisner et al. 2004). For example, two towns may have the same number of residents in tsunami hazard zones, but one town may be considered more sensitive because the majority of its at-risk residents are elderly and therefore may face greater difficulties evacuating from an imminent tsunami threat. Variations in demographic sensitivity can be documented by inventorying certain demographic attributes for populations in tsunami-hazard zones (e.g., Wood and Soulard 2008). Sensitivity can also be modeled by developing composite metrics that reflect the principal components of all relevant demographic characteristics across a study area either in isolation from hazards (Cutter et al. 2003) or relative to a given tsunami hazard (Wood et al. 2010).

Understanding pre-disaster demographic and societal conditions improves our understanding of population vulnerability, but it does not provide a complete picture because it does not account for the adaptive capacity of an at-risk population. Adaptation in a hazards context can be defined as the actions taken or adjustments made in a system (e.g., household, community, country) that enable it to better cope with or manage an external stress (Brooks 2003; Smit and Wandel 2006). Examples in a tsunami context include tsunami-warning systems, evacuation training for at-risk individuals, vertical-evacuation structures, and functional exercises for emergency responders. Increasing the adaptive capacity of the human system focuses attention on controllable societal consequences of future tsunamis instead of uncontrollable natural processes (Wood 2011).

In the absence of perception and preparedness studies, the adaptive capacity of at-risk individuals is often inferred using demographic data, such as assuming a lower adaptive capacity for elderly populations because of potential mobility issues during an evacuation. However, these assumptions do not account for adjustments made by at-risk individuals, such as an elderly person walking an evacuation route on a daily basis to reduce travel times to safety. It also does not take into account the environmental conditions that influence their adaptive capacity. For example, in the case of near-field tsunami threats, the adaptive capacity of individuals is influenced by how far they would need to walk or run to escape tsunami waves. Using our two towns discussed earlier, the high elderly population in one town may only be 100 meters from high ground and the other town may be 20 km from high ground. If potential tsunamis could impact these two coastal communities within 20 min after a tsunamigenic earthquake, then the town at a farther distance to high ground would be considered more vulnerable to tsunami threats, since a successful evacuation over 20 km in 20 min is not likely. While age is one element in each person's vulnerability, it is only one factor that influences whether or not individuals could successfully evacuate.

There have been several efforts to model evacuation potential for at-risk individuals threatened by hazards with quick arrival times. Examples include traffic simulation models (Franzese and Sorenson 2004; Marrero et al. 2010), egress simulations for building evacuations (Averill et al. 2005), agent-based models of movement along road networks (Jonkmann et al. 2008; Yeh et al. 2009), and cost-distance models to incorporate landscape variability (Graehl 2009; Post et al. 2009; Wood and Schmidtlein 2012). While the assumptions and purposes vary, outputs from these various case studies typically focus on a specific location and include maps of travel times and casualty estimates based on specific hazard scenarios and population distributions.

Site-specific case studies are useful for emergency planning at those specific locations but do not provide the regional perspective that emergency managers need for prioritizing risk-reduction strategies across multiple jurisdictions that may be threatened by the same hazard. This is especially critical for coastal communities threatened by near-field tsunami hazards that could strike minutes after a major earthquake. For example, tsunamis generated by an earthquake associated with the Cascadia subduction zone (CSZ) could inundate over 1,000 km of coastline from northern California (USA) to southern British Columbia (Canada) in as little as 15 min after the earthquake (Cascadia Region Earthquake Workgroup 2005). Successful evacuations may be feasible in some communities and not in others due to the presence or absence of natural high ground. Because of these potential variations in evacuation capabilities, appropriate adaptation strategies could include evacuation training in some communities and vertical evacuation structures in others

(Engstfeld et al. 2010). However, to date, this level of community comparisons has not occurred in the United States (National Research Council 2011) but would provide additional resolution to ongoing discussions for tsunami risk reduction and resource prioritization as part of the National Tsunami Hazard Mitigation Program (2012).

The objective of this paper is to discuss community variations in population exposure to tsunamis that account for the evacuation potential of the at-risk population. We integrate previous efforts that have examined the exposure and sensitivity of at-risk populations with efforts to model their evacuation potential out of hazard zones. Evacuation potential is modeled using geographic information system (GIS) software with an anisotropic geospatial approach that uses path distance algorithms and accounts for the directionality of movement. To demonstrate this integrated approach to population vulnerability to tsunamis, we focus on the multiple coastal communities in Pacific and Grays Harbor counties in southwestern Washington State (United States) that all are threatened by CSZ-related earthquakes and tsunamis. Population exposure estimates based on traditional spatial coincidence of people and hazard zones will be contrasted with exposure estimates that incorporate travel times to safety. Because all models are simplified representations of reality, we discuss the use and limitations of results for tsunami risk-reduction planning, and discuss areas for continued evacuation modeling research and application. Research outputs will improve our understanding of evacuation challenges for near-field tsunamis among multiple communities, a topic largely undocumented in the United States (National Research Council 2011). This information supports emergency managers in their efforts to develop adaptation strategies that reflect the needs and risk conditions of an at-risk population and to develop regional risk-reduction plans when population exposure and evacuation potential vary among communities.

2 Study area

This study of population exposure to near-field tsunamis as a function of travel time is set in Pacific and Grays Harbor counties on the open-ocean, southwest coast of Washington (United States) (Fig. 1). The low-lying portion of the two counties includes nine incorporated cities (e.g., Long Beach, Ocean Shores) and sixteen unincorporated communities (e.g., Taholah, Ocean Park), as delineated by census-designated place boundaries (Washington Office of Financial Management 2012). We chose these coastal counties because emergency managers there already question the ability of the at-risk population to evacuate low-lying areas before tsunami inundation occurs related to a CSZ earthquake (Cascadia Region Earthquake Workgroup 2005). Tsunami preparedness in this area has included evacuation maps, route planning, and various outreach efforts (Washington Military Department Emergency Management Division 2012), but questions concerning the likelihood of successful evacuations led to a series of community workshops that explored tsunami vertical-evacuation options (Engstfeld et al. 2010). A future CSZ earthquake (likely magnitude 8 or greater) could shake coastal areas for more than 3 min, the coast would likely subside on the order of 1–2 m, liquefaction of unconsolidated sediment would create sand boils on cracked paved surfaces, and the first of several large tsunami waves likely would arrive within 20–30 min after the initial earthquake and inundate low-lying areas of both counties (Fig. 1; Walsh et al. 2000). Pedestrian evacuations are more probable because road networks would likely be compromised for vehicle-based evacuations due to cracked roads, sand boils, and downed electrical lines (Cascadia Region Earthquake Workgroup 2005). Tsunami-prone areas of the two counties contain tens of thousands of residents and employees, as well as several public venues, hotels and restaurants, dependent-care facilities, and critical facilities (Wood and Soulard 2008).

Fig. 1 *Maps* of **a** the communities of Pacific and Grays Harbor counties in a tsunami-hazard zone (Walsh et al. 2000) related to a potential Cascadia subduction zone earthquake, and **b** the study area relative to the State of Washington, United States of America (USA)

3 Methods

Population exposure to tsunami hazards is based on the spatial coincidence of a hazard zone and a population. We build on this traditional approach by incorporating evacuation times to safety for at-risk populations and aggregate information at the community level to enable regional discussions of tsunami risk-reduction planning. The following sections provide additional information on the various input data and geospatial analytical methods.

3.1 Evacuation modeling

The two most common approaches to modeling pedestrian evacuations are agent-based models and least-cost-distance (LCD) models. Agent-based models focus on the evacuee (i.e., the agent) and use defined relationships to account for evacuee behavior and dynamic travel costs (e.g., reduced speeds at congestion points) (Yeh et al. 2009). LCD models focus on characteristics of the evacuation landscape, such as slope and land cover, to calculate the shortest path to safety from every location in a hazard zone, with the difficulty of traveling through each location represented as a cost surface. Although both approaches are useful and complementary, we use LCD methods in this study because we are interested in understanding the spatial distributions of evacuation times across a region that are not contingent on the initial distribution and magnitudes of at-risk individuals for a specific scenario. The spatially explicit representation of best-case evacuation times provided by LCD modeling offers emergency managers the ability to identify locations from which horizontal pedestrian evacuation may not be feasible and where vertical-evacuation strategies may be warranted.

The specific LCD method used in this evacuation analysis is based on the anisotropic, path distance approach described in Wood and Schmidtlein (2012; Fig. 2) and implemented in ESRI's ArcMap 9.3 geographic information system (GIS) software. Geospatial algorithms are used to find the most efficient route from each starting point in the hazard zone to the closest destination out of the hazard zone based on various cost surfaces. Inputs include hazard zones, safe areas (i.e., areas outside of the hazard zone and considered destinations), elevation, land cover, and slope. Land cover and elevation-derived slope data are transformed into speed conservation values (SCVs) and represent the proportion of maximum travel speeds that are expected on areas with given conditions. Land cover SCVs are based on Soule and Goldman's (1972) energy-cost terrain coefficients for certain land cover types. Slope SCVs are based on Tobler's (1993) hiking function. An anisotropic approach incorporates slope based on the direction in which the evacuee is moving (e.g., the influence of a given slope will vary whether travel is uphill, downhill, or perpendicular to the slope). The path distance tool calculates distances between cells of varying elevations, as well as the path of travel and slope from a given cell to each of its neighbors.

The tsunami-hazard zone used in this study (Fig. 1) is based on scenario 1A (with and without areas on the fault that are stuck, also known as asperities) in Walsh et al. (2000), which denotes a magnitude (M_w) 9.1 earthquake along the Cascadia subduction zone. Sources of error in the inundation modeling are discussed in detail in Priest et al. (1997), but the largest source of uncertainty is in the earthquake parameterization (Walsh et al. 2000). Horizontal resolution errors are as large as 50 meters, and modeled inundation lines were smoothed to account for resolution limitations and to reflect logical topographic boundaries (Walsh et al. 2000; Washington Division of Geology and Earth Resources 2008). The first tsunami wave is predicted to arrive at the study area approximately 25 min after a CSZ earthquake (Walsh et al. 2000).

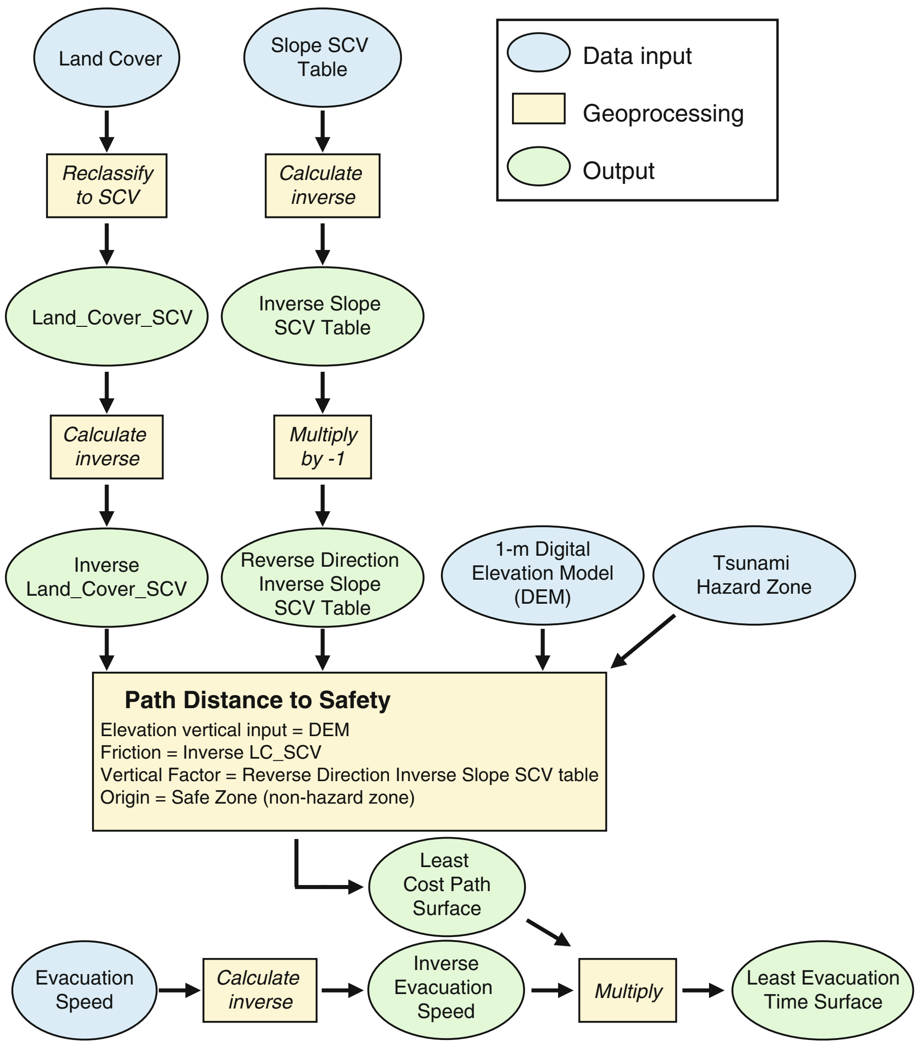

Fig. 2 Model diagram of the anisotropic path distance approach from Wood and Schmidtlein (2012)

Land cover data for land in tsunami-hazard zone were derived from the integration of several datasets. Boundaries between varying land cover types were first delineated using eCognition object-oriented, image analysis software and 2009 1-m pixel resolution, orthorectified color imagery provided by the US National Agriculture Imagery Program (NAIP; United States Department of Agriculture 2009). This automated analysis uses the red, green, and blue bands of the NAIP imagery, and polygons were generated using a scale factor of 200. Polygons were then manually classified into one of the seven categories shown in Table 1. Additional steps were taken in processing the land cover data to improve the identification of large pedestrian obstacles, such as water bodies and structures. Rivers that did not show up in the eCognition-derived polygons were manually digitized based on the NAIP imagery. Structure that did not show up in the eCognition-derived polygons, such as homes and sheds, was manually digitized as points using the 2009 NAIP imagery and a land-use field in tax parcel data for Grays Harbor and Pacific counties (Pacific County Department of Public Works 2011; Grays Harbor County 2011). A square buffer with a 12-m diameter was then created around each point to act as a surrogate for the building footprint for structures not identified using eCognition, based on visual interpretation of these excluded structures in the imagery. Fences were not considered in this regional analysis due to the limitations of the imagery and elevation data, as well as field observations, suggesting that fences, if present, typically were on single properties and not continuous obstacles for substantial distances. Road-centerline data from the State of Washington (Washington Office of Financial Management 2012) and trail information from Open Street Maps (CloudMade 2011) were used to improve roadway boundaries. To convert the centerline data to polygons, we sampled segments of different classes of roads/trails and buffered their centerlines based on the average widths. All of these inputs were converted to raster grid formats and combined to form the final land cover model input. SCVs were then assigned based on the inverse of the terrain energy coefficients derived by Soule and Goldman (1972). Tsunami inundation and evacuation zones from Walsh et al. (2000) were combined and extended 30 meters inland to represent the tsunami-hazard zone to eliminate sliver issues due to gaps in the two layers, which otherwise would appear erroneously as safe high ground to the evacuation model.

Elevation and slope data were derived from a 1-m, LiDAR-derived digital elevation model (WatershedSciences 2010). This slope is then used to retrieve the anisotropic cost from a lookup table that contains inverse slope SCV derived from Tobler's hiking function. We reversed the direction of the inverse slope SCV table because the search direction in the path distance algorithm is from the origin to destination. Because we wanted to know the evacuation times from all locations in the hazard zone to the closest safe zone, we entered the safe zone locations as the origin, meaning that the path distance tool started the search for the shortest paths in the safe zone and moves toward the hazard zone. This search direction is opposite the direction of evacuation, and so we reversed the direction of the inverse slope SCV table accordingly.

To generate an anisotropic LCD surface, the land cover SCV raster grid, slope SCV look-up table, digital elevation model (DEM), and safe zone raster grid were entered into the path distance tool. LCD values should be considered approximations and not definitive statements, because it assumes pedestrians take the optimal routes to safety, such as through a natural backyard instead of walking around a field on a paved surface. Whether or not individuals take optimal route is likely influenced by their knowledge of the area and the environmental conditions at the time of the evacuation. For example, someone with deep knowledge of a neighborhood may still decide to remain on roads and not take a short cut through low-lying natural areas if an evacuation was at night, during a heavy rainstorm,

Table 1 Types of land cover and associated speed conservation values

Land cover	Speed conservation value (SCV)
Roads	1
Developed	0.9091
Light brush	0.8333
Heavy brush	0.6667
Unconsolidated	0.5556
Buildings	No through travel allowed
Water	No through travel allowed

and if they were guiding someone with mobility issues. In addition, the modeling assumes individuals will evacuate instantly after an earthquake, whereas in reality, many individuals will delay their evacuation to collect belongings or to confirm their intentions with those around them or with trusted sources, such as family members.

The least-cost-distance surface is then multiplied by the inverse of various evacuation speeds to yield least-evacuation-time (LET) surfaces. Because pedestrians may have a range of physical abilities and caregiver roles during an evacuation, we calculated a range of evacuation times based on representative travel speeds. We derived evacuation time surface based on the three running and three walking speeds shown in Table 2. This allowed us to generate ranges of potential population vulnerability to tsunamis rather than simpler point estimates, better reflecting the mixed mobility of hazard zone residents. This approach also provides emergency managers a suite of travel time maps that could be used in different outreach efforts such as using more conservative speeds when educating managers and occupants of an adult residential care facility. Although multiple travel speeds are used, we acknowledge that the modeling simplifies actual travel and individuals will not travel at similar speeds, especially as fatigue sets in for those with longer travel distances and limited mobility.

3.2 Population distributions

After generating LET surfaces based on various travel speed assumptions, we performed spatial joins to integrate evacuation results (transformed to vector formats) with various population data. This geospatial function then allowed us to portray the distribution of populations as a function of minimum travel time to safe areas. The at-risk populations discussed in this study include residents, employees, tourists and residents at public venues, and individuals that depend on assistance to evacuate (e.g., children at schools, elderly at adult residential care facilities, and hospital patients). A resident-population point file was created by manually identifying residential structures from the 2009 NAIP imagery discussed earlier. Population within 2010 US Census Bureau counts at the block level (US Census Bureau 2011) were equally distributed among all identified residential structures within a specific block. Assigning population homogenously to residential structures within census blocks may lead to errors but determining exact population counts at each household was considered beyond the scope of this regional analysis. In addition to total population, populations that are over 65 years in age also were identified in the block data to highlight individuals more likely to have mobility issues during an evacuation.

An employee-population point file was developed using a spring 2011 version of the InfoGroup Employer Database (InfoGroup 2011), a proprietary database that includes

Table 2 Pedestrian travel speeds used in the evacuation model

Category	Speed (m/s)	Source
Slow walk	1.1	US Department of Transportation (2009)
Moderate walk	1.22	US Department of Transportation (2009), Langlois et al. (1997)
Fast walk	1.52	Knoblauch et al. (1995)
Slow run	1.79 (15-min mile)	MarathonGuide.com (2011)
Moderate run	2.68 (10-min mile)	MarathonGuide.com (2011)
Fast run	3.83 (7-min mile)	MarathonGuide.com (2011)

business locations, employee counts, and type based on the North American Industrial Classification System (NAICS). The NAICS codes enabled us to identify public venues that cater to tourists (e.g., hotels, attractions) and dependent-population facilities that contain individuals with limited mobility (e.g., child day care centers, hospitals, adult residential care centers). Unlike the resident and employee data, information on public venues and dependent-care facilities denotes the presence of such businesses and not the number of occupants. Estimates of employee exposure to tsunamis should be considered first approximations because the 1,851 businesses in the study area were not field-verified, although the data reported that 88 % of businesses had site-level positional accuracy and the remaining businesses had varying levels of zip code centroid accuracy. In addition, the Employer Database simply provides the total employee count at a business and not the typical number at any given time (e.g., shift or seasonal work); therefore, the actual number of employees at any given time likely will be lower and will vary depending on time of day and season.

After identifying the location, magnitude, and estimated travel times to safety of populations across tsunami-prone areas in our study region, we then determined the community to which they each belonged. This was done using a geospatial identity function to integrate the population data with 2010 US Census place boundaries, including incorporated cities and other census-designated places (Washington Office of Financial Management 2012). Population points that did not fall within any of the incorporated cities or unincorporated places were noted as being in the remaining land of either Pacific or Grays Harbor Counties.

3.3 Comparative indices of community exposure

To compare community exposure to tsunami hazards, we created relative indices that summarized communities in terms of the number of residents, residents over 65 years in age, employees, public venues, and dependent-care facilities. This was done to deal with the multiple ranges of the various population datasets (e.g., residents and employees in the thousands but venues and facilities under 100). For each attribute, values were normalized to the maximum value found in a specific category. Doing so creates a common range from 0 to 1 for each of the five attributes. The five normalized values in each community were then added, resulting in a composite index potentially ranging in value from 0 to 5 (lowest to highest relative exposure).

Two indices were created and compared. The first index simply summarized the total number of people (residents, residents over 65 years in age, and employees) and number of facilities (public venues and dependent care) in the tsunami-hazard zone of a community. The second index incorporated travel time to safety by multiplying the number of people or facilities (depending on the attribute) and the travel time to safety at that spot (e.g., two people requiring 10 min to evacuate result in a value of 20). Because of the mixed populations typical in the tsunami-hazard zone, we used travel times based on the least-evacuation-time surface that assumes a slow walking rate of 1.1 m/s. Values for all populations within a community were calculated in this way and then added to yield a final number for that community. These summed values for each of the 5 variables were then normalized to maximum values and summed in the same manner as in the first index, resulting also in community values with a range of 0–5. The absolute numbers that integrate populations and travel times have no meaning and are useful only in relative terms to compare communities.

4 Results

4.1 Number of residents in hazard zones

There are 40,081 residents in the tsunami-hazard zone of Pacific and Grays Harbor counties, based on the traditional population-exposure approach of using GIS tools to overlay 2010 US Census population counts and tsunami-hazard data (Fig. 3a). The majority of these at-risk populations are in Aberdeen, Hoquiam, Ocean Shores, Westport, and the areas of Pacific County outside of any incorporated cities or census-designated places. Aside from these four communities and the rural parts of Pacific County, the remaining communities have far fewer residents in the tsunami-hazard zone. However, the low numbers of residents in the tsunami-hazard zone of many of these communities represent high percentages of the total community population (Fig. 3b). This suggests that many of the communities are small and are located almost entirely in the tsunami-hazard zone. Therefore, while the total losses may not be as high in these areas as in larger communities, the smaller communities may be less likely to weather those losses.

Two communities that emerge as having both high numbers and high percentages of population exposure to CSZ-related tsunami are Aberdeen and Ocean Shores (Fig. 3). Aberdeen and Ocean Shores are within the top three communities based on total population exposure (11,844 and 5,568 residents, respectively), and both have high community percentages of their residents in the tsunami-hazard zone (70 and 100 %, respectively). Based on these results alone, we would expect the two communities to experience similarly high losses from a CSZ-related tsunami and have greater difficulty recovering from the event

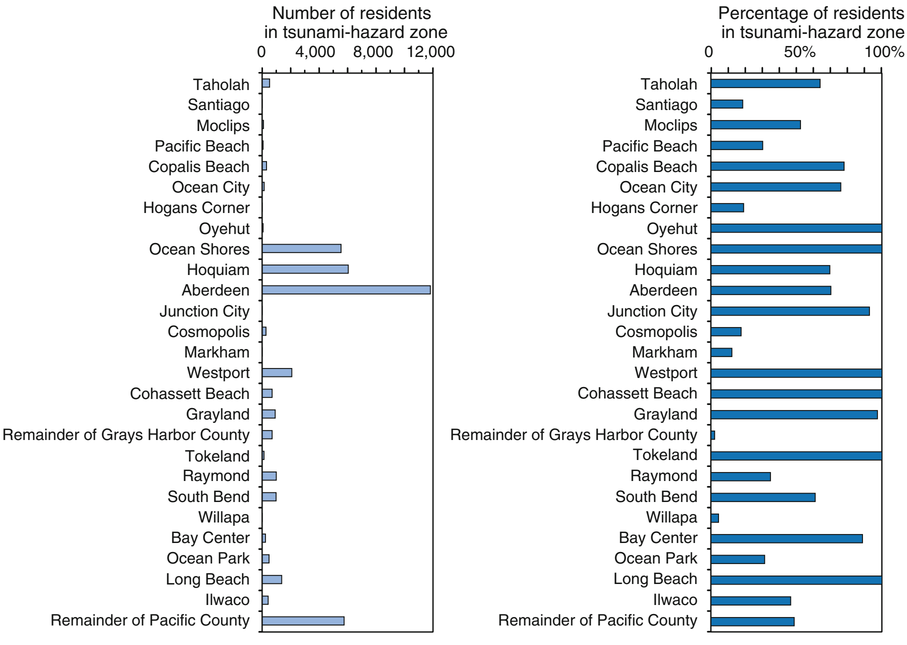

Fig. 3 *Graphs* showing the **a** number and **b** percentage of residents in tsunami-hazard zone for communities in Pacific and Grays Harbor counties, Washington, based on an overlay of census block and tsunami-hazard data

than other communities. However, as discussed earlier, this basic overlay approach ignores the ability of at-risk individuals to reach high ground before tsunami waves arrive. The next section documents how population-exposure estimates change once this factor is taken into account.

4.2 Modeled evacuation times

Figure 4 demonstrates the evacuation-modeling inputs, such as land cover and elevation (Fig. 4a) and the resulting pedestrian-evacuation travel times to high ground (Fig. 4b) assuming a travel speed of 1.1 m/s (referred to as a slow walk) for the central part of Ocean Shores. We chose Ocean Shores to demonstrate the input data and resulting modeled pedestrian travel times because of the complex nature of the landscape here. Unlike many coastal communities in this study area, much of Ocean Shores is punctuated by a series of narrow canals that provide residential-boat access to Grays Harbor Bay. It is situated on the Point Brown peninsula on the north of the mouth of Grays Harbor Bay (Fig. 1), and the closest safe area for evacuees is to the north, off of the peninsula. Modeled pedestrian-evacuation times for areas in Fig. 4b are on the order of 70–140 min, which is substantially higher than the predicted 25 min between the CSZ earthquake and the resulting tsunami waves. The impact of the canals on evacuation times is also apparent; for example, in the lower half of Fig. 4b, some residents are in areas where they will need to evacuate toward the ocean and the approaching tsunami waves to get to north-trending roads that would lead them to natural high ground (site 1). Others in this area are surrounded by canals and will need to first move south away from high ground to the north of the community, then east over a bridge (that may or may not survive the initial earthquake ground shaking), and finally north to evacuate to high ground (site 2).

Across the entire study area, pedestrian-evacuation times to high ground (assuming a slow walking speed) range from a few minutes to more than 200 min (Fig. 5). The highest

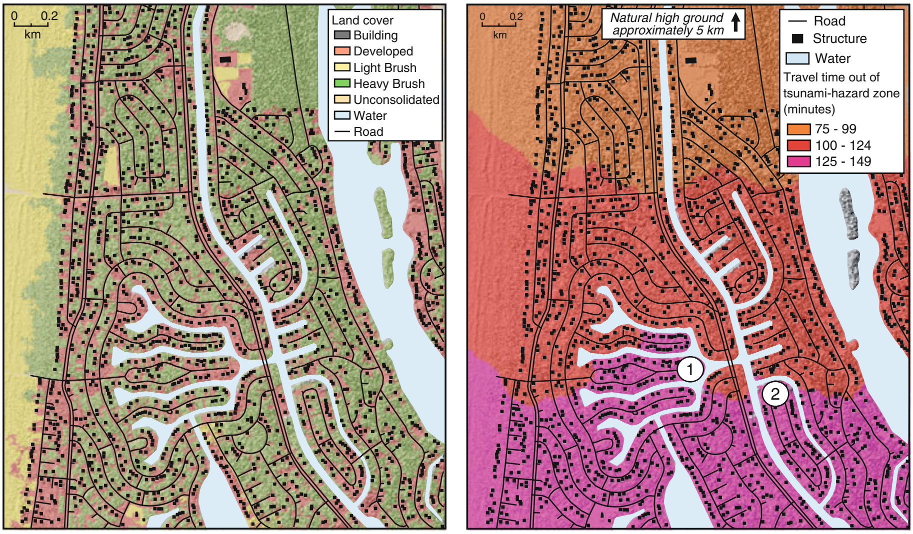

Fig. 4 *Maps* showing **a** modeling inputs and **b** least-cost, pedestrian-evacuation travel times (based on a travel speed of 1.1 m/s) for the central portion of the incorporated city of Ocean Shores, Washington

pedestrian-evacuation times are at the southeastern tip of Point Brown peninsula in Ocean Shores. Communities with modeled pedestrian-evacuation times that are substantially higher than predicted wave arrival times include segments of Ocean Shores and Westport in Grays Harbor County and the Long Beach peninsula and Tokeland in Pacific County. Modeled travel times for Ocean Shores and Aberdeen highlight a key difference between the vulnerability of these two communities (Fig. 5b, c, respectively). Although Aberdeen has the largest population in the tsunami-hazard zone, the evacuation times in Aberdeen overall are low (Fig. 5c). Most structures in Aberdeen are in areas that would require fewer than 25 min of pedestrian travel time (yellow zones), with travel times up to 49 min in waterfront areas (orange zones). Ocean Shores has a substantially lower exposed population, but this population is entirely within the tsunami-evacuation zone and has dramatically higher evacuation times to safe areas that are located to the north near the community of Hogans Corner (Fig. 5b).

4.3 Distribution of residents on the evacuation landscape

Modeled pedestrian-evacuation times visualized in Figs. 4 and 5 simply focus on the land surface, regardless of where people actually are. These evacuation travel time maps (based on a slow walking speed) were merged with various population data to get a sense of how communities varied in their evacuation challenges from a future CSZ-related tsunami. The distribution of residents as a function of travel time to safety for the various communities (Fig. 6) demonstrates that certain communities are more likely than others to have problems evacuating if the first tsunami waves arrive 25 min after the initial earthquake. Most or all of the residents may have enough time to successfully evacuate from many of the smaller communities, except for portions of Ocean Shores, Westport, Cohassett Beach, Grayland, Tokeland, and the rural portions of the Long Beach peninsula in Pacific County. In Aberdeen, the majority of the city's large population has evacuation times shorter than the expected time to tsunami arrival. For example, 30 % of the residents are not in the tsunami-hazard zone, 60 % are in areas where evacuations may take less than 25 min, and 10 % are in areas that would require more time to evacuate (up to a maximum modeled

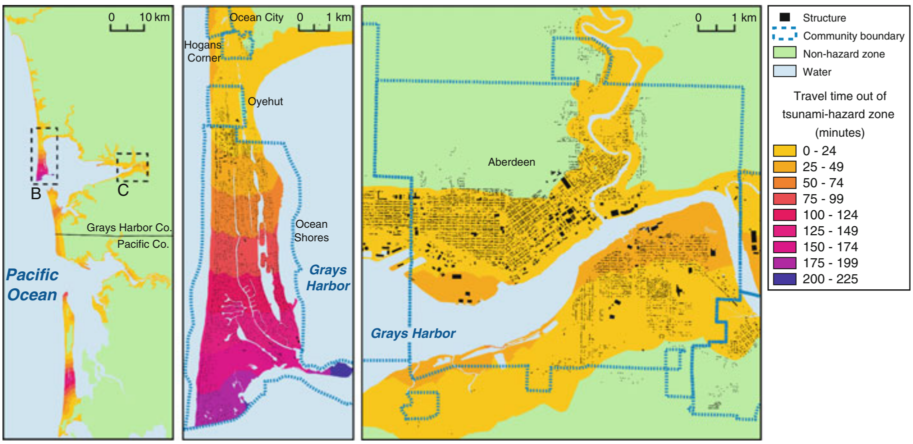

Fig. 5 *Maps* of **a** the study area, **b** Ocean Shores and surrounding communities and **c** Aberdeen showing modeled pedestrian travel times to safety, assuming a travel speed of 1.1 m/s

value of 34 min). In Ocean Shores, evacuation times have a much greater range, from less than a minute to more than 190 min, and 90 % of the residential population is in areas that may require more than 25 min to evacuate.

To further demonstrate the difference in population-exposure estimates, we plot the number of residents in the tsunami-hazard zone for each community against the number of residents in those communities that would require more than 25 min evacuating by foot (Fig. 7). We include a hypothetical line representing an r^2 value of 1.0 to show where complete agreement would occur between the population estimates for the communities. Complete agreement would mean that all individuals in each community would have difficulty evacuating in 25 min or less and that there is no difference in evacuation potential among the communities. A trendline based on our data has an r^2 value of 0.38, suggesting a low correlation between the two datasets. This indicates that some communities have populations that will be able to evacuate in 25 min or less, while other communities do not. The majority of the communities are clustered near the origin due to their low residential populations that have evacuation times that are likely fewer than 25 min. A few of the larger communities, such as Aberdeen, Hoquiam, and Westport, have several thousands of residents in the tsunami-hazard zone but are located relatively close to safety and few would require more than 25 min to evacuate (e.g., none in Hoquiam, 10 % of Aberdeen, and 18 % of Westport). Four communities, include Ocean Shores, Long Beach, Grayland, and the rural areas of Pacific County, fall close to the hypothetical line, indicating that the majority of their at-risk residents may need more than 25 min to evacuate

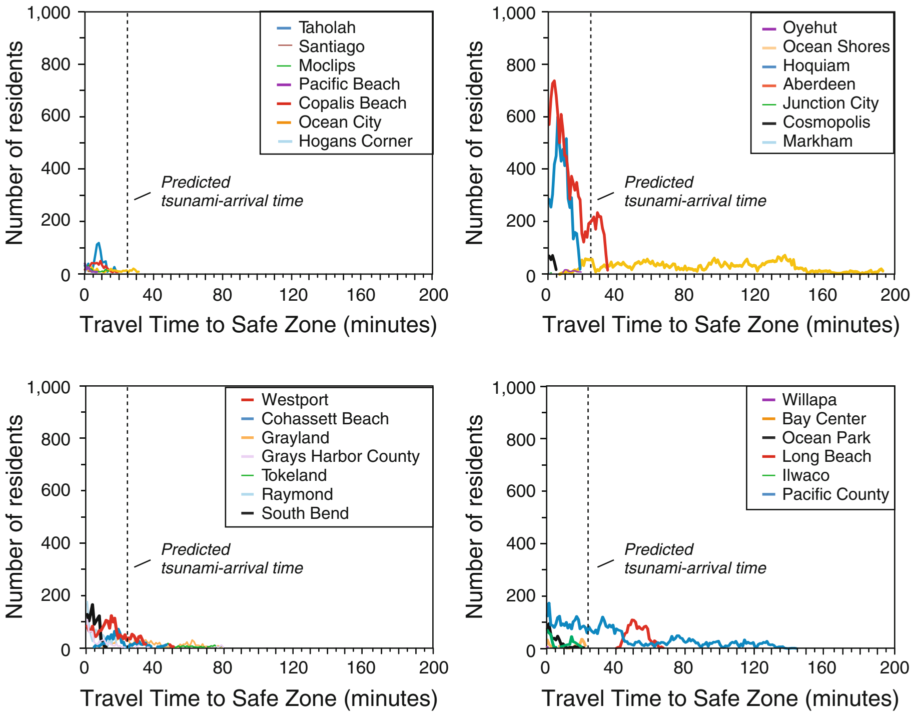

Fig. 6 Graph of the distribution of residents, organized by community, as a function of modeled pedestrian travel time to safety. Communities in the line graphs are organized geographically north (Taholah) to south (remaining portions of Pacific County)

(i.e., population exposure approximately equals the number of residents that may require more than 25 min). Of these communities, Ocean Shores has the largest exposed residential population and, as noted earlier, 90 % of them may require more than 25 min to evacuate. The rural areas of Pacific County follow, where approximately half of the 6,000 residents in the tsunami-hazard zone may need this amount of time as well.

Varying travel speed assumptions in the pedestrian evacuations yields additional insights into residential-population exposure in the study area. For this, we modeled the distribution of residents as a function of travel time to safety using slow, moderate, and fast walking speeds (1.1, 1.2, and 1.5 m/s, respectively) and one slow running speed (1.8 m/s). Figure 8 summarizes the cumulative totals of at-risk individuals with fewer than 25 min of travel time to safety with increasing travel speed assumptions. For example, the number of individuals walking at 1.1 m/s that could likely evacuate in 25 min or less is noted in the green bars, and those walking at 1.2 m/s are summarized by the green and yellow bars. We assume that most people would be unable to reach and maintain a moderate or fast running speed; therefore, we summed the number of people that would require more than 25 min at the slow running speed and did not model any faster speeds (dark red bar in Fig. 8).

Modeling results suggest that a base walking speed of 1.1 m/s may be sufficient for residents to reach high ground before tsunami wave arrival in many communities, such as Taholah, Copalis Beach, Hoquiam, Raymond, South Bend, Ilwaco, and the majority of Aberdeen (Fig. 8). The remaining 10 % of Aberdeen residents may be able to reach higher ground in 25 min or less if they can walk at faster rates of 1.2 and 1.5 m/s (yellow and orange bars, respectively). Some residents in parts of Ocean Shores and on the Long Beach Peninsula (noted as the remainder of Pacific County in Fig. 8) may also be able to successfully evacuate before wave arrival at similar speeds. However, many more people in

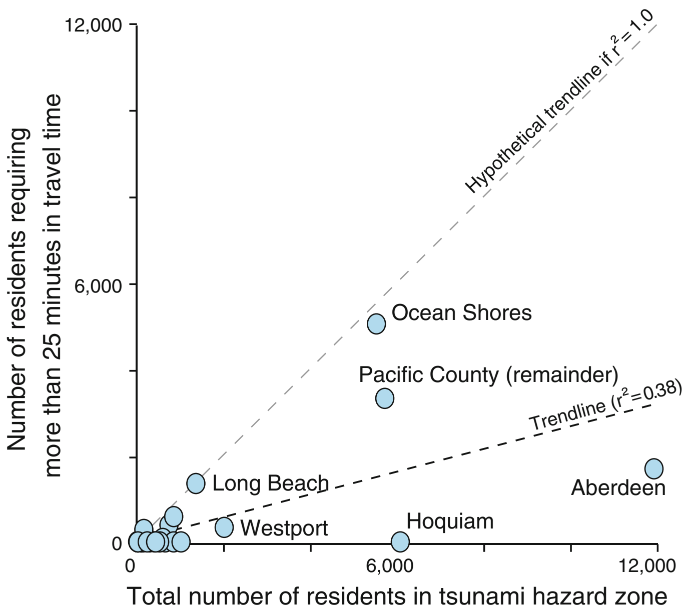

Fig. 7 *Graph* comparing communities in terms of the total number of residents in the tsunami-hazard zone and the total number of residents requiring more than 25 min of travel time to evacuate tsunami-prone areas in each community

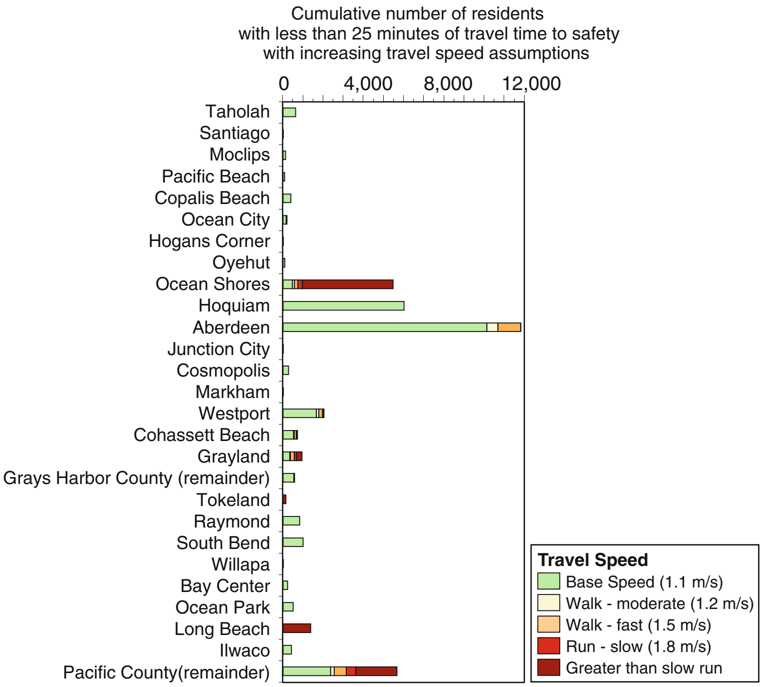

Fig. 8 *Graph* showing the cumulative number of residents with 25 min or less of travel time to safety based on increasing travel speed assumptions

these areas, plus the majority of residents in the community of Long Beach, will have difficulty evacuating even if they are able to maintain a slow running speed (Fig. 8).

4.4 Comparative indices of population exposure as a function of travel time to safety

To fully address population exposure to tsunamis in coastal communities, one must do more than simply inventory residents because employees and visitors often outnumber residents in the tsunami-hazard zones of some coastal communities (Wood and Good 2004). Therefore, we merged evacuation travel time maps with several population datasets to more fully explore community variations in population exposure as a function of travel time to safety. Because of the number of population types and communities, we summarized results in a series of stacked bar graphs where evacuation times are binned in 25-min increments (Fig. 9). In addition to total residents (Fig. 9a), we also inventoried the number of residents over 65 years in age (Fig. 9b) because of potential mobility issues during an evacuation. The number of public venues (Fig. 9c) and dependent-care facilities (Fig. 9d) are inventoried to provide some insight on the exposure of service populations, defined as those that enter a given area at a given time to access services, such as tourists and customers. We chose to inventory the number of facilities and not number of service populations at each facility because of the dynamic nature of the populations. We did, however, inventory the number of employees at all businesses in the tsunami-hazard zone (Fig. 9e).

Results indicate that Aberdeen and Hoquiam consistently show the highest numbers for most of the population groups within the tsunami-hazard zone and that the majority of them have slow walk evacuation times that are shorter than the expected tsunami arrival time (Fig. 9). The only exception to this is the number of residents that are older than 65 years, which was documented in Ocean Shores (Fig. 9b). As was discussed earlier with regard to residents, Ocean Shores also stands out by having high numbers of employees, public venues, and dependent-care facilities in areas where successful evacuations may be difficult. The comparison between population categories also reveals interesting patterns. The large communities of Grays Harbor County, for example, have higher residential and employee populations in the tsunami-hazard zone than those in Pacific County. Certain communities, such as Hoquiam and Aberdeen, demonstrate relative consistency across the different population groups. Others, however, do not and vary depending on the population type. Raymond, for example, has a relatively low number of residents but relatively higher number of public venues and dependent-care facilities in the tsunami-hazard zone. Ocean City also has a relatively low number of residents but several public venues in the zone. Although the majority of residents in Ocean Shores have evacuation times longer than the expected tsunami arrival time, the majority of their dependent-care facilities are within the slow walk 25-min evacuation time.

The composite index based on the number of residents, residents over 65 years in age, employees, public venues, and dependent-population facilities in the tsunami-hazard zone (each normalized to maximum values) indicates that Aberdeen has the highest exposure, followed by the rural portion of Pacific County, Hoquiam, and Ocean Shores (Fig. 10a). Aberdeen has the highest number of individuals and facilities in all categories, except for residents over 65 years in age that are found in greater numbers in Ocean Shores and the rural portions of Pacific County. When populations and relevant facilities are adjusted in the relative composite index to include travel time to natural high ground (Fig. 10b), Aberdeen remains high in the relative rankings, but it is surpassed by Ocean Shores and the

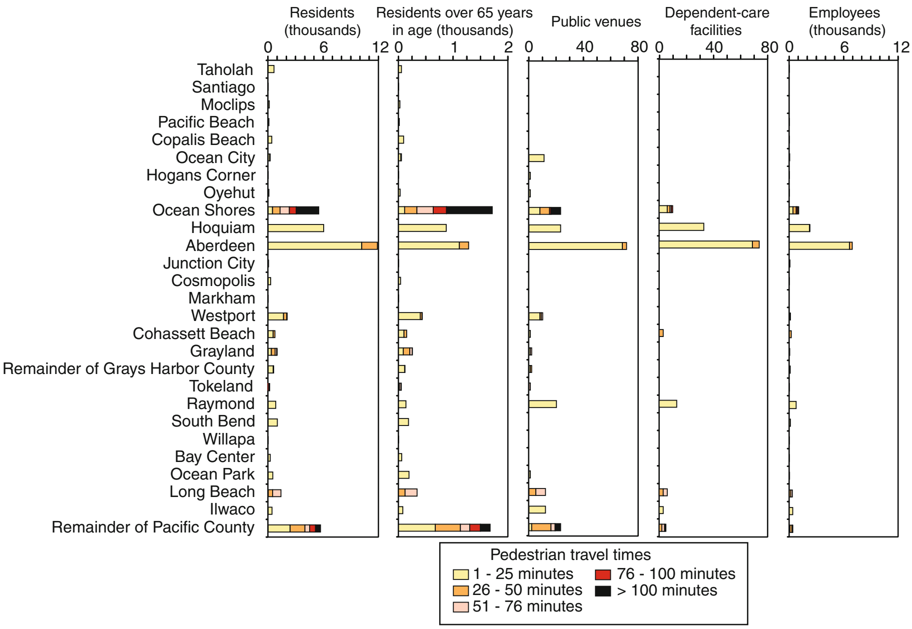

Fig. 9 *Graphs* showing community variations (organized north to south) in the number of **a** residents, **b** residents over 65 years in age, **c** public venues, **d** dependent-care facilities, and **e** employees, as a function of travel times to safety assuming a travel speed of 1.1 m/s

rural portion of Pacific County (which is the Long Beach Peninsula). Certain communities, such as Hoquim, Raymond, and Illwaco, saw their levels of population exposure decrease when evacuation times were included. Another set of smaller communities, such as Westport, Cohassett Beach, and Long Beach, increased in the relative rankings when evacuation time is included.

5 Discussion

Recent catastrophic near-field tsunami disasters (e.g., 2004 Indian Ocean, 2010 Chile, and 2011 Tohoku) have raised global awareness of coastal community vulnerability to tsunamis. Previous efforts have framed population vulnerability to tsunamis only by the number and type of people in tsunami-prone areas. For far-field tsunami threats, this approach may be sufficient for guiding tsunami risk-reduction efforts because of the significant amount of time between wave generation and arrival at coastal communities, the ability to rely on tsunami-warning centers for advanced warnings, and the involvement of multiple levels of government agencies to coordinate evacuations. Near-field tsunami threats, however, pose significant challenges to at-risk populations because their survival is influenced by whether or not they recognize natural precursors to tsunamis and by how far they would need to go to evacuate. Characterizing population vulnerability to near-field tsunami threats therefore requires an understanding of the evacuation potential for at-risk populations and if this potential varies across multiple communities faced by the same

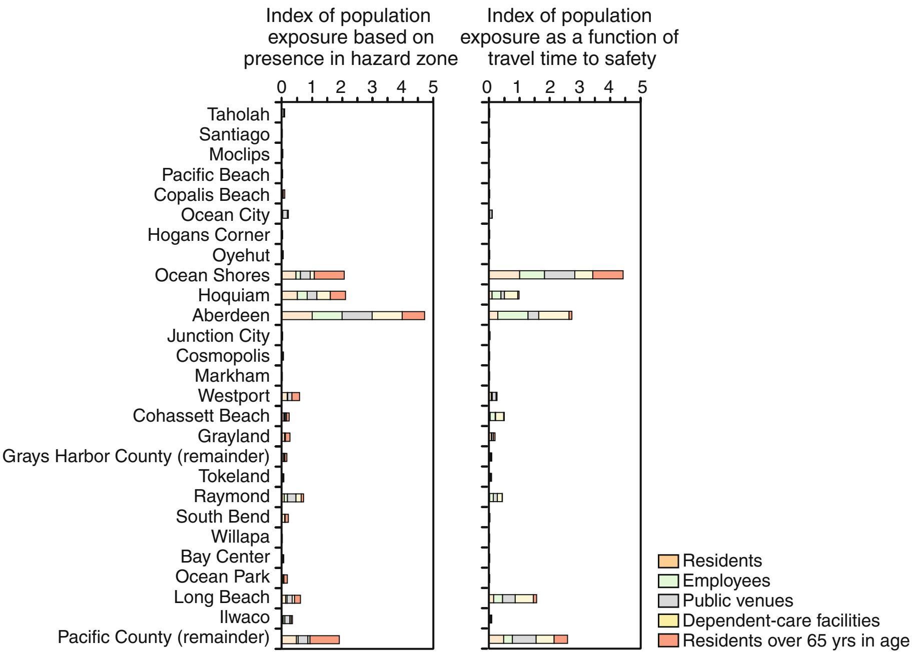

Fig. 10 Comparison of normalized indices for the **a** total population number and **b** total population multiplied by evacuation time of various population groups (total residents, employees, public venues, dependent-population facilities, and residents over 65 years in age) in the tsunami-hazard zone

tsunami threat. In this section, we discuss how results can be used to target tsunami risk-reduction planning, and where future research is needed.

5.1 Use of results in tsunami risk-reduction planning

Differences between the results based on the simple hazard zone overlay and those based on the addition of evacuation times demonstrate that existing assessment approaches do not sufficiently capture the variations in population vulnerability to tsunamis in coastal communities. For example, the community of Aberdeen has the largest population in tsunami-prone areas, whereas the community of Ocean Shores has the largest population that may have difficulty evacuating in the small window of time between tsunami generation and arrival. This additional aspect of evacuation potential for the various at-risk populations in a hazard zone strengthens the connections between the three primary elements of vulnerability, namely the exposure, sensitivity, and adaptive capacity of the threatened population.

This is not to suggest that the total population exposure in the hazard zone is not an important piece of information. Although the majority of the population of Aberdeen, for example, may be able to successfully evacuate before the expected tsunami arrival time if they were able to move at a fast walk, this does not negate the fact that Aberdeen still has the highest total population in the hazard zone. But the inclusion of evacuation times helps us to gain a better understanding of what may be required in the period between tsunami generation and arrival. In Aberdeen, the challenge in the pre-onset period will be for a large number of people to recognize natural cues of the imminent waves, to realize that self-initiated evacuations are needed to save their lives, and then to move a relatively short distance. In communities such as Ocean Shores and Long Beach, the populations may be able to recognize the natural cues but the majority of them may not be able to move at the speeds required to complete a successful horizontal evacuation prior to tsunami inundation.

The combination of evacuations times and population estimates also provides insight on potential priorities of risk-reduction resources by community and by type. Although all communities can benefit from risk-reduction efforts to minimize future losses and prepare for future tsunamis, the type of risk-reduction effort may vary depending on the evacuation context and this information may help guide and prioritize limited tsunami resources, both at a local and national scale. In communities where the entire population theoretically could reach safety at the base slow walk travel speed (e.g., Hoquiam, Raymond, and Taholah), risk-reduction efforts could focus on education campaigns to help residents recognize natural cues, to minimize milling time with others for validating the decision to evacuate (Wood et al. 2011; Ohno and Isagawa 2012), and to learn the most-effective evacuation route. From a risk psychology perspective, model results that suggest successful evacuations could be used in tsunami outreach to raise positive outcome expectancy, which is the degree to which people believe risk to hazards can be reduced. For example, people are more likely to prepare for future tsunamis and take action during an event if they believe successful evacuations are possible and that their actions will have a positive outcome (Paton et al. 2008).

In communities where model results suggest an increase in travel speeds could result in a successful evacuation for the entire population (e.g., Aberdeen), risk-reduction efforts could focus on similar outreach efforts as discussed in the earlier communities, but with added emphasis on the need to increase travel speeds. As noted earlier, this message could possibly raise positive outcome expectancy beliefs in the at-risk populations. Emergency managers could work with public health officials to connect life safety from natural hazards with everyday personal health, such as implementing a fitness program that includes daily walks along evacuation routes. Model results may compel at-risk populations to strive to reduce travel times through training, which empowers the individual to take ownership of their personal safety and frames tsunami risk reduction as a daily issue, instead of as a special topic taught sporadically through outreach efforts.

In communities where results suggest successful evacuations are unlikely (e.g., portions of Ocean Shores, Westport, Cohassett Beach, and the Long Beach peninsula), tsunami risk-reduction efforts could include discussions of vertical-evacuation strategies. Community workshops could be held to discuss vertical-evacuation options and the risk tolerance of the at-risk population (e.g., Engstfeld et al. 2010). In doing so, managers and at-risk populations can proactively address their evacuation challenges, instead of simply assuming survival is not possible. The success of this approach may require outreach that combats any fatalism or negative outcome expectancy that may exist within the at-risk population.

In addition to supporting preparedness and evacuation planning, results demonstrating long evacuation times in certain areas may be useful in local land-use planning. This information provides local planners and policy makers with additional information for their consideration during the development of comprehensive plans and zoning codes. For example, they may decide to limit or restrict zoning in these areas that allows for the development of new dependent-care facilities, such as hospitals, adult residential care centers, or child day care centers.

In this paper, we also showed how multiple populations groups, as well as multiple evacuation times, could be included in an analysis. While we presented the majority of the results based on the base slow walk evacuation speed, it is possible to explicitly link particular population groups with specific travel speeds to further refine the assessment process. The distribution of resident care facilities, populations over 65 years of age, and public venues where high numbers of tourists are to be expected, for example, could be compared to the slow walk travel evacuation times. Additional population variables could also be included and compared to various evacuation time surfaces. Households with young adults and no children could perhaps be more appropriately compared to evacuation times for fast walk or slow run speeds. This explicit linkage of population subgroups with various least-evacuation-time surfaces could also allow for greater flexibility in dealing with differences in the time required for populations to begin their evacuations. For example, households with small children may take longer to begin their evacuation because the caretakers in the home will wait to evacuate until all family members are collected. These households may also travel at lower speeds. Both of these adjustments could be made for each individual population subgroup, better representing real differences in evacuation behavior.

Although this paper focused exclusively on evacuation potential for a local CSZ tsunami scenario, results can also help inform preparedness planning for distant events in which there will be more time available to evacuate before wave arrival. For example, tsunami waves associated with the 1964 magnitude 9.2 earthquake in the eastern Aleutian-Alaska Subduction Zone arrived at the open-ocean coast of Washington approximately 4 h after the initial earthquake (Lander and Lockridge 1989; National Geophysical Data Center, 2012). More time to evacuate before a CSZ-related tsunami may be available if the earthquake is due to a partial rupture of the southern CSZ margin closer to northern California and southern Oregon (Goldfinger et al. 2012), instead of a full rupture which is the basis for the arrival times discussed here. Evacuation planning for these scenarios could include vehicle-based options for those communities where pedestrian evacuations are not realistic and road networks will be less likely to be compromised by the initial earthquake.

For these scenarios, a hybrid model of least-cost-distance modeling for pedestrians across the landscape and agent-based modeling for vehicles along road networks may be appropriate for certain communities.

5.2 Areas for future research

Whether or not someone survives a near-field tsunami is a complex question that requires a solid understanding of where they are at the time of the event, their physical and mental state at the time, their pre-existing beliefs toward the event, the state of the surrounding environment that may or may not create barriers to movement, the extent to which they delay an evacuation due to caregiver roles or to milling needs, and their ability to adapt as waves approach (e.g., climb a tree, hold on to floating debris). Therefore, pedestrian-evacuation modeling is an important step in understanding the evacuation potential for at-risk populations but is not a definitive assessment of their mortality.

Previous research on least-cost-distance modeling for tsunami evacuations has summarized some areas for future efforts, such as accounting for the interdependent nature of land cover and slope SCVs, evacuation fatigue over long distances and varied terrain, individuals not taking the optimal routes in the evacuation models, wave propagation over the land, the behavior of evacuees, and the dynamic nature of land cover (Wood and Schmidtlein 2012). Another issue raised by the current work summarized here is the occasional influence on crowding. In general, we do not consider crowding to be a significant issue in this study area because of the wide roads, open downtown areas with parking lots, and fairly rural development. It was this assumption that led us to pursue least-cost-distance approaches and not agent-based modeling which is designed for handling dynamic travel costs due to crowding. However, crowding may become an issue for beach visitors attempting to use beach-access stairwells, which are often the width of one or two people. Although the horizontal distance may be 3 meters or less, these stairwells could be overwhelmed during an evacuation and substantially slow down evacuations off of the beach. In these short distances from beach to developed areas, it may be wise to use agent-based models or at least account for the likely crowding at these potential chokepoints. In this study area, the issue of beach-access crowding is more of an issue in summer months, which is the primary tourist season. Crowding at other times of the year is less likely because of the cold, wet weather that is typical during off-season months.

Another route-related issue to be examined in future work is the state of the post-earthquake landscape to determine the impact to and availability of evacuation routes due to damaged structures, vegetation, and infrastructure. For example, we assume that bridges will survive the initial earthquake hazards, such as ground shaking, regional subsidence, and liquefaction of the ground surrounding bridge supports. There are several locations in Ocean Shores where functioning bridges after an earthquake are critical for pedestrian evacuations, especially for any homes that may be on islands (Fig. 4b). Certain roads also may be compromised if supporting dikes fail because of the ground shaking and liquefaction. Future research could focus on modeling the post-earthquake landscape and the integrity of transportation networks to estimate potential impacts to evacuation routes. This also could inform the possibility (and perhaps probability) of successful vehicle-based evacuations in communities where pedestrian evacuations are not realistic.

Probably the largest unknown in pedestrian-evacuation modeling is the behavior of at-risk populations immediately after the tsunami-generating earthquake. There is a well-documented literature that demonstrates the effects of perceived risk, trust, beliefs, and willingness to pay (among other psychological and sociological concepts) on whether or not at-risk individuals will take steps to prepare themselves for future extreme events and react properly when the event occurs (Mileti and Sorenson 1990; Tierney et al. 2001; Slovic 2002). As noted earlier, the pedestrian-evacuation modeling summarized here assumes at-risk individuals will begin an evacuation immediately after the earthquake. However, social science research suggests that individuals do not immediately evacuate and often delay movement to internalize the threat, recognize the need to evacuate, confirm with others nearby this need, and perform any caregiver roles (Wood et al. 2011). For example, in their study of evacuation behavior after the 2011 Tohoku tsunami, Ohno and Isagawa (2012) document that approximately 25 % of people in Onjuku, Japan, did not decide to evacuate until they saw neighbors evacuating, received a warning from family members, or received news about destructive damage elsewhere. Therefore, at-risk individuals in our study area may behave in a similar way and delay their evacuations for various reasons. In addition, the speed of evacuees may decrease over time due to fatigue or stress and future work may wish to consider speed decay functions as a function of distance. For this study, we did not model this fatigue and instead chose to use a conservative slow walking speed that likely could be maintained. Ultimately, this level of modeling detail would be based on discussions with the at-risk community and most critical in vertical-evacuation site planning.

To simplify the evacuation discussion here, we summarized the number of individuals and facilities that would require up to 25 min for evacuating, because the waves are predicted to arrive 25 min after the earthquake; however, some individuals in these estimates may take additional time to evacuate. To better account for delayed evacuations, it may be more appropriate to summarize the number of at-risk individuals in areas that would require fewer than 20 min and to consider only those people potentially safe, which assumes that some people in the 20–24 min window of time may delay their evacuations and, as a result, be caught by the tsunami waves. In our study area, this assumption translates to an additional 1,982 residents (or 2 % of the total) who may not have enough time to evacuate. The highest number of these additional residents is in Aberdeen (823), where earlier results indicate a faster walking speed may result in a successful city-wide evacuation. The other primary areas for additional residents are the remaining portions of Pacific County (387 residents or 3 % of the area population), Ocean Shores (264 residents, 5 %), and Westport (188 residents or 5 % of the community)—all areas where modeling results suggest that the majority of the residents already will have difficulty evacuating before wave arrival. In these communities, the overarching message that the community faces evacuation challenges does not change, even if the percentages increase slightly. Therefore, for our study area, the difference due to delayed evacuations does not substantially change the overall message that certain communities will have greater difficulty than others in successfully evacuating their populations before wave arrival. However, from a conceptual standpoint, the issue of delayed evacuations remains an important topic for further studies, especially as communities begin to discuss locations for vertical-evacuation structures.

Another area for future research is the inclusion of local knowledge in evacuation modeling. Modeling will always be a simplified representation of reality and the stakes are too high to solely rely on digital representations of elevation, land cover, and population distributions collected over large areas. Active engagement with the at-risk population and emergency managers will provide additional insight on the evacuation context, such as local variations in land cover conditions (e.g., fences, vegetation thickness, crowding potential at beach-access sites), access (e.g., private land owners may be concerned that their land may be advertised as an evacuation route), and population distributions (e.g., high concentrations of tourists that are ignored in residential and employee counts). For example, although our modeling assumes all areas are available for evacuation routes (except for water and structural barriers), evacuees may choose to alter their routes and remain on roads if vegetation is perceived to be too thick or goes on for too long before a road is available again. Although heavy brush can be accounted for in the land cover SCV, these perceived limitations on evacuations could lengthen evacuation times and reduce the likelihood of a successful evacuation for certain individuals. Similarly, fences around one property may make evacuees remain on roads until the fence ends at that property. Although the regional message and mapped results of evacuation potential may not change (i.e., certain areas will need substantially more time than 25 min to evacuate), these issues may alter local evacuation potential in certain places. This information would be important for localized studies related to vertical-evacuation site planning and a specific at-risk population. Greater involvement by decision-makers (in this case, the at-risk population and emergency managers) follows the analytic deliberate process of risk characterization described in greater detail by the National Research Council (1996).

As noted earlier, the results summarized here likely underestimate travel times because of assumptions of perfect behavior of evacuees and landscape conditions. Differences of a few minutes due to these modeling issues or delayed evacuations have little effect on the multiple communities that would require more than an hour to evacuate areas where waves will arrive 25 min after a CSZ earthquake (e.g., Ocean Shores). This issue does, however, become more important as communities begin to discuss and locate vertical-evacuation strategies, where the difference between life and death may come down to a matter of minutes. Even as these modeling inputs are further refined, determining actual evacuation timetables or the placement of vertical-evacuation structures will still require active involvement of the at-risk population and the managers who serve to protect lives. Our intention for this modeling is that results help initiate and continue to support discussions on how to survive near-field tsunami threats. As with all modeling efforts, results are to be perceived as starting points and not end points for tsunami risk-reduction discussions.

6 Conclusions

This study of population exposure to tsunamis focused on the addition of travel times to safety and how this new information can be used to target risk-reduction efforts. Based on our analysis, we reach several conclusions that bear on future population-exposure studies related to sudden-onset hazards, such as tsunamis.

- Understanding total population exposure based on spatial coincidence with hazard zones is important, because it helps us to understand the scope of a community's vulnerability but does not help inform the context or potential adaptations of the problem.
- There are several communities where successful evacuations to high ground are unlikely due to the substantial distances and limited time.
- In some communities, an increase in travel speeds to a fast walking speed may enable all at-risk individuals to successfully evacuate, suggesting the need to link public health initiatives and tsunami risk-reduction strategies.
- Linking population subgroups with various least-evacuation-time surfaces can allow for greater flexibility in dealing with differences in the time required for populations to begin their evacuations.

- The addition of travel times to safety changes the relative rankings of community exposure to tsunamis; for example, although Aberdeen has the highest population in tsunami-prone areas, Ocean Shores has the highest population that may require more time than available to successfully evacuate.
- Data on travel time to safety can help guide the type of risk-reduction strategies that may be most needed—outreach and training in communities where a successful evacuation is plausible and vertical-evacuation planning in communities where it is not.

These conclusions support the notion that population evacuation times should be considered in population-exposure assessments for sudden-onset hazards, such as tsunamis, flash floods, and volcanic lahars. Risk-reduction efforts based purely on simple inventories of populations in hazard zones may be well meaning but may focus on the wrong type of risk-reduction strategy (e.g., evacuation education in communities where successful evacuations are unlikely) or place less emphasis on communities that may need the greatest assistance. To fully appreciate the threat that near-field tsunamis pose to nearby coastal communities, managers need to understand the context and challenges of evacuating their at-risk populations in the limited time they will have between tsunami generation and arrival. This information can then help inform not only local risk-reduction efforts but also regional and national tsunami plans, policies, and priorities.

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