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Pedestrian flow-path modeling to support tsunami evacuation and disaster relief planning in the U.S. Pacific Northwest

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ABSTRACT

Successful evacuations are critical to saving lives from future tsunamis. Pedestrian-evacuation modeling related to tsunami hazards primarily has focused on identifying areas and the number of people in these areas where successful evacuations are unlikely. Less attention has been paid to identifying evacuation pathways and population demand at assembly areas for at-risk individuals that may have sufficient time to evacuate. We use the neighboring coastal communities of Hoquiam, Aberdeen, and Cosmopolis (Washington, USA) and the local tsunami threat posed by Cascadia subduction zone earthquakes as a case study to explore the use of geospatial, least-cost-distance evacuation modeling for supporting evacuation outreach, response, and relief planning. We demonstrate an approach that uses geospatial evacuation modeling to (a) map the minimum pedestrian travel speeds to safety, the most efficient paths, and collective evacuation basins, (b) estimate the total number and demographic description of evacuees at predetermined assembly areas, and (c) determine which paths may be compromised due to earthquake-induced ground failure. Results suggest a wide range in the magnitude and type of evacuees at predetermined assembly areas and highlight parts of the communities with no readily accessible assembly area. Earthquake-induced ground failures could obstruct access to some assembly areas, cause evacuees to reroute to get to other assembly areas, and isolate some evacuees from relief personnel. Evacuation-modeling methods and results discussed here have implications and application to tsunami-evacuation outreach, training, response procedures, mitigation, and long-term land use planning to increase community resilience.

1. Introduction

In the aftermath of recent tsunami disasters (e.g., from the 2004 Indian Ocean earthquake to the 2015 Chilean Illapel earthquake), there has been an increase in efforts to better understand and communicate the vulnerability of coastal communities to future tsunamis. Much of the work has focused on life safety issues for individuals located in tsunami-hazard zones, such as population-exposure assessments [24], demographic-sensitivity analyses [50], and pedestrian-evacuation modeling (e.g., [10,11,33]). The focus of most evacuation-modeling studies has been on identifying areas where at-risk individuals may have insufficient time to evacuate before arrival of the first tsunami wave, thereby suggesting potential loss of life. In few cases, pedestrian evacuation modeling has gone further to examine alternatives for minimizing the potential loss of life, such as vertical-evacuation siting [29,51] or urban design changes [19,20].

Pedestrian-evacuation modeling to estimate the magnitude of at-risk individuals in areas of unlikely evacuations helps elected and appointed officials to better understand potential losses and possible risk-reducing mitigation alternatives. There has been less discussion, however, on evacuation pathways and response issues for at-risk individuals in areas where successful evacuations are more likely. For example, Wood et al. [52] estimate that 83% of the approximately 95,000 residents in tsunami-hazard zones associated with a local Cascadia subduction zone earthquake in the U.S. Pacific Northwest may have sufficient time to reach high ground before wave arrival. Efforts to build vertical-evacuation refuges for at-risk individuals that may not have sufficient time to evacuate are appropriate and important (e.g., [8]); however, equally

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important are planning efforts to support the remaining 79,000 residents that likely have sufficient time but are not guaranteed a successful evacuation if they fail to evacuate appropriately.

As pedestrian-evacuation modeling matures in the literature, one area that warrants greater attention relates to likely pathways for evacuees. An improved understanding of evacuation pathways could help emergency managers, land use planners, and traffic management officials to identify heavily used routes that then could be prioritized for road improvements, such as evacuation lighting and signage (e.g., [19,32]). Understanding likely evacuation corridors could be used in education and training efforts to help neighborhood leaders to build community cohesion on tsunami preparedness, as well as the creation of support networks during an evacuation, such as for individuals with limited mobility. Understanding the magnitude of evacuees along specific pathways also can help emergency managers understand population demand and capacity issues at pre-determined assembly areas. Having a sense of whether an assembly area could expect 100 or 1000 evacuees will help emergency managers develop realistic response plans to assist survivors and to direct relief personnel. This insight could guide post-tsunami reconnaissance efforts (e.g., [47]) by prioritizing corridors heavily used by a coastal community. Priest et al. [36] discusses the modeling of evacuation pathways, but do not address population magnitudes along pathways or potential population demand at assembly areas.

Another area for improvement in pedestrian-evacuation modeling is in recognizing potential changes in the evacuation landscape due to the initial earthquake. Local earthquakes large enough to generate tsunamis (typically M_w 7.0 and greater) will produce relatively instant geomorphic changes to the landscape, such as liquefaction, lateral spread, subsidence, and landslides [38]. These earthquake-induced ground failures could block certain evacuation routes, either by surface debris or by significant cracks in the ground. These impediments can slow or restrict evacuees from reaching higher ground, making them susceptible to approaching tsunami waves. Roads closed to landslide debris could also cut off survivors at an assembly area from emergency responders and relief personnel. To date, we are not aware of any pedestrian-evacuation modeling efforts that recognize or account for earthquake-induced ground failures.

The objective of this paper is to demonstrate a new application of geospatial, pedestrian-evacuation modeling that helps inform evacuation and relief planning for tsunami hazards. To demonstrate this approach, we focus on the coastal communities of Aberdeen, Hoquiam, and Cosmopolis (Fig. 1), located in southwestern Grays Harbor County in the State of Washington (USA). Like other coastal communities in the U.S. Pacific Northwest, these neighboring communities are threatened by local tsunamis associated with Cascadia subduction zone earthquakes. First, we use geospatial, anisotropic, path distance models to map the most efficient paths for pedestrians from within a tsunami-hazard zone to high ground. We then use this information to identify evacuation basins, which outline neighborhoods that share common evacuation pathways to safety. This information can help guide individuals to safety in dense urban areas where optimal routes may be difficult to discern. Second, we estimate the number of people traveling along certain evacuation pathways and arriving at pre-determined assembly areas, which helps gauge shelter demand and determine the need for additional relief support (e.g., for elderly individuals, children, or tourists). Third, we determine which paths could be inaccessible due to earthquake-induced ground failures or bridge failures, which may influence whether or not individuals can reach safety. Finally, we discuss the implications and application of our analysis for tsunami-evacuation outreach, training, response planning, mitigation, and long-term land use planning to increase community resilience.

2. Study area

The neighboring cities of Aberdeen, Hoquiam, and Cosmopolis in southwestern Grays Harbor County, Washington (Fig. 1), are situated on the seismically active Pacific Ocean basin and therefore are threatened by distant tsunamis generated by earthquakes elsewhere (e.g., 2011 Tohoku) and by those generated locally by earthquakes within the Cascadia subduction zone (CSZ). Tsunami waves associated with a CSZ-related earthquake are estimated to arrive along the southwest Washington coast approximately 25 min after the initial earthquake [4,43]. Thirteen assembly areas have been proposed for tsunami evacuation in these communities and are identified on publicly available evacuation brochures [44].

Wood et al. [52] estimates there are approximately 20,600 residents in Aberdeen, Hoquiam, and Cosmopolis that are in CSZ-related, tsunami-hazard zones, representing 75% of the total

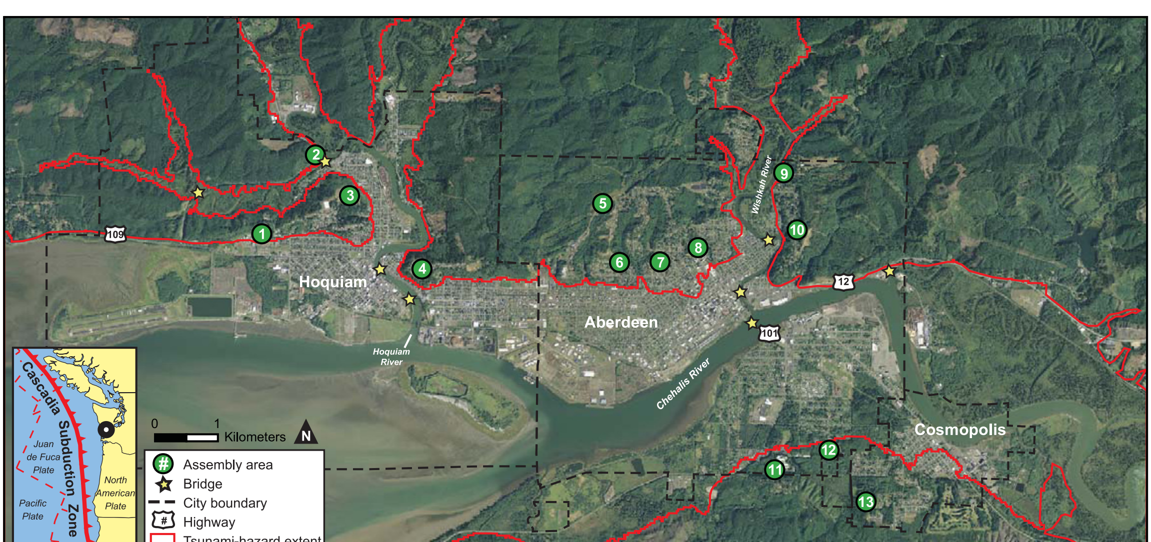

Fig. 1. Study area map of Aberdeen, Hoquiam, and Cosmopolis, Washington, including official assembly areas [44] and a tsunami-hazard zone associated with Walsh et al. [43] and model outputs provided by the State of Washington Department of Natural Resources based on Priest et al. [35] (T. Walsh, written communication, August 20, 2014).

residents in these three communities. Pedestrian-evacuation modeling in this same study estimates that approximately 99% of the at-risk residents in these three communities may be able to reach high ground assuming they move at a speed regarded as a fast walk (1.52 m/s). This area likely represents the highest concentration of tsunami survivors for the entire coastline directly affected by CSZ-related waves and account for 22% of all residents in CSZ-related tsunami hazard zones [52]. Successful evacuations are not guaranteed in these communities, however, because individuals will need to take self-protective action (i.e., no official evacuation organized by public officials) and take the appropriate paths to safety depending on where they are when the earthquake occurs.

Because of the high number and percentage of residents that may be able to reach high ground before first wave arrival, these three communities represent an ideal case study for examining the distribution of survivors after the first wave, as well as conditions during an evacuation that may inhibit a successful evacuation. One issue that may affect evacuations is earthquake-related ground failures, such as landslides or liquefaction, along an evacuation route. The three towns are on the banks of the Chehalis, Wishkah, and Hoquiam rivers (Fig. 1) and the underlying unconsolidated sediment of the river floodplain is susceptible to earthquake liquefaction [38], likely causing significant damage to the road network and preventing vehicular evacuation. Earthquake-induced landslides on the bluffs surrounding the cities also have the potential to cut off evacuation routes to high ground [38], including those along certain roadways leading to predetermined assembly areas [44].

Pedestrian-evacuation modeling summarized in Wood et al. [52] suggests that some residents and visitors may need to cross bridges, such as Highway 101 over the Chehalis River connecting central and South Aberdeen (Fig. 1), in order to reach high ground and the nearest designated assembly area in the least amount of time. The study area contains several bridges and evacuees in these areas may face a difficult choice of relying on an evacuation path over a potentially damaged bridge or taking a longer path over land to safety. In other parts of these communities, residents and visitors are located relatively close to high ground for successful self-evacuations. In this paper, we examine the evacuation pathways to estimate population counts at the assembly areas and highlight potential evacuation challenges for emergency managers.

3. Methods

Our analysis focuses on identifying tsunami-evacuation pathways, basins of converging pathways, and potential obstacles to effective evacuations within the cities of Aberdeen, Hoquiam, and Cosmopolis, Washington. We also estimate the number and types of people that may arrive at assembly areas previously identified by local emergency managers. We discuss here the various input data and geospatial analytical methods related to geospatial, pedestrian-evacuation modeling to characterize the evacuation landscape and to estimate population demand at assembly areas.

3.1. Pedestrian evacuation modeling

Pedestrian travel times to safety are based on a least-cost-distance (LCD) model implemented in ESRI's ArcMap 10.2 geographic information system (GIS) software that takes into account the slope and land cover of an area to calculate the most efficient (i.e., least cost) paths on foot to safety from every location in a hazard zone [16,48,49]. We do not evaluate vehicular evacuations due to the probable earthquake damage to roads and the emphasis on pedestrian evacuations in regional tsunami outreach efforts [4]. The tsunami-hazard zone used in this analysis reflects a combination of two previously published tsunami-hazard zones. The first hazard zone is summarized in Walsh et al. [43] and is associated with a “1A with asperity” deterministic scenario for an M_w 9.1 earthquake within the Cascadia Subduction Zone (CSZ) that assumes 450 years of slip accumulation. A more recent tsunami-hazard zone provided by the State of Washington Department of Natural Resources is associated with an M_w 9.0 CSZ earthquake with source parameters referred regionally as the “L1” scenario, which is a deterministic scenario assuming 650–800 years of slip accumulation and a 95% confidence interval ([35]; T. Walsh, written communication, August 20, 2014). The decision to combine the two tsunami-hazard zones (Fig. 1) was based on input from State, Tribal, and local emergency managers, who wished to be conservative in their understanding of where inundation was possible.

The specific LCD method used in this evacuation analysis is based on an anisotropic, path distance approach in which surface distances are calculated between cells of varying elevations and are then multiplied by travel costs to estimate the amount of time it takes to cross a cell. Travel costs are classified as speed conservation values (SCV), where each value represents the percent of base travel speed for crossing that cell, given the local land cover type and slope. The modeling then estimates travel directions based on optimal routes of least costs (lowest amount of time in our case), which can be used to estimate overall travel times along an evacuation path for any maximum speed under ideal conditions (i.e., slightly downhill, paved streets). Slope SCVs are based on Tobler's hiking function [40], and slopes were derived from 1-m resolution digital elevation model (DEM; [46]). Land cover SCVs are based on Soule and Goldman's [39] energy cost terrain coefficients for certain land cover types [49], and land cover was derived from a supervised and manual classification of 1-m resolution, red-green-blue (RGB)-band orthorectified imagery taken between 2009 and 2012 [42]. Maps of minimum travel times to safety are generated by path distance outputs based on surface distance, slope, and land cover SCVs and a maximum travel speed under ideal conditions (e.g., [49]).

While previous efforts to model pedestrian evacuations from tsunamis have focused on travel across all landcover types (e.g., [52]), we constrained travel in this case study to road networks. This is because pedestrian evacuation routing, signage, and training within an urban area will likely focus on roads and sidewalks. Although one could characterize a roads-only evacuation using an agent-based network analysis that models movement of individuals (e.g., [17,34,53]), we continued our use of a LCD-based modeling approach to allow for future work that could allow for travel across certain land cover types (e.g., public fields, parking lots) but barring it from crossing private property. It is unlikely that people will only stay on roads if presented with a more direct and obviously shorter path across a parking lot or maintained field but it is also unlikely that people will know of or have access to every short path through private property. Therefore, we feel our use of the LCD modeling environment with the ability to constrain various aspects of the evacuation landscape provides the greatest flexibility to emergency managers in future applications. In addition, an LCD-based approach provides evacuation insight on all areas of a hazard zone across a community, whereas an agent-based approach only models where populations are located for a specific scenario. The spatially explicit representation of evacuation times provided by LCD modeling offers emergency managers the ability understand the entire evacuation landscape in their community and not simply clearance times for a specific scenario of population distribution.

One complication of a roads-only, evacuation-modeling approach is that population locations (e.g., households, businesses)

Fig. 2. Comparison of (a) original road network and (b) added segments ("artificial driveways") to connect residential and business population counts to road networks.

are not located directly on street networks and need to be geospatially connected to roads for the model to incorporate population counts. To connect business and residential locations with road-centerline data from the State of Washington [45], we used the ArcMap Near tool [9] to return the nearest point on a road line for each population point and then constructed line segments using a custom Python script based on the original point and the new point on the road. This approach effectively creates a driveway or business entrance for each original population point. The new line segments are then buffered by 2 m to give the segment width and then merged with the similarly buffered roads layer (Fig. 2). The original population point is then located at the end of each of the newly generated line segments. The final roads layer is used to create the cost surface with a travel cost of 1.0 assigned to the entire surface (i.e., no energy reduction due to land cover), and LCD modeling is performed using this landcover SCV surface in combination with the 1-m slope SCV grid. Multiple time maps then are generated at different travel speeds to determine the speed necessary for successful evacuation of all residents and businesses before first wave arrival.

Maps visualizing the minimum travel speeds necessary to reach safety before first wave arrival have been created based solely on surface distances [36]. To better account for land cover and slope influences on an evacuation, we generated minimum travel speed maps by combining maps of travel times based on various maximum speeds for the study area (Fig. 3). This is done because the mathematical underpinning of the anisotropic, path distance modeling is based on the user establishing a maximum speed for the study area and individual grid cells having reduced speeds due to local landcover and slope conditions. Travel-time maps based on various maximum travel speeds can be then compared to determine the minimum speed necessary to reach safety from a given grid cell. We ran path distance models for several maximum travel speeds, including 0.89 m/s for impaired

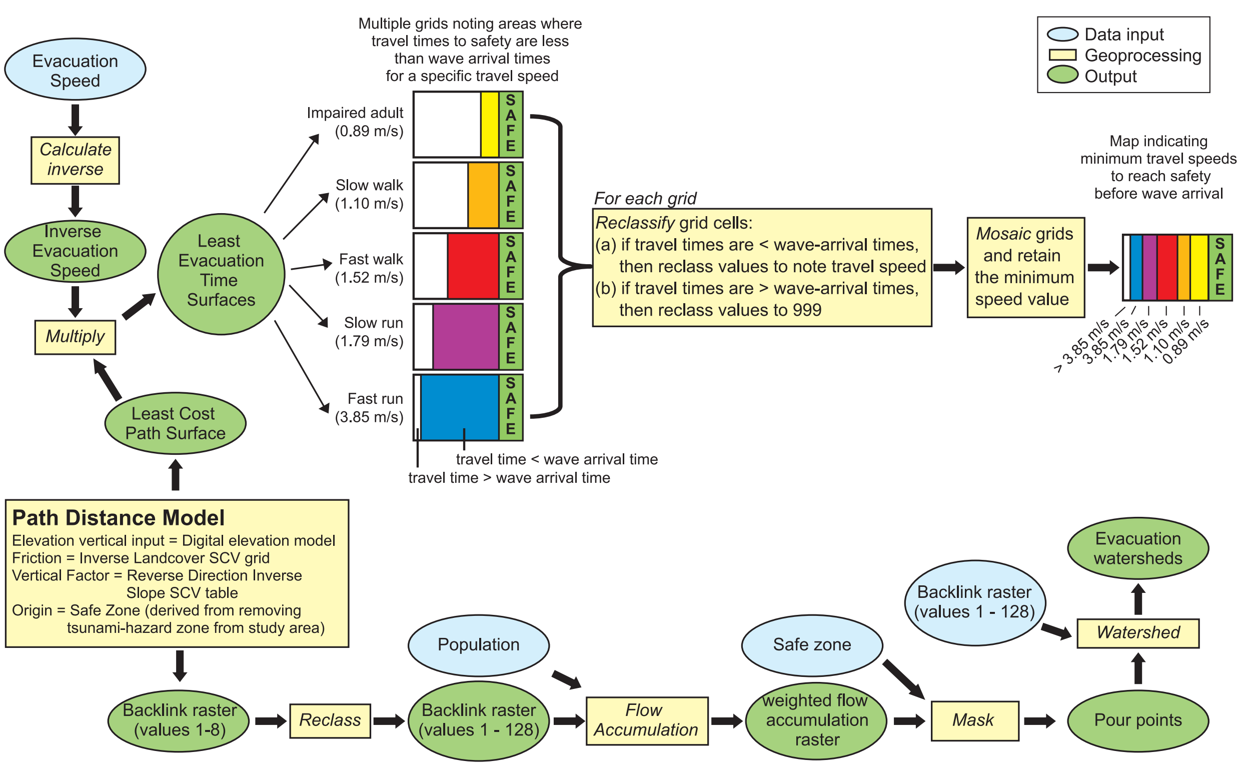

Fig. 3. Model diagram of the geospatial processing to generate travel speed maps and evacuation basins.

adults, 1.10 m/s for a slow walking speed, 1.52 m/s for a fast walking speed, 1.79 m/s for a slow running speed, and 3.85 m/s for a fast running speed [16]. Each of the resulting travel time maps were then reclassified based on the amount of time available for an evacuation. For example, if we assume evacuees have 25 min before wave arrival, we identified areas in each of the travel-time maps where times were less than 25 min. Values for those cells in these areas were reclassified to denote the travel speed and the remaining portions of the hazard zone were reclassified with values of 999. The five reclassified maps were then mosaicked together and combined where cells reflected the minimum value of the five maps. The final map summarizes the minimum travel speed (binned based on the five maximum speeds noted above) for each cell along an optimal evacuation path to safety. For this case study, we generated three different minimum travel speeds based on different assumptions for evacuation time, including (a) 25 min, which is assumed to be wave arrival after the beginning of the initiating CSZ earthquake [4,43], (b) 20 min, which subtracts 5 min due to the expected duration of the CSZ earthquake (i.e., people are unlikely to evacuate while the ground is shaking), and (c) 15 min, which subtracts an additional five minutes to account for evacuation delays due to human behavior.

Population locations were estimated using various data sources. Business locations for our study area came from a 2012 Employer Database [12], which includes information on the number of onsite employees and business type based on the North American Industrial Classification System (NAICS) code (U.S. Census Bureau [41]). NAICS codes were used to identify community support businesses (e.g., banks, government offices, grocery stores, and religious organizations), dependent-care facilities (e.g., child and elderly services, schools, and medical facilities), and public venues (e.g., accommodations and outdoor venues). We focus on the number of businesses and offices in tsunami-hazard zones and not the number of individuals at each site, given that the number of customers at commercial stores and offices, visitors at public venues, and people at schools and medical facilities varies greatly throughout the day, week, and year. However, one could work with emergency managers to assume a certain range of individuals for a given set of businesses or offices for a specific planning and exercise scenario. The high number of combinations of daytime vs. nighttime, weekday vs. weekend, and time of year scenarios precludes our ability to choose one over other possibilities. For this reason, we focus only on the number of businesses in hazard zones.

Residential sites were manually derived from the previously described imagery. Residential-population counts and related demographic attributes at each residence were determined by disaggregating block-level 2010 Census data [41] to the residential locations falling within their boundaries. In addition to general population counts, we also calculated the number of residents that are less than 5 years in age and greater than 65 years in age, which are two demographic groups considered to be more vulnerable than other age groups to sudden-onset hazards because of potential mobility and health issues [3,25,26,28]. Individuals less than 5 years in age are considered to have heightened vulnerability because they often require direction and assistance to evacuate due to their immaturity, size, and potential inability to comprehend what self-protective actions to take [3]. Individuals older than 65 years are considered also to have heightened vulnerability due to potential mobility and health issues, reluctance to evacuate, and the need for special medical equipment at shelters [25]. This discussion of demographic sensitivities is not based on extensive studies of residents in our study area, but instead on past social-science research of many types of extreme events (e.g., earthquakes, tornadoes, and hurricanes). Therefore, the extent of these demographic sensitivities for a specific individual in our study area is influenced by his or her physical condition, social context, level of preparedness before a tsunami, and adaptive capacity during an event.

3.2. Evacuation pathways and basins

Determining evacuation pathways is analogous to some degree with modeling water flow on a surface. In geospatial hydrological modeling, the direction that water would flow across the landscape is modeled by using a DEM to determine the direction of the steepest slope from a cell to each one of its eight nearest neighbors [15]. Knowing which direction water flows across each pixel in a study area allows analysts to identify both the drainage areas that contribute flow to any given location, as well as in which locations flow is concentrated enough to form stream channels.

In addition to pedestrian evacuation time surfaces, path-distance analyses also generate backlink rasters, which show the direction evacuees would travel from each cell towards safe zones. The backlink raster can be used as a substitute for the flow direction raster with hydrology modeling approaches to identify both evacuation basins, as well as "channels" or pathways that are expected to have higher concentrations of evacuees (Fig. 3). Before backlink rasters can be used to identify pathways, they must be transformed because they are encoded in different ways than ArcMap Flow Direction outputs (Fig. 4). Direction values in backlink rasters are encoded from 1 to 8 starting with a value of one indicating movement to the right, with increasing numbers indicating movement in towards the next direction clockwise from there. Flow direction rasters are similarly encoded, but start with a value of one to the right and doubling every cell in a clockwise direction (i.e., 1, 2, 4, 8, 16, 32, 64, and 128). Once backlink rasters values are transformed to match Flow Direction values, then they can be used as input for subsequent pathway analyses, including the creation of evacuation networks and basins.

The reclassified backlink rasters were used along with population data as an input to the ArcMap Flow Accumulation tool to produce a weighted, evacuation flow accumulation raster (Fig. 3). This raster layer records the total evacuees expected to pass through each cell in the study area on their way to safety. This layer also allows for a visual identification of common stream-like "channels" through which a high number of evacuees would move. Evacuation pour points were identified where these channels crossed into the safe zones, and then entered in conjunction with the reclassified backlink raster into the watershed tool to identify the area from which the evacuees reaching that point came. These evacuation watersheds or "evacuation-sheds" identify neighborhood flow paths for evacuation and can be used to estimate the number and types of residents and businesses moving along similar routes, and when overlaid on the travel time maps, provide information on the travel time it would take to empty each evacuation basin.

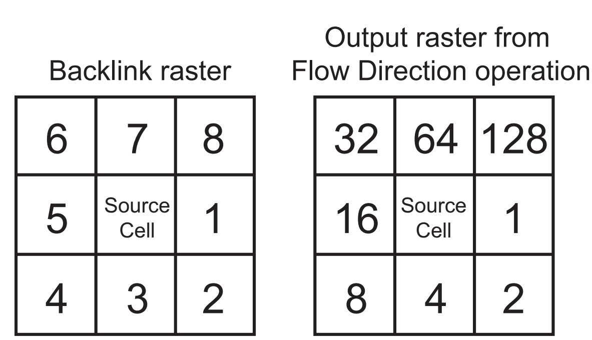

Fig. 4. Comparison of numbering conventions for backlink rasters and Flow Direction modeling outputs.

3.3. Estimating the number of survivors at assembly areas

Thirteen assembly areas have been identified for our study area (Fig. 1) and it would aid the emergency managers and first responders to have some idea of the volume of people likely to reach each area and the population breakdown by such factors as age or other demographic characteristics. To estimate population magnitudes and characteristics at each assembly area, we manually grouped each of the pour points identified above with the nearest assembly area (Fig. 1) based on proximity and ease of movement along the road network. The evacuation-sheds corresponding to the pour points assigned to each assembly area were merged together to produce evacuation basins, providing both a clear visual indicator of flow neighborhoods and a means of quantifying counts and types of population likely to reach each assembly area. Evacuation sheds distant enough from assembly areas that evacuees reaching them would likely be isolated are also identified to highlight areas that may warrant new assembly areas and to provide additional information for first responders searching for survivors.

3.4. Physical barriers to evacuation

To estimate potential evacuation impacts from earthquake-related ground failures, we integrated our evacuation-pathways outputs with an analysis of earthquake-induced shallow landslides for the Hoquiam-Aberdeen-Cosmopolis area summarized in Slaughter et al. [38]. Landslide susceptibility maps in Slaughter et al. [38] were created by calculating a grid cell's critical acceleration (a_c), which is the earthquake-induced ground acceleration at which the slope exceeds static stability and is a function of the static factor of safety (based on soil characteristics), the expected acceleration due to gravity, and the angle of the slope [13,14]. Critical-acceleration estimates were modeled using 3-feet elevation data (resampled to 10-feet) and 1:100,000 geologic maps that included 1:6000-scale agricultural soil data. We use a landslide-susceptibility map from Slaughter et al. [38] that can be considered a worst-case scenario and winter conditions, because it assumes a fully saturated, 10-foot soil column. We extracted cells identified as having high (a_c=0.0–0.2) or medium (a_c=0.2–0.3) likelihood of landslides from this susceptibility map. Overlaying this surface on both the evacuation watersheds and the pre-assigned evacuation routes [44], we identified escape routes in danger of blockage by earthquake-triggered landslides either underneath evacuation routes or on bluffs adjacent to these routes. Using the flow lines, we quantified the number of people using each evacuation route who may be unable to evacuate in the event of a slide. Whether people will be able to traverse or go around every slide deposit is unknown and likely is influenced by the site-specific conditions and the mobility of an individual. Therefore, this analysis is only to highlight potential obstacles and is not a definitive statement on evacuation-path integrity. Follow-up work to gauge perceptions, tolerance, and abilities for moving over landslide deposits is warranted in certain sections of a community. This issue also exists for travel around road debris related with seismically induced liquefaction, another hazard discussed in Slaughter et al. [38]. We do not explicitly identify evacuation corridors that could be impacted by liquefaction-related debris because liquefaction hazard zones are more generalized than site-specific landslide hazard zones (e.g., Aberdeen is covered by three relative-hazard zones) and evacuation delays to move around individual sand boils that result from liquefaction under roads are likely on the order of less than a minute. In addition to earthquake-induced landslides, we also identified potential blockages for flow paths crossing bridges in the study area, since earthquake ground shaking could make bridges impassable. For this case study, we assume all bridges could potentially fail and do not take into account the structural integrity of any individual bridge.

4. Results

4.1. Evacuation potential

Modeling results suggest that the majority of the study area could be evacuated in less than 20–25 min, assuming at-risk individuals are moving at a fast walk (1.52 m/s) and remaining on roads during the evacuation (Fig. 5). Isolated areas of Aberdeen have clearance times on the order 25–32 min. Of the estimated 20,878 residents and 9876 employees in tsunami-hazard zones shown in Fig. 5, modeling results suggest that 97.5% of all at-risk residents and 99.8% of employees may have sufficient time to evacuate if they evacuate immediately at the start of the CSZ earthquake (i.e., an assumption of 25 min available for evacuation). The remaining at-risk population with evacuation travel times greater than 25 min may still be able to reach safety because (1) they could be trained to move at a faster speed, and (2) the 25-min for wave arrival time is based on arrival times on the open-ocean coast to the west of Aberdeen and it will take additional time for waves to travel across Grays Harbor Bay.

The percentages of successful evacuations drop to 91.2% and 95.8% for residents and employees, respectively, if at-risk individuals wait to evacuate until earthquake-related ground shaking ends (i.e., an assumption of 20 min for an evacuation). Although it may be difficult, if not impossible, to initiate an evacuation during the initial ground shaking, an additional 1313 residents and 327 employees may not reach high ground therefore if they take initial earthquake safety measures during an earthquake and wait to evacuate those five minutes during ground shaking. The percentages of successful evacuations further drop to 85.2% and 90.3% for residents and employees, respectively, if individuals take an additional five minutes after ground shaking ceases to initiate an evacuation. This translates to an additional 1473 residents and 751 employees not reach reaching high ground before wave arrival. The two population groups should not be added to estimate the total number of people, since the amount of overlap between groups is unknown and will vary based on location within the community and time of day when a tsunami occurs. Local emergency managers are better suited for making these assumptions given their local knowledge.

Mapped estimates of travel time shown in Fig. 5 and the number of residents and employees that may or may not reach high ground before wave arrival are based on an assumption that individuals evacuate at a constant base evacuation speed of 1.52 m/s. In reality, travel speeds of evacuees will vary depending on their ability, the distance they must travel to high ground, and the landscape conditions along an evacuation route. We therefore created a series of maps that summarizes the minimum travel speed that must be maintained for at-risk individuals to reach high ground before wave arrival (Fig. 6). Three maps of minimum travel speeds were created to reflect three evacuation scenarios: (a) individuals immediately evacuating as soon as the earthquake ground shaking begins (i.e., a 25-min evacuation window), (b) individuals waiting until earthquake ground shaking ceases before evacuating (i.e., a 20-min evacuation window), and (c) individuals waiting until earthquake ground shaking ceases and then taking an additional five minutes to evacuate (i.e., a 15-min evacuation window). Based on historical accounts of evacuations in Alaskan coastal communities during the 1964 Good Friday earthquake and tsunami disaster [5], the most likely scenario is that individuals will not evacuate immediately but instead wait until ground shaking ceases (i.e., Fig. 6(b)). This scenario is also

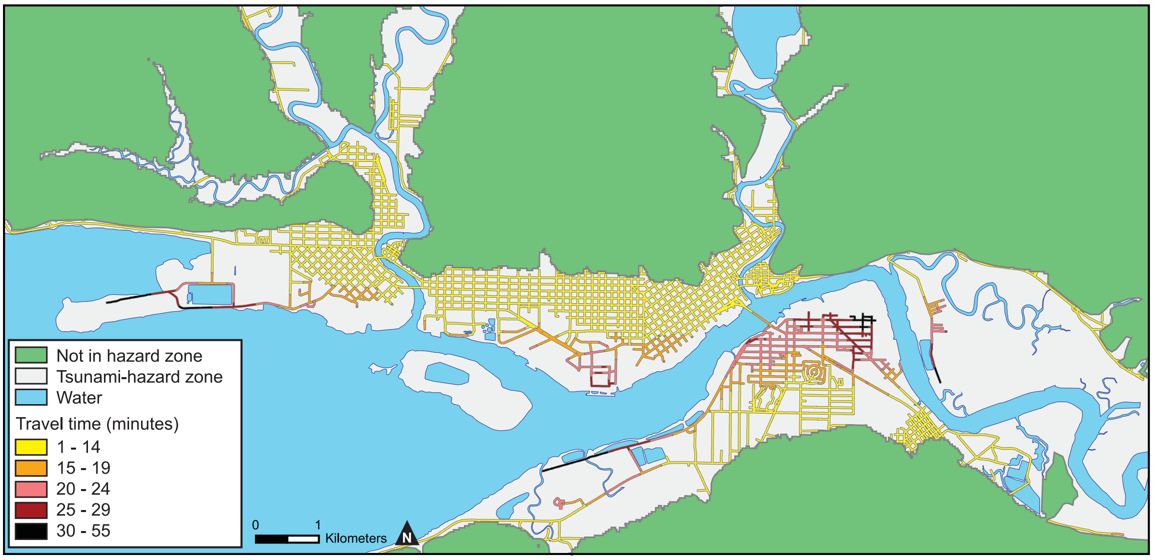

Fig. 5. Map of estimated travel times out of tsunami-hazard zone using only roads and assuming a fast walking speed (1.52 m/s).

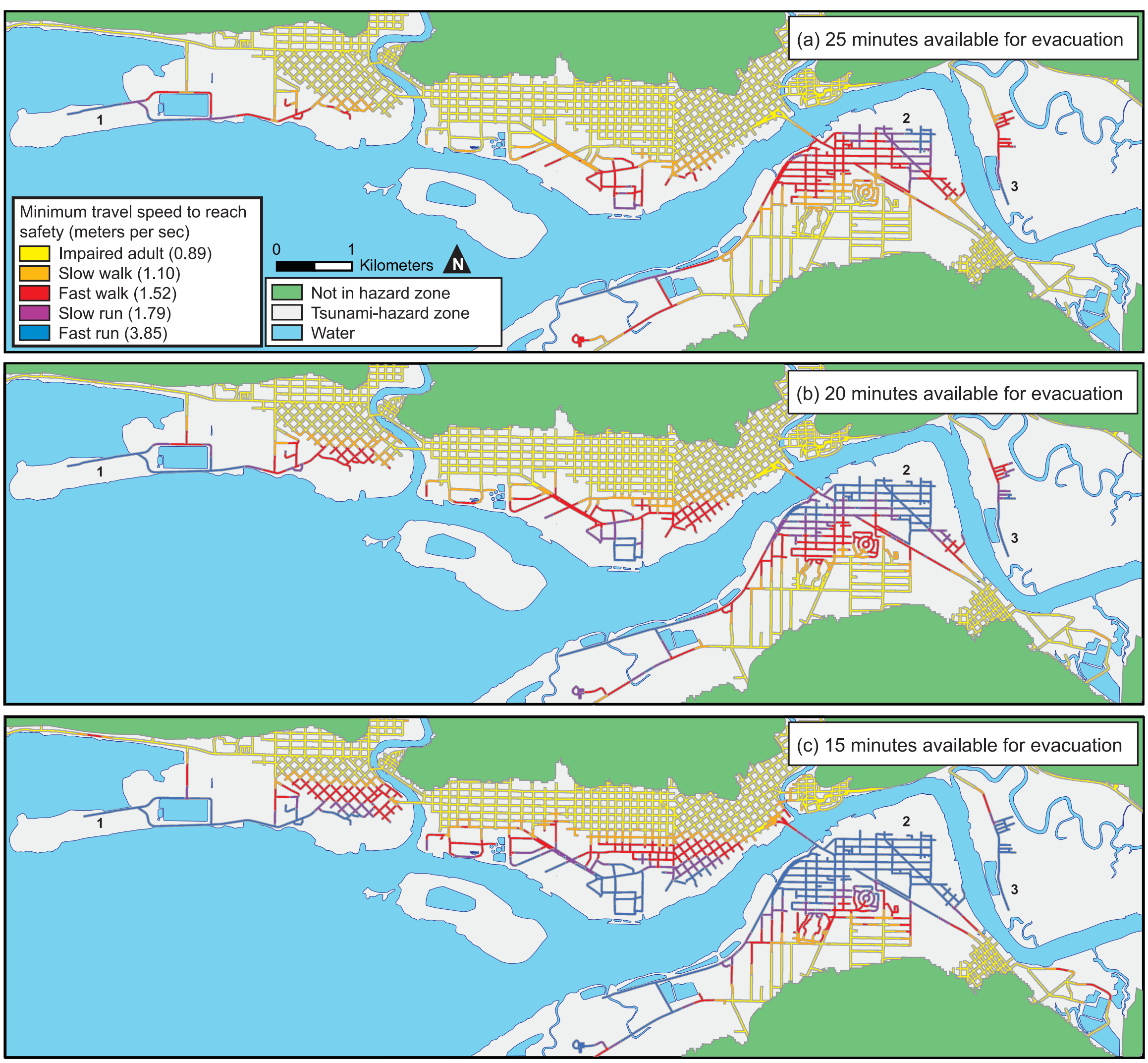

Fig. 6. Maps of estimated minimum travel speeds along road networks that pedestrian must maintain to evacuate out of tsunami-hazard zones, based on time windows of (a) 25 min, (b) 20 min, and (c) 15 min. Sites 1-3 identified on maps are discussed in the article and denote areas where fast-running speeds are required to evacuate out of hazard zones before wave arrival.

likely given the prolific nature of the “drop, cover, and hold” outreach strategy, which is necessary to protect building occupants during initial ground shaking and ensure that they survive a preceding earthquake before attempting to move to high ground.

Fig. 6a–c demonstrate how the majority of individuals in tsunami-prone areas of Hoquiam, Aberdeen, and Cosmopolis may be able to evacuate to high ground moving at rates ranging from that of an impaired adult (0.89 m/s) to a fast walk (1.52 m/s). Areas where individuals will need to maintain running speeds are primarily on an airport runway in west Hoquiam (site 1), near a lumber processing plant on the southern banks of the Chehalis River in Aberdeen (site 2), and a rural road east of Cosmopolis (site 3). Overall, Fig. 6a demonstrates that all of the study area can be evacuated at a fast walk or slower if at-risk individuals immediately evacuate when ground shaking begins, although maintaining these higher rates during ground shaking may be difficult. A comparison of minimum travel speeds in Fig. 6a–c demonstrate how decreases in the amount of time available for an evacuation from 25 down to 15 min requires more people to achieve and maintain quicker travel speeds.

The breakdown of population exposure as a function of minimum travel speed necessary to reach high ground before wave arrival (Fig. 7) indicates that the majority of residents (76%), employees (82%), customers at community businesses (82%), individuals at dependent-care facilities (83%), and tourists at public venues (77%) may be able to reach safety if they maintain at least the speed of an impaired adult (0.89 m/s). These percentages assume individuals wait until ground shaking ends before they initiate an evacuation (i.e., 20 min are available to evacuate) and increase in the less likely scenario of people instantly leaving at the onset of the earthquake. For this scenario, there are approximately 1300 residents, 261 employees, 18 community businesses, 5 dependent-care facilities, and 2 public venues in areas that would require evacuees to achieve and maintain a slow running speed of 3.85 m/s.

4.2. Evacuation flowlines and basins

Fig. 8 summarizes the thirteen evacuation basins based on modeled flowlines, watershed pour points (i.e., grid cells where flowlines cross into safe areas), and a manual grouping of pour points with the nearest assembly area. The manual grouping of pour points was based on their proximity to assembly areas and ease of movement along the road network. For example, a segment of highway 109 west of Hoquiam is considered not part of basin #1 because residents in this area would need to travel a great distance eastward through the tsunami-hazard zone to reach assembly area #1, instead of moving approximately 50 m to the north behind their homes to safety. In other cases, rivers separate evacuees from nearby assembly areas, such as residents in the Woodlawn neighborhood and Upper Hoquiam River of northeast Hoquiam and assembly areas #2 and #3 (Fig. 8).

When population values are used as weights for the evacuation flow accumulation, each cell value reports the total count of all population values ‘upstream.’ For example, by examining the value of the resident and business pathways on highway 101 crossing the Chehalis River, we estimate that 114 residents and 87 employees use the bridge crossing south to north for evacuation to assembly area #8. This functionality is key to understanding population demand at assembly areas, as well as estimating the number of evacuees that could be cut off from high ground and assembly areas due to ground failures. Fig. 9 portrays the major evacuation corridors, based on the population weighted flow accumulation channels. Cell values in Fig. 9 represent the combined population of residents and employees for cartographic purposes (i.e., having separate lines would be difficult to discern); therefore, this combined value may overestimate the number in a particular cell because an individual working in the hazard zone may also live near their place of employment. However, since these estimates do not include customers or tourists, then the potential over-count is less significant than potential undercounts.

Recognizing this caveat of potential over- and under-counts, Fig. 9 indicates the roads that may receive the highest number of evacuees during a CSZ earthquake and subsequent tsunami. Six roads are expected to have in excess of 1000 people attempting to reach high ground. Fig. 9 also portrays evacuation routes that are noted on official evacuation maps for this area (Washington Department of Natural Resource, 2007). Our modeled flowlines correspond well with the established evacuation routes with only a few exceptions. Two exceptions include the flowlines in north Aberdeen that end with 1587 and 1072 individuals (Fig. 9) but official routes are only one block away from the optimal flowline, suggesting an insignificant difference in evacuation times. Another exception is in south Aberdeen where a flowline along South Lewis Street ends with 1365 individuals (Fig. 9). The official evacuation route is to the west along highway 105 (also known locally as South Boone Street). The two roads are only one block apart at one point, therefore individuals during an actual evacuation would have little difficulty shifting over to highway 105 if they have been trained to do so or are directed by public safety officials.

4.3. Population demand at assembly areas

Likely population demand at pre-determined assembly areas varies considerably in our study area. The number of residents varies from a low of 33 residents and 4 employees at assembly

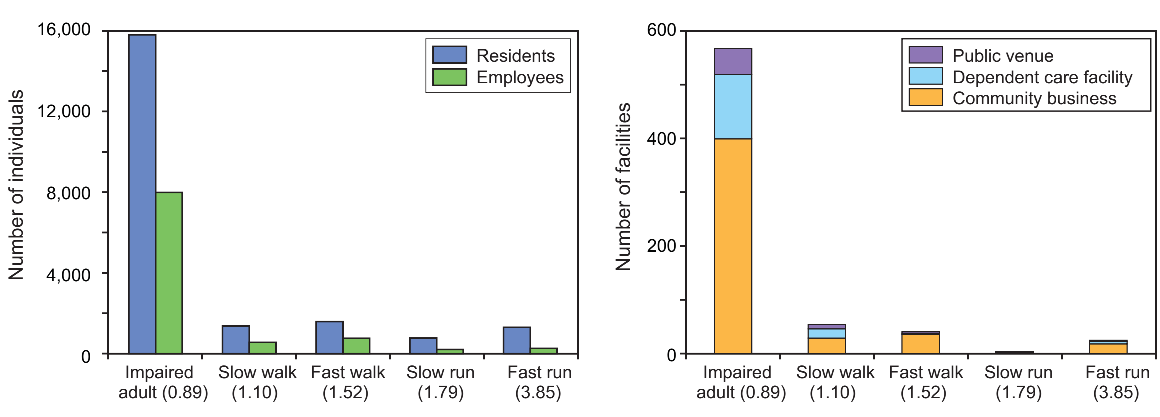

Fig. 7. Graphs of the distribution of (a) residents and employees, and (b) various business types, as a function of minimum travel speeds required to reach safety, given a 20-min evacuation window before wave arrival.

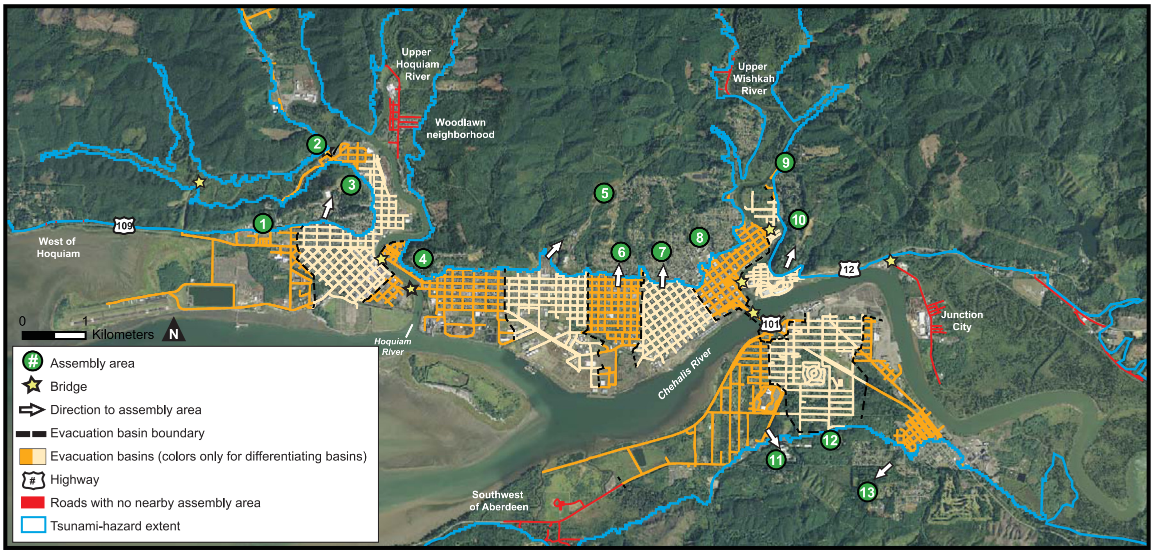

Fig. 8. Map showing evacuation basins and related assembly areas, as well as areas with no nearby assembly areas based on optimal pedestrian evacuation modeling.

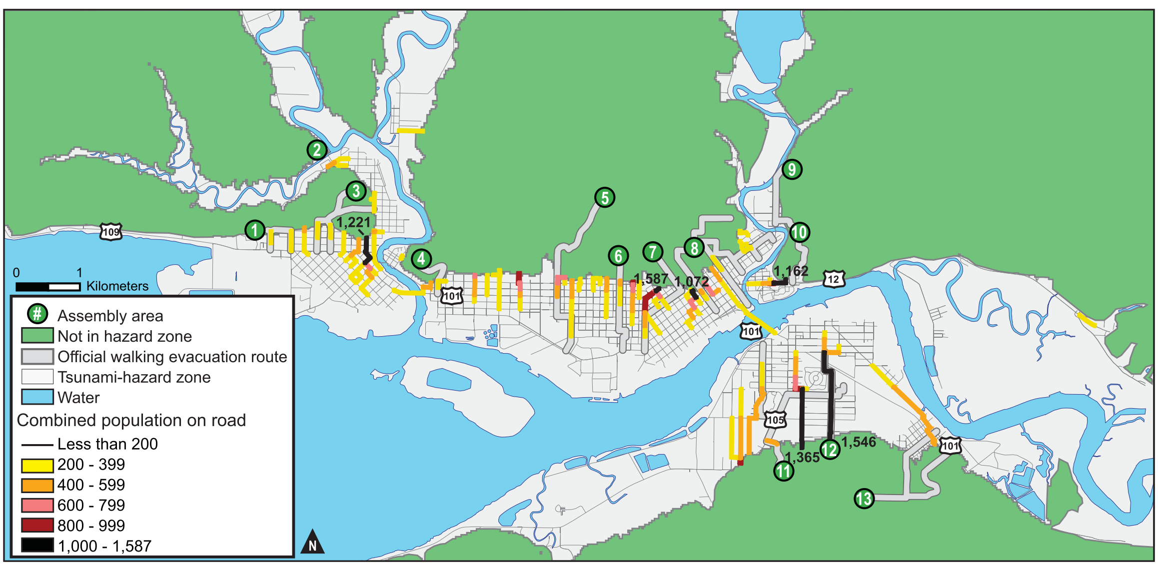

Fig. 9. Map of assembly areas, official walking evacuation routes (both from [44]), and modeled weighted evacuation flow accumulation raster values. Values on the map refer to the highest combined population at the pour point.

area #9 to a high of 3699 residents and 1010 employees to assembly area #3 (Fig. 10a). Although assembly area #3 has both high resident and employee counts, other assembly areas vary depending on the population type. For example, assembly areas #4, #11, and #12 have high estimated residential counts but relatively lower employee counts, whereas assembly area #10 has a high employee count and a relatively lower residential count. Assembly area #8 has the highest combined number of community business (99), dependent-care facilities (19), and public venues (9) (Fig. 10b). Other assembly areas likely to have high customer counts include site #3 (69 community businesses, 32 dependent-care facilities, and 7 public venues) and site #7 (85 community businesses, 19 dependent-care facilities, and 12 public venues). Local emergency managers, working in collaboration with business owners, could further improve these estimates by determining which of these businesses or locations (e.g., a park near a business) are likely to generate higher volumes of evacuees overall or at a given time during the day, week, or year. This information could also be used to better understand the amount of overlap of resident and employee counts for a given assembly area.

Using census-block information also provides insight on the type of residents that may be at various assembly areas. This information can help guide relief planning, such as stocked caches of relief supplies at an assembly area. For example, Fig. 10c summarizes the distribution of residents less than 5 years in age and greater than 65 years in age, which are two demographic groups that may have additional physical, emotional, or dietetic needs after a catastrophic event. Demographic data suggest that the residential evacuee population in our study area contains 1593 children less than 5 years and 2562 individuals older than 65 years. Results suggest that the number of children under 5 years in age at a given assembly area is fairly consistent when compared to the total number of residents estimated at the same site. The number of residents over 65 years in age is not as consistent. For example, although assembly areas #4–7 and #11–12 have similar numbers of children less than 5 years in age (a range of 137–171 individuals), the number of older residents varies considerably for these same assembly areas (141–407 individuals).

Not all at-risk individuals will have easy access to assembly areas after the earthquake and tsunami. Based on our analysis of

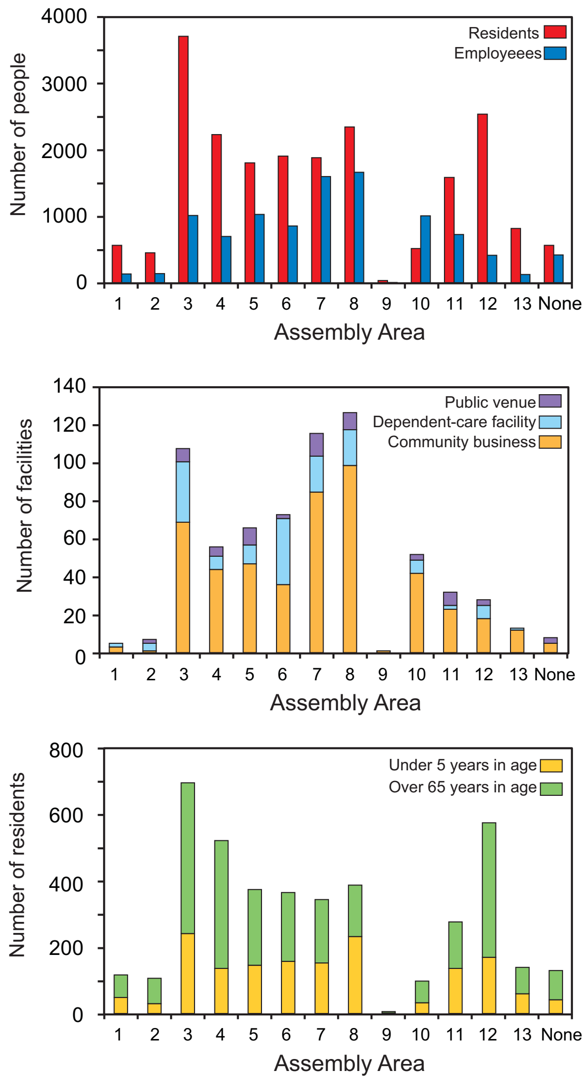

Fig. 10. Graphs of estimated population demand for each assembly area in the study area, including (a) residents and employees, (b) community businesses, dependent-care facilities, and public venues, and (c) the number of residents less than 5 years and more than 65 years in age.

evacuation pathways and basins, we estimate that there are approximately 560 residents, 417 employees, 5 community businesses, and 3 public venues in areas that do not have an official assembly area reasonably near them (Fig. 11). At-risk individuals in areas with no official assembly area may choose to shelter in place at high ground near their homes or make their way if possible to the nearest assembly area after tsunami waves have receded. The decision to move to assembly areas between the arrival of tsunami waves may be discouraged by emergency managers in pre-event education efforts given the uncertainty of arrival times and heights for an entire suite of tsunami waves associated with a Cascadia subduction zone earthquake. Another issue is the likely difficulty in sending out "all-clear" messages due to damaged telecommunication facilities from the initial earthquake and subsequent tsunami waves. We estimate that 400 of the 560 residents are in the Woodlawn neighborhood of northeast Hoquiam (Fig. 8). This is understandable since this area is considered in tsunami-hazard zones associated with newer inundation modeling, but is not considered at risk in the publicly available, previously published tsunami-evacuation brochure. Therefore, no assembly areas have been officially determined for this upriver community. We estimate that 397 of the 417 employees with no clear assembly area are in Junction City, which is east of Aberdeen and east of the Chehalis River (Fig. 8). There are also public venues in and near Junction City with no nearby assembly area, as well as community businesses there and in the Woodlawn community northeast of Hoquiam (Fig. 11).

4.4. Evacuation obstacles

An overlay of potential earthquake-induced ground failures and evacuation pathways suggests that most at-risk individuals should be able to reach assembly areas. Across the study area, no landslide-hazard zones directly overlap evacuation routes. We then turned our attention to identifying landslide-hazard zones for bluffs adjacent to evacuation routes, which indicate the potential for debris from a nearby landslide blocking a route. Imagery interpretation suggests main evacuation pathways to assembly areas #1, #3, #7, #8, and #11–13 do not have landslide hazards on adjacent hillsides (Fig. 12). Landslides are possible along highways near assembly areas #2 and #9, but routes to the assembly areas are not expected to be impacted. However, landslide on these sections of highways could affect post-tsunami response efforts

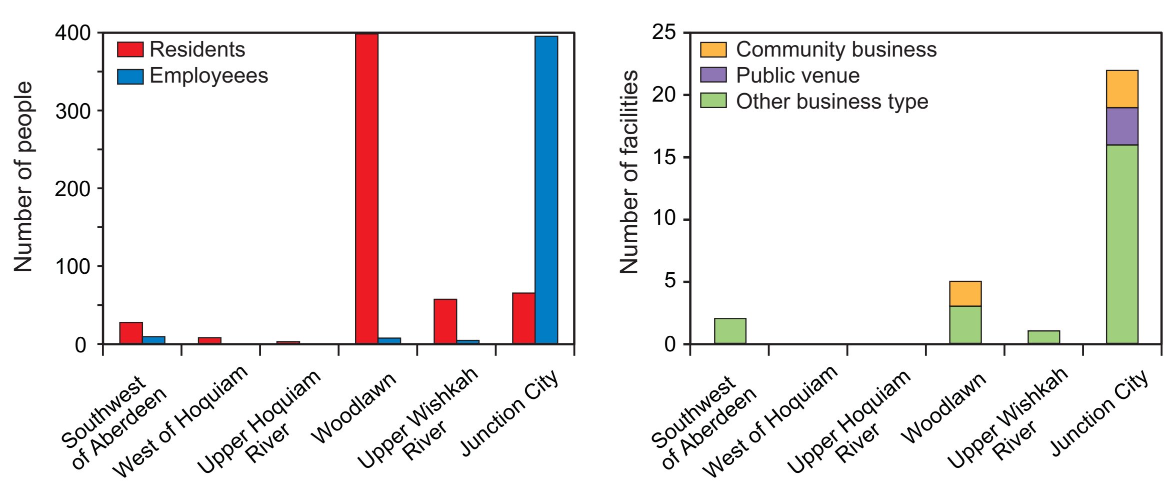

Fig. 11. Graphs showing estimated population demand at the areas not covered by existing assembly areas, including (a) residents and employees, (b) community businesses, dependent-care facilities, and public venues.

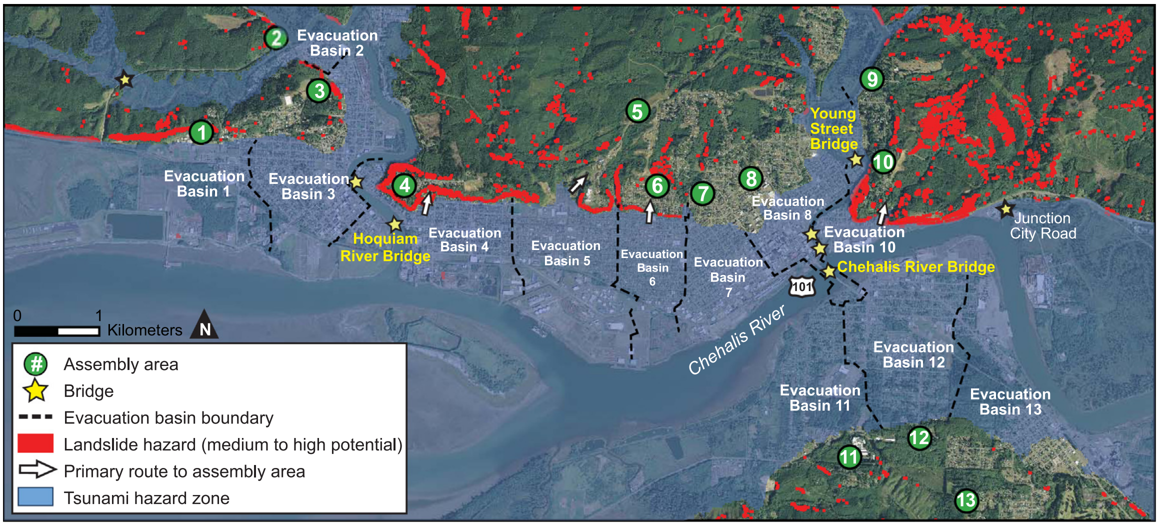

Fig. 12. Map of areas where evacuation pathways may be interrupted by landslide debris or bridge failure. Landslide susceptibility data are from Slaughter et al. [38].

and the delivery of relief supplies because they may sever primary transportation routes to rural areas outside of the three communities. This is also the case near the Woodlawn neighborhood, Highway 101 southeast of Cosmopolis, Highway 109 west of Hoquiam, and Wishkah Road north of Aberdeen.

Evacuation pathways to assembly areas #4–6 may be compromised because each have medium to high landslide hazards on bluffs adjacent to their routes (Fig. 12). There is a medium to high likelihood of landslide hazards surrounding the majority of assembly area #4, including bluffs adjacent to the primary road to it. There is also landslide potential for the route to assembly area #5, although the hazard zones are well into the area considered safe; therefore, individuals would be able to establish an unofficial assembly area before the road segment that may be covered in landslide debris. Finally, three of the six roads leading to assembly area #6 have landslide hazards, suggesting that at-risk individuals may be able to take alternate routes to safety.

Another potential obstacle for an evacuee is a bridge failure from the initial earthquake. A visual interpretation of imagery and spatial overlay of evacuation basins and pathways suggest that some at-risk individuals may be unable to reach assembly areas #4, #8, and #10, as well as evacuate Junction City east of Aberdeen if bridges were to fail during the initial earthquake (Fig. 12). The Hoquiam River Bridge, Chehalis River Bridge, and the Young Street Bridge into North Aberdeen are all used in the modeling as shortest distance evacuation paths. The Hoquiam River Bridge is considered an optimal evacuation route for 228 residents and 101 employees from Hoquiam into East Hoquiam and upward to assembly area #4. If the bridge failed, assembly area #3 would be the closest site on the west side of the river and clearance times would be on the order of 20 min (an increase of approximately 8 min over routes that involve crossing eastward on the Hoquiam River Bridge). The Chehalis River Bridge is considered an optimal route for 114 residents and 87 employees on the south side of the river to assembly area #8. If this bridge failed during the earthquake, evacuees would be forced to move south to assembly areas #11 and #12; however, clearance times for the area just south of the bridge would rise from approximately 21 min for the route that crosses the bridge to 30 min for the southern route. The Young Street Bridge in northeast Aberdeen is considered the optimal evacuation route for 91 residents and 1 business to assembly area #10. If the Young Street Bridge were to fail, individuals on the south side of the bridge could move west to assembly area #8 and clearance times to high ground would still be less than 15 min.

5. Discussion

Successful evacuations are critical to saving lives from future tsunamis. Pedestrian-evacuation modeling related to tsunami hazards has primarily focused on identifying areas and the number of people in these areas where successful evacuations are unlikely before first wave arrival. The purpose of this article is to focus on modeling that supports risk-reduction planning for at-risk individuals in areas where successful evacuations are likely, providing they recognize the need to take self-protective action and move efficiently to high ground. In this section, we discuss the implications of our results on evacuation and response planning, mitigation and long-term comprehensive planning, and areas for further research.

5.1. Implications for evacuation and response planning

The ability to identify likely evacuation pathways, the spatial distribution of survivors, and impediments along pathways provides emergency managers with actionable information for outreach, evacuation route planning, and post-disaster relief planning. In addition, it also provides local planners with new information that could be used when assessing or siting potential locations of critical facilities or those that may house vulnerable populations. With regard to evacuation outreach, maps that demonstrate evacuation success for most at-risk individuals at various pedestrian travel speeds (Fig. 6) can be used to increase positive outcome expectancy in individuals, which is considered a significant factor in motivating people to prepare [30]. Elected officials, the public, and the media often interpret extreme events (e.g., Cascadia subduction zone earthquake and tsunami) as not survivable (e.g., [37]) and as such, at-risk individuals may not see a reason to take preventative steps. Our maps of travel speed tied to a credible CSZ tsunami scenario indicate that the majority of people in our study area would have sufficient time to evacuate.

Evacuation travel-speed maps also provide actionable information to at-risk individuals on how fast they would need to move based on their evacuation decisions. For example, Fig. 6 demonstrates how minimum travel speeds to evacuate out of hazard zones vary if individuals evacuate at the onset of the earthquake, wait five minutes until the earthquake ground shaking ends, or take an additional five minutes after the earthquake to evacuate. Results suggest that the majority of the residents and employees in our study area (97.5% and 99.8%, respectively) could evacuate out of the tsunami-hazard zone before wave arrival if they immediately started to move to high ground at the beginning of the earthquake and moved at a reasonable "fast walk" speed of 1.52 m/s. Because it may be difficult to move during the intense ground shaking [5] and the widespread training to "drop, cover, and hold" during an earthquake, waiting until ground shaking ends to evacuate may be more likely and prudent for many individuals. However, this evacuation decision to wait until ground shaking ends may result in 1313 residents and 327 employees potentially not reaching high ground. Such information may provide additional motivation and impetus to enhance the travel speed of populations within this area and practice evacuations on a more routine basis. Additionally, it demonstrates the value of retrofitting structures in tsunami inundation zones, both for structural and non-structural hazards. If a building and its contents are secured, it will enable occupants to evacuate more quickly. These numbers increase by 1473 residents and 751 employees if people take an additional five minutes to evacuate. Emergency managers can use these results and maps in evacuation education and training efforts to discuss with some at-risk individuals the benefits of improved mitigation measures to exit buildings more quickly after the earthquake shaking subsides. This may motivate faster speeds than expected given the potential evacuation delays.

Understanding evacuee demographics relative to minimum travel speeds can also help emergency managers determine the likelihood of successful evacuations, combat potential fatalism through improved public education, and reinforce the positive outcomes that can be achieved by practicing tsunami evacuations. Results suggest that the majority of residents, employees, tourists at public venues, customers at community businesses, schoolchildren, and patients at dependent care facilities in our study area can reach safety moving at the relatively slow speed (0.89 m/s) of an impaired adult (Fig. 7). However, there are some at-risk individuals in areas where minimum travel speeds are higher, which may not be feasible for individuals with mobility issues. Depending on the amount of available time for an evacuation, the number of residents over 65 years in age in areas where they would need to maintain a fast running speed (i.e., 3.85 m/s) ranges from 20 residents (no delay for a 25-min evacuation window) to 266 residents (waiting for ground shaking to end plus an additional five-minute delay for a 15-min evacuation window). The number of younger residents (i.e., less than five years in age) that would also have difficulty maintaining the fast running speed ranges from 22 to 203, given the same evacuation delay scenarios. Comparing travel time maps with local demographics help emergency managers and state agencies responsible for permitting the use of adult family homes to better understand where evacuations may be successful for some but not all at-risk individuals, where to target evacuation training, and where to develop vertical-evacuation refuges or consider alternative locations for adult family homes.

In addition to framing evacuation education and training, results can help emergency managers evaluate the utility and availability of predetermined evacuation corridors. Many, but not all, of the predetermined evacuation corridors in our study area align with our modeled results of optimal paths to safety. Next steps could include re-examining the predetermined routes and determining if and where changes may be warranted. For example, revisions may not be warranted based on our modeling because earlier discussions within the community may have incorporated route preferences of evacuees that were not incorporated into our analysis. Another use of modeling results is in determining impediments along evacuation routes, such as heavy brush or vegetation, fences or hedge lines, water obstacles, narrow paths that limit evacuations, as well as potential impediments related to bridge failure or landslide-debris blockages. With regard to the potential impacts of bridge failures on evacuation potential, alternative routes are possible for all evacuation pathways over the three primary bridges (Hoquiam River Bridge, Chehalis River Bridge, and the Young Street Bridge), although evacuation clearance times would increase if bridges were to fail. The increase in clearance time for seeking alternative routes is most pronounced for the estimated 200 evacuees traveling over the Chehalis River Bridge; however, the difference is from 21 to 30 min, which is relatively close to the wave arrival and likely could be accounted for by an increase in travel speed by evacuees. Such information may benefit transportation planners, city, county engineers, and others when prioritizing potential bridge retrofitting or replacement options.

Knowing the approximate number and demographics of evacuees along certain evacuation corridors helps emergency managers with developing effective assembly areas, both in their ability to accommodate the magnitude and type of evacuees. For example, the estimated magnitude of evacuees at predetermined assembly areas varies considerably from 33 residents at assembly area #9 to 3699 residents at assembly area #3. Follow-up discussions may involve determining whether each assembly area could handle the estimated magnitude and what, if anything, could be done to better balance the number of evacuees among neighboring assembly areas. It will also enable communities to work more effectively amongst themselves and in conjunction with emergency managers to receive and manage evacuees until larger-scale response operations can be mobilized. Research presented here also supports the coordination of public health officials and emergency managers to adequately staff personnel and stage resources at assembly areas to match likely evacuee demographics. For example, an assembly area that is expected to handle a high number of older evacuees (e.g., site #3, Fig. 10c) may require greater medical supplies to deal with pre-existing health issues or with injuries sustained during an evacuation, be able to accommodate greater dietary restrictions with regard to relief supplies, and be identified for pre-scripted emergency supply packages that will be deployed immediately following a catastrophic local earthquake. Results can also determine gaps in assembly areas, either because certain areas of the community are not realistically served by a nearby assembly area (Fig. 11) or because routes to assembly areas may be compromised by post-earthquake ground failures (Fig. 12).

5.2. Implications for mitigation planning

In addition to supporting evacuation and response planning, methods described here also provide support for efforts to mitigate current development and to guide future land use planning. Identifying the major pathways and the impediments along these pathways can be used to understand if and where structural and non-structural mitigation alternatives could be implemented to increase the likelihood of successful evacuations. Community-based mitigation scenarios could be modeled based on structure type and existing occupancy classification to visualize and quantify changes in minimum pedestrian travel speeds, the number of people that can successfully evacuate, and assembly area capacity. Site-specific mitigation strategies along major evacuation corridors could include landscape maintenance to ensure undeveloped fields are clear and available for use (e.g., removing seasonal vegetation), improved lighting to support nighttime evacuations, rerouting bike or walking paths to align with major evacuation corridors, paving existing pedestrian trails, or building steps in steep areas. Mitigation strategies may be demographic dependent; for example, elderly populations may find it more difficult to climb steps and therefore a sloped paved path might be preferable in certain areas. Larger mitigation strategies could include the construction of pedestrian bridges over water obstacles, the creation of new trails or roads outside of the hazard zone to connect evacuees with assembly areas, or enhancing the road network within the hazard zone (e.g., road widening to ease congestion potential or extending dead-end roads out of the hazard zone). In addition, infrastructure maintenance and seismic upgrades to roads and bridges could be prioritized based on their ability to reduce evacuation clearance times.

Infrastructure strengthening or rerouting is especially critical in areas where post-earthquake ground failures could impede evacuations. In our study area, landslide potential could obstruct access to assembly area #4, cause evacuees to reroute to get to assembly areas #5 and #6, and disrupt the ability of response personnel to reach evacuees at assembly areas #2 and #9 due to road blockages (Fig. 12). Bridge failures could block evacuations to assembly areas #4, #8, and #10, as well as those evacuating from Junction City. Understanding where landslides and other post-earthquake ground failures may impact evacuation pathways can assist emergency managers in determining if and where to prioritize structural improvements to the roadways.

In addition to identifying short-term mitigation strategies, evacuation-modeling results could be used for guiding long-range comprehensive land use planning. Plans for new residential or commercial development could be evaluated, either qualitatively with existing evacuation maps or quantitatively with new scenario modeling, in terms of the volume of new evacuees using existing evacuation corridors, the demographic mix at assembly areas, the volume of people that may have insufficient time to evacuate, and the range of options to improve evacuations. In situations where new development creates significant evacuation issues, conditions for development approval could include vertical-evacuation refuges if natural high ground is not accessible or evacuation easements using privately owned lands to ensure direct routes to safety during a tsunami. For example, the Revised Code of Washington Chapter 38.52, Section 180 permits the State of Washington to indemnify and hold harmless persons, partnerships, corporations, or political subdivisions that evacuate onto private land when it has been officially designated as a shelter. Such agreements have been successfully executed in the past between the State of Washington and private timber companies.

The potential use of evacuation modeling as a land-use planning tool is similar to Allan et al.'s [1] discussion of the influence of urban morphology (e.g., modularity and connectivity) on a city's capacity to respond quickly to extreme events, as well as its long-term resilience. For example, Allan et al. [1] assert that tsunami evacuations were hampered in Concepcion, Chile following the 2010 earthquake and tsunami due to dense urban centers, a small number of narrow, winding roads, and pedestrian congestion at the junctions between the low-lying plains and the hills with safer higher ground. Leon and March [19] take this concept further by implementing evacuation modeling in the Chilean city of Talcahuano (also severely affected by the 2010 earthquake and tsunami) to gauge the impact of changes in urban design on improving tsunami-evacuation clearance times. Their results clearly demonstrate how mitigation efforts that increase network connectivity, such as road extensions or new access roads, can improve the community's evacuation potential (or "rapid resilience" as termed by the authors). Leon and March [20] addresses similar issues of changes in urban design to improve tsunami evacuations, but focus on modeling pedestrian evacuations in light of the interplay of macroscale aspects of urban configuration (e.g., road networks) and micro-scale aspects of the built environment (e.g., street lighting and signage).

5.3. Areas for future research

Building on methods presented here, research in several areas would further the understanding of evacuation procedures, response challenges, and relief planning for local tsunami threats. Although not an exhaustive list, we discuss four areas for continued research – mixed LCD and network analysis, congestion analysis, preferred wayfinding of evacuees, and evacuation behavior of at-risk individuals. A mixed evacuation model that leverages LCD and network-based analytical approaches may provide gains in geospatial data processing time and flexibility in analysis. For example, LCD-based approaches could model movement in less constrained areas (e.g., rural areas with large, open lots) but could be explicitly linked to network-based approaches in more constrained areas (e.g., dense urban environments).

A natural next step to population-based, flowline analysis is in identifying choke points along evacuation corridors. Priest et al. [36] discuss evacuation choke points for bridges within a hazard zone that are cut off because tsunami waves may travel faster up creeks and rivers than overland flow from the ocean. Choke point analysis that builds on our population-based flowlines could focus instead on congestion hotspots due to the convergence of high population-magnitude flow lines. Although this congestion analysis could be based on a common travel-speed assumption (as was done in this analysis), one would ideally take into account varying travel speed assumptions for the different type of people that may be attempting to use similar evacuation corridors. Recognizing the range of travel speeds for people converging towards common pathways would provide the most realistic estimate of congestion potential.

A third area of future research is improving our understanding of preferred evacuation routes and wayfinding of at-risk individuals. Evacuation-modeling results presented here are considered optimal routes; however, individuals may take alternate routes for various reasons, such as habits engrained by daily routines. A logical next step is to compare optimal routes based on modeling with preferred routes by geospatially tracking volunteers in a local evacuation exercise. Such data would provide insight on evacuation preferences and best case versus likely case in terms of potential congestion points and the distribution of survivors at assembly areas.

Another area of research that can build off results presented here is the behavioral and sociological aspects of an evacuation. Our current work makes the geographic case that evacuations are possible for many individuals due to proximity to high ground; however, it does not address the range of people's perceptions and behaviors that would influence their decision-making process for evacuating and taking appropriate self-protective actions. There is currently a lack of sociological or psychological literature on evacuation behavior during tsunamis, particularly in the United States [22,27]; however, insights could be gained from the literature on evacuation decision-making for other sudden-onset hazards [6,18,23]. For example, there is evidence that individuals make evacuation decisions in the context of perceptions and conditions of other members of a household [7,31]. The Protection Action Decision Model (PADM) is a theoretical behavior framework that suggests decisions are made based on variables such as environmental and social cues, receiver characteristics, and information sources [21], and it has been used to explain evacuation behavior in American Samoa during the 2009 Samoa Islands tsunami [2]. Areas for future research to better understand evacuation behavior from future Cascadia-related tsunamis could include whether people perceive the need to evacuate given the environmental cue of earthquake ground shaking, what additional social cues would result in quicker individual decision making, and the influence of household characteristics (e.g., caregiver status for children or pets) on evacuation decision making. The intention is to build on our understanding of the landscape of possible evacuations with insights on the likelihood that at-risk individuals take the proper self-protective actions to reach high ground.

6. Conclusions

The objective of this paper is to demonstrate the development and use of geospatial, path distance modeling approaches to estimate tsunami-evacuation pathways, basins, population demand at assembly areas, and potential obstacles to safety. Based on our analysis, we reach several conclusions that bear on future tsunami risk-reduction research and application to at-risk communities.

- Maps visualizing minimum travel speeds to evacuate hazard zones provide actionable information on where and how fast individuals may need to move. This information may raise positive outcome expectancy for motivating people to prepare.
- Maps of minimum travel speeds to safety that are based on varying amounts of available evacuation time demonstrate how required speeds change due to individual evacuation decisions.
- Modeled evacuation pathways and basins linked with population data provide emergency managers with the ability to determine the magnitude and demographics of evacuees along evacuation corridors and at predetermined assembly areas, which can be used to develop realistic response and relief.
- Results suggest a wide range in the magnitude and type of evacuees at predetermined assembly areas, as well as identifying other parts of the three communities not realistically served by an assembly area.
- Earthquake-induced ground failures could obstruct access to some assembly areas, cause evacuees to reroute to get to other assembly areas, and isolate some evacuees from relief personnel.
- Evacuation modeling can be used to identify opportunities for outreach, response planning and mitigation strategies to enhance the likelihood of successful evacuations.

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