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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

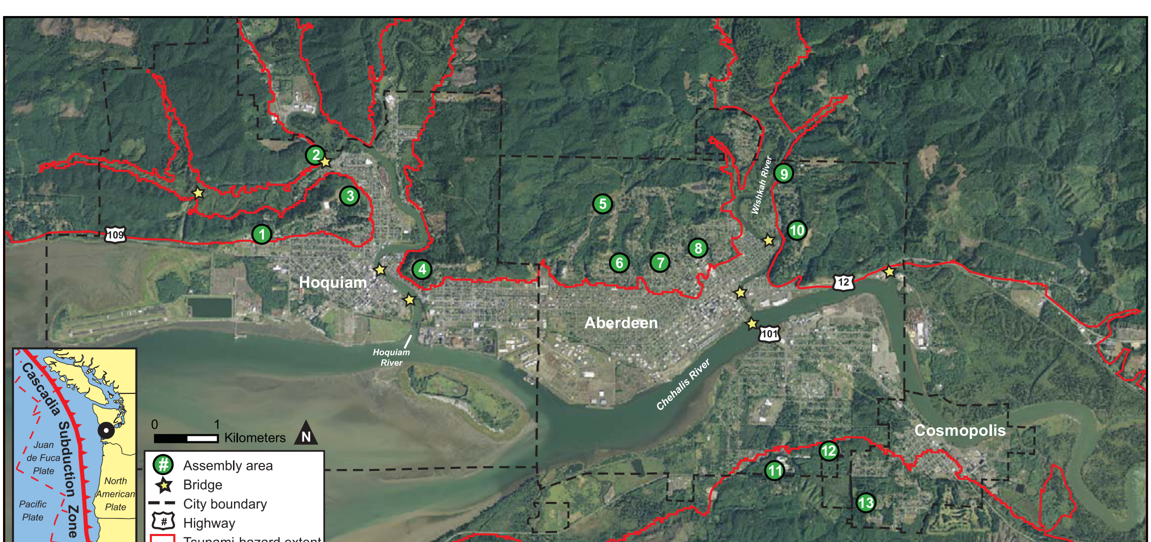

Fig. 1. Study area map of Aberdeen, Hoquiam, and Cosmopolis, Washington, including official assembly areas [44] and a tsunami-hazard zone associated with Walsh et al. [43] and model outputs provided by the State of Washington Department of Natural Resources based on Priest et al. [35] (T. Walsh, written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