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Sensitivity of tsunami evacuation modeling to direction and land cover assumptions

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ABSTRACT

Although anisotropic least-cost-distance (LCD) modeling is becoming a common tool for estimating pedestrian-evacuation travel times out of tsunami hazard zones, there has been insufficient attention paid to understanding model sensitivity behind the estimates. To support tsunami risk-reduction planning, we explore two aspects of LCD modeling as it applies to pedestrian evacuations and use the coastal community of Seward, Alaska, as our case study. First, we explore the sensitivity of modeling to the direction of movement by comparing standard safety-to-hazard evacuation times to hazard-to-safety evacuation times for a sample of 3985 points in Seward's tsunami-hazard zone. Safety-to-hazard evacuation times slightly overestimated hazard-to-safety evacuation times but the strong relationship to the hazard-to-safety evacuation times, slightly conservative bias, and shorter processing times of the safety-to-hazard approach make it the preferred approach. Second, we explore how variations in land cover speed conservation values (SCVs) influence model performance using a Monte Carlo approach with one thousand sets of land cover SCVs. The LCD model was relatively robust to changes in land cover SCVs with the magnitude of local model sensitivity greatest in areas with higher evacuation times or with wetland or shore land cover types, where model results may slightly underestimate travel times. This study demonstrates that emergency managers should be concerned not only with populations in locations with evacuation times greater than wave arrival times, but also with populations with evacuation times lower than but close to expected wave arrival times, particularly if they are required to cross wetlands or beaches.

Introduction

Tsunami hazards threaten coastal communities throughout the world. Of particular concern are waves that could inundate low-lying areas within minutes after being generated by a local source, such as offshore earthquakes. Evacuations from local tsunamis likely will be self-initiated and pedestrian-based due to the short time scale and likely damage to road networks from the initial earthquake. Following the life loss witnessed during recent tsunami disasters (e.g., 2004 Indian Ocean, 2009 Samoa, 2010 Chile, and 2011 Tohoku), there have been considerable efforts to model pedestrian evacuations out of tsunami-hazard zones (e.g., Laghi, Cavalletti, & Polo, 2006; Jonkmann, Vrijling, & Vrouwenvelder, 2008; Yeh, Fiez, & Karon, 2009; Johnstone, & Lence, 2012; Wood & Schmidtlein, 2012, 2013). Maps of travel times to safety based on pedestrian-evacuation modeling help emergency managers understand where successful evacuations may be possible and where vertical-evacuation strategies may be warranted.

One approach to model pedestrian evacuations has focused on generating spatial surfaces that represent the minimal costs in travel across a landscape. Cost heuristics used in previous way-finding modeling have varied, such as shortest path length (Dijkstra, 1959; Wood & Schmidtlein, 2013), simplest path (Duckham & Kulik, 2003), and least risk paths (Vanclooster et al. 2014). Least-cost distance (LCD) models based on shortest path algorithms are generated typically as a function of land surface slope, land cover type, and travel speed assumptions. Recent tsunami-related efforts have improved how slope is included in the modeling by incorporating the directionality of movement; for example, Wood and Schmidtlein (2012) demonstrate how isotropic assumptions (constant slope regardless of travel direction)

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consistently underestimated the travel times for safety out of tsunami-hazard zones compared to an anisotropic approach for slope calculations that reflected the direction of movement.

A related, yet unexplored, question in LCD modeling is how well the direction of movement is characterized in the actual least-cost-surface computations. LCD models use approaches based on Dijkstra's (1959) algorithm for finding the minimum length path between two points. This approach can be used in raster contexts to find the minimum distance from a given origin cell to all remaining cells in the study area. In order to generate an evacuation time map for the entire tsunami hazard area, this standard approach would require a separate LCD analysis to be run for each individual cell in the hazard zone. Laghi et al. (2006) proposed that a more computationally efficient approach would be to treat the safe zones as the origins, and calculate the time it would take to move from these safe areas to each cell in the hazard zone, in effect reversing the direction of the LCD analysis. Subsequent pedestrian-evacuation modeling efforts (e.g., Wood & Schmidtlein, 2012) followed this approach in their anisotropic LCD models, and used a reversed direction look up table to represent the impact of slope on travel times, since the model LCD search direction was the opposite of actual pedestrian travel direction (from safety to hazard, rather than from hazard to safety). Although reversed direction modeling is conceptually satisfying, we are not aware of any efforts to determine the sensitivity of the LCD modeling and subsequent travel-time maps to this assumption.

In addition to examining the effect of slope anisotropy on LCD models, another unexplored model-sensitivity question relates to how travel costs are assigned to land cover categories. Currently, travel constraints due to landcover variations are expressed through speed conservation values (SCVs; Laghi et al. 2006) that represent the percent of maximum travel speed that a pedestrian would be expected to have on a given land cover. Because no consistent, empirically based relationship between land cover and travel speeds could be identified in the literature, current land cover SCVs used by Wood & Schmidtlein, 2012 are based on differences in the amount of energy used to move across different land cover types (Soule & Goldman, 1972). This is an oversimplification of the actual processes which relate land cover to pedestrian evacuation speeds and it is unclear how sensitive model results are to fluctuations in land cover SCVs.

The objective of this paper is to explore the sensitivity of pedestrian-evacuation time modeling to assumptions made in characterizations of the path of movement and in the landcover surface. These lead to two distinct research questions. First, do modeled evacuation times differ depending on the direction of

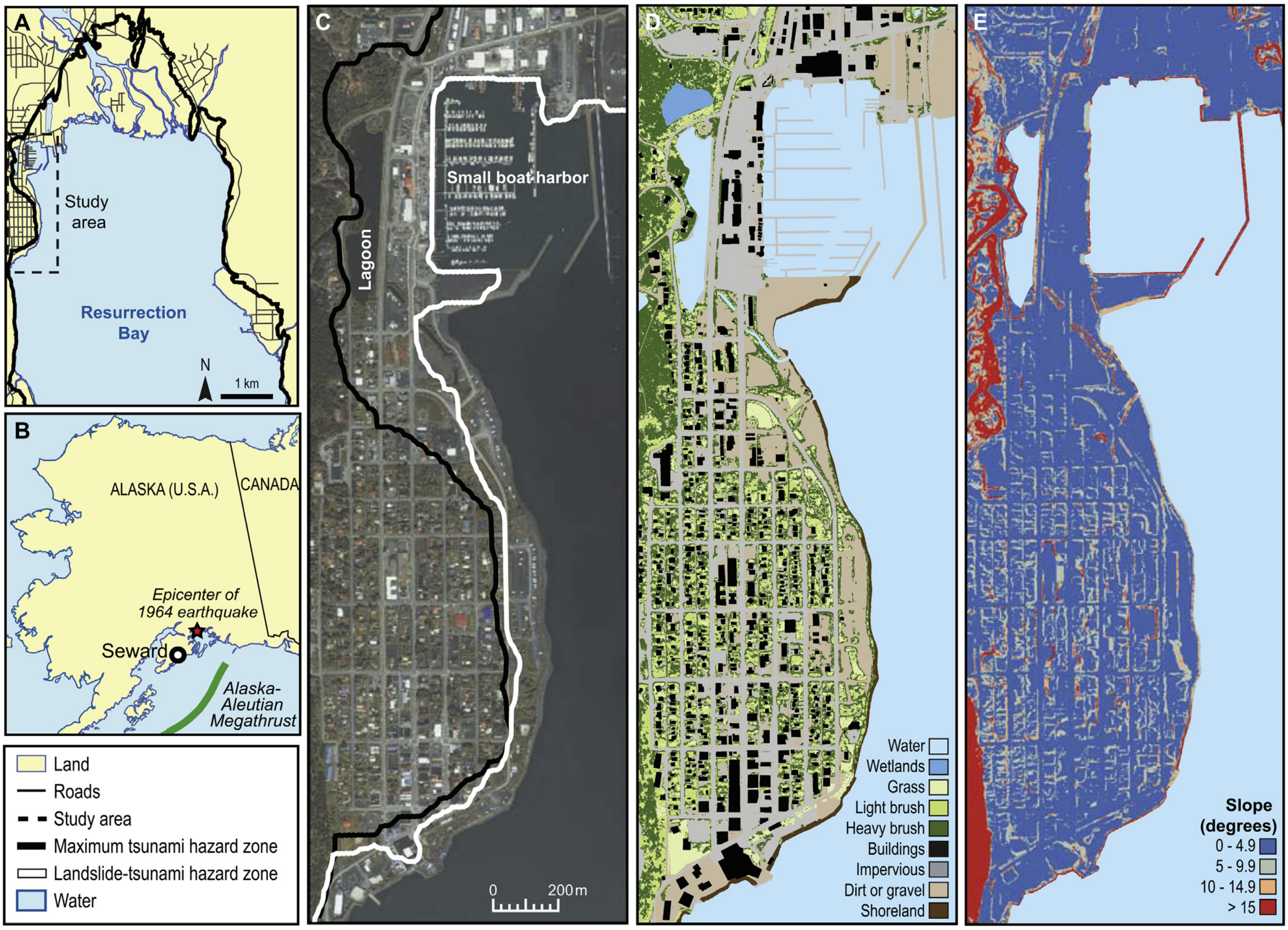

Fig. 1. Study area of Seward, Alaska, including (A) Seward's location in Resurrection Bay, Alaska, (B) Seward's location in the State of Alaska, (C) a 2005 image of downtown Seward including lines noting a maximum tsunami-hazard zone (black line) and potential inundation caused by submarine landslides (white line), (D) land cover in Seward based on a manual interpretation of 2005, 1-m resolution, RGB-band orthorectified IKONOS imagery, and (E) slope based on a 2009 5-foot (1.5 m) LiDAR-derived digital elevation model of the area (elevation and imagery from Kenai Peninsula Borough GIS Division, 2013).