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TSUNAMI EVACUATION ANALYSIS OF SOME UNINCORPORATED TILLAMOOK COUNTY COMMUNITIES: BUILDING COMMUNITY RESILIENCE ON THE OREGON COAST

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.

Geodatabase is Esri® version 10.1 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

Tillamook_County_Tsunami_Evacuation_Modeling.gdb:

XXL1_BridgesOut feature dataset:

XXL1_BridgesOut_EvacuationFlowZones
XXL1_BridgesOut_EvacuationRoutes
XXL1_BridgesOut_WalkingSpeeds_Roads
XXL1_BridgesOut_WalkingSpeeds_Trails

XXL1_BridgesIn feature dataset:

XXL1_BridgesIn_EvacuationFlowZones
XXL1_BridgesIn_EvacuationRoutes
XXL1_BridgesIn_WalkingSpeeds_Roads
XXL1_BridgesIn_WalkingSpeeds_Trails

L1_BridgesOut feature dataset:

L1_BridgesOut_EvacuationFlowZones
L1_BridgesOut_EvacuationRoutes
L1_BridgesOut_WalkingSpeeds_Roads
L1_BridgesOut_WalkingSpeeds_Trails

Rasters

MaxTsunamiFlowDepth_XXL1
TsunamiWaveArrival_XXL1

Metadata in .xml file format:

Each feature class listed above has an associated, standalone .xml file containing metadata in the Federal Geographic Data Committee Content Standard for Digital Geospatial Metadata format.

ABSTRACT

Pedestrian evacuation routes were evaluated for a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) in the Tillamook County communities of Cape Meares, Bayocean Spit, Oceanside, Netarts, Cape Lookout State Park, and Neskowin. Our analyses focused on a maximum-considered CSZ tsunami event covering 100% of potential variability, termed XXL and generated by a magnitude 9.1 earthquake. Evacuation paths were limited to established roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

To assist in pedestrian tsunami evacuation, we produced maps and digital data that include the following:

- Tsunami wave advance for an XXL event,
- Detailed "Beat the Wave" (BTW) results for the XXL scenario, including evacuation routes and minimum walking speeds,
- Detailed BTW results for the L1 scenario in select locations,
- BTW results for multiple hypothetical scenarios, and
- Socioeconomic analysis that provides insights into the unique preparation, response, and recovery challenges that communities may face due to vulnerable populations.

The BTW maps depict the ***minimum evacuation speed*** required to stay ahead of the tsunami wave given a variety of scenarios that will increase evacuation difficulty. The base scenario uses the existing road network and includes a 10-minute delay from start of earthquake before beginning evacuation. Additional challenges to evacuation are discussed, including failure of non-retrofitted bridges and effects from landslides and liquefaction. In all cases, ***the identified minimum speeds must be maintained for the entire time it takes to evacuate from the inundation zone.***

Given the model limitations defined in the Methods section, results show that evacuation for most of the Tillamook County communities examined is achievable at a moderate walking speed (4 fps or 2.7 mph). Even for those with mobility limitations (i.e., those who cannot travel at speeds more than 4 fps), safety can be reached ahead of the wave from nearly every location. Exceptions to this arise on Bayocean Spit, Cape Lookout State Park, and Neskowin. For the latter, longer distances to high ground and limited evacuation routes make this an especially difficult location to reach safety prior to the arrival of the tsunami. Liquefaction could present a significant challenge to evacuation across the region.

For the purposes of this report, we refer to tsunami mitigation in terms of actions used to improve the survivability of a local community population. Thus, the results presented in this study are about evaluating ways to help move people out of the tsunami zone in the shortest amount of time possible between the start of earthquake shaking and the arrival of the tsunami. Given this context, mitigation options may include adding new evacuation routes, constructing earthquake-hardened roads (built or remodeled to withstand shaking from a major earthquake and liquefaction), enhancing tsunami wayfinding signage along core routes, and/or installing a tsunami refuge, otherwise known as a vertical evacuation structure.

1.0 INTRODUCTION

The objective of this study is to provide local government with a quantitative assessment of challenges affecting tsunami evacuation for the Cascadia subduction zone XXL scenario in the unincorporated Tillamook County coastal communities of Cape Meares, Bayocean Spit, Oceanside, Netarts, Cape Lookout State Park, and Neskowin. (Pacific City is not included here because it is part of a separate study [Gabel and others, 2018]; Neahkahnie is part of a study to be published next year.) These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, land use planning, and potential vertical evacuation options. A similar study is available for Rockaway Beach (Gabel and Allan, 2017).

A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For the majority of the population, spontaneous evacuation on foot will be the only effective means of limiting loss of life, because vehicle evacuation would be quickly compromised by traffic congestion and road blockages. CSZ earthquakes affecting the Oregon coast will likely be on the order of ~Mw 9.0 (Priest and others, 2009; Witter and others, 2011), severely damaging bridges and other infrastructure that may be critical to evacuation. To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic scenarios, five of which are mapped statewide, each covering the following percentages of potential variability of Cascadia tsunami inundation (Priest and others, 2013b):

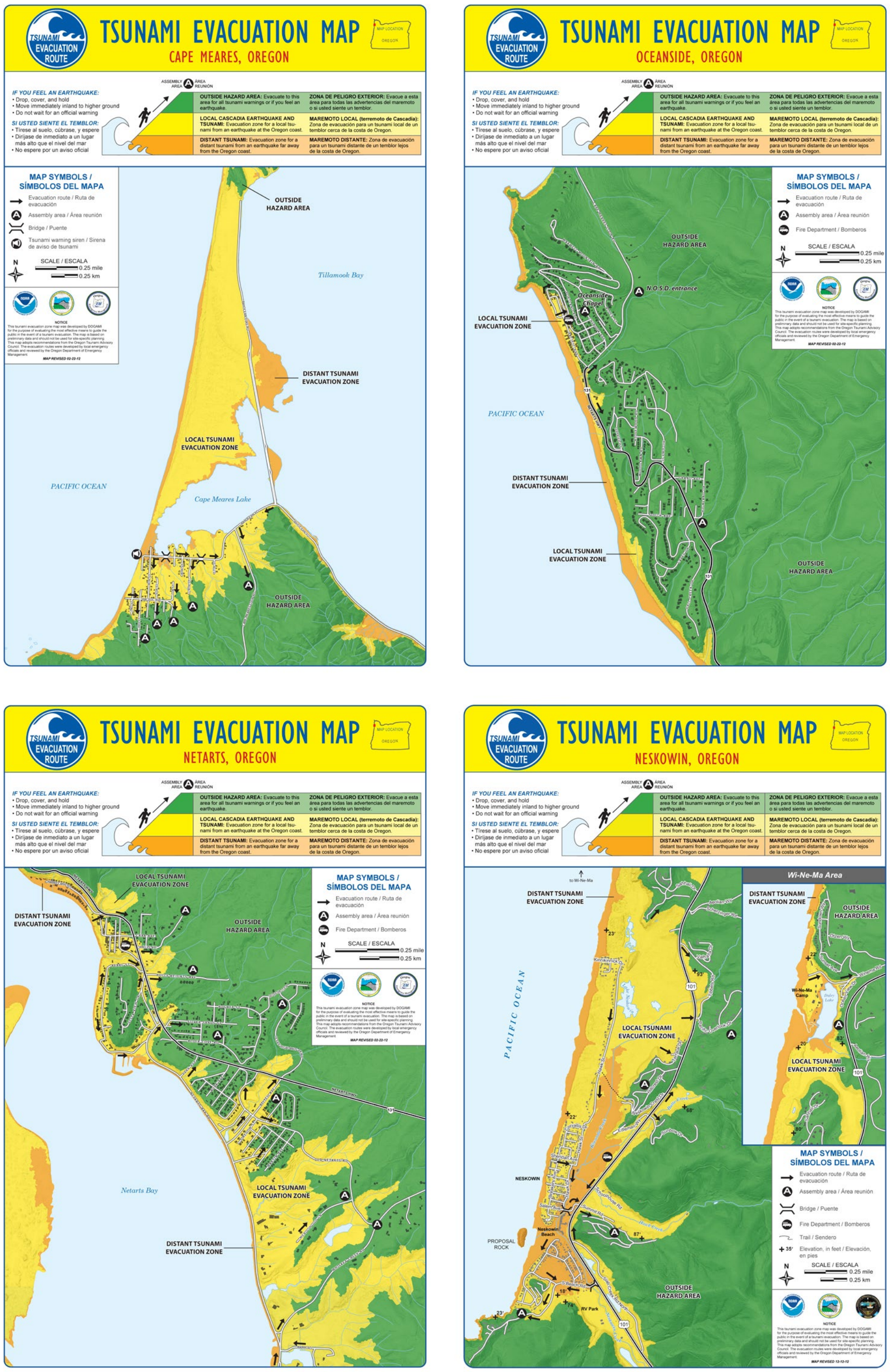
- Extra-extra-large (XXL1) (100%)
- Extra-large (XL1) (98%)
- Large (L1) (95%)
- Medium (M1) (79%)
- Small (SM1) (26%)

The maximum-considered CSZ tsunami (XXL1, referred to as “XXL” for much of the remainder of this report) inundates some portion of all Tillamook County communities included in this study and in some cases, the entire community (**Figure 1-1**). Much of the area will start to be flooded within 20 minutes of the start of earthquake shaking.

A Note about Bridges and Tsunami Evacuation Tillamook County

Bridges can further complicate tsunami evacuation if they prove to be essential to a route and are not built to withstand the shaking from the earthquake. Because of this, DOGAMI tsunami evacuation analyses include both “Bridges In” and “Bridges Out” Beat the Wave (BTW) scenario modeling. Except for Neskowin, modeling indicates bridges in this area are not essential for tsunami evacuation (i.e., safety can be reached without needing to cross bridges). Because “Bridges In” and “Bridges Out” Beat the Wave results are similar—and in most cases identical—only “Bridges Out” results are included in this report for the complete study area. In Neskowin, the Salem Avenue Bridge is important to evacuation, so modeling results for “Bridges In” are included for Neskowin.

Figure 1-1. DOGAMI (2012a,b,c,d) tsunami evacuation maps for communities included in this study, including (top left) Cape Meares, (top right) Oceanside, (bottom left) Netarts, and (bottom right) Neskowin and (insert) Wi-Ne-Ma area (maps are at various scales). Inundation for a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL) is shown in yellow, while the maximum-considered distant tsunami scenario is shown in orange. (Note: the Cascadia scenario encompasses BOTH the yellow and orange zones.) High ground outside the XXL hazard area is green. See Witter and others (2011) for detailed explanations of the tsunami scenarios shown on this map. Full-scale versions of these maps are available at https://www.oregontsunami.org.



To further understand the evacuation landscape, we undertook a socioeconomic analysis to assess the numbers and types of people, businesses, and critical facilities (schools, hospitals, police, and fire) in the XXL, Large (L) and Medium (M) scenario tsunami zones. To date, socioeconomic exposure analyses have been completed for the Oregon coast using only the DOGAMI Large scenario (Wood and others, 2016), which covers ~95% of potential CSZ inundation variability. By performing similar analyses for XXL and Medium scenarios, we are now beginning to have a better understanding about the range of socioeconomic impacts the next CSZ tsunami is likely to have. To further improve our understanding of the likely socio-economic effects the next Cascadia earthquake and accompanying tsunami will have on coastal communities, DOGAMI has initiated a more comprehensive risk assessment project using the Federal Emergency Management Agency Hazus tool in order to determine more detailed exposure impact data (fatalities, injuries, buildings damaged, debris volumes etc.) for the Medium through XXL local tsunami scenarios. The timeline for these data becoming available for north coast communities is ~1-2 years.

We evaluate tsunami evacuation difficulty by:

1. Illustrating how quickly the wave front of an XXL tsunami advances across the area after the earthquake,
2. Determining whether an evacuee can stay ahead of the tsunami all the way to safety on the routes defined by the LCD analysis, termed "Beat the Wave" (BTW),
3. Running multiple BTW scenarios to investigate potential vulnerabilities and mitigation options, and,
4. Providing a socioeconomic analysis that provides insights into the unique preparation, response, and recovery challenges that communities may face due to vulnerable populations.

2.0 METHODS

Agent-based and LCD modeling are the two most common approaches for simulating pedestrian evacuation difficulty. Agent-based modeling focuses on the individual and how travel would most likely occur across various cost conditions, such as congestion points (Yeh and others, 2009). LCD modeling focuses on characteristics across the evacuation landscape, such as slope and land cover type (e.g., roads, trails, and beaches). LCD modeling calculates a least-cost path to the tsunami inundation limit for every point in the inundation zone, artificially increasing distances for non-optimal walking conditions (e.g., steep slopes, difficult land cover) and choosing the best routes accordingly. Time to traverse a route can then be estimated by dividing the least-cost path by a single pedestrian walking speed. We used the LCD model of Wood and Schmidtlein (2012) to understand better the spatial distributions of evacuation times without having to create a large number of scenarios for specific starting points required by agent-based models. BTW models integrate tsunami wave arrival data directly into the LCD analysis to produce map of ***minimum*** speeds that must be maintained to reach safety. Additional information on the methodology is given by Gabel and Allan (2017) and Priest and others (2015, 2016).

2.1 Road and trail network

We used a model that considered only roads, paths, and the dry sand backshore of beaches as evacuation pathways; all other land cover classes were essentially excluded. This removes the complication of crossing private property and allows us to generate informative maps. Geospatial data representing roads, pedestrian paths, and beaches were generated through manual classification of imagery, were field verified, and then were reviewed by local officials. The backshore is defined as areas landward of the beach-dune junction approximated by the 18-ft NAVD88 (North American Vertical Datum of 1988) contour. The beach (below 18 ft) was excluded owing to uncertainty of travel difficulty (cost) on wet versus dry sand and potentially liquefied sand during a local subduction zone earthquake. Due to the wide variety of beach surfaces, modeled BTW speeds on beach "trails" is intended to provide only a rough approximation of the time and speeds required to evacuate the area. We chose to ignore travel time from buildings or other parts of urban areas to the roads, because there is large uncertainty in conditions both before (e.g., fenced yards) and after the earthquake (e.g., fallen debris). Because of these assumptions and factors, the modeling approach produces ***minimum*** evacuation speeds to evacuate safely from the inundation zone.

2.2 Hypothetical scenarios

The evacuation landscape was first evaluated by using the existing road, trail, and bridge network. An inventory of infrastructure at risk of failure during the earthquake was collected and a suite of scenarios was developed to investigate the resulting evacuation route challenges. These include the potential failure of bridges and road blockages (slowdowns) caused by landslides or liquefaction. Additional scenarios reflecting hypothetical mitigation options were then considered to address these challenges, including constructing new trails, hardening existing roads or trails, seismically retrofitting a bridge, constructing new pedestrian and/or car bridges, and building vertical evacuation structures. In some cases, no options were considered feasible and no hypothetical scenarios were modeled. Multiple review sessions with community officials ensured local needs and concerns were addressed by the scenarios.

We simulated bridge failure by removing that section of the road network, forcing the model to recalculate routes that originally relied on bridge connectivity. Which bridges to remove for the simulations was based on conversation with local officials and on information about which bridges had been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. We always begin our simulation set with a "base" run that includes all bridges. Subsequent simulations without bridges allow us to compare the results with the base run and highlights which bridges are important for evacuation. These results can be important when prioritizing which bridges to retrofit or to construct as part of a long-term resilience plan.

In coastal towns, landslide-prone slopes and saturated sandy soils are common; therefore slides, liquefaction (**Figure 2-1, left**), and lateral spreading (**Figure 2-1, right**) are likely to occur during an earthquake (Madin and Wang, 1999). These hazards will damage roads and reduce walking speeds by significant but indeterminate amounts. Because knowing where to remove routes remains highly uncertain and site specific, we did not model the effect of lateral spreading on evacuation difficulty. However, we did evaluate evacuation difficulty due to liquefaction in areas with high susceptibility (Madin and Burns, 2013). This was achieved by adjusting the land cover values to reflect loose sand instead of pavement for those roads potentially susceptible to liquefaction, thereby increasing the time it would take to evacuate along these roads; additional information describing land cover values is provided in section **2.3.3**. By identifying at-risk areas, a community can focus additional efforts on possible mitigation options like retaining walls, soil replacement, vibrocompaction, and construction of liquefaction-proof paths.

Figure 2-1. Water-saturated sand can turn to quicksand during strong shaking, forming sand boils, ponding, and sunken roads. In these examples, (A) extensive liquefaction occurred along River Road in Christchurch, New Zealand following the February 2011 earthquake, while (B) effects from lateral spreading along numerous Christchurch roads constructed next to waterways resulted in major failures to road infrastructure as roads slumped toward river channels. During a Cascadia subduction zone event, such processes could compromise tsunami evacuation routes as well as the time and speed to safety in areas prone to liquefaction. (Photo credits: Martin Luff, licensed under CC BY-SA 2.0)

For landslide potential, we used the Statewide Landslide Information Database for Oregon (SLIDO, version 3.4, https://www.oregongeology.org/slido/index.htm) to evaluate previously identified landslides in the area. We also considered possible landslide activity based on susceptibility mapping by Burns and others (2016). For areas where landslides have the potential to remove completely an evacuation route, we created hypothetical scenarios to reflect that. There may be areas where landslide activity may make evacuation difficult but not impossible, and in those cases, we did not always model a landslide scenario. It is also likely that the area will be littered with smaller shallow slides (and possibly new deep-seated slides) after the earthquake, which will likely affect many roads; evaluating such landslides is beyond the scope of this study.

In some localities, safe and effective evacuation to high ground may not be feasible due to terrain challenges (high ground is too far away) or to potential failure of critical evacuation infrastructure such as bridges. Given these circumstances, communities may want to explore the construction of a vertical evacuation structure, designed to withstand the forces directed at it by the tsunami. Such structures include soil berms or structures that can serve dual purposes as parking garages, community facilities, commercial facilities (e.g., hotels), and schools (Applied Technology Council, 2012). In the United States, the first vertical evacuation structure was opened in June 2016 at the Ocosta Elementary School on the Westport Peninsula in Washington State. The structure is the school’s new gymnasium and has unrestricted (open) access to its rooftop, where schoolchildren and residents may congregate during a tsunami evacuation. The second of its kind in the country is currently being built at Hatfield Marine Science Center (HMSC) in south Newport, Oregon, with expected completion in 2020. We incorporate vertical evacuation structures into BTW modeling by editing the tsunami hazard zone to exclude a small polygon of safety at the location of a hypothetical structure.

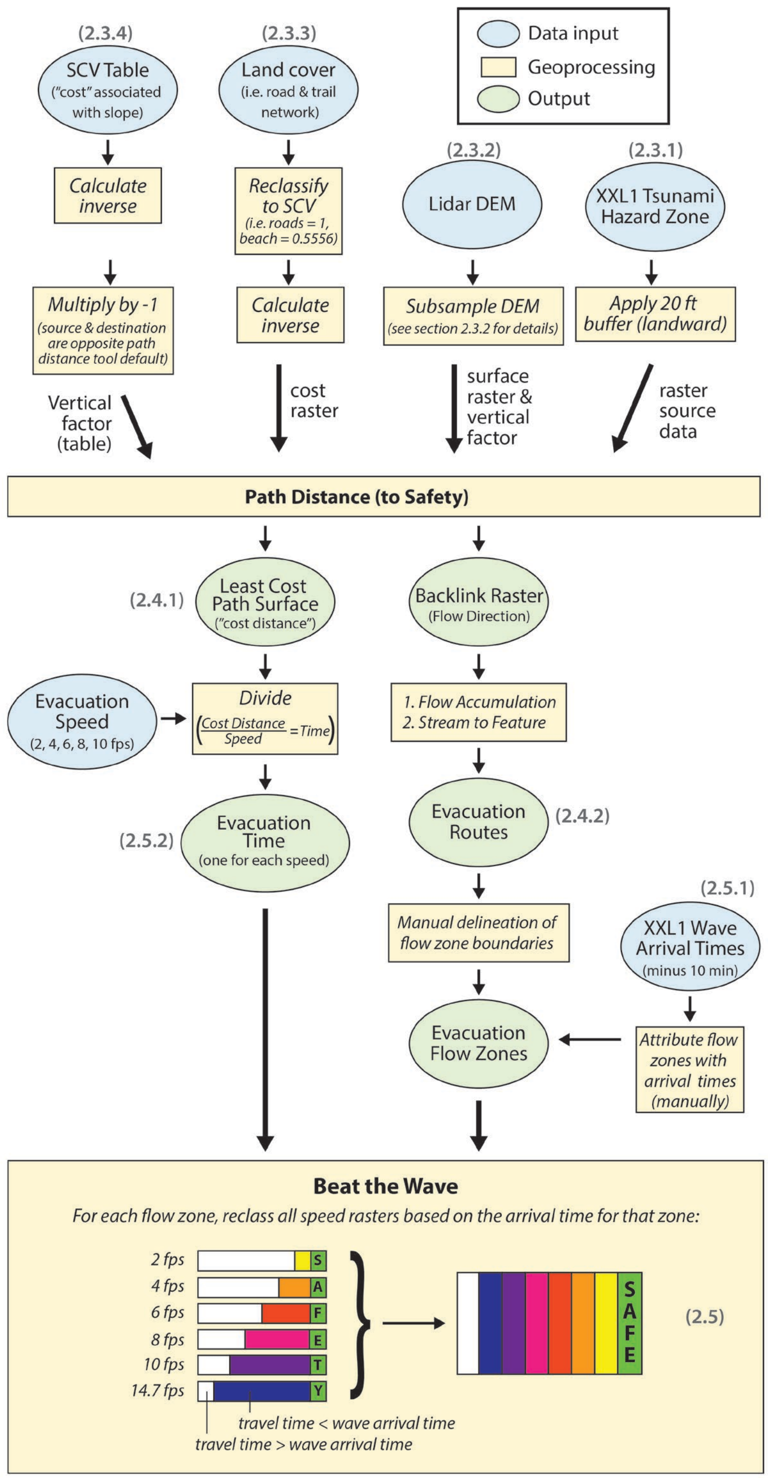
Regardless of infrastructure improvements considered for an area, wayfinding and outreach will always be an essential part of tsunami evacuation planning.

2.3 LCD model inputs

LCD modeling is based on four inputs: the XXL tsunami inundation limit, a digital elevation model (DEM), a land surface cost raster, and a table relating slope to cost. The road and trail network is provided via the land surface cost raster. The tsunami inundation limit (plus 20 lateral feet for conservatism) serves as the destination for all evacuation routes. The DEM is used to determine actual distances and slopes. The slope data, in conjunction with the slope table, are used to apply a cost reflecting evacuation difficulty due to hilliness. The land cost raster contains a second set of cost values reflecting evacuation difficulty due to terrain. A detailed discussion of all four inputs is presented in the following sections.

We implemented LCD modeling by using Esri® ArcGIS® 10.6 software. The path distance tool uses geospatial algorithms to calculate the most efficient route from each point in the evacuation zone to "safety," defined for the purposes of this study as ~20 lateral feet (6 m) outside the maximum inundation limit; this is where the tsunami flow depth and velocity are effectively zero. The product of this tool is referred to as the least-cost path distance surface, and it reflects an artificial distance to safety for every point in the evacuation zone that contains the difficulty of walking that route. **Figure 2-2** summarizes the steps and inputs into the path distance tool as well as the subsequent BTW approach.

Figure 2-2. Model diagram of Beat the Wave tsunami evacuation methodology using the path distance approach from Wood and Schmidtlein (2012) and Wood and others (2016). SCV is speed conservation value; DEM is digital elevation model. The methodology was first detailed by Priest and others (2015, 2016). XXL is the maximum-considered Cascadia subduction zone (CSZ) tsunami scenario, covering 100 percent of potential CSZ tsunami inundation (Witter and others, 2011, Priest and others, 2013b). Unit fps is feet per second. Grey numbers indicate sections in this report where a step is discussed in detail.



2.3.1 Tsunami hazard zone

The inundation zone used in this study is XXL1, derived from digital data of Priest and others (2013a,b). This zone covers 100 percent of potential CSZ inundation (Witter and others, 2011), meaning it is the largest CSZ event likely to occur based on the 10,000 year record and reflects the zone used for evacuation as shown in DOGAMI evacuation brochures (https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm) and online (http://nvs.nanoos.org/TsunamiEvac) for the entire Oregon coast. In extreme cases where evacuation from XXL is unlikely due to long distances to safety, results are shown for the L1 tsunami scenario (Priest and others, 2013a,b). This zone covers 95% of potential CSZ inundation, meaning that there is only a 5% chance that high ground outside L1 will be inundated by a larger tsunami.

For the purposes of this study, safety is reached when an evacuee has walked ~20 feet beyond the limit of tsunami inundation. Safety is also referred to as "high ground" throughout the remainder of this report. Safety *destinations* represent locations on the road and trail network that are ~20 feet beyond the limit of inundation (primarily XXL). These locations were created by applying a buffer of 20 feet (6 m) on the landward side of the inundation boundary polyline and converting this into a raster data file.

2.3.2 DEM

Initially, we created a high-resolution digital elevation model (DEM) by interpolating lidar ground points into a 6-ft-resolution raster; in areas characterized by bridges, we used lidar highest-hit data to define the bridge walking surface. We smoothed the DEM grid, because generated slope profiles are too noisy, introducing slope artifacts of significant amplitude (e.g., a 3-inch elevation difference between cells 1 foot apart yields a 14° slope) that add significantly more time to the total calculated time (Priest and others, 2015, 2016). To smooth the data, we created points at 50-foot intervals along all evacuation paths including major roads and at intersections, and we attributed those points with elevation values from the native 3-foot-cell lidar DEM. Priest and others (2015, 2016) performed trials at 25, 50, and 100 feet and found that the 50-foot interval achieved the best compromise between accuracy and smoothness. The final sampling interval was ~50 feet on straight paths and somewhat less for curved paths in order to depict accurately the curvatures. We then interpolated those points using an Esri Natural Neighbor function to produce a smoothed DEM that closely emulated the actual elevation values of the lidar while dramatically reducing slope noise.

2.3.3 Land cover raster

The land cover raster serves two purposes: 1) it defines the spatial extent of the road and trail network, and 2) it describes the land cover for all surfaces in the region, by assigning a specific level of difficulty of movement across the surface for each pixel. In the Wood and Schmidtlein (2012) approach these difficulty or cost values are categorized as speed conservation values (SCV), where each value is representative of a land cover type across the landscape. Land cover SCVs adjust the base travel speed by using terrain-energy coefficients as discussed by Soule and Goldman (1972), including "No Data" to note where travel is not allowed (e.g., over water, through fences or buildings, and across most natural/undeveloped areas for this study). The base travel speed assumes constant energy expenditure. Conversely, the constant energy expenditure assumption yields slower walking speeds under non-ideal walking conditions. Ultimately, the SCVs artificially increase the path distance across a pixel (6 ft) to reflect the difficulty in walking that section of road or trail. The SCV values used are shown in **Table 2-1**, and an example land cover raster is shown in **Figure 2-3**.

Table 2-1. Speed conservation values used in modeling pedestrian evacuation difficulty in this study.

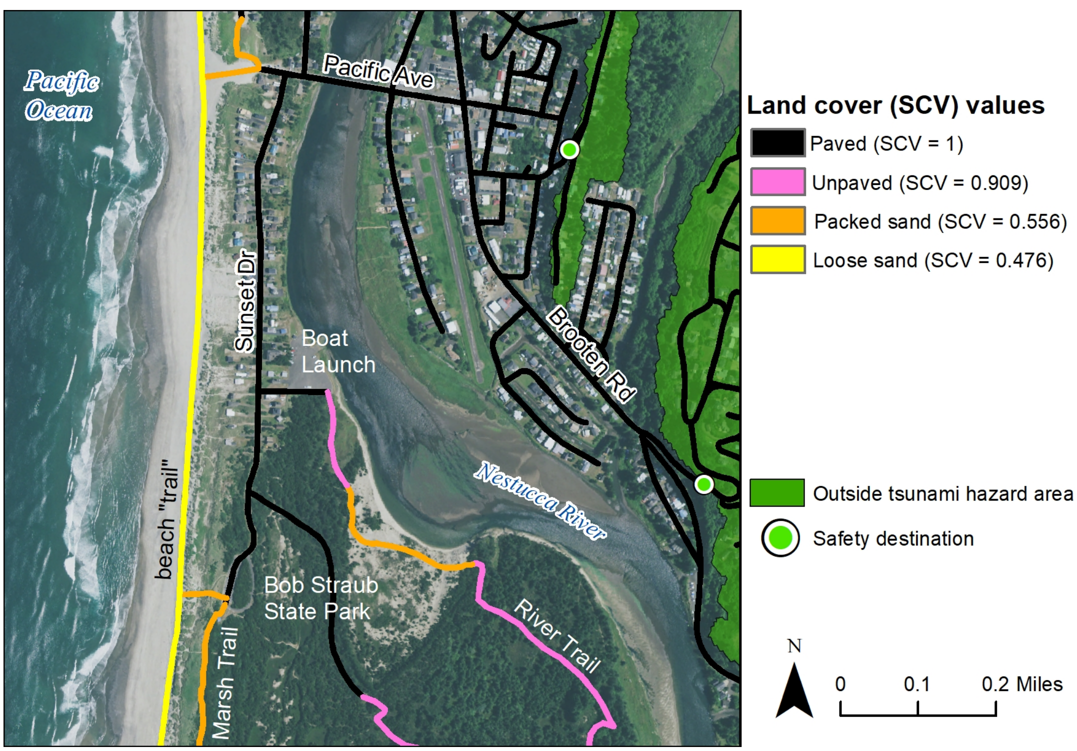
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

*Speed conservation values (SCV) are derived from Soule and Goldman (1972).

**Trails in the dune areas given the same SCV as sand given by Wood and Schmidtlein (2012).

GIS polylines representing all roads and trails in the project area were converted to polygons and attributed with land cover values (i.e., 1 for paved surfaces, 0.556 for packed sand, etc.). The polygons were then converted into a raster (6 ft cell size) for input into the LCD model.

Figure 2-3. Example of a land cover raster in Pacific City, Tillamook County, Oregon, which serves the dual purpose of defining the road and trail network and classifying it with land cover values. Base map is 2016 National Agriculture Imagery Program (NAIP) imagery; the XXL inundation zone (the non-green area) on this and following figures is from Priest and others (2013b).



2.3.4 Speed conservation value (SCV) slope table

We created a table that associates slopes with a specific SCV value. This table uses the same values as those of Wood and Schmidtlein (2012), and, as in their approach, we estimated the effect of slope on speed from Tobler's (1993) hiking function:

$$\text{walking speed (km/hr)} = 6e^{-3.5 \times \text{abs}(\text{slope}+0.05)}$$

where slope is equal to the tangent of the slope angle. This formula is based on empirical data of Imhof (1950) and predicts that speed is fastest on gentle (−3°) downslopes. **Table 2-2** presents an example set of slope and SCV values. The actual table used includes slope values from −90° to +90° in 0.5° increments. A positive slope (upward) results in a slower walking speed and is assigned a larger cost. The same applies for a large negative slope (steeply downward), while a slight decline (~3°) in the slope reflects the optimal condition.

Table 2-2. Speed conservation values used to calculate evacuation difficulty due to traversing hills, with slope determined for each pixel from the digital elevation model.

Slope (degrees)	Tobler (1993) Walking Speed (fps)	Speed Conservation Value*
−10	3.6	1.5
−5	4.8	1.1
−2.75 (ideal)	5.5	1
5	3.4	1.6
10	2.5	2.2

*Table displays an example set of values. Actual table used in modeling includes slope values from −90° to +90° in 0.5° increments. fps is feet per second.

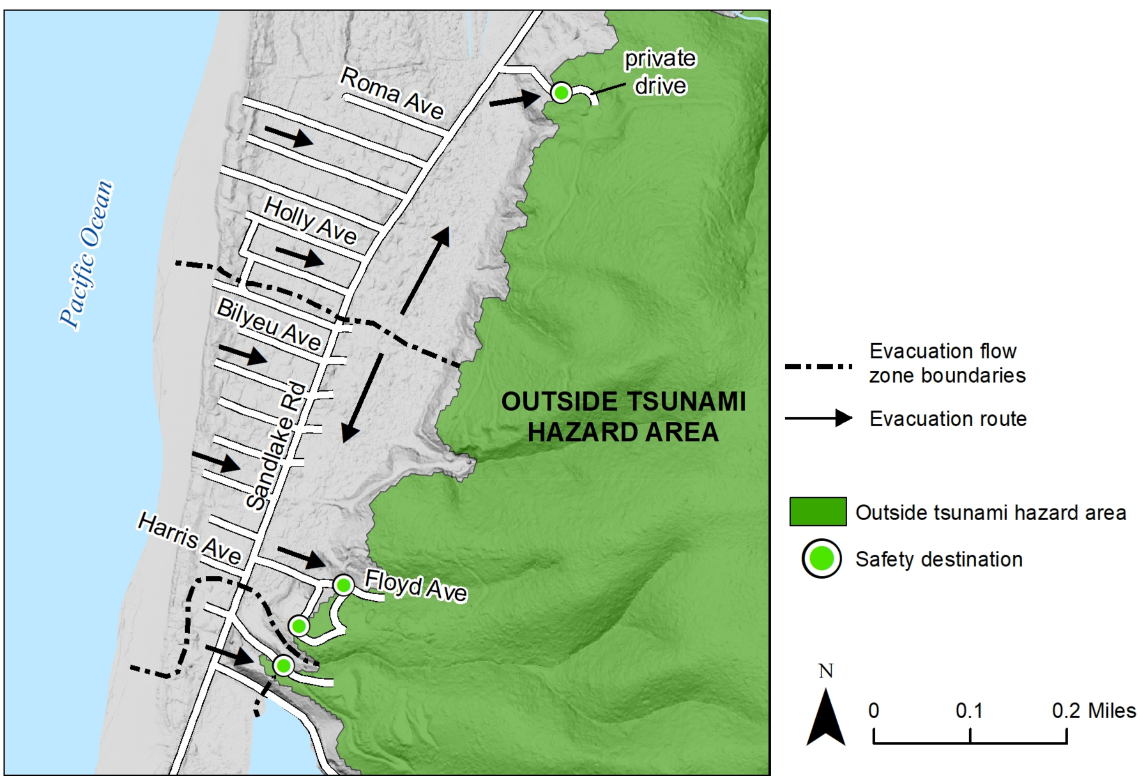
2.4 LCD model outputs

The LCD model outputs a path distance surface showing the effective distance to safety from each pixel and a flow direction raster containing detailed route information. From these data we create evacuation route, flow zone, and BTW maps.

2.4.1 Path distance surface

The pixel values on the path distance surface represent the effective distance, along the least-cost path, from the pixel to the point where the path intersects safety. For example, from the intersection of Sandlake Road and Bilyeu Avenue in Tierra Del Mar (**Figure 2-4**), the actual distance to safety up Floyd Avenue is 1,700 feet, while the least-cost path distance is 2,700 feet (path distances not shown on map). This difference is due to the model accounting for variations in slope and landcover along the entire route (although in this case the entire route is paved, meaning the cost is entirely due to the significant slope on Floyd Avenue).

Figure 2-4. Example of a network of generalized evacuation flow zones and select evacuation route arrows from a least-cost-distance analysis limited to trails and streets in Tierra Del Mar, Tillamook County, Oregon. Base map on this and subsequent figures is shaded relief from 2009 lidar data (Oregon Lidar Consortium North Coast Project, https://www.oregongeology.org/lidar/index.htm).



2.4.2 Evacuation routes and flow zones

The LCD backlink raster shows, for each cell, the direction of the next cell on the least-cost path. This raster makes it possible to trace the path to safety from any pixel and is equivalent to a flow direction raster, which is the first step in hydrologic modeling of topographic surfaces. We use the hydrologic tools in ArcGIS 10.6 and the backlink raster to extract a "stream" network to visualize the paths depicting the most efficient pedestrian flow for evacuation on trails and roads. Evacuation flow zones with arrows depicting the most efficient routes are shown in **Figure 2-4**. These paths represent the shortest effective distances to the nearest safety destination and are referred to as evacuation routes. **Figure 2-4** shows what we call "generalized evacuation routes," meaning the arrows illustrate the overall direction of travel toward a safety destination and are not turn-by-turn directions. Detailed evacuation routes are found in the digital data.

The routes can be simplified by identifying the boundaries of evacuation flow toward the nearest safety location. At these boundaries, one could travel in alternate directions to reach safety on separate paths that require equal amounts of effort (distance with slope and land cover effects included). These evacuation flow zones are directly analogous to watershed boundaries or drainage divides in hydrologic modeling. As an example, **Figure 2-4** shows that the nearest safety destination for people on Bilyeu Avenue in Tierra Del Mar is Floyd Avenue while the nearest safety destination for people on Holly Avenue is a private drive off Sandlake Road north of town. The dashed black line delineates the evacuation flow zone boundary.

Flow zone polygons are drawn manually using the evacuation routes as a guide. Flow zone rasters may also be generated by using the Esri Watershed tool in the Hydrology toolset; however, we found this method useful as a guide only, not as a source of functional data.

The importance of flow zone boundaries varies depending on the area. In some areas, so many roads head toward high ground that the decision to take one road versus another is minor. In other locations, flow zone boundaries inform the decision to travel in potentially opposite directions (for example, **Figure 2-4**).

2.5 Beat the Wave (BTW) modeling

BTW modeling integrates the results of the tsunami wave arrival times and the least-cost path distance analyses to enable the public to better understand the ***minimum speeds*** required to evacuate the inundation zone to avoid being caught by the approaching tsunami. BTW modeling is done by producing a suite of evacuation time maps at different walking speeds and combining them into one map based on unique wave arrivals for each evacuation flow zone. The goal of BTW maps is to highlight areas that have elevated evacuation difficulty in order to direct future mitigation efforts and educate the public on where to go and how fast to travel.

2.5.1 Wave arrival times

To understand the complexities of tsunami wave advance across the landscape, we extracted the time after the CSZ earthquake at which the XXL tsunami flow depth reached more than 0.5 ft at each computational grid point and interpolated those arrival data to create a continuous map showing wave arrival time.

Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted 10 minutes from the simulated tsunami arrival times to account for the time in which earthquake shaking takes place, as well as disorientation, and the time required to evacuate buildings. Using the March 11, 2011, Tohoku earthquake (U.S. Geological Survey, 2012) as an analogue to an XXL or L1 scenario, the minimum delay is probably ~3–5 minutes of strong shaking for an ~Mw 9.0 event. There are few empirical data on how long it takes people to begin evacuation after shaking, but Mas and others (2013) determined a mean of 7 minutes in 2010 and 2011 surveys at La Punta, Peru, which has experienced several local earthquakes and tsunamis over the last ~400 years, the last being in 1974. We therefore simulate a delay of 10 minutes mainly for earthquake shaking (the minimum of 3 minutes for shaking plus 7 minutes based on the La Punta survey). This is a rough estimate meant to account for many possible actions taken by evacuees such as looking for family members, digging out of rubble, or packing a bag prior to evacuating.

For areas with large campgrounds and few to no permanent residents, we reduced the delay from 10 minutes to 5 minutes to reflect the likelihood of people being outdoors (or inside an RV or tent) when the earthquake begins. We anticipate a shorter delay between earthquake shaking and evacuating for someone in a tent or RV compared with someone in a building.

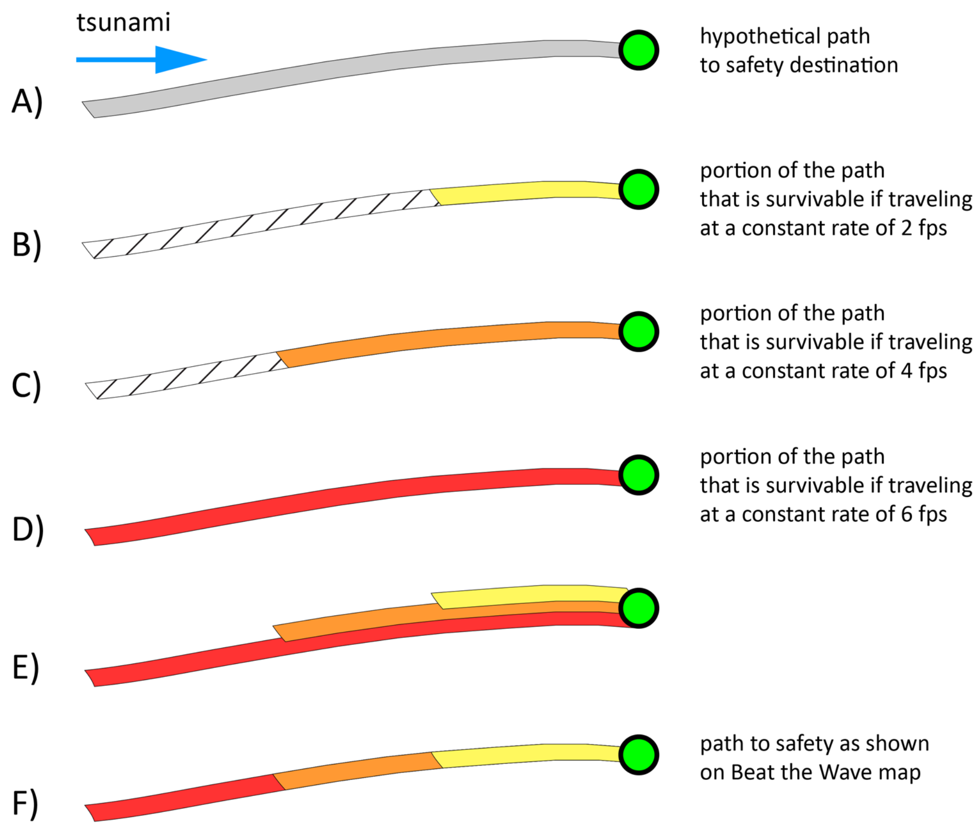
2.5.2 Evacuation time maps

We converted the path distance surfaces to walking times to compare tsunami arrival times to pedestrian arrival at various critical junctures. We did this by dividing the path distance surface raster by a constant speed (distance ÷ speed = time). We started by assuming a pedestrian walking speed of 4 feet per second (fps) (22 minutes/mile; 1.22 meters/second), a pace listed as a moderate walk by Wood and Schmidtlein (2012). This is the speed generally required to cross from curb to curb at signalized intersections (Langlois and others, 1997; U.S. Department of Transportation, 2012).

In order to explore fully an array of evacuation speeds appropriate for specific populations (e.g., elderly or small children versus able-bodied adults) we generated multiple evacuation time maps using pre-determined evacuation speeds (2, 4, 6, 8, 10, and 15 fps). We then "clipped"[1] these time maps twice: once to separate flow zones and again based on the unique wave arrival time for each zone. For each evacuation speed within a flow zone, the surface was clipped at the point where the time to reach safety was greater than the wave arrival time. These clipped grids were then mosaicked together, with the minimum speed for each cell maintained. These steps are described graphically in **Figure 2-5** and in the final step of **Figure 2-2**. By integrating evacuation time maps with tsunami wave arrival data, we can now produce Beat the Wave (BTW) maps that estimate the ***minimum speed*** needed to reach safety ahead of the wave.

[1] "Clip" is a GIS command that "extracts features from one feature class that reside entirely within a boundary defined by features in another feature class" (https://support.esri.com/en/other-resources/gis-dictionary).

Figure 2-5. Beat the Wave (BTW) tsunami evacuation map construction. (A) shows a hypothetical evacuation route. (B), (C), and (D) show the path with constant walking speeds of 2 fps, 4 fps, and 6 fps, respectively. The farther away from safety (green dot) evacuees begin the route, the faster they must walk at a constant rate to reach safety ahead of the tsunami. At 2 fps only a relatively small amount of the route is survivable (hashed areas denote unsurvivable sections of the path at given walking speed); however, at faster walking speeds, evacuees can cover more distance and reach safety if they maintain the initial walking speed. (E) displays how the different constant walking speeds are combined to create the (F) final BTW map. The BTW map shows minimum constant speeds necessary to reach safety ahead of the tsunami.



Evacuation speeds were initially grouped into five categories, which allow enough contrast in color choice that areas can be easily perceived on the map. A literature review of typical pedestrian speeds by Fraser and others (2014) found five travel speed groups: adult impaired, adult unimpaired, child, elderly, and running (**Table 2-3**). The ranges of speeds for these groups at one standard deviation (the last two rows of **Table 2-3**) provide some guidance for establishing bins that would be useful on the BTW map. We then gave speed categories in the map explanation qualitative names such as “slow walking” and “running,” so the public could relate speed bins to their experience. Of particular interest are population groups that will be most vulnerable, such as impaired adults and the elderly, with mean speeds of 3 fps and a range of ~2–4 fps (**Table 2-3**). In an earlier Seaside BTW study (Priest and others, 2015) we examined the range of BTW speeds and reviewed a number of references describing speed categories (Paul, 2013; Margaria, 1968) to settle on the following five speed bins:

- Very slow walking at 0–2 fps
- Slow walking at 2–4 fps for elderly and impaired adults
- Walking at 4–6 fps for unimpaired adults
- Fast walking to slow jogging at 6–8 fps for fit adults
- Running at >8 fps

However, for extremely long path distances and fast wave-arrival times, we further divided the highest bin (>8 fps) into three bins to understand better the likelihood of survivability:

- Running at 8–10 fps
- Sprinting at 10–14.7 fps (14.7 fps = 10 mph)
- Unlikely to survive (must sprint at > 14.7 fps)

A small experiment was conducted at Seaside to evaluate the validity of the ***walk***, ***fast walk***, and ***slow jog*** BTW evacuation speed bins and to assess the difficulty in maintaining a constant minimum speed over the course of an entire evacuation route (Gabel and Allan, 2016). Five key routes were traversed by Gabel and Allan, who recorded their average speed along the route and the times when they reached critical locations (bridges, low areas, and safety). Overall, the tests indicated that when traveling at the speed specified by the BTW data, an evacuee will reach safety ahead of the tsunami. However, as speeds fall below the prescribed BTW speeds, the results of Gabel and Allan confirmed that the tsunami could overrun the individual. This limited test of BTW data suggests that the data are reasonable guides to minimum evacuation speeds necessary to reach safety ahead of the tsunami.

Table 2-3. Travel speed statistics for each travel speed group, compiled from travel speeds in the literature by Fraser and others (2014). Symbol σ denotes standard deviation.

	Adult Impaired	Adult Unimpaired	Child	Elderly	Running
Minimum	1.9 fps	2.9 fps	1.8 fps	0.7 fps	5.9 fps
Maximum	3.5 fps	9.2 fps	6.9 fps	4.3 fps	12.6 fps
Mean	2.9 fps	4.7 fps	4.2 fps	3.0 fps	9.1 fps
σ	0.6 fps	1.6 fps	2.6 fps	1.0 fps	3.3 fps
Mean + 1σ	3.5 fps	6.3 fps	6.8 fps	4.0 fps	12.4 fps
Mean − 1σ	2.3 fps	3.1 fps	1.6 fps	2.0 fps	5.8 fps

2.5.3 Reading a BTW map

As previously stated, the modeling approach produces ***minimum*** evacuation speeds that must be maintained along the entire route to safety. Actual travel speeds on any evacuation route will require either variable expenditure of energy to maintain a constant speed in all conditions, or higher speeds in easier terrain (flat paved streets) to compensate for slower speeds in more difficult terrain (e.g., steep slopes or sand).

BTW map colors represent the speed that must be **maintained** from each location all the way to safety. If an evacuee slows down for some portion of the route, they must account for the time deficit by traveling faster than the required speed for the remainder of the route. We stress this point because the map can be misleading: as a route approaches safety the roads along which one travels show a slower BTW speed, but an evacuee cannot slow down. The slower speed is only relevant for someone starting evacuation from that closer location.

2.6 Socioeconomic analysis

We compiled socioeconomic data that provide insights into the unique preparation, response, and recovery challenges that communities may face from a CSZ-caused tsunami. For summarization purposes we used the boundaries contained within U.S. Census Bureau census-designated places (CDP) GIS dataset (U.S. Census Bureau, 2010). For incorporated cities, the CDPs use established city boundaries. For unincorporated communities, the US Census Bureau developed boundaries that contain a concentration of population. The figures and tables in this report used the CDP GIS dataset. We note that within Oregon, CDPs are non-legal entities and are for statistical summarization purposes.

DOGAMI processed geocoded Oregon Department of Motor Vehicles driver license records to quantify the overall number and age category of permanent residents in the tsunami zone. We used the 65 and over years of age as a single breakpoint to establish the percentage of the older population in the tsunami zone. Past studies have noted that older people tend to evacuate at slower rates or are more likely choose not to evacuate, compared to people under 65 years of age (González-Riancho and others, 2015). For each community we quantified the number of people per tsunami zone (Medium, Large, XX-Large) and the percentage of the people in the zone that are 65 years of age or older.

We obtained selected data from American Community Survey (ACS) 2013–2017 five-year averaged estimates (https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2017/). The ACS data are available at a city and CDP level. We note that the ACS data are presented for the entire community and not available by tsunami zone. Given that the ACS relies on statistical sampling, we include the 90% uncertainty boundaries to emphasize the uncertainty present in each estimate. In general, smaller communities have a wider range of uncertainty for each estimate. The two primary community characteristics we obtained were the number of people with disabilities and the number of households in which Spanish is primarily spoken (American Community Survey Tables S1810 [Disability Characteristics], and S1602 [Limited English Speaking Households], respectively [U.S. Census Bureau, 2018]).

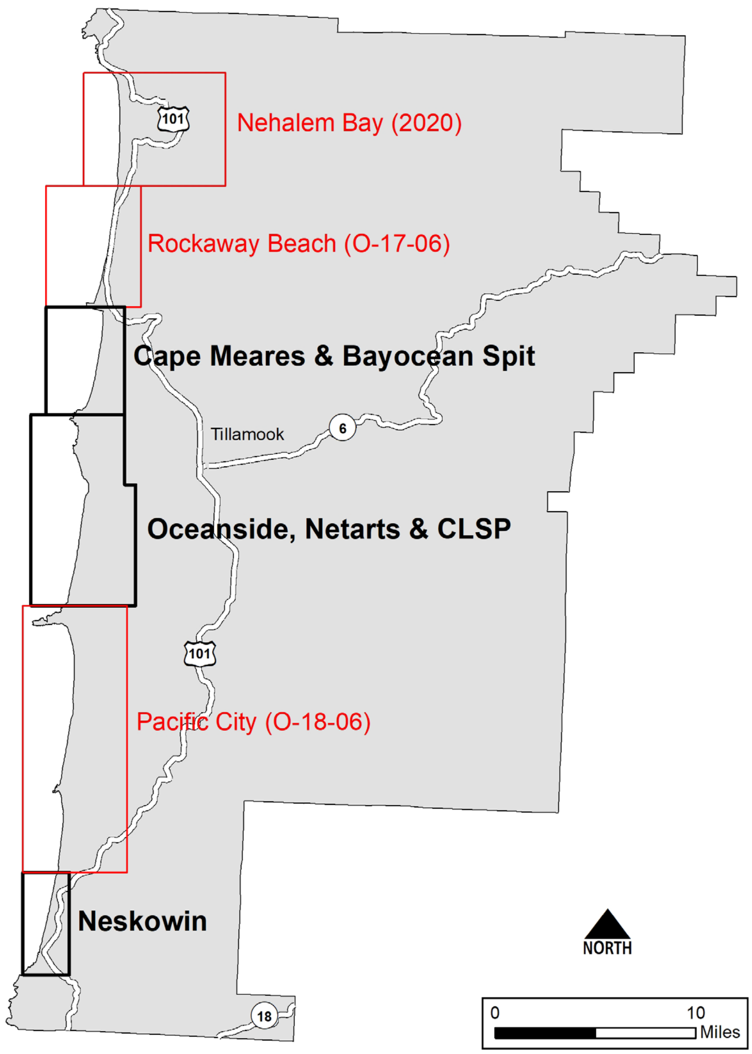
The replacement costs of buildings were obtained from detailed per-building databases constructed for ongoing DOGAMI risk assessments (M. Williams, written communication, 2019). We did not model building damage from a particular tsunami scenario; rather, we quantified the total replacement cost of the buildings for the entire community and for the buildings within the community's tsunami zone. Generally, given the predominance of light-frame construction in Oregon coastal communities and the hydraulic forces contained within in a CSZ-generated tsunami, overall building damage within a tsunami zone is likely to be extensive to nearly complete (J. Bauer, oral communication, 2019). We quantified the percentage of the communities' overall building replacement cost that is within the tsunami zone.

Geocoded Quarterly Census of Employment and Wages (QCEW) data obtained from Oregon Employment Division (written communications; dataset dated September 25, 2018) were used to quantify the overall number of employers, jobs, and annual wages paid in the community and within the tsunami zone. The QCEW data were also queried to identify the largest employment sector, by number of jobs, within each community's tsunami zone. Where needed, we limited reporting on selected data to honor the employer privacy restrictions outlined in our QCEW data sharing agreement. A more detailed description of methods used for socioeconomic analysis will be available in a report from a study underway at DOGAMI (John Bauer, oral communication, 2019).

3.0 RESULTS AND DISCUSSION

This report covers the communities of Cape Meares and Bayocean Spit, Oceanside, Netarts, Cape Lookout State Park, and Neskowin (**Figure 3-1**). Section 3.1 presents our tsunami evacuation analysis (Beat the Wave) including detailed wave arrivals; a brief socioeconomic analysis follows in section 3.2. A BTW analysis of Rockaway Beach was completed in 2017 (Gabel and Allan, 2017) and Pacific City in 2018 (Gabel and others, 2018). We expect to complete a BTW analysis for communities of Nehalem Bay in 2020.

Figure 3-1. Tillamook County project area map. Results will be discussed separately for each area outlined in black. Published and planned future BTW sites are outlined in red. CLSP is Cape Lookout State Park. Published open-file reports are Rockway Beach (Gabel and Allan 2017) and Pacific City (Gabel and others, 2018).



3.1 Beat the Wave

Of the communities examined in this report, we find that evacuees in Cape Meares, Oceanside, and Netarts can escape a maximum-considered Cascadia tsunami by walking at a minimum speed of 4 fps (***walk***). In areas of Bayocean Spit, Cape Lookout State Park, and Neskowin, evacuees must travel a significant distance to reach the nearest safety destination, and the minimum walking speeds necessary to survive are greater.

BTW evacuation modeling results for a "base" run reflecting the existing road and trail network will be presented for each community. Bridges are deemed passable if they are known to have been built or retrofitted to withstand the shaking of a Cascadia earthquake. If that is not the case, this base run will not allow passage across a bridge. When applicable, hypothetical scenarios such as liquefaction, evacuation trails, vertical evacuation structures, and bridge retrofits will be included. Results are shown for a path on the beach itself and are included in the digital GIS deliverables but will not be discussed in the report. For most communities, we show evacuation flow zones as separate images for the base scenario to identify which safety destination is ideal for each part of an area. Planners and local decision-makers may find this a useful tool to assist with mitigation efforts including signage and evacuation drills. Detailed wave arrivals will also be presented for each community. Base BTW results and tsunami arrival data can be found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase.

All scenarios include a 10-minute delay before beginning evacuation to account for the expected disoriented state of people following severe earthquake shaking and for the time required to exit buildings. **Table 3-1** represents a summary of the range of speeds and their conversions that will be used throughout the remainder of this report. Tsunami wave arrival figures do not include this delay.

One important note—it is inevitable that following a disaster other factors will contribute to impede travel times. This modeling does not account for these ancillary effects. As a result, ***the public should maintain the overarching goal of immediately evacuating after the earthquake and moving as rapidly as possible in order to ensure they reach safety with ample time to spare.***

Table 3-1. Pedestrian evacuation speed categories and their conversions.

Description	Feet per Second (fps)	Miles per Hour (mph)	Minutes per Mile
Slow walk	>0–2	>0–1.4	>44
Walk	2–4	1.4–2.7	44–22
Fast walk	4–6	2.7–4.1	22–14.7
Jog	6–8	4.1–5.5	14.7–11
Run	8–10	5.5–6.8	11–8.8
Sprint	10–14.7	6.8–10	8.8–6.0
Unlikely to survive	>14.7	>10	<6.0

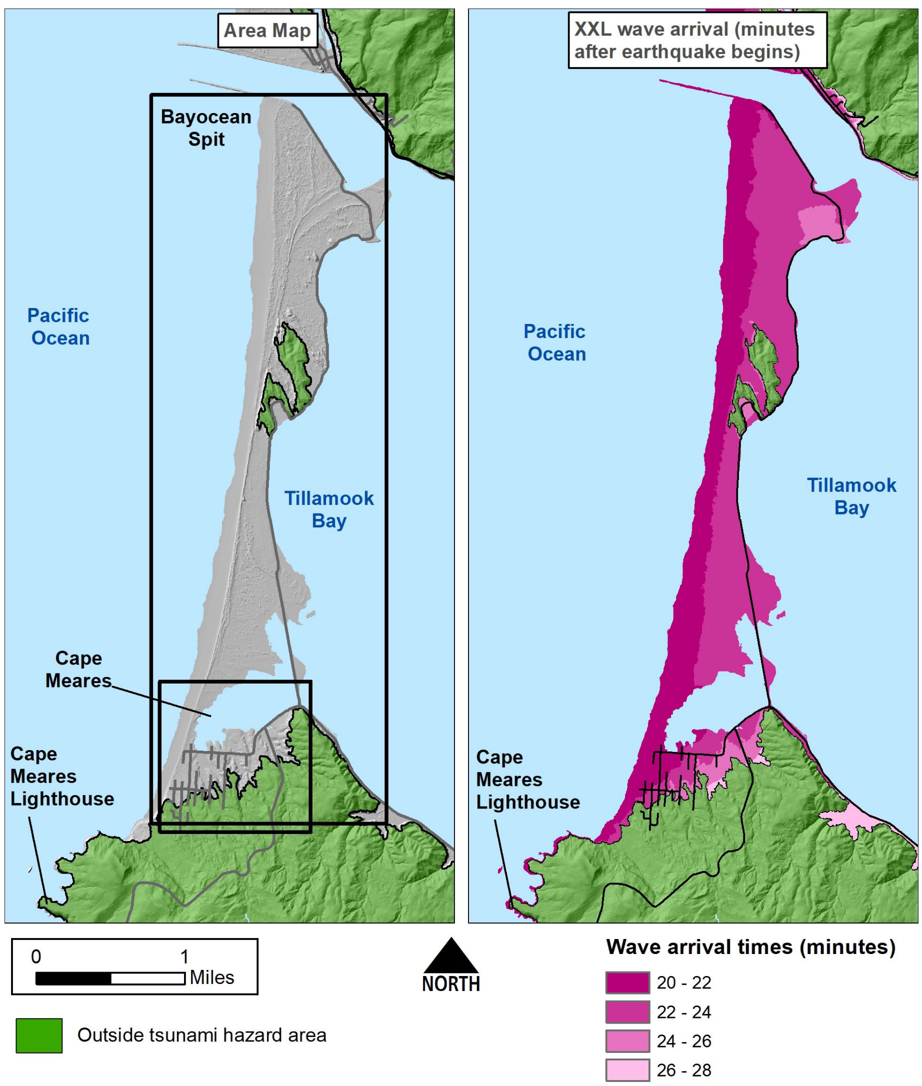
Note: walking at speeds of 2–4 fps is considered a reasonable measure for the elderly and for adults who may be mobility impaired (see Figure 6 of Fraser and others, 2014).

3.1.1 Cape Meares and Bayocean Spit

Cape Meares and Bayocean Spit have significantly different evacuation challenges but are intrinsically connected because they sit on the ocean side of Tillamook Bay, cut off from neighboring towns by many miles of road that will most likely be impassable after the CSZ event. Results will be discussed separately for each community, as outlined in **Figure 3-2, left**. BTW Walking speeds on the roads and trails as well as evacuation flow zone data for the base scenario are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

Figure 3-2, right shows estimated arrival times for an XXL tsunami in this area. The earliest wave arrivals are along the open coast; the tsunami reaches the beach ~20 minutes after the start of the earthquake shaking. By 24 minutes the spit has been overtopped, and by 26 minutes Cape Meares has been fully impacted. A detailed wave arrival figure is provided for Cape Meares (**Figure 3-3**, left). Tsunami wave arrival time data are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

Figure 3-2. Cape Meares and Bayocean Spit area map showing (left) figure extents and (right) modeled tsunami wave arrival times after the XXL Cascadia subduction zone earthquake.



3.1.1.1 Cape Meares

Cape Meares is a small oceanfront community located on the northern slopes of Cape Meares. Although much of town is within the XXL tsunami inundation zone, including Tillamook County Fire Station 73, the headland provides accessible high ground. The biggest challenge facing this community will be landslides: much of town is affected by landslides today (source: SLIDO, https://www.oregongeology.org/slido/index.htm), and shaking from a Cascadia earthquake will likely cause further slope instabilities that may compromise evacuation routes.

Figure 3-3, left demonstrates tsunami arrival times for an XXL tsunami in Cape Meares. The tsunami reaches the beach ~20 minutes after the start of the earthquake shaking and has flooded town within ~6 minutes. **Figure 3-4, left** presents BTW results for a base run in Cape Meares. The entire community can reach safety ahead of the tsunami at a minimum speed of ***walk*** (4 fps or 2.7 mph). **Figure 3-3, right** presents evacuation flow zones for the base scenario. These define the nearest safety destination for everyone in the neighborhood and may be useful for personal evacuation route planning as well as community-wide wayfinding efforts. Because virtually all north-south streets intersect high ground, Cape Meares is characterized by numerous evacuation flow zones—some zones were combined to simplify the figure.

Figure 3-3. (left) Modeled tsunami wave arrival times for Cape Meares after a XXL Cascadia subduction zone earthquake, and (right) evacuation flow zones (base scenario).

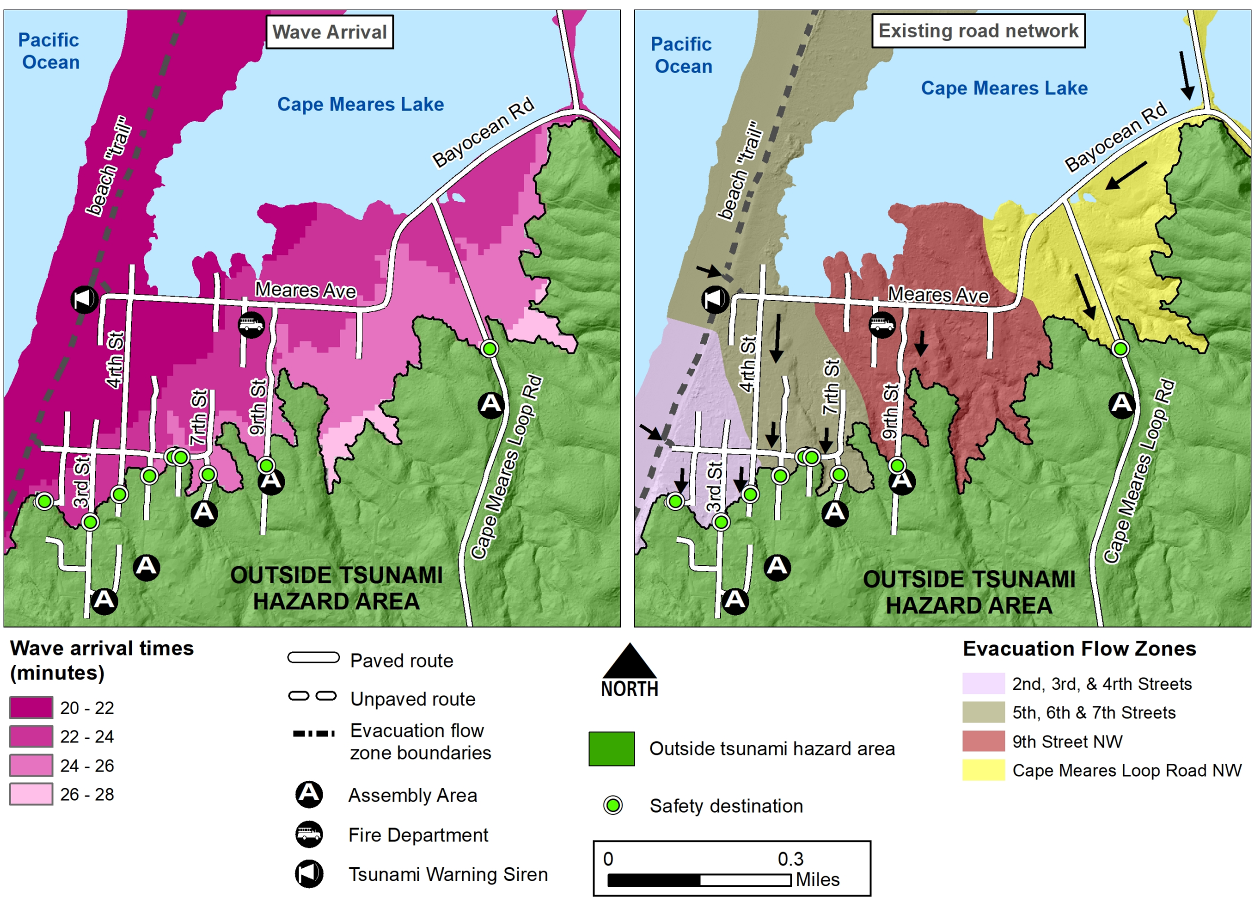
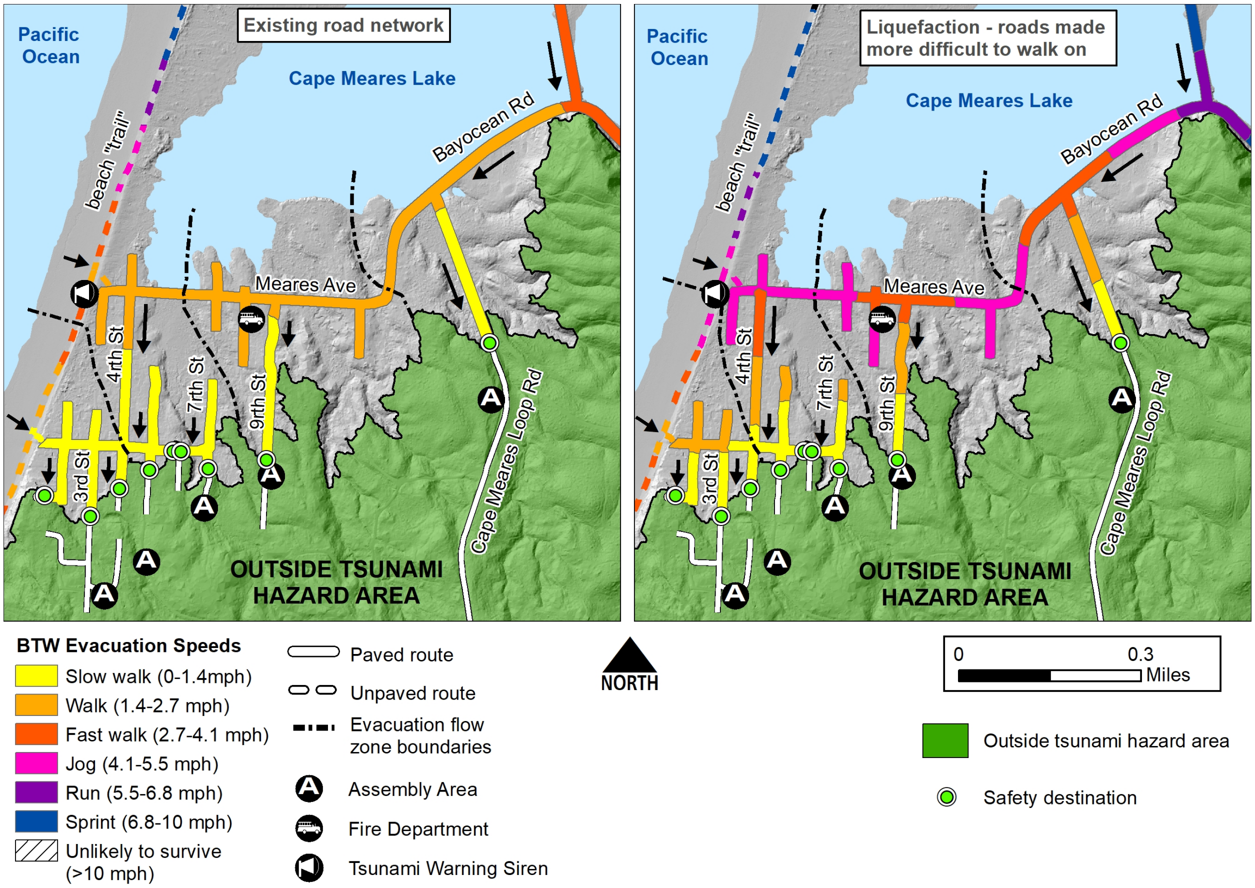


Figure 3-4. Beat the Wave modeling in Cape Meares for (left) base scenario depicting the existing road and trail network and (right) with liquefaction. Colors on top of the road network reflect minimum BTW walking speeds, and black dashed lines define evacuation flow zone boundaries.



We are aware of the low spot on Meares Ave adjacent to Cape Meares Lake that is frequently flooded (Sarah Absher, Tillamook County, oral communication, 2018) and may not be passable after the earthquake. The low spot turned out to be a natural boundary between evacuation flow zones, so we did not find it necessary to rerun the model with a break in the road at that location. Evacuees west of this low point move up 5th, 6th, or 7th Streets (tan polygon in **Figure 3-3, right**), and evacuees east of the low point move up 9th St NW (dark brown polygon in **Figure 3-3, right**).

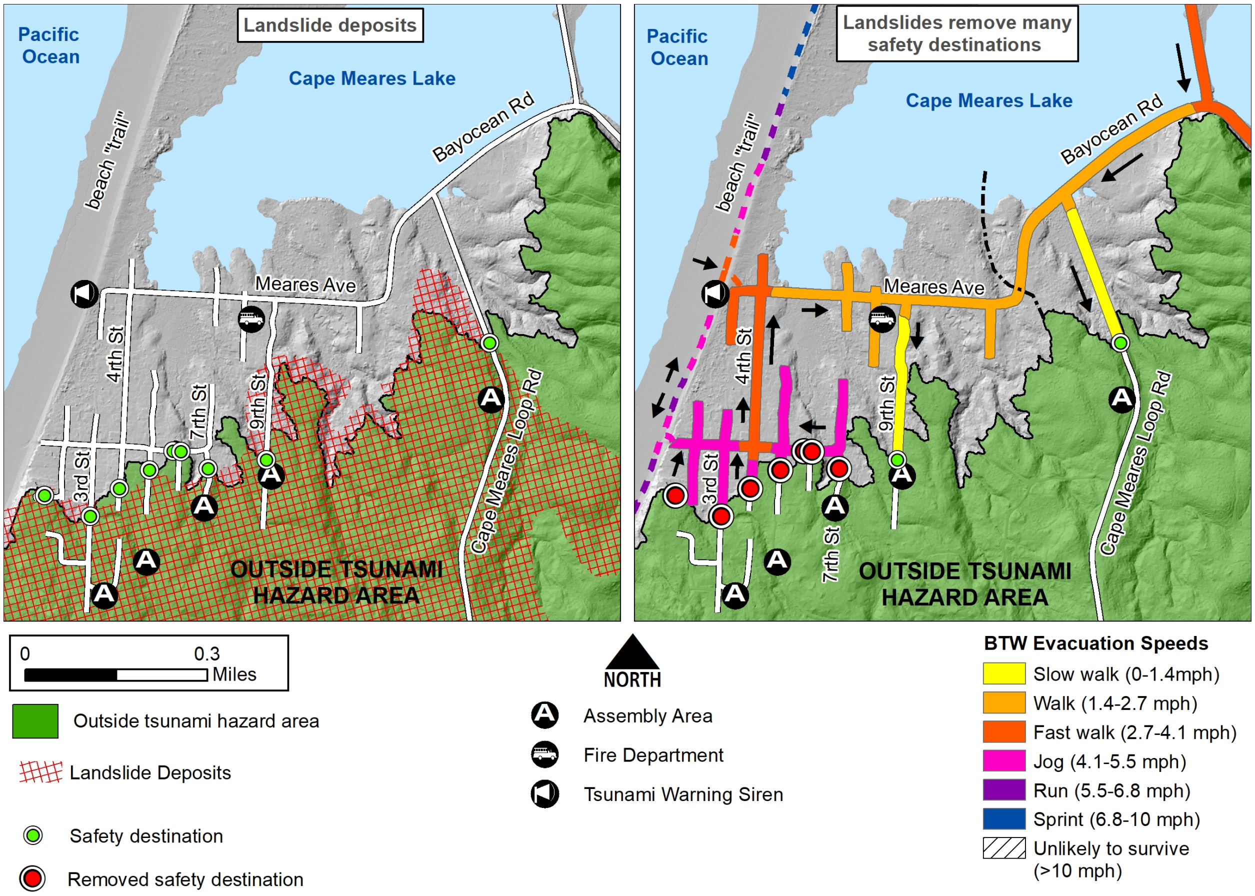
As discussed in section 2.2, liquefaction is a site-specific hazard associated with earthquake shaking. Because we do not have the ability to predict precisely where liquefaction will occur, we present a conservative look at how liquefaction would impact evacuation by assuming liquefaction affects all streets that have a moderate or high susceptibility. In Cape Meares, this includes all roads inside the inundation zone. The liquefaction scenario presented in **Figure 3-4, right** illustrates the dramatic increase in minimum walking speeds necessary to reach high ground before the tsunami arrives. The most significant changes occur on streets farthest away from high ground, where speeds increase to ***jog*** (8 fps or 5.5 mph). As a reminder, these speeds must be maintained for the duration of a person's evacuation.

As previously mentioned, landslides are a large concern for the community of Cape Meares. A persistent slow-moving landslide (SLIDO: reference ID AllaJC2001) plagues roads and structures today, and there is little doubt that earthquake shaking will activate new and existing landslides that are likely to affect roads important for evacuation. **Figure 3-5, left** presents known landslide activity in Cape Meares. Immediately apparent is the almost perfect match between known landslide activity and the XXL inundation limit. This makes it very difficult to model effectively the hazard because we are limited to the simple act of removing safety destinations. In this case, if we remove all safety destinations that are within the landslide area, there is nowhere to go. Because the western section of the landslide is currently more active than the eastern section, our simple solution was to remove safety destinations west of 9th St. Affected evacuees are forced to walk back downhill and seek safety further east. **Figure 3-5, right** shows that BTW minimum walking speeds for this scenario increase significantly from the base run (**Figure 3-4, left**), reaching ***jog***.

Results for this hypothetical scenario are meant to provide a general understanding of how minimum walking speeds will increase if evacuees must walk farther to reach high ground. Evacuees may have to walk over landslide terrain as best they can to reach high ground if no roads are available to them and there is not time to walk around the landslide to find a new route.

Overall, BTW results in this community suggest that many will be able to reach safety using the existing road network, but large-scale mitigation efforts related to stabilizing the landslide or hardening key routes against liquefaction would improve life safety. Despite the short distances to safety, clear and plentiful wayfinding signage is important to guide people in the right direction during a time of panic and confusion.

Figure 3-5. (left) Existing landslide deposit in Cape Meares. (right) Beat the Wave modeling in Cape Meares for a hypothetical scenario that asumes many safety destinations on the west side of town are unavailable due to landslides.



3.1.1.2 Bayocean Spit

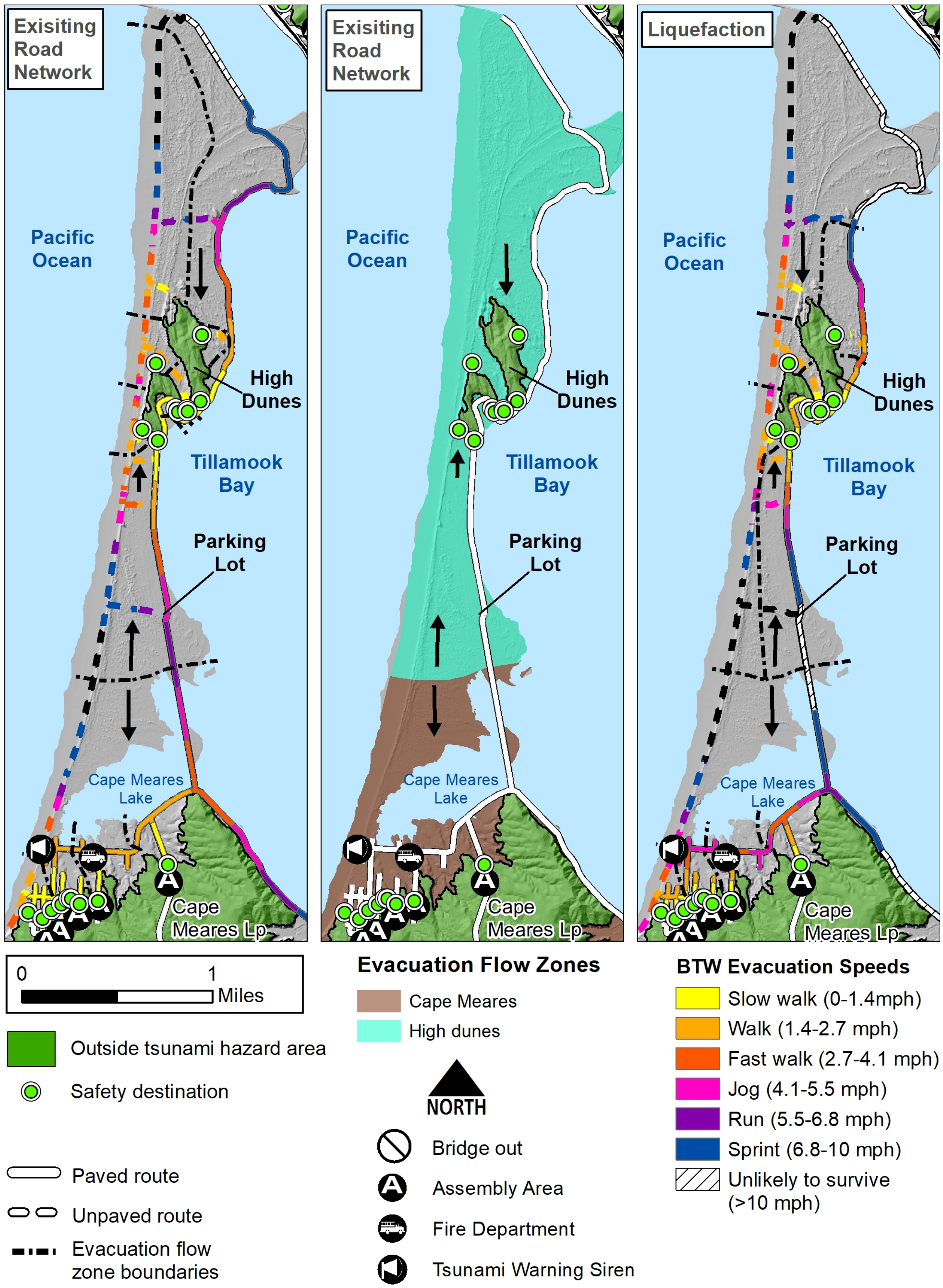
Bayocean Spit extends ~4 miles from the mouth of Tillamook Bay in the north to the community of Cape Meares to the south. A single road, Bayocean Dike Road, extends the length of the spit, but there is no vehicle access beyond the parking lot. Unlike some other spits on the Oregon coast, Bayocean has a series of high dunes approximately midway up the spit that are expected to stay dry during an XXL event and will provide safety for people on the spit. The tsunami arrives and overtops the spit except the high dunes in ~20–24 minutes (**Figure 3-2, left**).

Figure 3-6, left presents results for the base scenario. Despite there being safety on the spit itself, those at the north end of the spit must ***sprint*** (15 fps or 10 mph) and at the extreme end are ***unlikely to survive*** (>15 fps or 10 mph). Those in the parking lot near the south end must ***jog*** to the high dunes in order to survive. **Figure 3-6, middle** presents evacuation flow zones for the base scenario. This figure emphasizes the divide for evacuees who should move to the high dunes on the spit and those who should move south into Cape Meares. Basically, anyone in the parking lot or farther north should move to the dunes. Those on the Dike Road south of the parking lot should move south to Cape Meares.

There are many access points to the high dunes, from both the bay and ocean sides and from the north and south. However, the access points consist of a few actual trails and many more game trails. Clearing these trails and providing evacuation signage from all four directions would assist evacuation on the spit.

The spit is long. Additional high ground in the form of a vertical evacuation structure would help reduce walking speeds. We did not model this scenario because the spit is not a highly populated area, and people visiting the spit are widely dispersed. One structure would likely not assist enough people to justify the cost. However, if a structure is considered, we suggest locating one adjacent to the parking lot. Everyone visiting the spit would then have a chance to learn, through outreach signs and the structure itself, about the structure and the tsunami hazard before recreating.

Figure 3-6. Beat the Wave modeling on Bayocean Spit. (left) Base scenario: Minimum BTW walking speeds (colors on top of road network) with evacuation flow zone boundaries (black dashed lines), (middle) Base scenario: evacuation flow zones alone, emphasizing the divide between heading to dunes on the spit or south to Cape Meares, and (right) Liquefaction scenario.

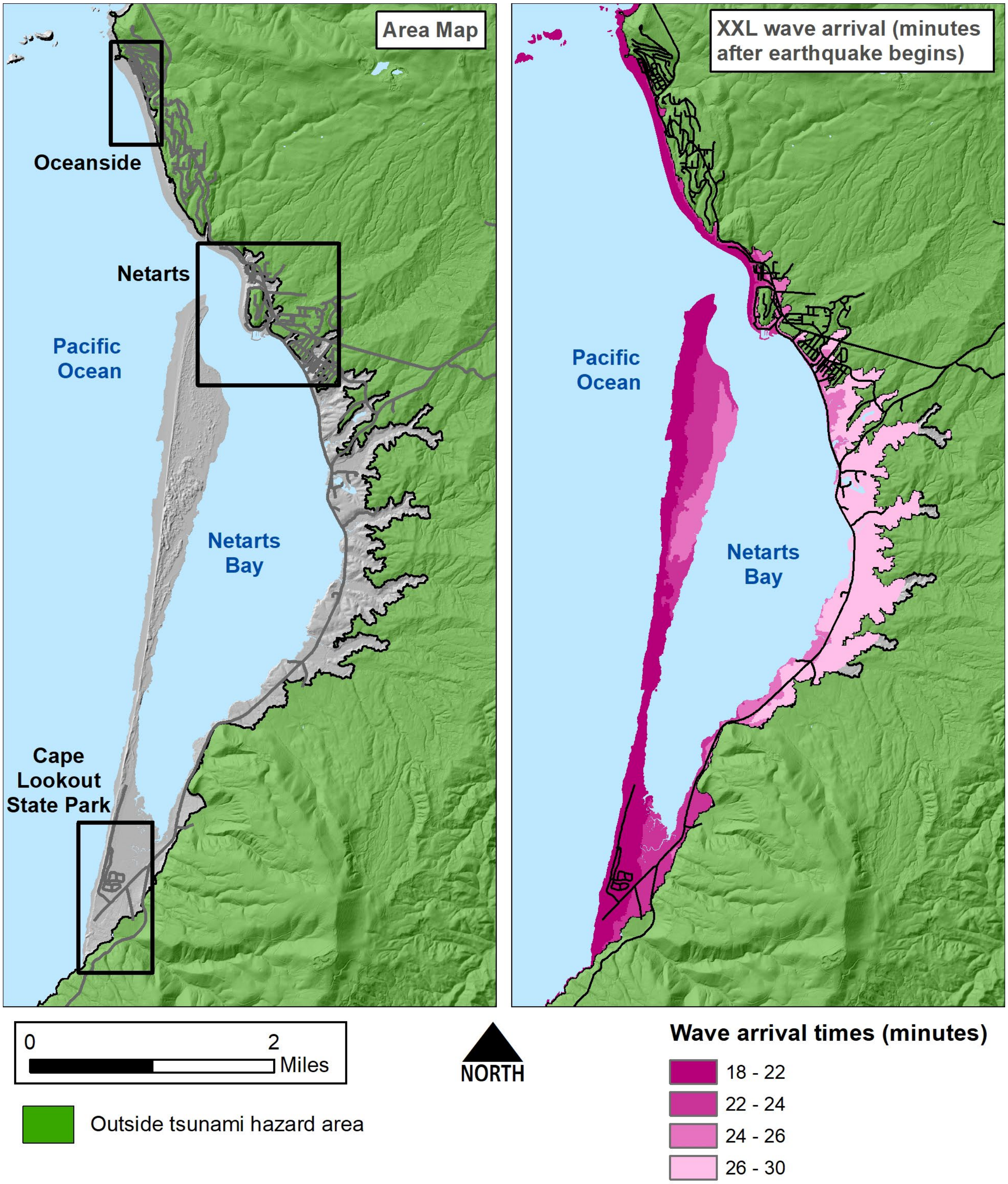


3.1.2 Oceanside, Netarts and Cape Lookout State Park

Oceanside, Netarts, and Cape Lookout State Park have significantly different evacuation challenges. We will discuss results separately for each area, as outlined in **Figure 3-7, left**. BTW walking speeds on the roads and trails as well as evacuation flow zone data for the base scenario are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

Figure 3-7, right shows the estimated arrival times for an XXL tsunami in this area. The earliest wave arrivals are along the open coast; the tsunami reaches the beach ~20 minutes after the start of the earthquake shaking. By 23 minutes the state park is expected to be inundated and by 26 minutes Netarts Spit except the high dunes is overtopped. Detailed wave arrival figures are provided for each community. Tsunami wave arrival time data are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

Figure 3-7. Netarts Bay area map showing (left) figure extents and (right) modeled tsunami wave arrival times after XXL Cascadia subduction zone earthquake.



3.1.2.1 Oceanside

The steep hillside community of Oceanside is along the open coast just north of the mouth of Netarts Bay. Because of its geography, Oceanside's inundation zone is narrow and is essentially limited to the Netarts Oceanside Highway. However, the zone does include Netarts-Oceanside Fire District Station 62. The tsunami reaches Oceanside in ~20 minutes (**Figure 3-8**). People in the entire inundated area can reach safety ahead of the tsunami at a ***slow walk*** (2 fps or 1.4 mph) (**Figure 3-9**, **left**). **Figure 3-9**, **right** shows evacuation flow zones for the base scenario. Liquefaction and landslides will likely occur as a result of earthquake shaking, but these hazards were not modeled as a part of this study due to the short distances to safety—a limitation of the model is its inability to account for such changes over short distances. However, evacuees should plan for additional effort due to liquefaction. If an evacuee's first choice for high ground is removed by landslide, there are many other road and off-road options to get uphill to high ground.

Figure 3-8. Modeled tsunami wave arrival times for Oceanside after XXL Cascadia subduction zone earthquake.

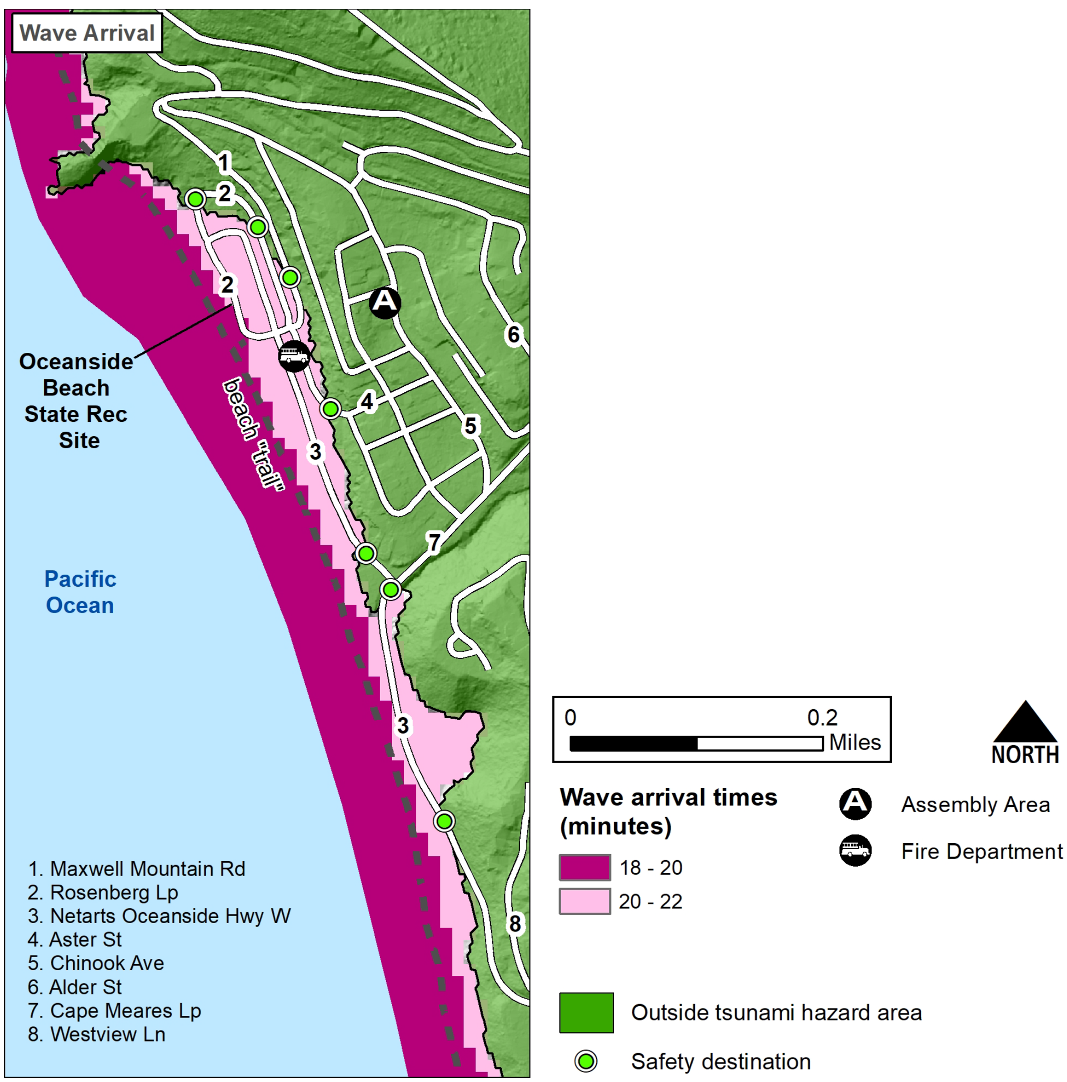
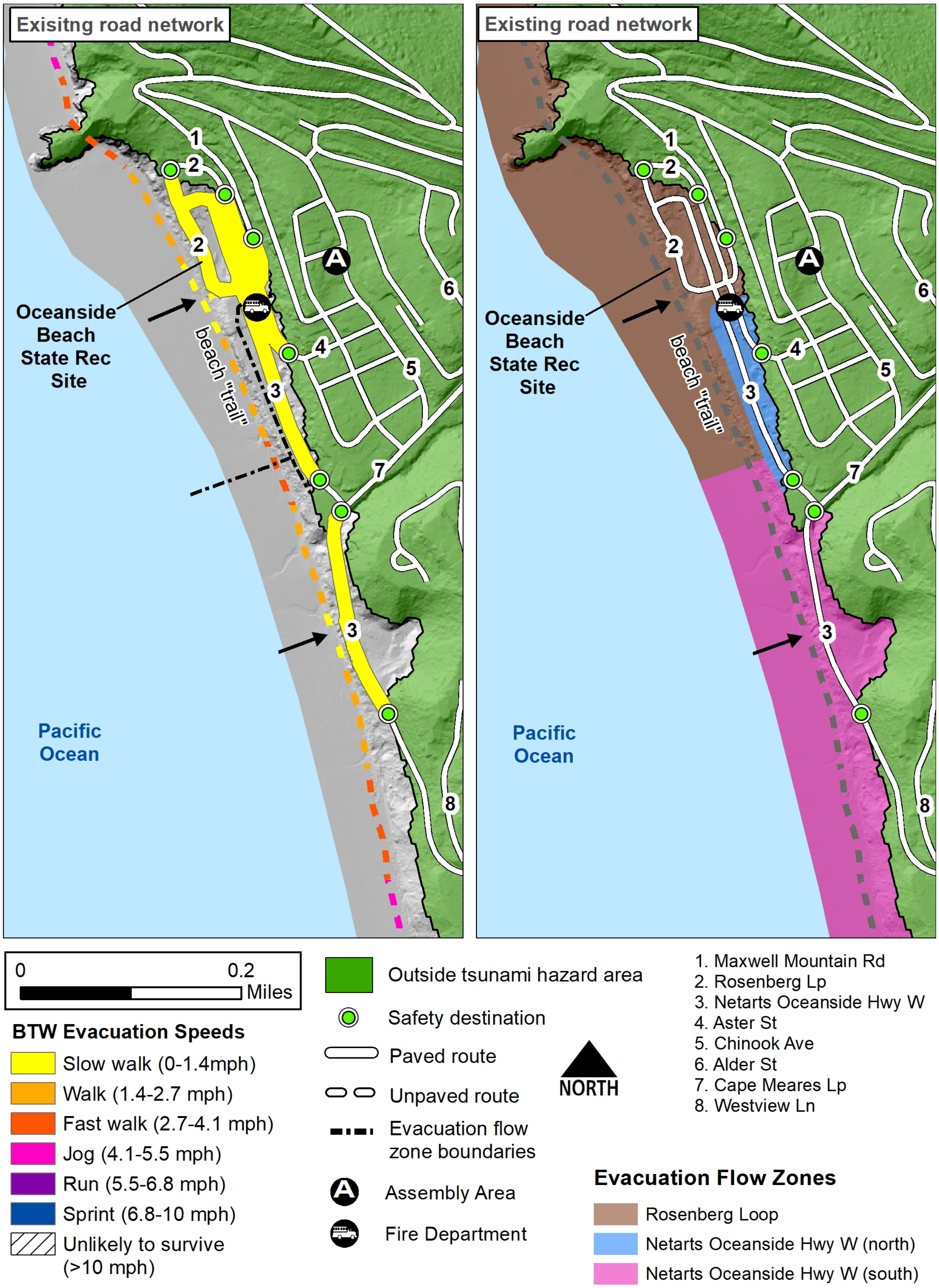


Figure 3-9. Beat the Wave modeling in Oceanside for the base scenario depicting the existing road and trail network. (left) Colors on top of the road network reflect minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones shown as colored polygons instead of black dashed lines.



3.1.2.2 Netarts

The steep hillside community of Netarts lies at the mouth of Netarts Bay. Because of its geography, Netarts inundation zone is narrow, but the zone does encompass some of the more heavily visited sections of town including Netarts Boat Basin; Happy Camp lodging and a nearby popular beach access parking lot; the Netarts-Oceanside Fire District Station 61; and an RV park on Bilyeu Avenue West. The tsunami reaches Netarts in ~20 minutes (**Figure 3-10**). The Netarts Bay Drive bridge near Bilyeu Avenue West is not expected to survive the earthquake shaking. Evacuees on nearly every road inside the inundation zone can reach safety ahead of the tsunami at a ***slow walk*** (2 fps or 1.4 mph) (**Figure 3-11, left**). There are so many safety destinations in Netarts that evacuation flow zones cannot be distinguished at the scale of these figures. Therefore, we provide flow zone data in digital format only.

The liquefaction scenario presented in **Figure 3-11, right** shows the slight increase in minimum walking speeds necessary to reach high ground before the tsunami arrives given this additional hazard. The most significant changes occur on streets along the bay shoreline (Happy Camp Road, Pearl Street, Netarts Boat Basin Road, and Netarts Bay Drive). Speeds generally increase from ***slow walk*** to ***walk*** (4 fps or 2.7 mph) in these areas. As a reminder, walking speeds must be maintained for the duration of a person's evacuation.

Landslides will likely occur as a result of earthquake shaking, but we did not model landslides as a part of this study due to the small inundation area. If an evacuee's first choice for high ground is removed by a landslide, there are many other road and off-road options to get uphill to high ground.

Figure 3-10. Modeled tsunami wave arrival times for Netarts after XXL Cascadia subduction zone earthquake.

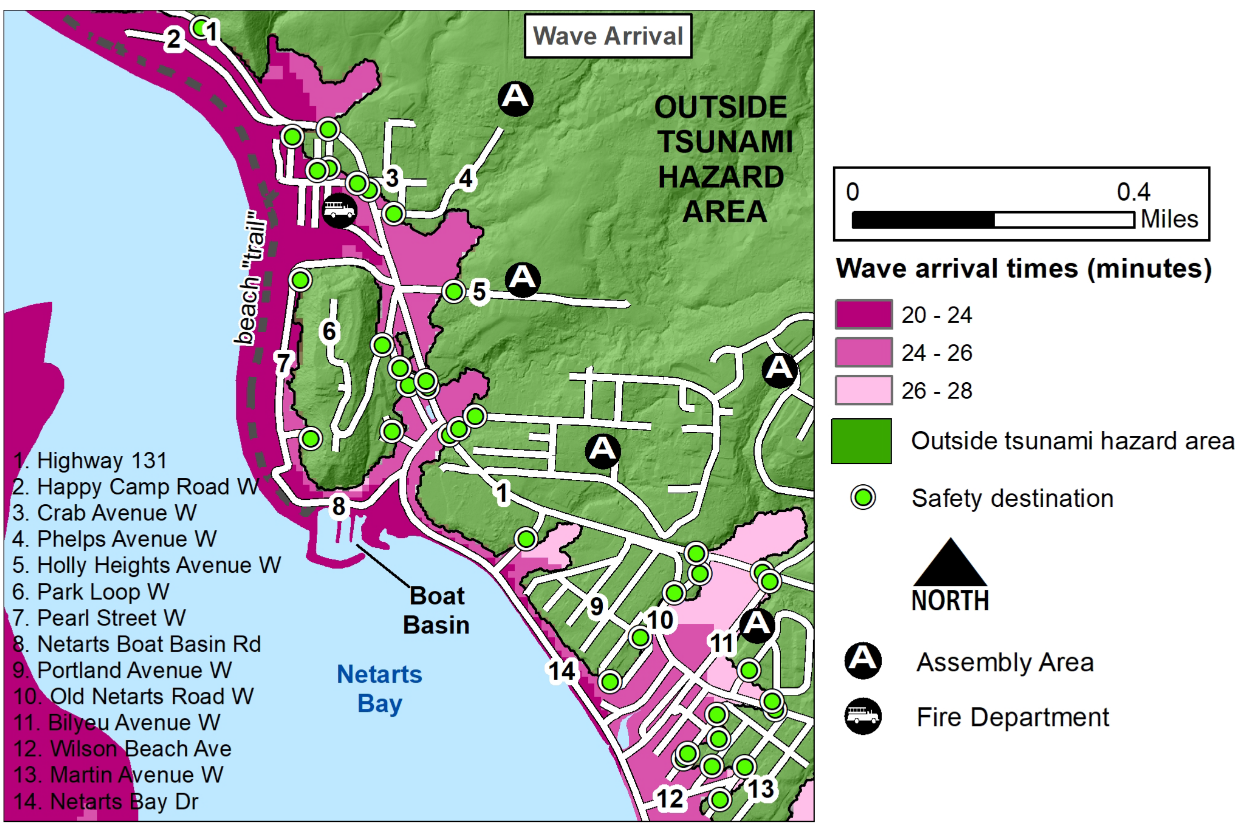
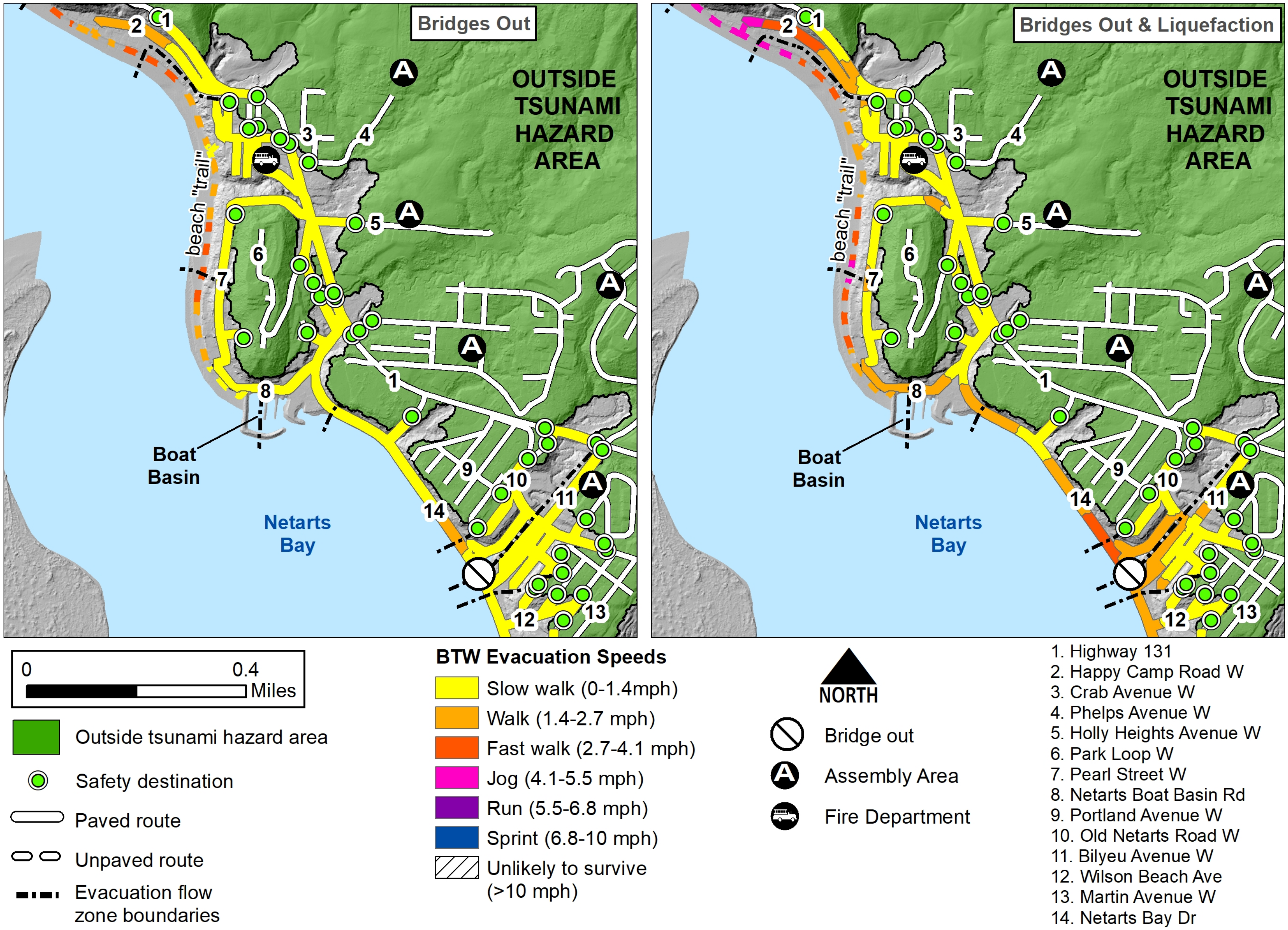


Figure 3-11. Beat the Wave modeling in Netarts for (A) base scenario depicting the existing road and trail network and (B) with liquefaction.



3.1.2.3 Cape Lookout State Park

Cape Lookout State Park sits on the open coast at the southern end of Netarts Bay. It is bordered to the north by wetlands and to the south by Cape Lookout. There is one access road into the park. Safety from an XXL tsunami can be reached from a few directions; the most well known is out the park entrance road and then ~0.3 miles south on Cape Lookout Road. High ground can also be reached via an unmarked logging road leading to the park's new drain field as well as up a trail leading up to Cape Lookout to the south. The first tsunami wave will reach the beach in ~18–20 minutes, and within another 2–4 minutes the entire area is expected to be inundated (**Figure 3-12**). We discuss evacuation improvements due to the presence of the logging road, the trail leading up to Cape Lookout, and hypothetical trails in the campgrounds as well as the evacuation challenge introduced by liquefaction.

Figure 3-12. Modeled tsunami wave arrival times for Cape Lookout State Park after XXL Cascadia subduction zone earthquake.

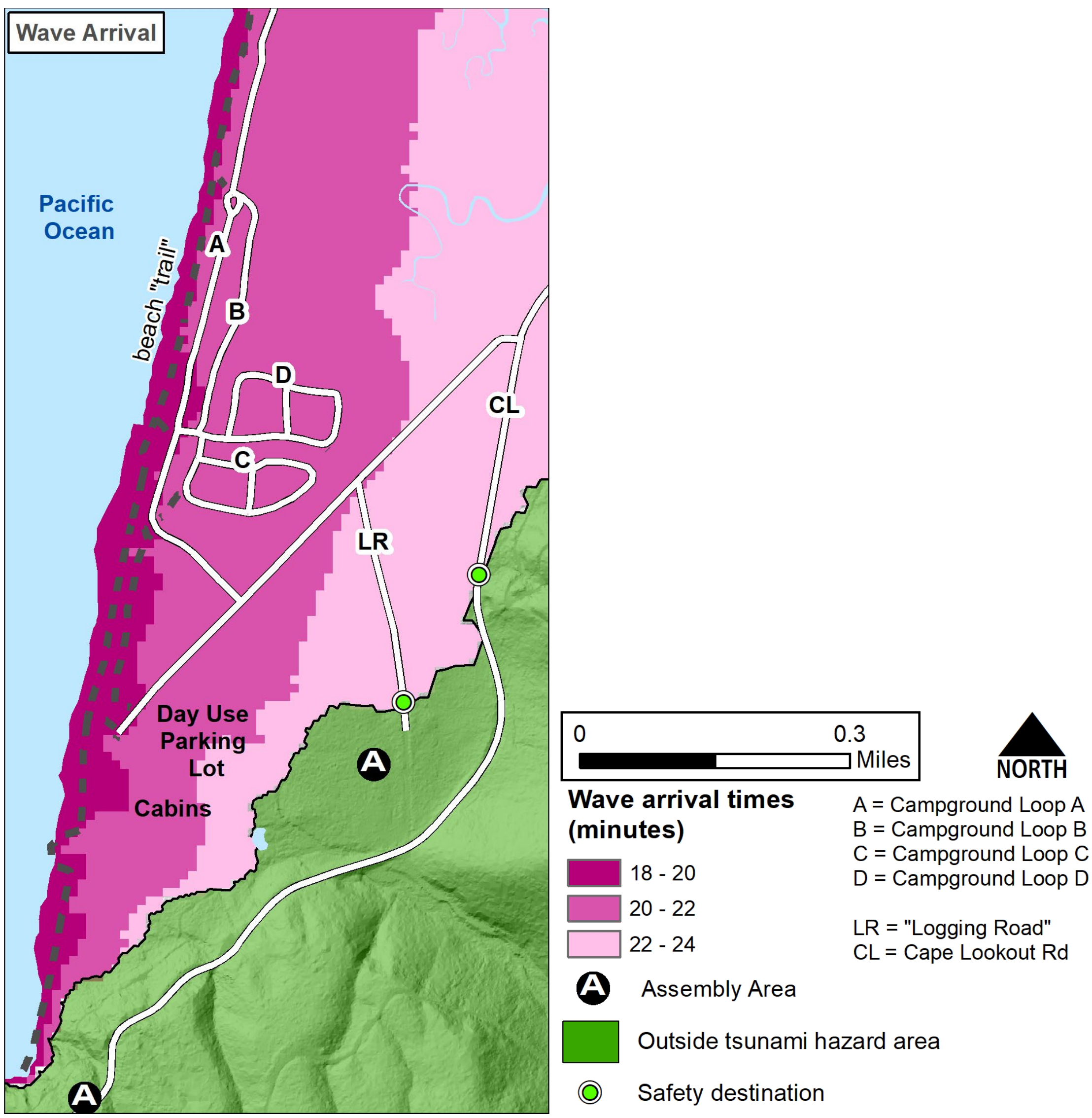
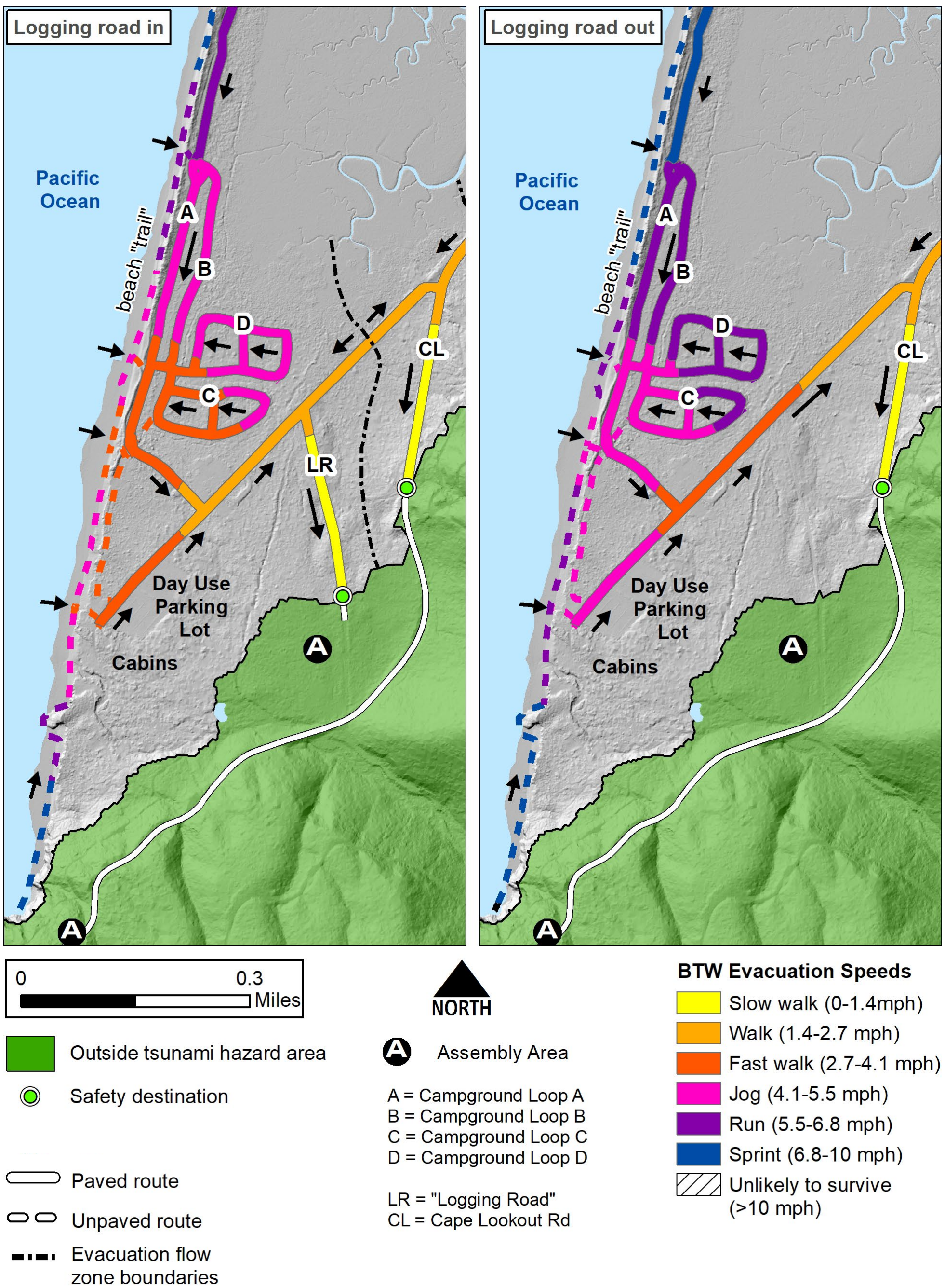


Figure 3-13 presents two BTW scenarios for Cape Lookout State Park that evaluate the importance of the logging road leading to high ground at the park's new drain field by including it (**Figure 3-13, left**) and excluding it (**Figure 3-13, right**) from the road network. The logging road provides closer high ground and lower minimum walking speeds for all park visitors: minimum speeds for visitors in the campground are reduced from ***jog*** (8 fps or 5.5 mph) and ***run*** (10 fps or 6.8 mph) to ***fast walk*** and ***jog*** with the logging road. This route is already available; no improvements other than signage and education are needed. It is also a designated assembly area, as shown on published evacuation maps (**Figure** 1-1).

Figure 3-13. Beat the Wave modeling in Cape Lookout State Park for (left) base scenario that includes the logging road and (right) without the logging road, forcing evacuation on Cape Lookout Road.

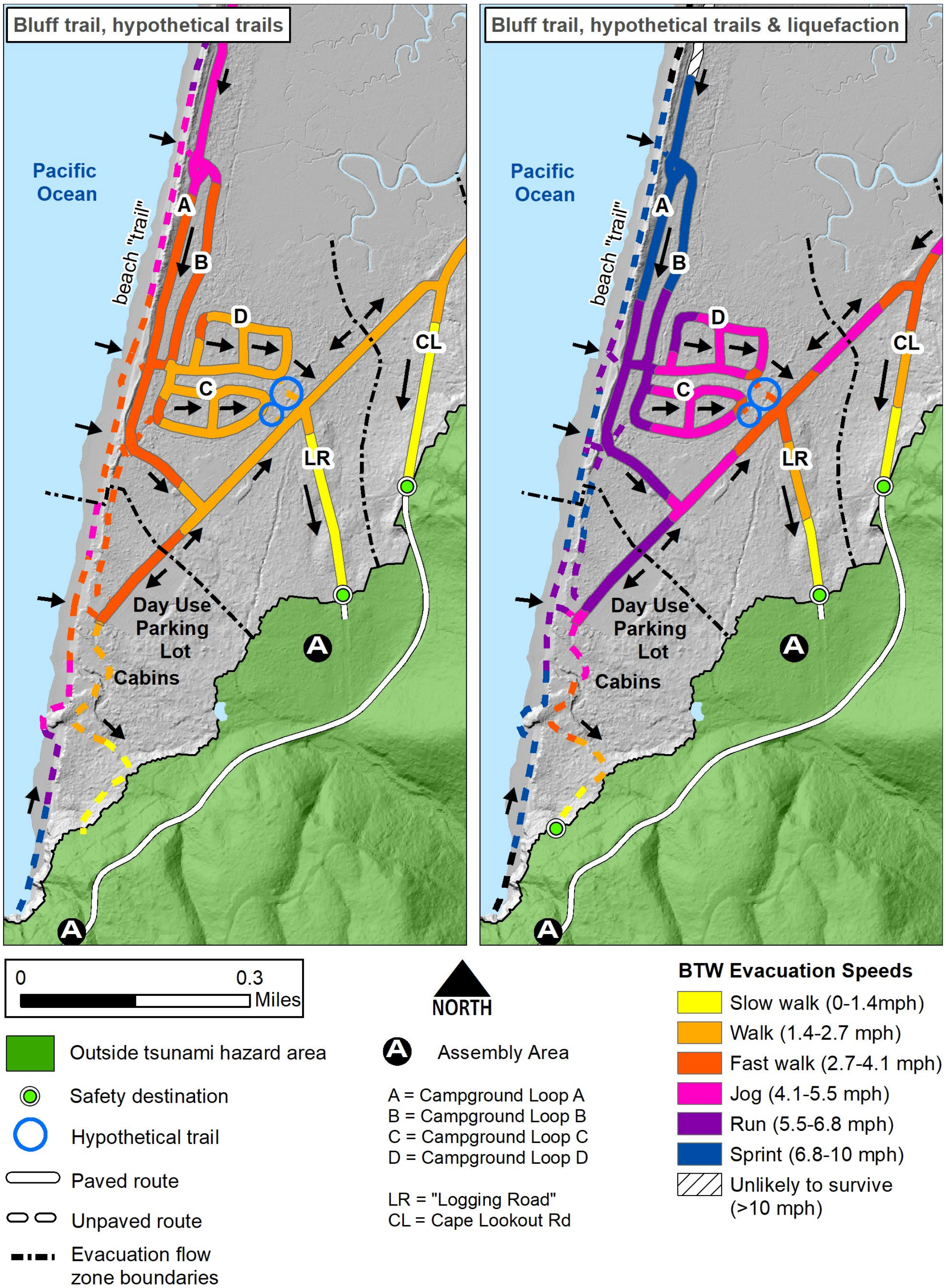


The addition of trails, existing and hypothetical, also improves evacuation for park visitors. The existing trail heading south from the day-use parking lot up to Cape Lookout is not currently signed as an evacuation route. However, evacuation flow zones in **Figure 3-14, left** (black dashed lines) indicate that people in the day-use parking lot (and cabins immediately to the south) should choose this route over the logging road or park entrance. Minimum walking speeds (***fast walk***) for those at the parking lot itself are unchanged, suggesting that either safety destination route, to the logging road or the trail heading south, is appropriate. There is likely to be a more significant improvement for people in the cabin area. Minimum evacuation speed in the cabin area is likely to be ***jog*** for those heading to the logging road, but the speed reduces to ***walk*** if taking the trail south to Cape Lookout instead (**Figure 3-14, left**).

Figure 3-14, left also introduces two hypothetical trails connecting campground loops C and D with the park entrance road. These trails provide a significant shortcut to high ground up the logging road or Cape Lookout Road for people in all four campground loops. Speeds drop from ***jog*** to ***walk*** and ***fast walk***. The dramatic improvements the trails provide could be worth the relatively low cost of clearing ~200–300 feet of vegetation and adding evacuation signage.

Liquefaction is distinct possibility in this low-lying marsh-adjacent area, so we considered a scenario where all roads are modeled as the consistency of loose beach sand. **Figure 3-14, right** shows results for this scenario. The scenario includes the Cape Lookout trail and hypothetical campground loop shortcuts. Even with the shortcuts, people in the campground loops still must ***jog***, ***run***, and in some areas ***sprint*** in order to survive. Without the shortcuts, minimum speeds for the campground will be even higher given the possibility of liquefaction.

Figure 3-14. Beat the Wave modeling in Cape Lookout State Park with inclusion of the trail to Cape Lookout and hypothetical evacuation trails connecting campground loops C and D with park entrance road. (left) using paved road land cover raster (existing conditions) and (right) with liquefaction.



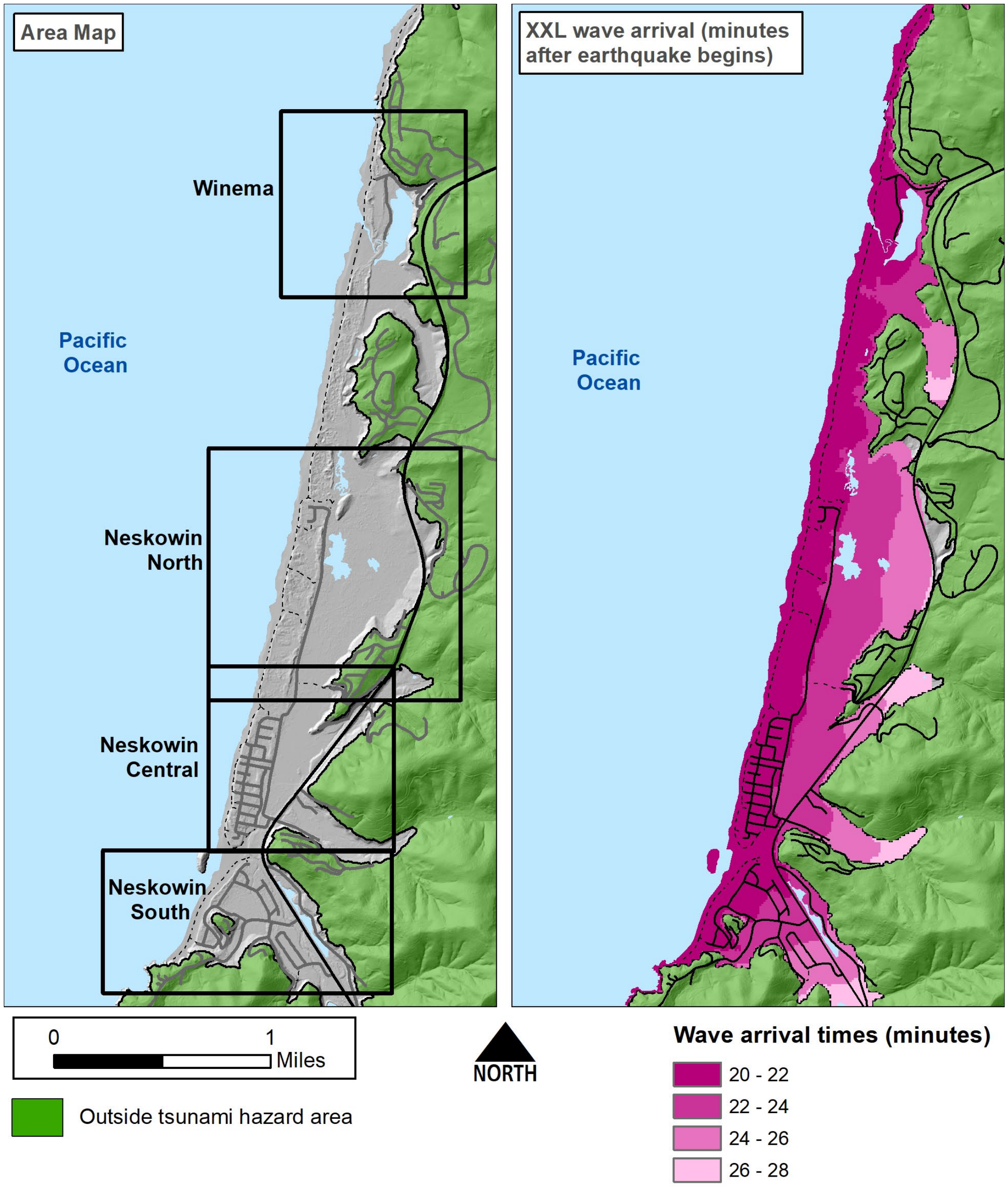
3.1.3 Neskowin

The oceanfront community of Neskowin lies between Cascade Head in the south and the mouth of Nestucca Bay in the north. The length of the community required us to separate it into four neighborhoods that we will discuss separately (**Figure 3-15, left**). Neskowin South includes the South Beach neighborhood as well as Neskowin Creek RV Park. We will focus our discussion here around bridges. Neskowin Central is essentially the heart of the community, containing the grocery store, the Neskowin Beach State Recreation Site parking lot (known locally as the Wayside) for visitors, and the only two access roads to the community (Salem Ave and Hawk St). This area is also referred to as the "Village." Discussion for this neighborhood will focus on the two access points. Neskowin North covers the less populous northern end of town, following Hawk St to its terminus at Kinnikinnick Dr. Of greatest concern here is the significant distance to safety and possible refuge that can be found on Bear Mountain. Neskowin North also contains the "tsunami trail," an existing trail the community as a whole maintains as a viable evacuation route. Winema in the north includes Wi-Ne-Ma Christian Camp and a popular beach access. Evacuation is relatively straightforward in this area.

A regional view of modeled tsunami wave arrivals is shown in **Figure 3-15, right**. Detailed wave arrival figures are provided for each neighborhood. The first tsunami wave reaches the beach in ~20 minutes, and within approximately 2 minutes all of Neskowin is expected to be inundated. Tsunami wave arrival time data are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

As with other areas presented in this report, the "base" scenario uses the existing road network and excludes any bridges that are not currently built to survive earthquake shaking. Walking speeds on the roads and trails as well as evacuation flow zone data for the base scenario are found in the Tillamook_County_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

Figure 3-15. Neskowin area map showing (A) figure extents and (B) modeled tsunami wave arrival times after XXL Cascadia subduction zone earthquake.



3.1.3.1 Neskowin South

Although much of the South Beach neighborhood is inside the XXL inundation zone, there are two areas of high ground: an "island" of high ground off S Beach Rd in the middle of the neighborhood, and South Beach Point on S Beach Rd to the south where Cascade Head begins its ascent. S Beach Rd crosses Neskowin Creek near Highway 101. This bridge is not expected to survive the earthquake. However, the bridge is not crucial for evacuation because residents and nearby high ground are on the west side of this bridge. The one exception is the Neskowin Regional Water District building immediately east of the bridge. People here must find high ground off Highway 101.

The RV park south of South Beach has a single access road that also crosses Neskowin Creek. This bridge is not expected to survive the earthquake. Although the RV park itself does not extend into high ground, there is an old logging road at the southwest corner of the park that reaches high ground nearby. There is also the option to access S Beach Rd on the north edge of the RV park and head uphill to the same safety destinations for South Beach. Therefore, although both Neskowin Creek bridges provide connectivity with Highway 101, they are not as important for tsunami evacuation. Signage directing people to nearby high ground in the hills to the west is important.

Figure 3-16, top presents first tsunami wave arrivals for Neskowin South. The tsunami reaches the beach in ~20 minutes and is expected to inundate South Beach within 4 minutes. The RV park will be reached by 24 minutes. **Figure 3-17, top** presents results for a base run that excludes bridge passage across S Beach Rd and the RV park entrance over Neskowin Creek. Evacuees in almost the entire area can reach safety at a ***walk*** (4 fps or 2.7 mph) or ***slow walk***. Evacuation flow zones are shown in **Figure 3-16, bottom**. Because this area has a moderate liquefaction susceptibility, we considered the possibility that this hazard will further challenge evacuation. **Figure 3-17, bottom** presents result of a liquefaction scenario. Minimum BTW speeds increase slightly; those in the areas farthest from safety must ***jog***.

Figure 3-16. (top) Modeled tsunami wave arrival times for Neskowin South after XXL Cascadia subduction zone earthquake, and (bottom) Beat the Wave modeling for base scenario showing evacuation flow zones only.

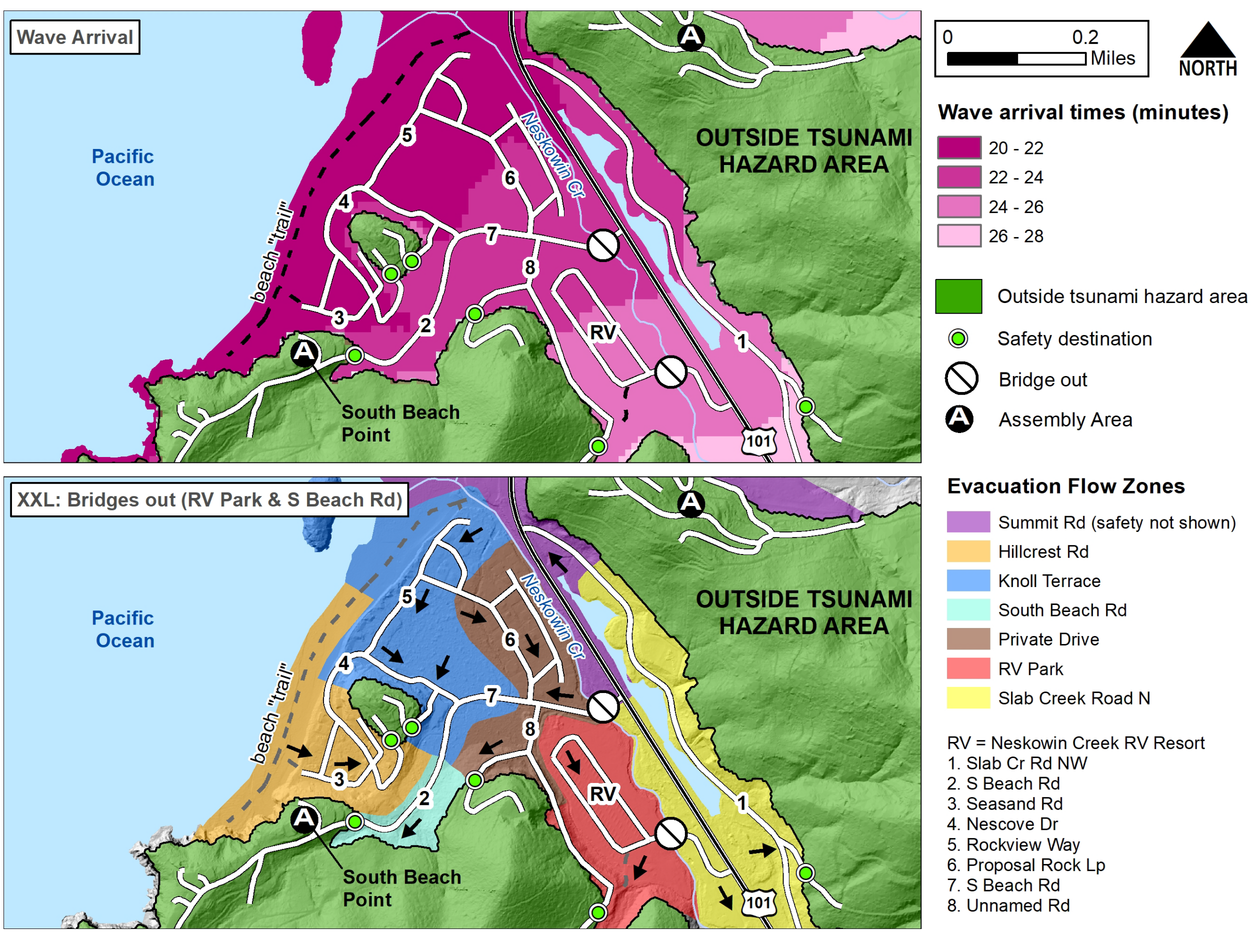
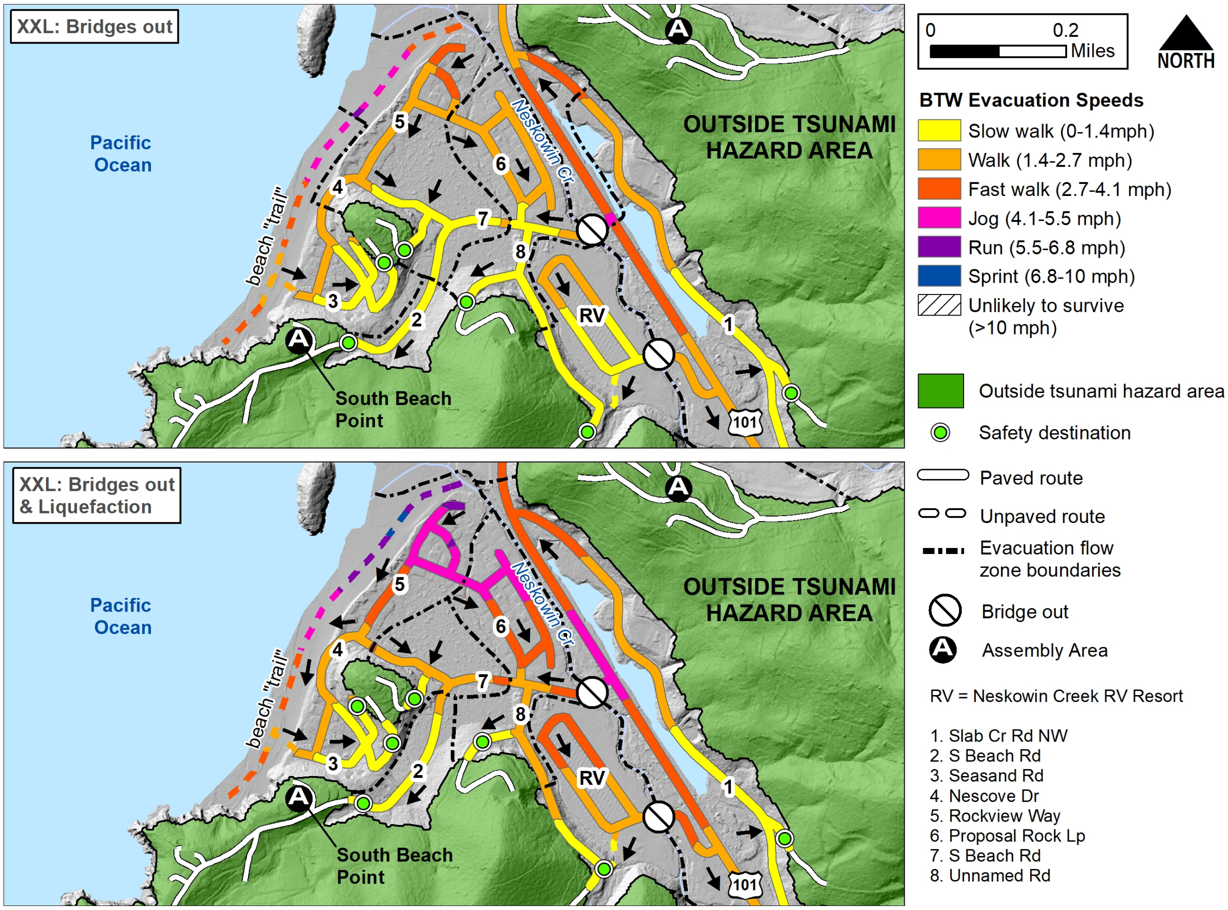


Figure 3-17. Beat the Wave modeling in Neskowin South for (top) base scenario depicting the existing road and trail network and (bottom) with liquefaction.



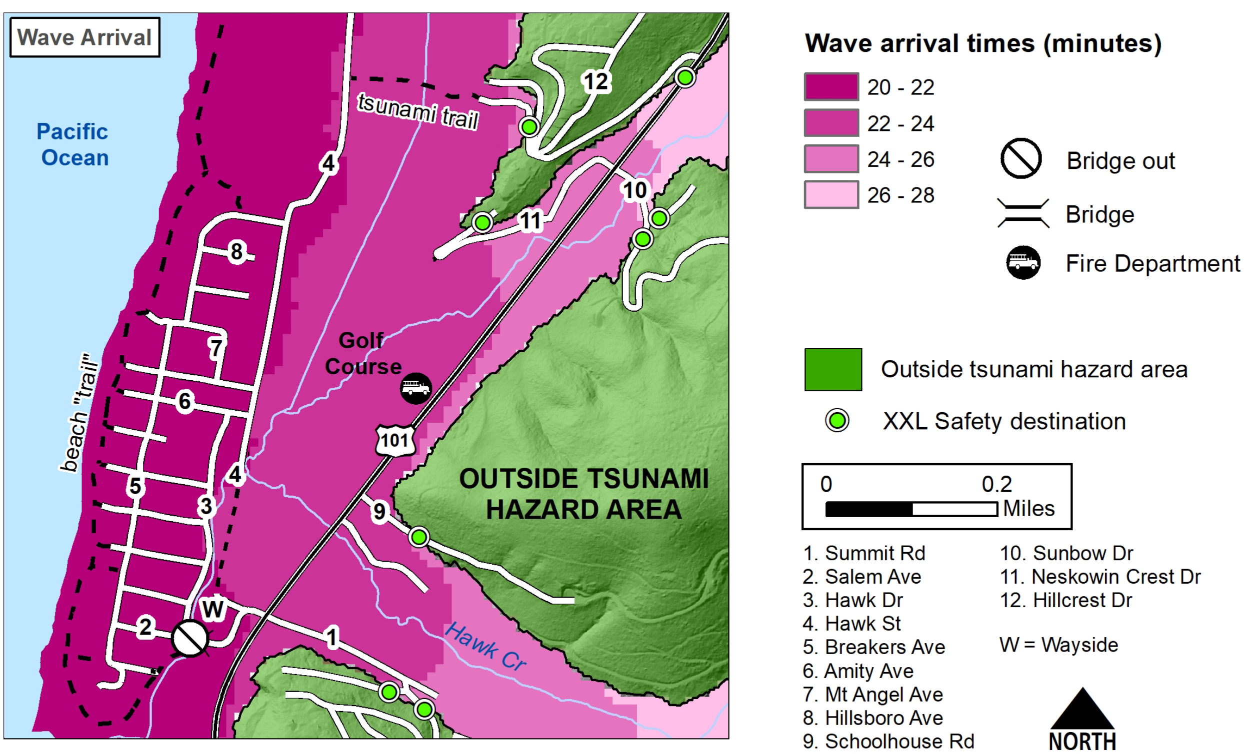
3.1.3.2 Neskowin Central

The Village is where most people live in Neskowin. It also includes the only parking lot available to visitors coming to recreate on the beach, called the Wayside, as well as Nestucca Rural Fire District Station 84. There is only one vehicle access road for the Village: a bridge over Hawk Creek on Salem Ave. There is a gated unimproved road connecting Hawk St with the Wayside, which we will refer to as the “Hawk St path” here. These two roads are the only ways to reach Highway 101 and then head east up Summit Rd to high ground. The significant distance evacuees must travel means time cannot be wasted figuring out how to cross Hawk Creek. We assume (from communication with Neskowin Citizen’s Advisory Committee, 2018, 2019) that the Salem Ave bridge will fail. Therefore evacuees must either scramble across the creek itself or travel north to Amity Ave and then south again on Hawk St, adding a significant distance to their route. There is also the concern that earthquake shaking will render the Hawk St path impassable due to failure of the road surface and deep standing water during winter flooding, thereby blocking the only other egress route from the Village.

A third evacuation route available to the Village, but the route is not located in the Village itself. The “tsunami trail” is a pedestrian path ~0.2 mile north of Corvallis Ave that connects Hawk St to high ground at the base of Hillcrest Dr. The trail itself is ~0.2 mile long and crosses a marsh that at certain times of the year can be covered by significant amounts of water. This is a long distance for an evacuee to travel, especially if starting at the south end of the Village, an additional ~0.5 mile to the south. We will discuss the importance of each of these three options for the Village along with the possibility of additional trails and a consideration of evacuation in Large (L) tsunami scenario.

The initial tsunami wave is expected to arrive on the beach in this area ~20–22 minutes after the start of earthquake shaking (**Figure 3-18**). It will take only about 2–4 minutes for the Village to be fully inundated.

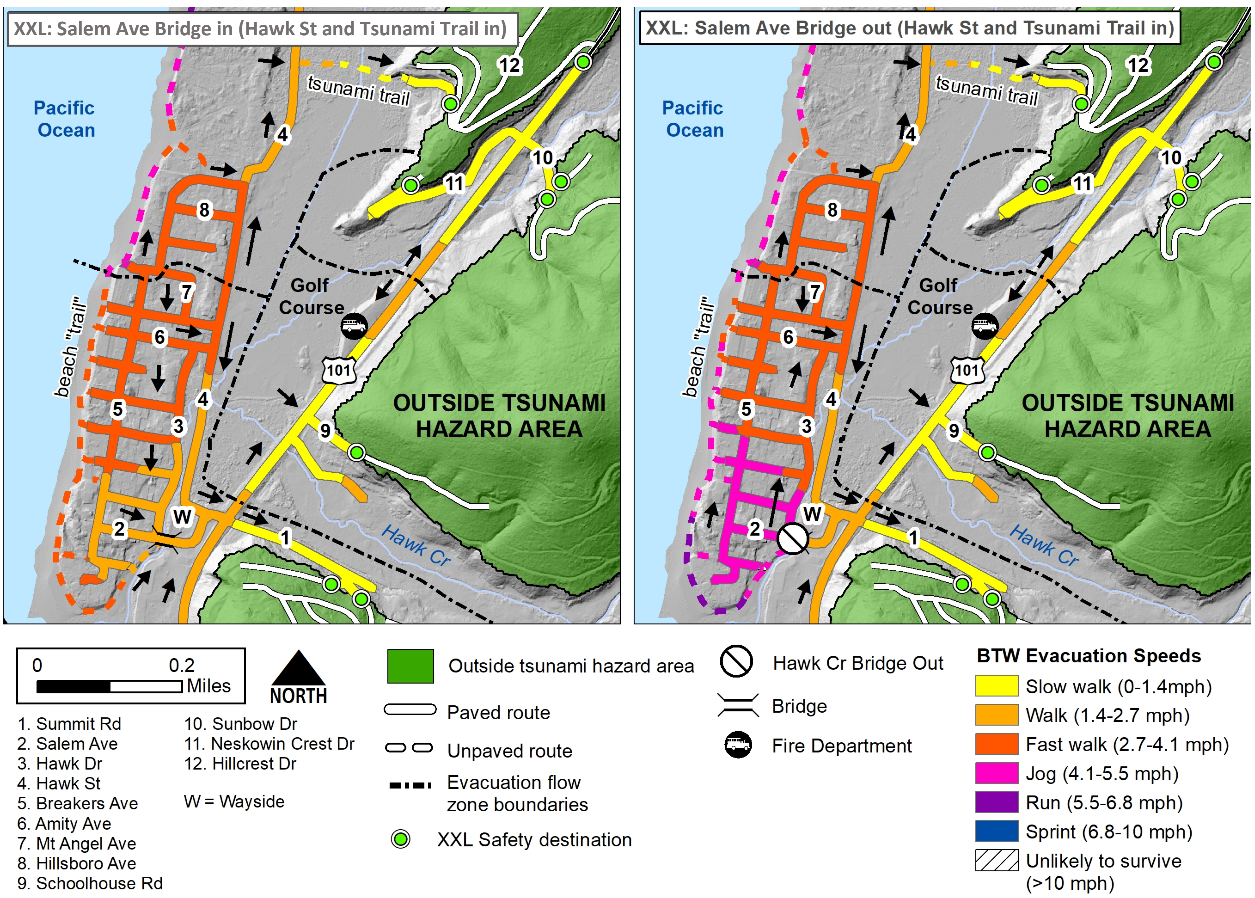
Figure 3-18. Modeled tsunami wave arrival times for Neskowin Central after XXL Cascadia subduction zone earthquake.



3.1.3.2.1 Salem Ave Bridge in/out

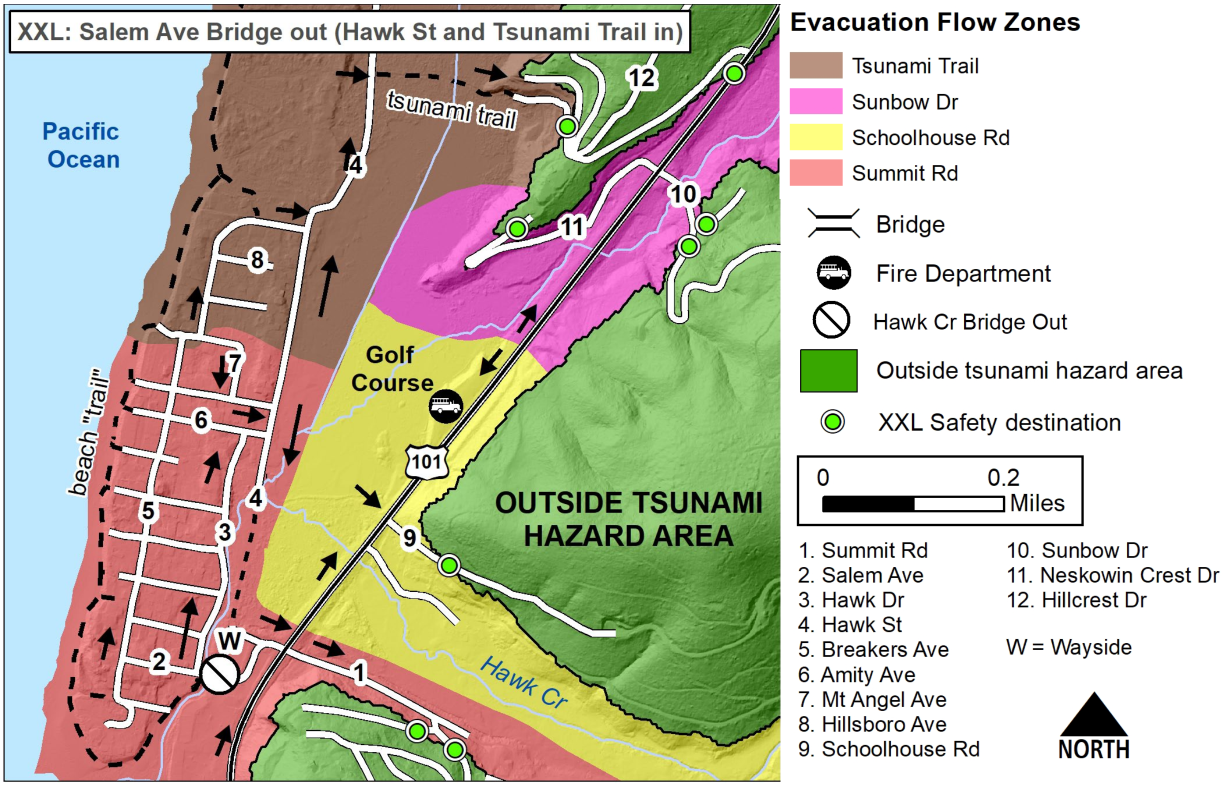
First, we evaluated the importance of the Salem Ave bridge by running scenarios with and without the bridge (**Figure 3-19**). The Hawk Street path and tsunami trail are available in both these scenarios. The first observation from this comparison is that the bridge is important for the southern half of the Village but not for the northern half, where minimum speeds remain are the same. For the southern end, the bridge is significant—without it, residents and beachgoers in this area must at a minimum pace of ***jog***, but with the bridge available evacuees may maintain a ***walk*** (4 fps or 2.7 mph) to reach high ground across Highway 101. These results present a compelling argument for the consideration of a seismic retrofit to the Salem Ave bridge.

Figure 3-19. Beat the Wave modeling in Neskowin Central assuming (A) the Salem Ave Bridge remains available for evacuation after the earthquake, and (B) the base scenario which assumes failure of the bridge.



After lengthy discussion with the Neskowin Citizen Advisory Committee (CAC) in 2018 and 2019 and our own fieldwork and geologic judgement, we consider **Figure 3-19, right** (bridge out) our "base scenario." The bridge is likely to fail, and although the Hawk Street path may be difficult to traverse due to potential road failures or standing water, it will likely be passable on foot. Therefore, we present evacuation flow zones for this base scenario (**Figure 3-20**).

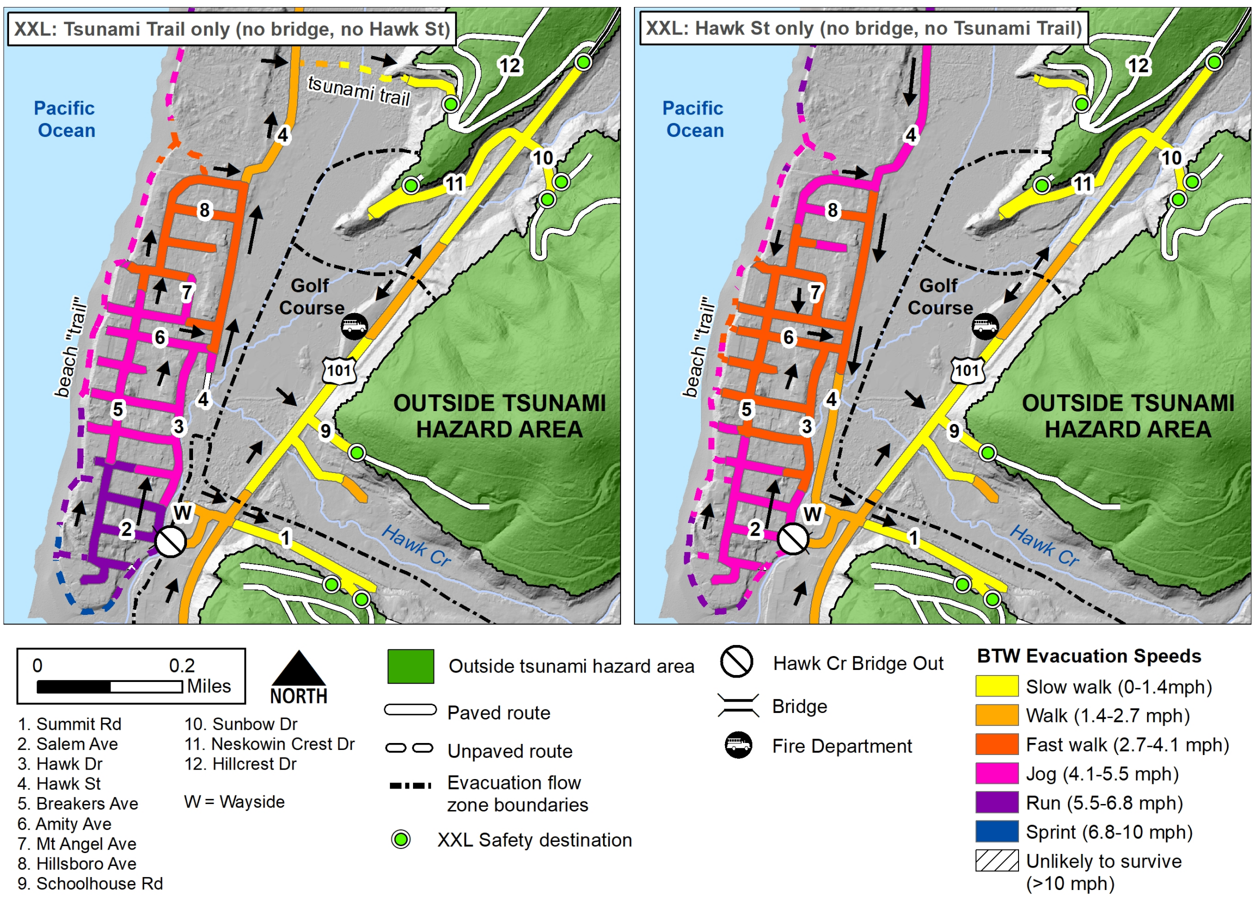
Figure 3-20. Beat the Wave modeling in Neskowin Central for the base scenario (Salem Ave bridge out, Hawk St path in) depicting the existing road and trail network. Evacuation flow zones are shown on their own as colored polygons instead of black dashed lines.



3.1.3.2.2 Hawk Street path and tsunami trail

Because the Salem Ave bridge is likely to fail, we compared the evacuation situation for the other two options (Hawk St path and tsunami trail) by running scenarios with only one of the two available. The bridge is unavailable for both. **Figure 3-21** presents the results of these two scenarios. With just the tsunami trail available for the Village, BTW minimum walking speeds range from ***fast walk*** to ***run*** (**Figure 3-21, left**). With Hawk St alone, minimum walking speeds are ***fast walk*** to ***jog***. It is clear from viewing these results side by side that Hawk St provides much better evacuation opportunities for the Village than the tsunami trail. This does not negate the importance of the tsunami trail; rather, this provides evidence to justify efforts to ensure Hawk St remains a viable evacuation route.

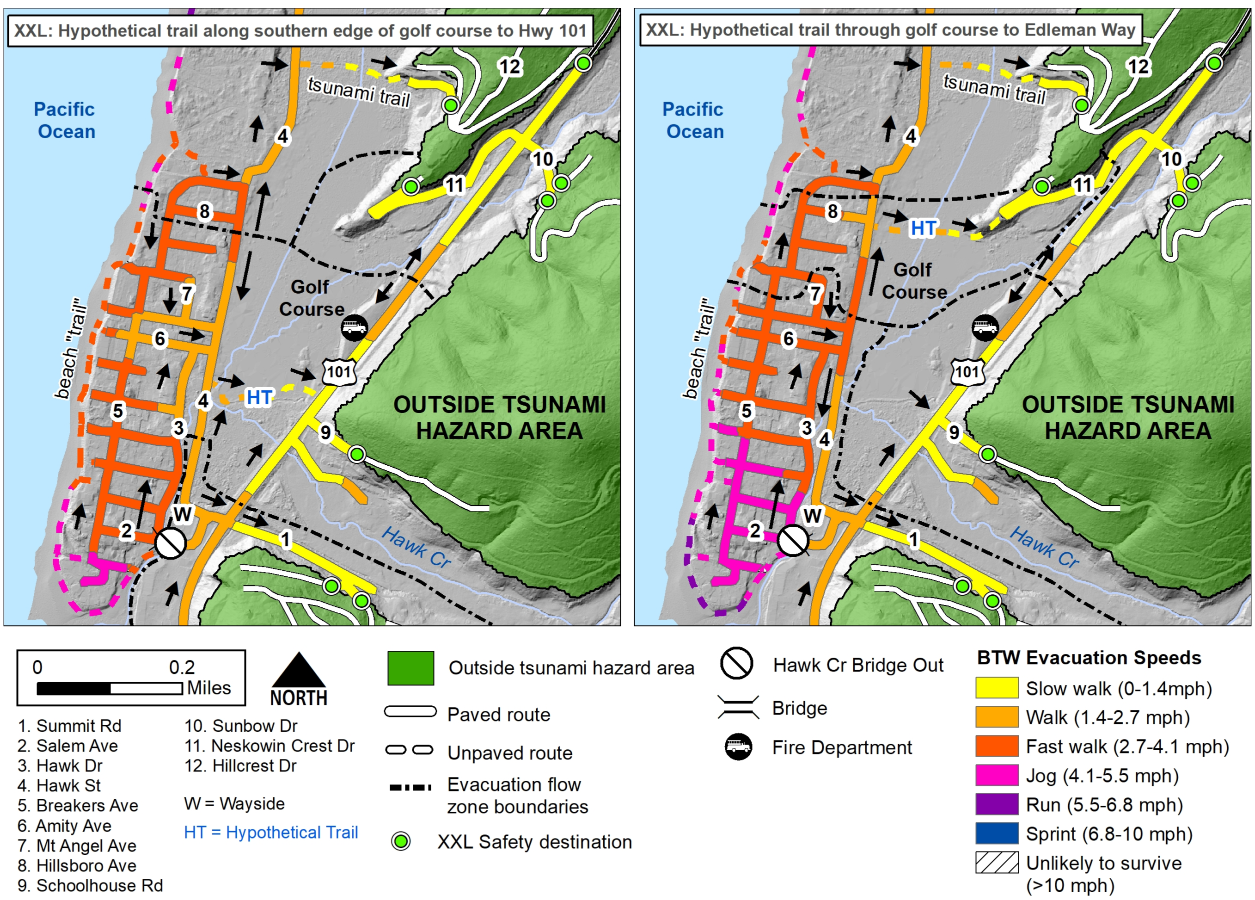
Figure 3-21. Beat the Wave modeling in Neskowin Central assuming (left) the tsunami trail is the only egress, and (right) Hawk Street is the only egress (both scenarios assume the Salem Avenue bridge is out).



3.1.3.2.3 New evacuation trails across the golf course

The Neskowin community is already looking into additional evacuation options. We present BTW results for two possible evacuation routes across the golf course currently being considered by the Neskowin CAC. Neskowin CAC told the authors that these trails exist but that no improvements have been made to ensure passage is maintained after the earthquake. As both trails cross an area that can be quite wet, improvements may be an important future consideration. **Figure 3-22, left** presents a path across the southern edge of the golf course connecting Hawk St by the clubhouse with Highway 101 near Schoolhouse Rd ("southern trail"). **Figure 3-22, right** presents a scenario containing a path connecting Hawk St by Hillsboro Avenue to the base of Neskowin Crest Dr ("northern trail"). Both scenarios demonstrate an improvement over the base run (**Figure 3-19, right**), but the southern trail has a greater impact. The southern trail effectively removes ***jog*** from the southern portion of the Village, while the northern trail improves evacuation only for those in the immediate vicinity of Hillsboro Ave.

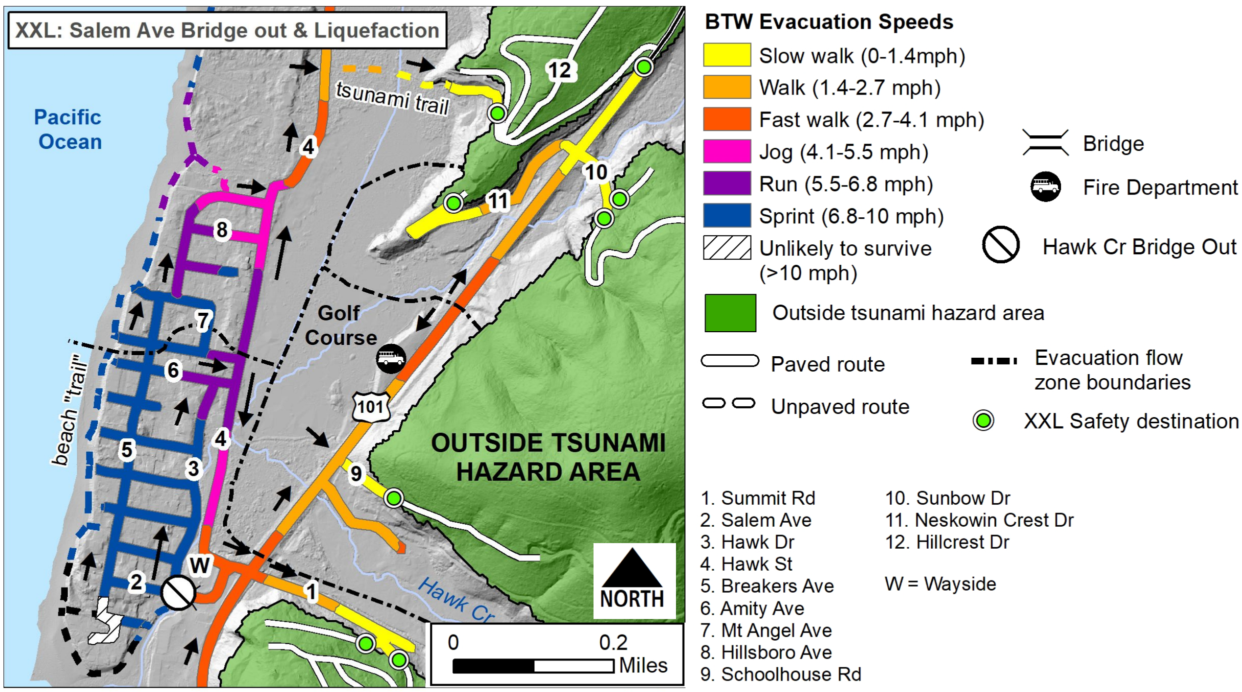
Figure 3-22. Beat the Wave modeling in Neskowin Central assuming an evacuation trail (labeld with "H") across (left) the southern edge of the golf course, and (right) across the northern edge of the golf course.



3.1.3.2.4 Liquefaction

Because of the high susceptibility of this area, we applied liquefaction to the base scenario. Adding this hazard dramatically increases the minimum required walking speeds (**Figure 3-23**) and emphasizes the importance of finding ways to improve surface conditions for evacuation, if possible. Keep in mind liquefaction is not necessarily going to affect every road in the community; this is a conservative look at how it might challenge evacuation.

Figure 3-23. Beat the Wave modeling in Neskowin Central using the base road and trail network with liquefaction.



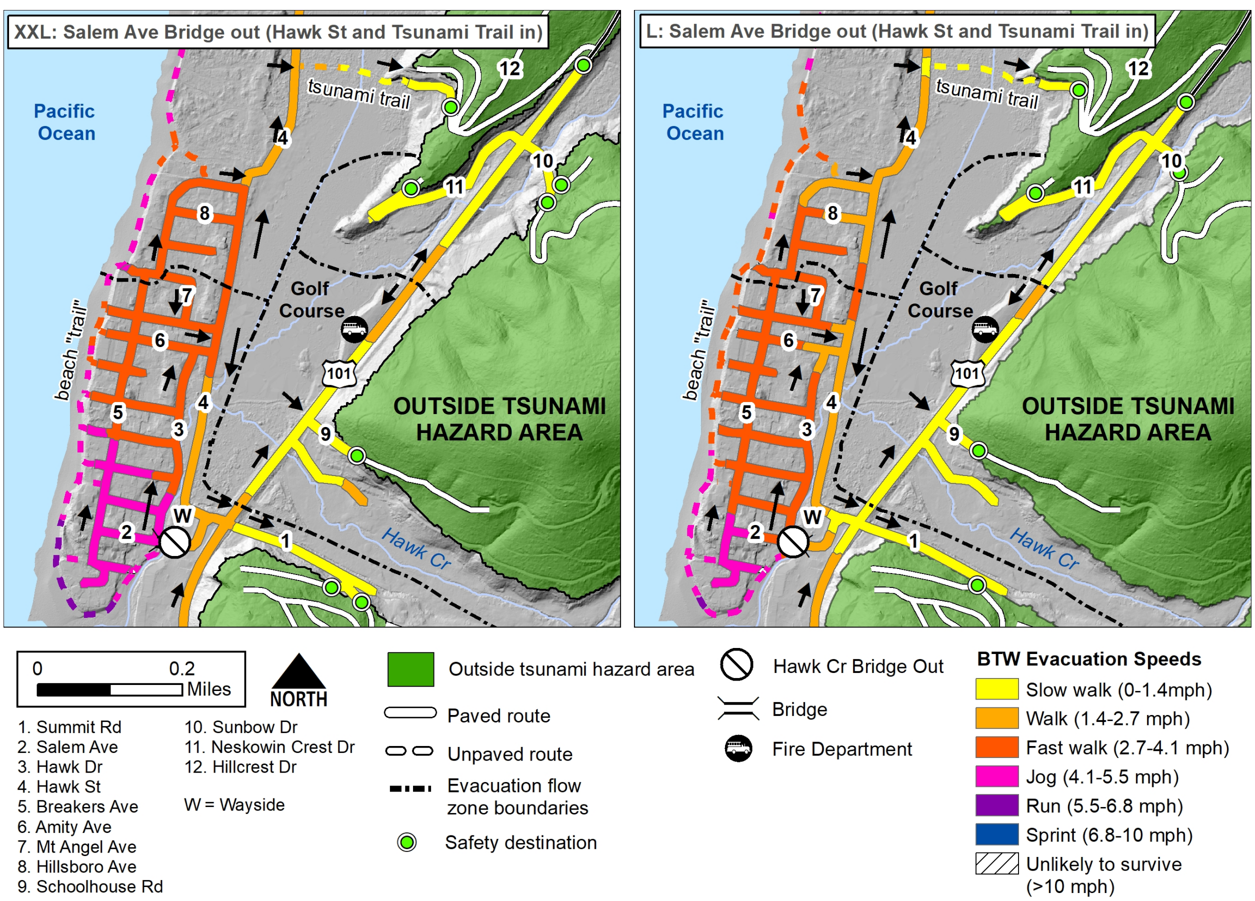
3.1.3.2.5 Large tsunami scenario

According to our modeling, surviving an XXL tsunami in Neskowin Central, especially at the southern end, will be difficult. Another option depending on an individual's acceptable level of risk is to consider the Large (L) tsunami scenario instead of XXL. The L1 scenario covers 95% of the likely inundation (XXL covers 100%), meaning that there is only a 5% chance that high ground outside L will be inundated by a larger tsunami. Because the L scenario is a smaller tsunami, high ground, and thus safety, is at a slightly lower elevation. The shorter distance to safety slightly reduces required minimum walking speeds.

Figure 3-24, right shows that when distances to safety on Summit Rd and on the tsunami trail are reduced by just a few hundred feet, minimum walking speeds are reduced at the far north and south ends of the Village. Minimum speeds for evacuees in several blocks at the south end decrease from ***jog*** to ***fast walk***, and minimum speeds for evacuees in a few blocks at the north end drop from ***fast walk*** to ***walk***. For comparison, we repeat the XXL base scenario (**Figure 3-19, right**) results in **Figure 3-24, left**.

We show these results to point out that every step taken toward high ground is important—no one will know how large a CSZ tsunami is until it arrives. XXL is the maximum-considered event; in the event of a smaller tsunami, evacuees will need to move to high ground but may not need to reach the XXL safety destinations shown in this report.

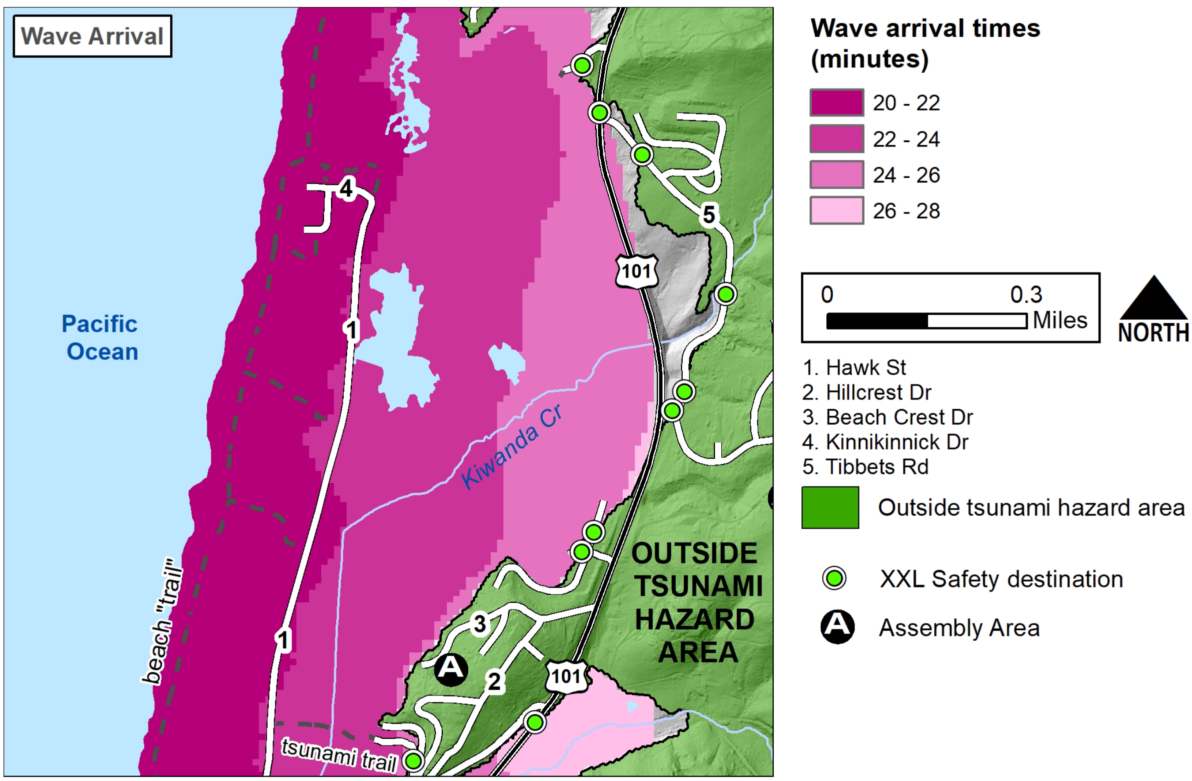
Figure 3-24. Beat the Wave modeling in Neskowin Central for two tsunami sizes: (left) XXL base scenario, and (right) Large (L1) tsunami scenario.



3.1.3.3 Neskowin North

Neskowin North covers Hawk St between Corvallis Ave and Kinnikinnick Dr. This stretch of Neskowin contains the tsunami trail, introduced in the previous section. This area contains year-round water bodies and is also separated from high ground to the east by a wide marsh that is wet for part of the year. As we will show, evacuation to the south via the Village is too far away and unlikely to succeed; the only option currently available for Neskowin North residents is the tsunami trail. For evacuation from this neighborhood we discuss Bear Mountain, a high point outside the Large (L) tsunami scenario (but not outside XXL) as a safety destination; a hypothetical trail across the marsh; and the liquefaction hazard. The tsunami reaches Hawk St approximately 22 minutes after the start of earthquake shaking (**Figure 3-25**).

Figure 3-25. Modeled tsunami wave arrival times for Neskowin North after XXL Cascadia subduction zone earthquake.

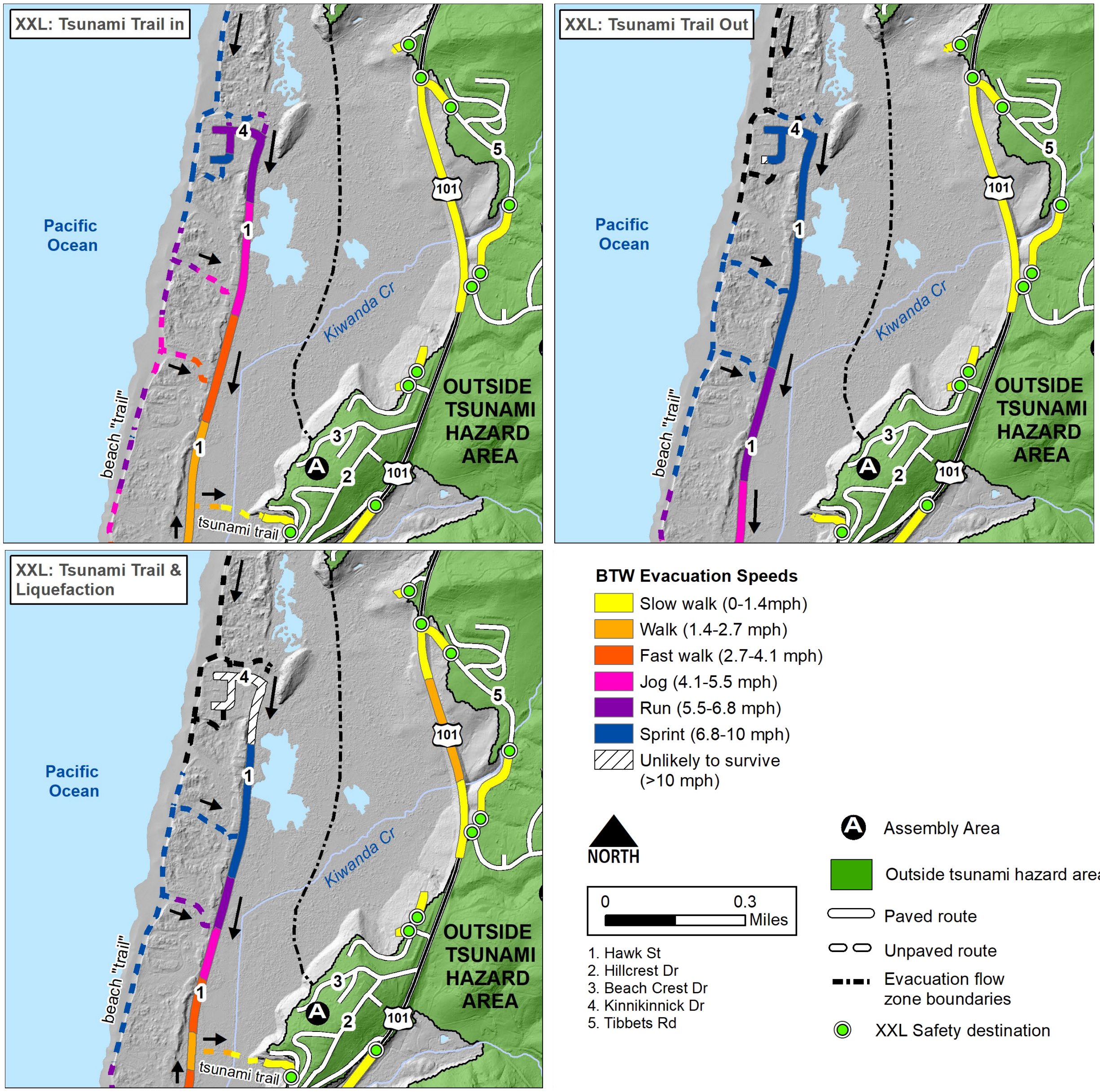


3.1.3.3.1 Tsunami trail

We started our evacuation analysis of Neskowin North by considering the importance of the tsunami trail. **Figure 3-26, top left** presents results with the trail included; minimum walking speeds reach ***run*** on Kinnikinnick Dr. **Figure 3-26, top right** presents results assuming the tsunami trail is not available. Everyone must evacuate via the Village, and evacuees from nearly the entire area must ***sprint*** (15 fps or 10 mph) to survive. Clearly, the tsunami trail is extremely important for this area of Neskowin.

Results for a liquefaction scenario, presented in **Figure 3-26, bottom left**, suggest that evacuees from Kinnikinnick Dr are ***unlikely to survive*** if there are any impediments to easy evacuation on road surfaces. These results, like the Village results for liquefaction, are a sobering reminder of the additional challenges that may be faced during evacuation. Any possible mitigation efforts, large or small, can make a difference.

Figure 3-26. Beat the Wave modeling for Neskowin North assuming (top left) the tsunami trail is available, (top right) the tsunami trail is unavailable and the area must evacuate via the Village to the south, and (bottom left) the tsunami trail is available with liquefaction.

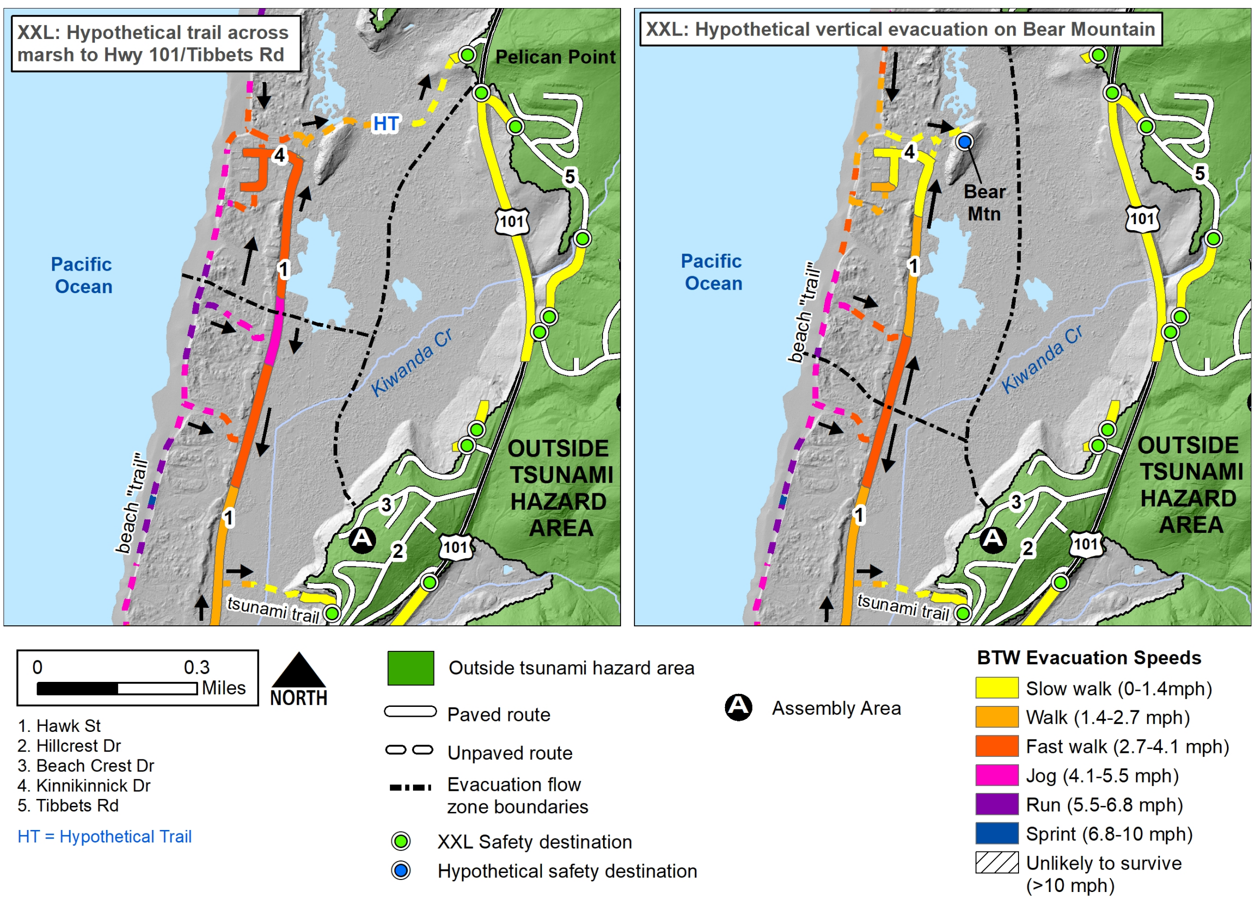


3.1.3.3.2 Hypothetical new trail or vertical evacuation structure

Although options are limited in this area due to its geography, there are mitigation possibilities. The modeling results shown here may help the community determine that the benefits outweigh the potential expense of one of these options. Our first consideration is the construction of a trail across the marsh, connecting Kinnikinnick Dr to Pelican Point. Neskowin CAC told the authors a trail of unknown condition exists, but that ensuring the trail is available year-round with appropriate engineering and signage is important for the trail's effectiveness as an evacuation route. Results for this scenario are shown in **Figure 3-27, left**. Kinnikinnick Dr minimum walking speeds drop from ***run*** (**Figure 3-26, top left**) to ***fast walk***.

Figure 3-27, right presents a more costly but effective mitigation strategy: vertical evacuation. Bear Mountain is a hill of solid bedrock that rises ~50 feet above the surrounding area, making it a natural location to build a structure. As expected, BTW results are dramatically improved: Kinnikinnick Dr minimum walking speeds drop to ***slow walk*** and the greatest minimum speed for the area is ***fast walk***.

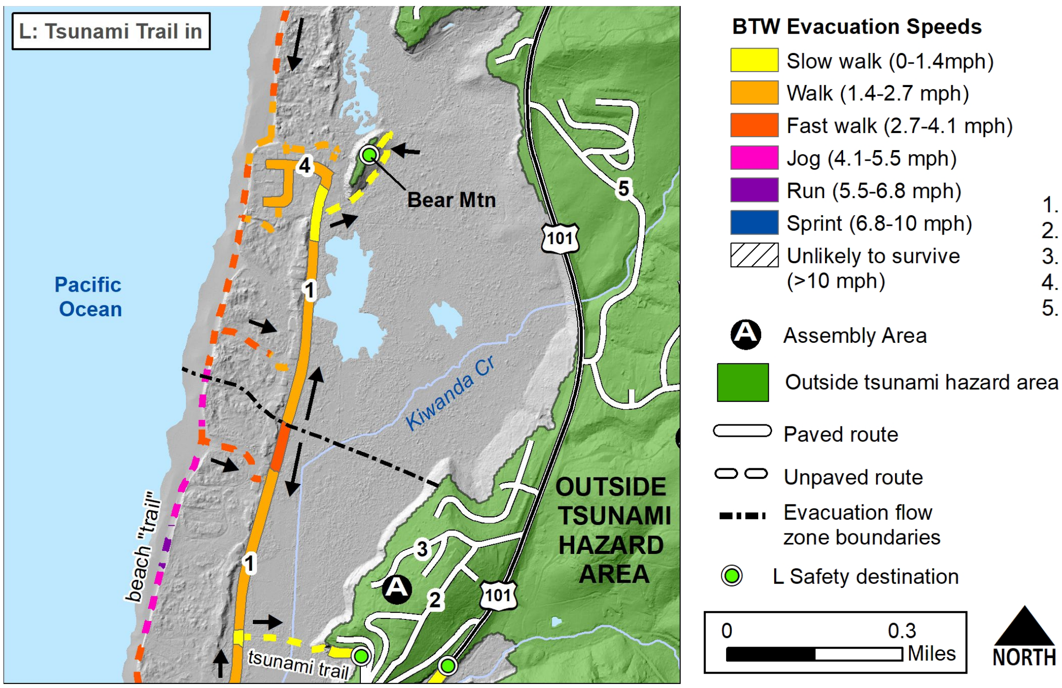
Figure 3-27. Beat the Wave modeling for Neskowin North assuming (left) an evacuation trail across the marsh toward Pelican Point, and (right) a vertical evacuation structure on Bear Mountain.



3.1.3.3.3 Large tsunami scenario

Even more so than the Village, Neskowin North may want to consider the Large (L) tsunami scenario instead of XXL. The L scenario covers 95% of the likely inundation (XXL covers 100%), meaning that there is only a 5% chance that high ground outside L will be inundated by a larger tsunami. In the L scenario, besides the slightly shorter distance to safety on the tsunami trail, Bear Mountain provides a nearby "island" of high ground that improves the odds of successful evacuation for Neskowin North. Results for this scenario (**Figure 3-28**) are similar to those for the XXL vertical evacuation structure (**Figure 3-27, right**). Planning for the L scenario and Bear Mountain safety destination may be acceptable based on an individual's or community's acceptable level of risk.

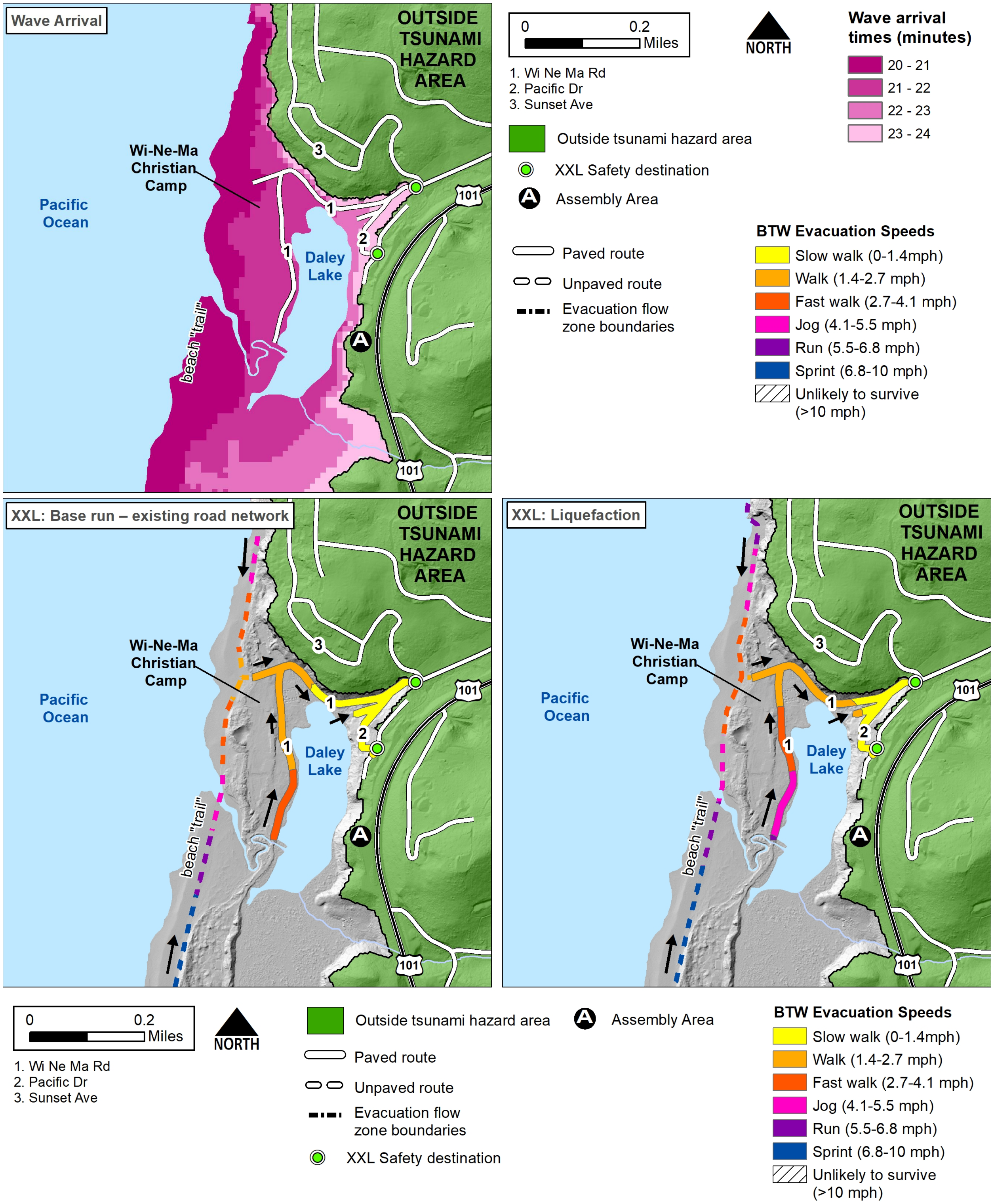
Figure 3-28. Beat the Wave modeling for Neskowin North for Large (L) tsunami rather than XXL tsunami (Figure 3-26, top left).



3.1.3.4 Winema

The small inundated area immediately south of the mouth of Nestucca Bay includes Wi-Ne-Ma Christian Camp and a small but popular beach access parking lot at the west end of Wi ne Ma Rd. Evacuation from this area is relatively easy, with high ground a short distance up Wi Ne Ma Rd toward Highway 101. **Figure 3-29, top left** presents wave arrival times for the area; the tsunami reaches the beach ~20 minutes after the start of earthquake shaking, and it will take approximately 3 minutes to inundate the area. Minimum BTW walking speeds for the base scenario are ***slow walk*** and ***walk*** (4 fps or 2.7 mph) (**Figure 3-29, bottom left**), but the added challenges of liquefaction may result in minimum speeds of ***fast walk*** and ***jog*** for the Wi-Ne-Ma Christian Camp (**Figure 3-29, bottom right**).

Figure 3-29. (top left) Modeled tsunami wave arrival times for Winema after XXL Cascadia subduction zone earthquake, and (bottom left) Beat the Wave modeling for base run, and (bottom right) with liquefaction.



3.2 Socioeconomic analysis

Many Tillamook County communities have a large percentage of buildings, residents, and jobs within the tsunami zone, which present evacuation, response, and recovery challenges. In this section we provide socioeconomic perspectives of four unincorporated Tillamook County communities: Cape Meares, Neskowin, Netarts, and Oceanside U.S. Census Bureau (2017) census-designated places (CDPs) (**Figure 3-30** through **Figure 3-33**).

Figure 3-30. Cape Meares census-designated place (CDP), showing buildings, roads, and XXL tsunami zone. Only the inhabited portion of Cape Meares CDP is shown. Tsunami XXL zone from Priest and others (2013b). CDP and city boundaries from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).

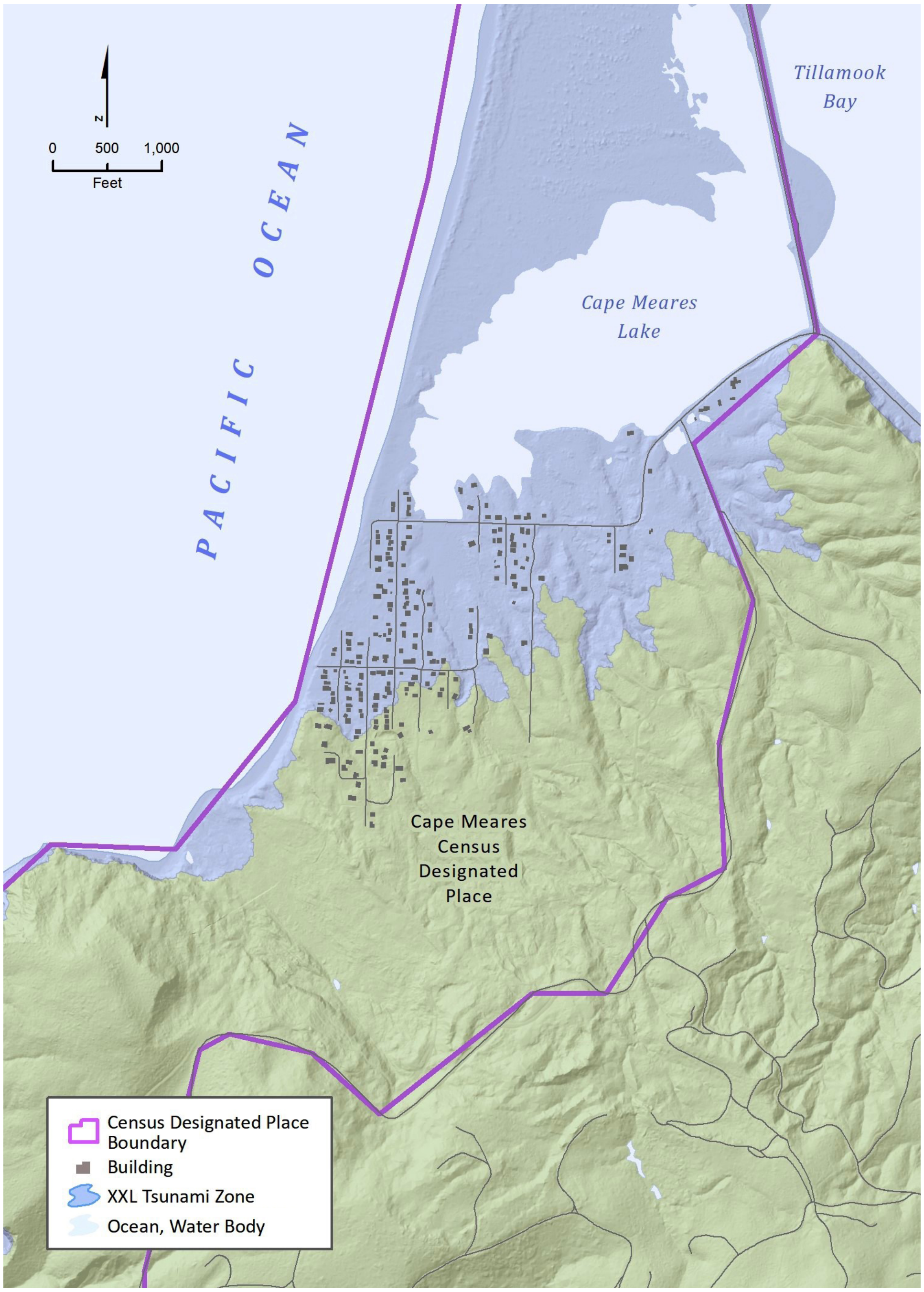


Figure 3-31. Neskowin census-designated place (CDP), showing buildings, roads, and XXL tsunami zone. Tsunami XXL zone from Priest and others (2013b). CDP boundary from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).

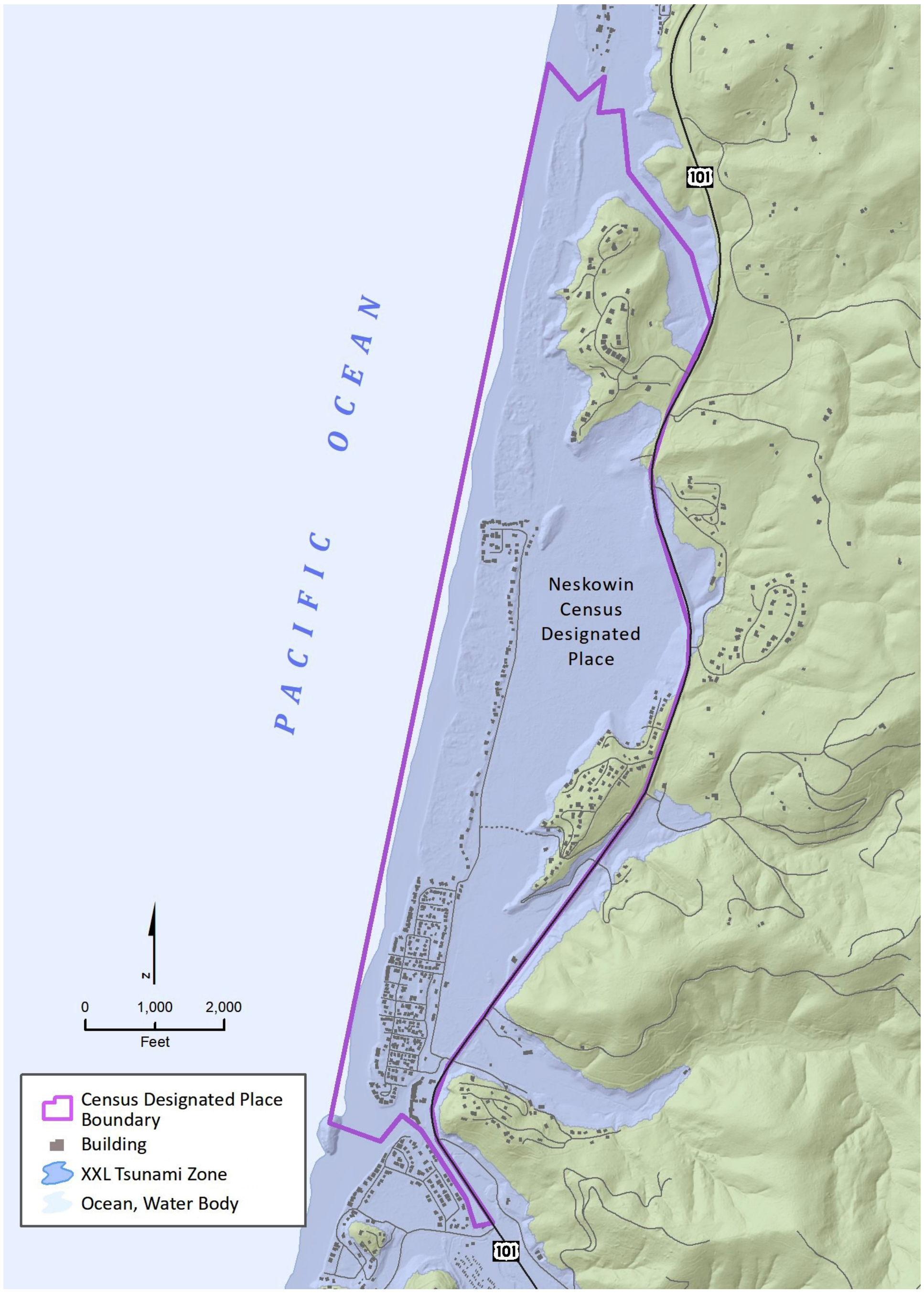


Figure 3-32. Netarts census-designated place (CDP), showing buildings, roads, and XXL tsunami zone. Tsunami XXL zone: Priest and others (2013b). CDP boundary from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).

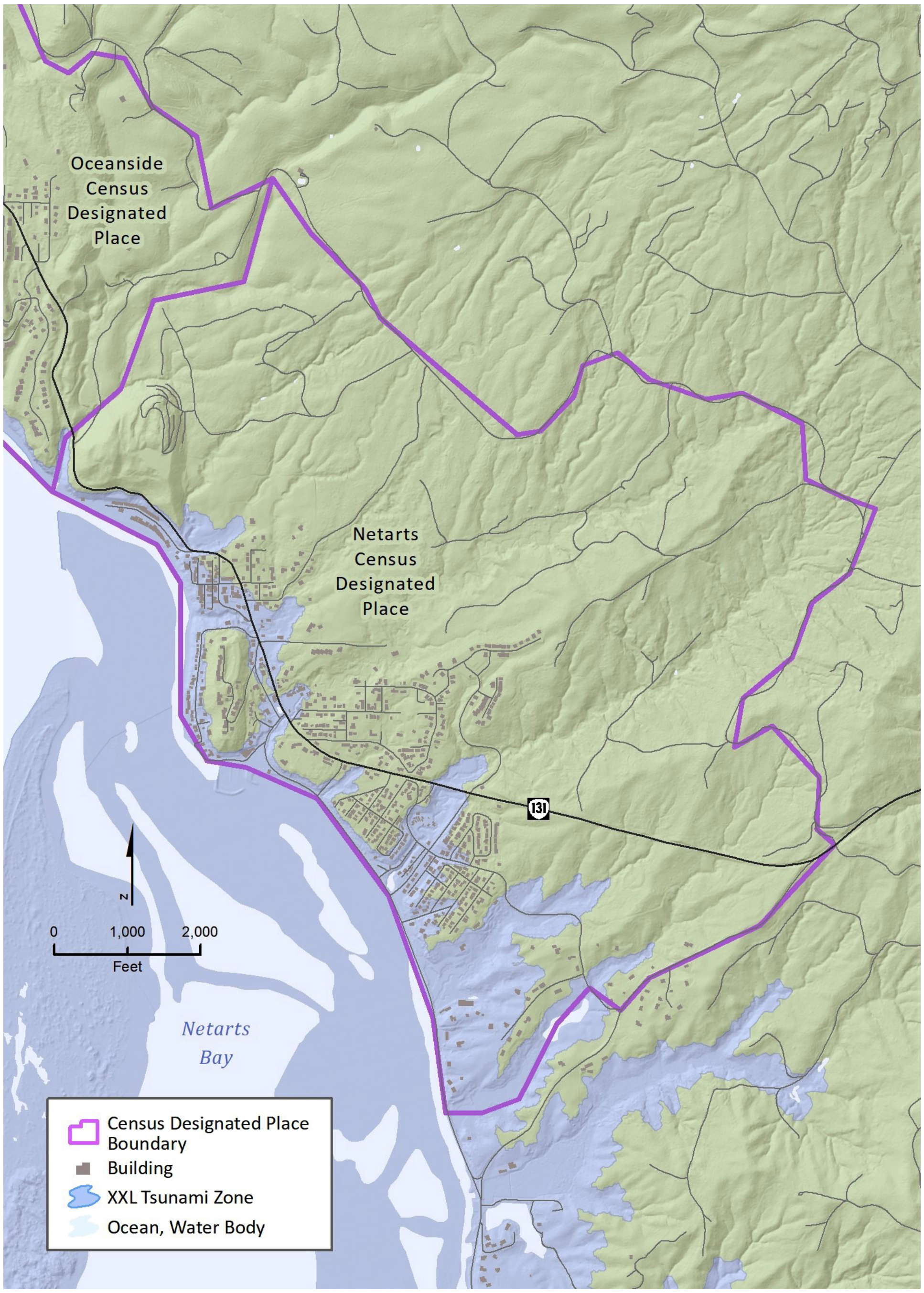
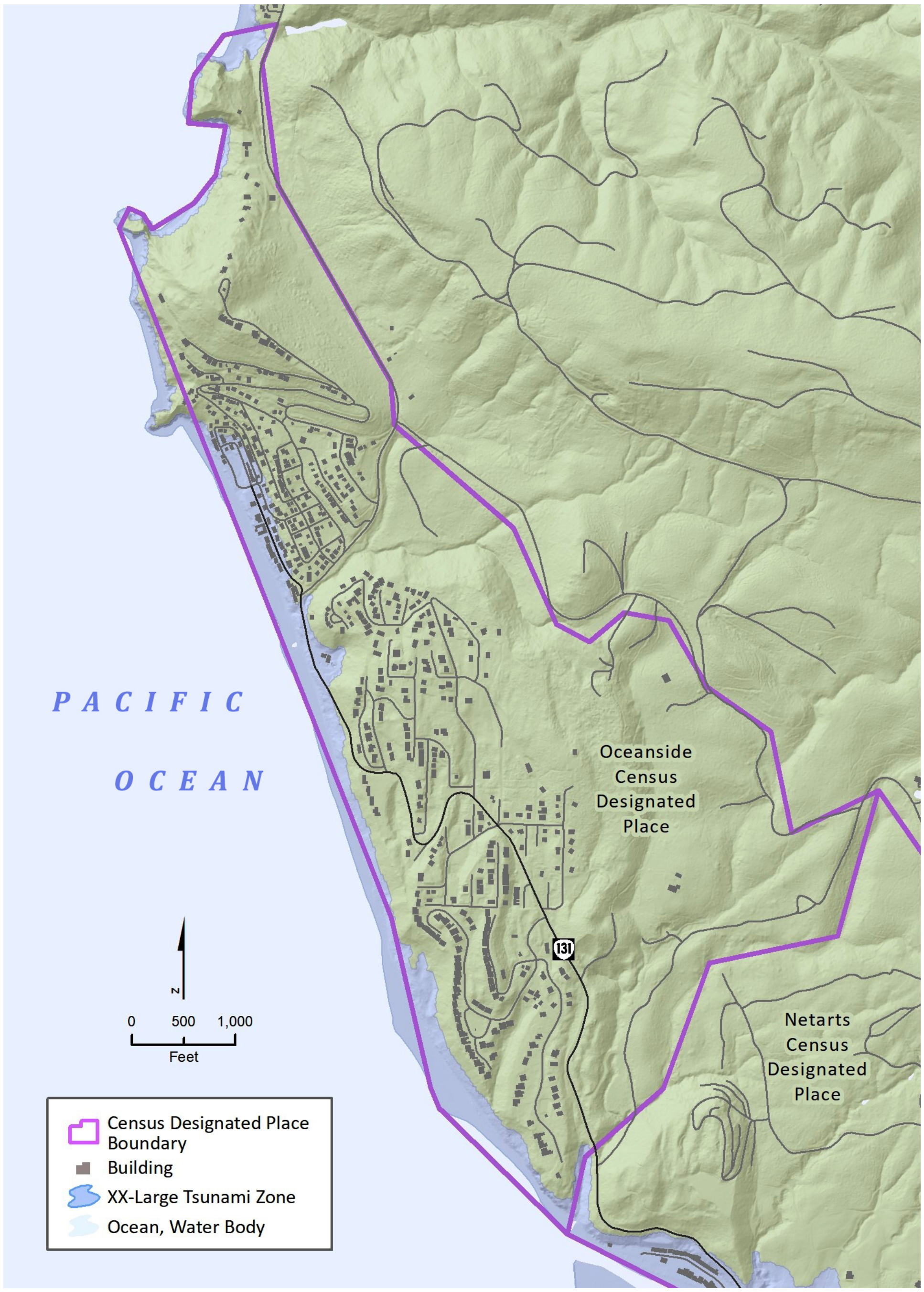


Figure 3-33. Oceanside census-designated place (CDP), showing buildings, roads, and XXL tsunami zone. Tsunami XXL zone from Priest and others (2013b). CDP boundaries from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).



In Oregon coastal communities, the percentage of a jurisdiction's permanent residents in the tsunami zone are often less than the percentage of building value in the tsunami zone (**Table 3-2**, **Figure 3-34**, **Figure 3-35**). The difference can be explained as follows: commercial and industrial development patterns with relatively expensive buildings are often concentrated around or adjacent to waterfronts and harbors, and large recreational-oriented facilities and motel-type housing are often concentrated near harbors and shorelines. In addition, real estate market dynamics in Oregon are such that many residential homes within the tsunami zone are second homes or vacation rentals that do not house permanent residents. Corresponding with the commercial and industrial development patterns, the percentage of jobs in the tsunami zone is typically higher than the percentage of permanent residents within the tsunami zone (**Table 3-3**, **Figure 3-36**). A concentration of jobs within the tsunami zone can present additional disaster recovery challenges, as it is likely the place of employment will be extensively damaged or destroyed by a tsunami. Within many Oregon coastal communities, the Accommodation and Food Services sector (North American Industry Classification System Sector 72) is the largest employer by sector within the tsunami zone. Such is the case for Tillamook County overall and for several of the CDPs analyzed in this report (**Table 3-3**). The Accommodation and Food Services sector comprises establishments providing customers with lodging and/or preparing meals, snacks, and beverages for immediate consumption. The sector includes both accommodation and food services establishments because the two activities are often combined at the same establishment. (https://www.census.gov/eos/www/naics/).

The percentage of people speaking Spanish at home is about 6% for Tillamook County (**Table 3-4**). Due to insufficient sampling size, the ACS data were not available for most of the CDPs in this report. Emergency planners can use the information to better understand the county and community diversity when creating tsunami preparation and evacuation messages.

Tsunami casualty models often assume all people within a tsunami zone can evacuate in a timely manner. **Table 3-5** quantifies the number and percentage of people within each community with a disability who may have challenges mobilizing in a timely manner after an earthquake. In addition, family members or caretakers may be delayed while assisting a person with a disability. We emphasize that the percentages in **Table 3-5** are for the entire community, and do not necessarily describe the population within the tsunami zone. We also caution that given the relatively small sample sizes, the confidence bounds for all CDPs are fairly large. Neskowin, Oceanside, Netarts and Cape Meares CDPs have larger percentages of people over 65 (**Table 3-2**, **Figure 3-36**) compared to the Tillamook County percentage. This can present additional evacuation challenges as the walking speeds of elderly people are on average slower than the walking speeds of people less than 65 years old.

Table 3-2. Permanent residents residing within selected tsunami zones for several Tillamook County communities, unincorporated Tillamook County (outside of all Tillamook County cities and CDPs), and overall Tillamook County. The tsunami zones are defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place.

		Tsunami Zone			
				XXL	
Community	Total Population	Medium	Large	Total	People 65 and Older
Cape Meares CDP	115	34	55	81	36
Neskowin CDP	193	89	96	120	49
Netarts CDP	881	16	48	193	64
Oceanside CDP	330	3	7	15	7
Uninc. Tillamook County*	13,035	1,076	1,473	2,112	567
Tillamook County Total	26,395	2,657	4,226	7,052	1,949

*People outside of city limits and CDP boundaries.

Population estimates: City and county population: Portland State University Population Research Center (PRC), 2018. CDPs: American Community Survey data 2013-2017 5-year estimates (U.S. Census Bureau, 2018).

Figure 3-34. Percentage of permanent residents residing within selected tsunami zones for several Tillamook County communities, unincorporated Tillamook County (outside of all Tillamook County cities and CDPs), and overall Tillamook County. The tsunami zones are defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place. Data based on analysis of Oregon Department of Motor Vehicles records.

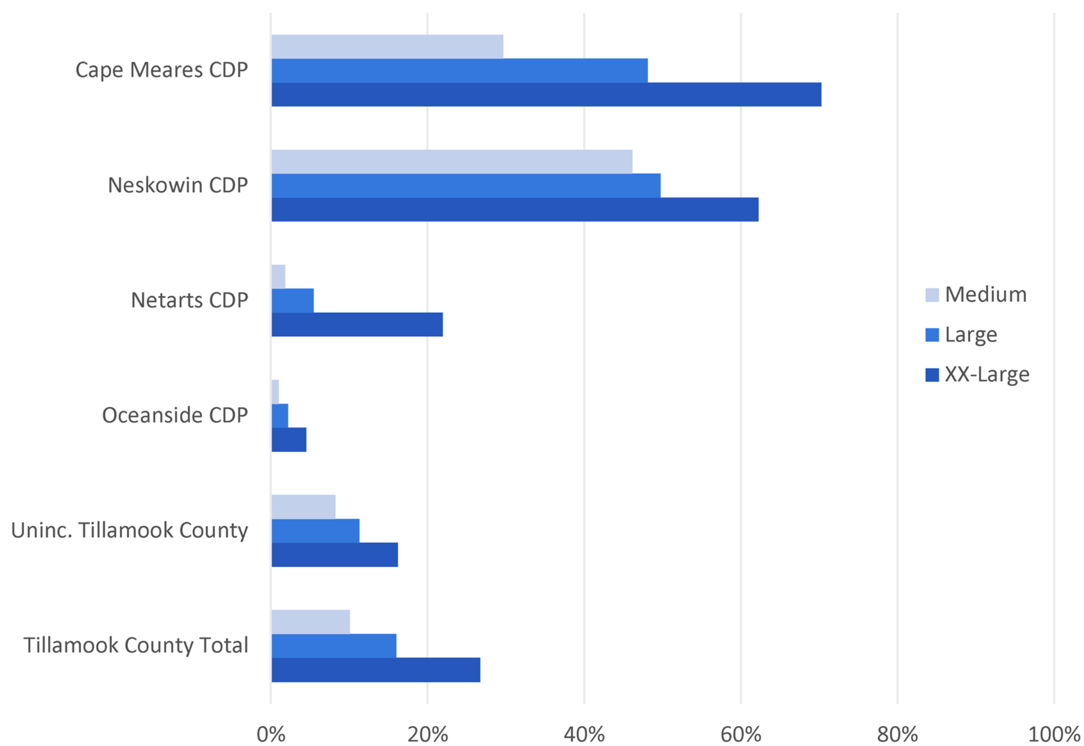


Figure 3-35. Percentage of community's building replacement cost within selected tsunami zones for several Tillamook County communities, unincorporated Tillamook County (outside of all Tillamook County cities and CDPs), and overall Tillamook County (M. Williams, written communication, 2019). Tsunami zones are defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place.

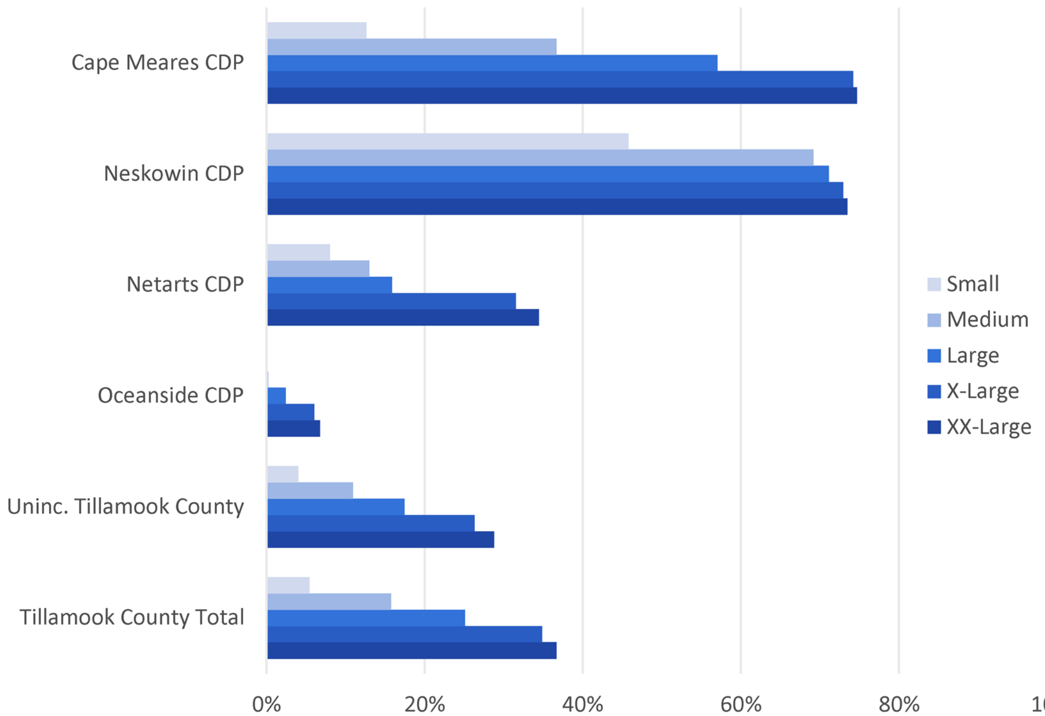


Table 3-3. Number of employers, employees, annual wages paid, and top employment sector for several Tillamook County communities, unincorporated Tillamook County (outside of all Tillamook County cities and CDPs), and overall Tillamook County. The tsunami zone is the XXL scenario as defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place.

	Employers		Employees		Top Employment Sector in Tsunami Zone		
	Total	Tsunami Zone	Total	Tsunami Zone	% of Jobs in Tsunami Zone for Given Sector	NAICS Code	NAICS Category+
Cape Meares CDP	—	—	—	—	—	—	—
Neskowin CDP	13	11	65	—	—	72	Accommodation and Food Services
Netarts CDP	20	11	87	59	—	72	Accommodation and Food Services
Oceanside CDP	10	—	51	—	—	72	Accommodation and Food Services
Uninc. Tillamook County*	341	80	3,486	1,707	—	—	—
Tillamook County Total	1,042	450	11,444	5,821	—	31	Manufacturing

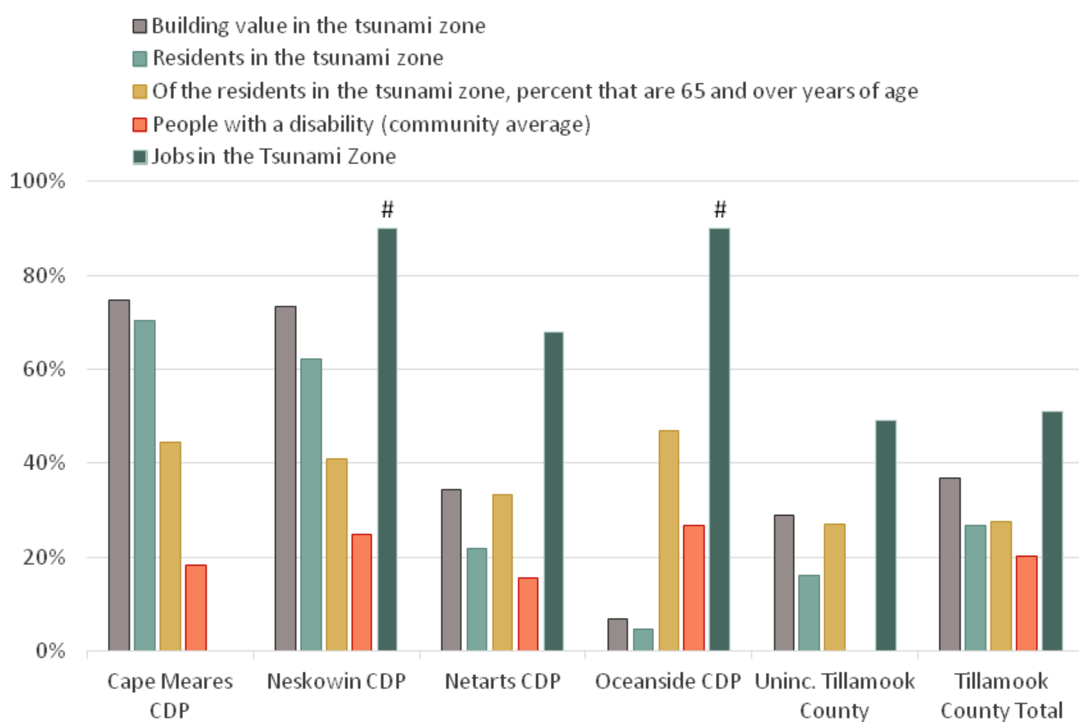
Employment data from Quarterly Census of Employment and Wages (second quarter, 2018; J. Mendez, Oregon Employment Division, written communication, September 28, 2018).

"—" indicates not reported for employer confidentiality reasons.

*Employers outside of *all* Tillamook County CDPs and cities.

+North American Industrial Classification System.

Figure 3-36. Socioeconomic data for several Tillamook County communities, unincorporated Tillamook County (outside of all Tillamook County cities and CDPs), and overall Tillamook County. Socioeconomic data sources are described in the text. The tsunami zone is defined by the XXL scenario (Priest and others, 2013b). Disability data are not available by tsunami zone but represents overall community percentage. Disability data are not available for unincorporated Tillamook County. CDP is U.S. Census Bureau census-designated place.



More than 90%. Exact percentage not reported for employer confidentiality reasons.

Table 3-4. Number of households and households speaking Spanish for several Tillamook County communities and overall Tillamook County. The household language assigned to the housing unit is the non-English language spoken by the first person with a non-English language. It is not an estimate of limited English fluency. CDP is U.S. Census Bureau census-designated place.

	Total Number of Households	Number of Households Speaking Spanish	Percent of Households with Margin of Error
Cape Meares CDP	63	—	—
Neskowin CDP	135	—	—
Netarts CDP	135	—	—
Oceanside CDP	398	6	1.5% ± 2.4%
Tillamook County Total	10,454	649	6.2% ± 1.0%

Data from https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2017/.
“—"indicates Insufficient sample size.

Table 3-5. Number of individuals with a disability for several Tillamook County communities and overall Tillamook County. The number of individuals is an estimate of civilian, non-institutionalized people in the community. A person with a disability may have more than one difficulty; thus, a sum of the individual difficulty categories will typically exceed the "individuals with a disability." Categories with a "—" have insufficient sampling to report an estimate. CDP is U.S. Census Bureau census-designated place.

Difficulty Category	Estimate	Margin of Error
Cape Meares CDP		
Individuals (estimate)	115	
Individuals with a disability	21	18.3% ± 14.6%
Hearing	5	4.3% ± 7.4%
Vision	12	8.7% ± 9.9%
Cognitive	5	4.5% ± 7.5%
Ambulatory	16	14.5% ± 13.9%
Self-care	11	10.0% ± 11.4%
Independent Living	12	10.2% ± 11.8%
Neskowin CDP		
Individuals (estimate)	193	
Individuals with a disability	48	24.9% ± 16.3%
Hearing	—	—
Vision	—	—
Cognitive	—	—
Ambulatory	48	24.9% ± 16.3%
Self-care	—	—
Independent Living	—	—
Netarts CDP		
Individuals (estimate)	881	
Individuals with a disability	137	15.6% ± 7.1%
Hearing	63	7.2% ± 4.9%
Vision	40	3.2% ± 4.2%
Cognitive	59	6.9% ± 5.7%
Ambulatory	80	9.3% ± 6.7%
Self-care	37	4.3% ± 4.3%
Independent Living	62	9.0% ± 7.4%
Oceanside CDP		
Individuals (estimate)	330	
Individuals with a disability	88	26.7% ± 22.0%
Hearing	37	11.2% ± 14.4%
Vision	—	—
Cognitive	—	—
Ambulatory	78	23.6% ± 21.2%
Self-care	—	—
Independent Living	—	—
Tillamook County Total		
Individuals (estimate)	25,201	
Individuals with a disability	5,085	20.2% ± 1.7%
Hearing	1,866	7.4% ± 0.9%
Vision	731	2.9% ± 0.7%
Cognitive	1,887	7.9% ± 1.2%
Ambulatory	2,644	11.0% ± 1.3%
Self-care	1,045	4.4% ± 1.0%
Independent Living	1,878	9.3% ± 1.5%

Data from https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2017/.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation provides a quantitative assessment of evacuation difficulty in the coastal communities of Tillamook County. The investigation implemented the Beat the Wave (BTW) approach to evacuation analysis developed by Priest and others (2015, 2016), with a major refinement in that we can now account for variable speeds along a route due to differences in the route characteristics (e.g., flat vs. steep, loose sand vs. paved). As a result, the BTW approach accomplishes in a single map what would require multiple maps in other approaches such as that of Wood and Schmidtlein (2012). In contrast, the single-evacuation-speed approach of Wood and Schmidtlein (2012) is more practical for regional analyses or where wave arrival times are not known.

The results of this study demonstrate that evacuation of the coastal communities in response to a maximum considered (XXL) Cascadia Subduction Zone tsunami is attainable with the notable exception of Neskowin, where moderate to high evacuation speeds are needed to survive. In this location, a robust education program and wayfinding signage is paramount to reduce evacuation delays and direct evacuation along the shortest route possible. Additional earthquake-hardened evacuation routes as well as vertical evacuation are other mitigation options because of the scarcity of natural high ground (outside XXL) in the immediate vicinity. A large enough vertical evacuation structure (e.g., a berm or building) capable of holding the estimated number of people in the relevant evacuation flow zone would need to be built to a sufficient height. We recommend further evaluation to assess the cost/benefits of this option.

Another option depending upon an individual's acceptable level of risk is to consider the Large (L1) tsunami scenario instead of XXL. Natural high ground is available on Bear Mountain, and the Large scenario covers 95% of the likely inundation (XXL covers 100%). The decision to direct people to nearby L1 high ground versus taking the tsunami trail to Cove Crest Drive (nearest XXL safety destinations) must be done with care and deliberation because this scenario requires a completely different evacuation route and carries a different set of risks, primarily that the tsunami will overtop the hill.

The socioeconomic analysis demonstrates that several Tillamook County communities have a large percentage of buildings, residents, and jobs within the tsunami zone, which present additional evacuation, response, and recovery challenges.

Regardless of walking speeds, physical limitations, and mitigation considerations, wayfinding through adequately spaced signage, battery-operated lighting, and other means is essential to survival. Even in areas where safety is nearby and all populations appear likely to survive, confusion about where to go will make the difference between life and death. Clear and visible signage placed in key locations is extremely important, especially for areas likely to experience large numbers of visitors. We also encourage individuals to practice their evacuation route to determine what works for them. It is only through quick, instinctive evacuation that lives will be saved. This can be achieved through ongoing education programs with a focus on regular community-wide evacuation drills (e.g., Connor, 2005).

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6.0 REFERENCES

Applied Technology Council, 2012, Guidelines for design of structures for vertical evacuation from tsunamis, 2nd ed. (FEMA P-646): Redwood City, Calif., Applied Technology Council, 174 p. https://www.fema.gov/media-library/assets/documents/14708

Burns, W. J., Mickelson, K. A., and Madin, I. P., 2016, Statewide landslides susceptibility overview map of Oregon: Oregon Department of Geology and Mineral Industries, Open-File Report O-16-02, 48 p., 1 pl., scale 1:750,000, GIS raster data. https://www.oregongeology.org/pubs/ofr/p-O-16-02.htm

Connor, D., 2005, The City of Seaside's Tsunami Awareness Program: outreach assessment—how to implement an effective tsunami preparedness outreach program: Oregon Department of Geology and Mineral Industries Open-File Report O-05-10, 86 p. https://www.oregongeology.org/pubs/ofr/O-05-10.pdf

Fraser, S. A., Wood, N. J., Johnston, D. M., Leonard, G. S., Greening, P. D., and Rossetto, T., 2014, Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling: Natural Hazards and Earth System Sciences, v. 14, no. 11, p. 2975–2991. https://doi.org/10.5194/nhess-14-2975-2014

Gabel, L. L. S., and Allan, J. C., 2016, Local tsunami evacuation analysis of Warrenton and Clatsop Spit, Clatsop County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-16-08, 56 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-16-08.htm

Gabel, L. L. S., and Allan, J. C., 2017, Local tsunami evacuation analysis of Rockaway Beach, Tillamook County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-17-06, 56 p., geodatabase. https://www.oregongeology.org/pubs/ofr/p-O-17-06.htm

Gabel, L. L. S., O'Brien, F. E., and Allan, J. C., 2018, Local tsunami evacuation analysis of Pacific City, Tillamook County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-18-06, 54 p., geodatabase. https://www.oregongeology.org/pubs/ofr/p-O-18-06.htm

González-Riancho, P., Aliaga, B., Hettiarachchi, S., Gonzáles, M., and Medina, R., 2015, A contribution to the selection of tsunami human vulnerability indicators: conclusions from tsunami impacts in Sri Lanka and Thailand (2004), Samoa (2009), Chile (2010), and Japan (2011). Natural Hazards and Earth System Sciences 15, p. 1493-1514. https://doi.org/10.5194/nhess-15-1493-2015

Imhof, E., 1950, Gelände und Karte: Erlenbach-Zürich, Eugen Rentsch Verlag, 255 p.

Langlois, J. A., Keyl, P. M., Guralnik, J. M., Foley, D. J., Marottoli, R. A., and Wallace, R. B., 1997, Characteristics of older pedestrians who have difficulty crossing the street: American Journal of Public Health, v. 87, no. 3, p. 393–397. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1381010/pdf/amjph00502-0075.pdf

Madin, I. P., and Burns, W. J., 2013, Ground motion, ground deformation, tsunami inundation, coseismic subsidence, and damage potential maps for the 2012 Oregon Resilience Plan for Cascadia Subduction Zone Earthquakes: Oregon Department of Geology and Mineral Industries Open-File Report O-13-06, 36 p., 38 pl., geodatabase. https://www.oregongeology.org/pubs/ofr/p-O-13-06.htm

Madin, I. P., and Wang, Z., 1999, Relative earthquake hazard maps for selected coastal communities in Oregon: Astoria–Warrenton, Brookings, Coquille, Florence–Dunes City, Lincoln City, Newport, Reedsport–Winchester Bay, Seaside–Gearhart–Cannon Beach, Tillamook: Oregon Department of Geology and Mineral Industries, Interpretive Map 10, 25 p., 2 pl., scale 1:24,000. https://www.oregongeology.org/pubs/ims/p-ims-010.htm

Margaria, R., 1968, Positive and negative work performances and their efficiencies in human locomotion: Internationale Zeitschrift für angewandte Physiologie, einschliesslich Arbeitsphysiologie, v. 25, p. 339–351. https://doi.org/10.1007/BF00699624

Mas, E., Adriano, B., and Koshimura, S., 2013, An integrated simulation of tsunami hazard and human evacuation in La Punta, Peru: Journal of Disaster Research, v. 8, no. 2, 285–295. doi: 10.20965/jdr.2013.p0285

Oregon Department of Geology and Mineral Industries, 2012a, Tsunami evacuation map for Cape Meares: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/CapeMearesEvac_onscreen.pdf

Oregon Department of Geology and Mineral Industries, 2012b, Tsunami evacuation map for Oceanside: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/OceansideEvac_onscreen.pdf

Oregon Department of Geology and Mineral Industries, 2012c, Tsunami evacuation map for Netarts: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/NetartsEvac_onscreen.pdf

Oregon Department of Geology and Mineral Industries, 2012c, Tsunami evacuation map for Neskowin: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/NeskowinEvacBrochure-12-12-12_onscreen.pdf

Paul, S., 2013, What are the right walking and running speeds?: Runner's World, online article, March 6, 2013. https://www.runnersworld.com/for-beginners-only/what-are-the-right-walking-and-running-speeds [accessed 4/17/2014]

Portland State University Population Research Center (PRC), 2018, July 1, 2018 Certified Population Estimates, Portland State University Population Research Center, https://www.pdx.edu/prc/population-reports-estimates

Priest, G. R., Goldfinger, C., Wang, K., Witter, R. C., Zhang, Y., and Baptista, A. M., 2009, Tsunami hazard assessment of the northern Oregon coast: a multi-deterministic approach tested at Cannon Beach, Oregon: Oregon Department of Geology and Mineral Industries Special Paper 41, 87 p. plus 7 p. app. Includes report, GIS set, time histories, and animations. https://www.oregongeology.org/pubs/sp/SP-41.zip

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013a, Tsunami animations, time histories, and digital point data for flow depth, elevation, and velocity for the Central Coast Project Area, Coos, Douglas, Lane, and Lincoln Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-16, GIS data. https://www.oregongeology.org/pubs/ofr/p-O-13-16.htm

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013b, Tsunami inundation scenarios for Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-19, 14 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-13-19.htm

Priest, G. R., Stimely, L. L., Madin, I. P., and Watzig, R. J., 2015, Local tsunami evacuation analysis of Seaside and Gearhart, Clatsop County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-15-02, 36 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-15-02.htm

Priest, G. R., Stimely, L. L., Wood, N. J., Madin, I. P., and Watzig, R. J., 2016, Beat the-wave evacuation mapping for tsunami hazards in Seaside, Oregon, USA: Natural Hazards, v. 80, no. 2, p. 1–26. https://dx.doi.org/10.1007/s11069-015-2011-4 [first online 10/19/2015]

Soule, R. G., and Goldman, R. F., 1972, Terrain coefficients for energy cost prediction: Journal of Applied Physiology, v. 32, no. 5, p. 706–708. https://doi.org/10.1152/jappl.1972.32.5.706

Tobler, W., 1993, Three presentations on geographical analysis and modeling: Non-isotropic geographic modeling; speculations on the geometry of geography; and global spatial analysis: University of Calif., Santa Barbara, National Center for Geographic Information and Analysis Technical Report 93-1, 24 p. https://escholarship.org/uc/item/05r820mz

U. S. Census Bureau, 2010, Master Address File/Topologically Integrated Geographic Encoding and Referencing system or database: Oregon census block: United States Census Bureau. ftp://ftp2.census.gov/geo/tiger/TIGER2010BLKPOPHU/tabblock2010_41_pophu.zip (login required)

U.S. Census Bureau, 2017, Series information file for the 2017 TIGER/Line shapefile, current place state-based. Metadata created date: November 17, 2017. GIS dataset downloaded on August 10, 2018, from https://catalog.data.gov/dataset/series-information-file-for-the-2017-tiger-line-shapefile-current-place-state-based

U.S. Census Bureau, 2018, Understanding and using American Community Survey data: what all data users need to know. U.S. Department of Commerce Economics and Statistics Administration, U.S. Government Printing Office, Washington D.C., 84 p. Issued July 2018. Available at: https://www.census.gov/content/dam/Census/library/publications/2018/acs/acs_general_handbook_2018.pdf

U.S. Department of Transportation, 2012, Manual on uniform traffic control devices for streets and highways [2009 edition with revisions 1 and 2]: Federal Highway Administration. https://mutcd.fhwa.dot.gov/kno_2009r1r2.htm [accessed 11/25/2014]

U.S. Geological Survey (USGS), 2012, The March 11 Tohoku earthquake, one year later. What have we learned?: U.S. Geological Survey, Science Features blog post, March 9, 2012. https://www2.usgs.gov/blogs/features/usgs_top_story/the-march-11-tohoku-earthquake-one-year-later-what-have-we-learned/ [accessed 9/9/2014]

Witter, R. C., Y. Zhang, Wang, K., Priest, G. R., Goldfinger, C., Stimely, L. L., English, J. T., and Ferro, P. A., 2011, Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios: Oregon Department of Geology and Mineral Industries Special Paper 43, 57 p., 3 pl., GIS files, animations. https://www.oregongeology.org/pubs/sp/p-SP-43.htm

Wood, N., and Schmidtlein, M., 2012, Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest: Natural Hazards, v. 62, no. 2, p. 275–300. doi: 10.1007/s11069-011-9994-2. https://link.springer.com/article/10.1007/s11069-011-9994-2

Wood, N., Jones, J., Schmidtlein, M., Schelling, J., and Frazier, T., 2016, Pedestrian flow-path modeling to support tsunami evacuation and disaster relief planning in the U.S. Pacific Northwest: International Journal of Disaster Risk Reduction, v. 18, 41–55. doi: 10.1016/j.ijdrr.2016.05.010. https://www.sciencedirect.com/science/article/pii/S2212420916300140

Yeh, H., Fiez, T., and Karon, J., 2009, A comprehensive tsunami simulator for Long Beach Peninsula, phase 1: framework development: Tacoma, Wash., Washington Military Department, 27 p.