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TSUNAMI EVACUATION ANALYSIS OF NEHALEM BAY, TILLAMOOK COUNTY, OREGON

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WHAT'S IN THIS REPORT?

This report shows modeled pedestrian evacuation routes to escape a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) for the communities of Nehalem Bay, Tillamook County.

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Geodatabase is Esri® version 10.6 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

Nehalem_Bay_Tsunami_Evacuation_Modeling.gdb:

XXL1_BridgesOut feature dataset:

XXL1_BridgesOut_EvacuationFlowZones
XXL1_BridgesOut_EvacuationRoutes
XXL1_BridgesOut_WalkingSpeeds_Roads
XXL1_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 Nehalem Bay region of Tillamook County, Oregon. Our analyses focused on a maximum-considered CSZ tsunami event covering 100 percent of potential variability, termed XXL and generated by a locally-generated 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 arrival times for an XXL event,
- Detailed "Beat the Wave" (BTW) results for the XXL scenario, including evacuation routes and minimum walking speeds, and
- BTW results for multiple hypothetical scenarios.

The BTW maps depict the ***minimum evacuation speed*** required to stay ahead of the tsunami wave in a given scenario. For planning purposes, we present a variety of scenarios that increase and decrease evacuation difficulty (due to additional complications and mitigation options, respectively). The base scenario uses the existing road and path 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 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 Nehalem Bay communities examined is achievable at a moderate walking speed (4 fps, or 2.7 mph). Exceptions to this arise at Nehalem Bay State Park (especially on Nehalem Spit), the Nehalem Bay boat launch, and Tohl Ranch Road. Longer distances to high ground and reliance on non-retrofitted bridges make it difficult for evacuees from these locations to reach safety prior to the arrival of the tsunami. Liquefaction could present a significant challenge to evacuation across the region.

In this report, tsunami mitigation means actions used to improve the survivability of a local community population. 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. Mitigation options may include adding new evacuation routes, constructing earthquake-hardened roads and trails (that is, 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 in the coastal communities of Nehalem Bay for the XXL scenario. These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, land use planning, and vertical evacuation options.

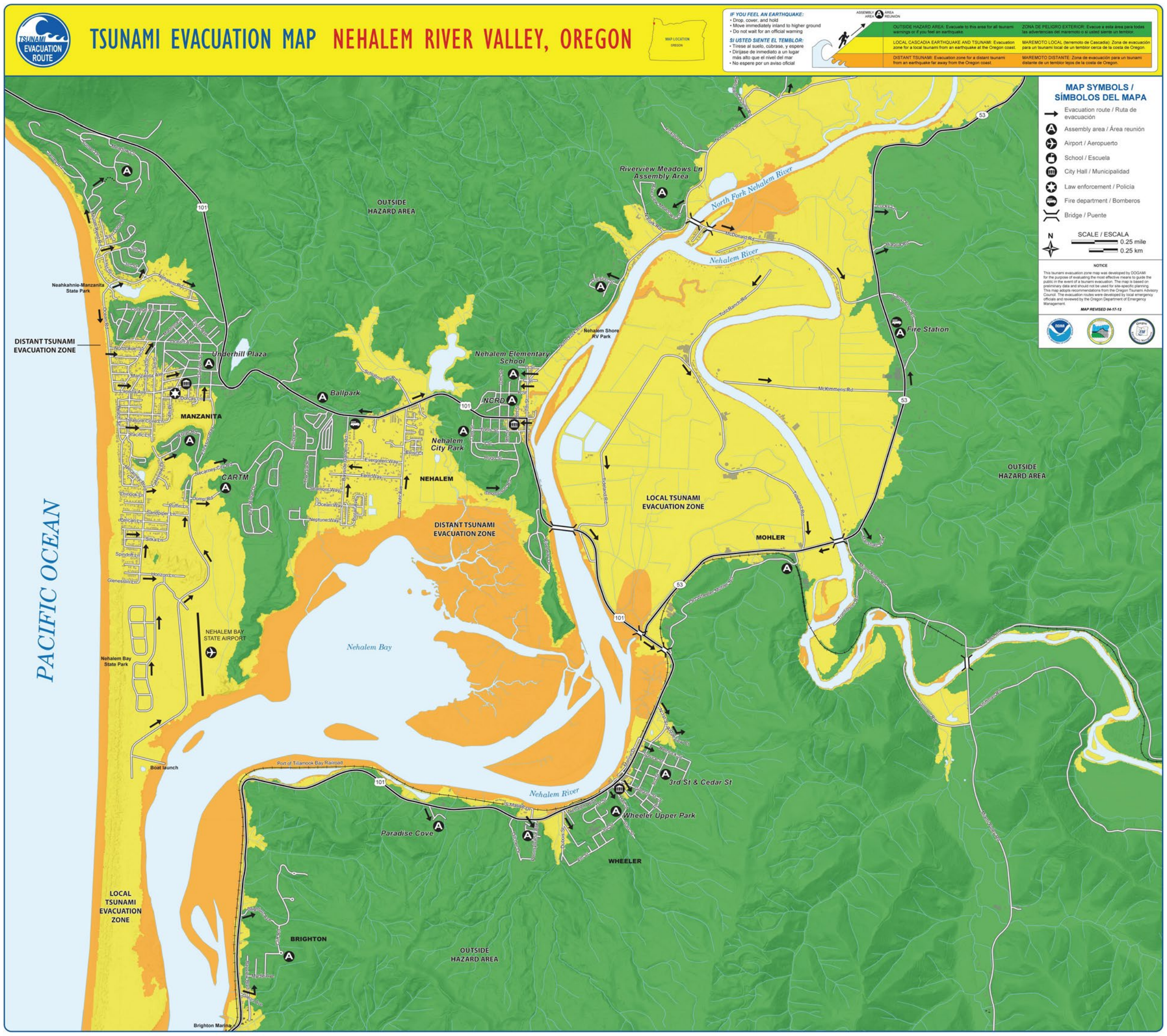
A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For the majority of the population, spontaneous evacuation on foot will be the only effective means of limiting loss of 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 magnitude ~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 scenario has a potential likelihood of being the size of the next Cascadia event. For example, 26% of past tsunamis were no larger than the Small scenario. This suggests that there is a 26% chance that the next CSZ event will also be size Small or smaller. XXL describes a scenario slightly larger than the largest tsunami in the 10,000-year historical record and therefore 100 percent of past tsunamis were smaller than this scenario. This implies that the XXL scenario encompasses the maximum possible tsunami that will occur next (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 the remainder of this report) inundates Nehalem Bay and many of the coastal communities in the area (**Figure 1-1**). The open coast, including much of Manzanita and Nehalem Bay State Park, will be flooded within 30 minutes of the start of earthquake shaking. The tsunami will continue up the Nehalem River Valley for another 30 minutes after that.

A Note about Bridges and Tsunami Evacuation in Nehalem Bay
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. For the Nehalem Bay area, "Bridges In" and "Bridges Out" Beat the Wave results are similar—and in most cases identical—so only "Bridges Out" results are included in this report.

Figure 1-1. DOGAMI (2013) tsunami evacuation map for Nehalem Bay. 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. The full-scale version of this map is available at https://www.oregongeology.org/tsuclearinghouse/.



We evaluate tsunami evacuation difficulty using an approach termed “Beat the Wave (BTW),” developed by Priest and others (2015, 2016). It uses the least-cost distance (LCD) approach of Wood and Schmidtlein (2012), which provides estimates of walking times to safety at a constant walking speed. We can now account for variable speeds along a route due to differences in route characteristics including terrain (e.g., flat vs. steep, loose sand vs. pavement) and precise wave arrival times. Evacuation routes are restricted to roads and trails to enable more informative maps as well as to remove the complication of crossing private property. 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.

This report provides the following maps and GIS data:

1. XXL wave arrivals: How quickly the wave front of an XXL tsunami advances across the area after the earthquake.
2. BTW results for existing road conditions: Determining whether an evacuee can stay ahead of the tsunami all the way to safety on the routes defined by the LCD analysis. Results include minimum walking speeds, the nearest safety destination, and detailed evacuation routes for every road in the community.
3. Hypothetical BTW scenarios to investigate potential vulnerabilities and mitigation options.

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 be impacted by localized effects in the landscape such as congestion points at bridges (Yeh and others, 2009). LCD modeling is similar but focuses more on evacuation difficulty across the landscape, which may be impacted by both slope and land cover type (e.g., navigating a road versus traveling over a wetland or dune). LCD modeling essentially defines the most efficient path to the tsunami inundation limit for every point in the inundation zone, artificially increasing distances as terrain conditions change (e.g., slope increases, a person travels across a wetland versus on pavement) and ultimately defining the best evacuation routes. Time to traverse a route can then be estimated by dividing the least-cost path by a particular pedestrian travel speed (e.g., walk, jog, or run). We used the LCD model of Wood and Schmidtlein (2012) because we wanted to understand the spatial distributions of evacuation times throughout Nehalem Bay, 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 maps of ***minimum*** speeds that must be maintained along the entire route in order to reach safety in time. Additional information on the methodology is provided by Priest and others (2015, 2016) and Gabel and Allan (2017).

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 excluded). This removes the complication of crossing private property and reflects the reality that most people will follow established roads to high ground rather than strike out cross county. Restricting evacuation to pathways also enables us to make more informative maps. Geospatial data representing roads, pedestrian paths, and beaches were generated through manual classification of imagery (lidar and aerial photographs), field verified, and then reviewed by local officials. The backshore is defined as areas landward of the beach-dune junction approximated by the 18-foot NAVD88 (North American Vertical Datum of 1988) contour. The beach (below 18 feet) 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” are intended to provide an approximation of the time and speeds required to evacuate those areas. We chose to ignore travel time from buildings or other parts of urban areas to the roads, because there is large uncertainty in conditions contributing to the time it will take an evacuee to reach the nearest road. For example, reaching the nearest road may require crossing a fenced yard. In addition, after the earthquake there will undoubtedly be fallen debris and other impediments. Because of these assumptions and factors, the modeling approach represents ***minimum*** evacuation speeds needed to safely evacuate 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 bridges, 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 hypothetical scenarios.

Bridge failure was simulated 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 discussion at a public town hall meeting 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. Our standard modeling process begins with a “base” scenario that includes all bridges, for comparison to scenarios without them. This highlights which bridges are important for evacuation and can be important when prioritizing which bridges to retrofit or to construct as part of a long-term resilience plan. For this area, modeling indicates local bridges are not essential for tsunami evacuation.

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; Madin and Burns, 2013). These hazards can damage roads and will 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. In areas with high liquefaction susceptibility we evaluate evacuation difficulty using data from 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, (left) extensive liquefaction occurred along River Road in Christchurch, New Zealand following the February 2011 earthquake, while (right) 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 completely remove an evacuation route, we created hypothetical scenarios to reflect that. There are many landslides in the Nehalem Bay area; however, none have the potential to significantly alter evacuation options. Therefore, we did not model any landslide scenarios. 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 can 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 include a small polygon of safety at the location of a hypothetical structure.

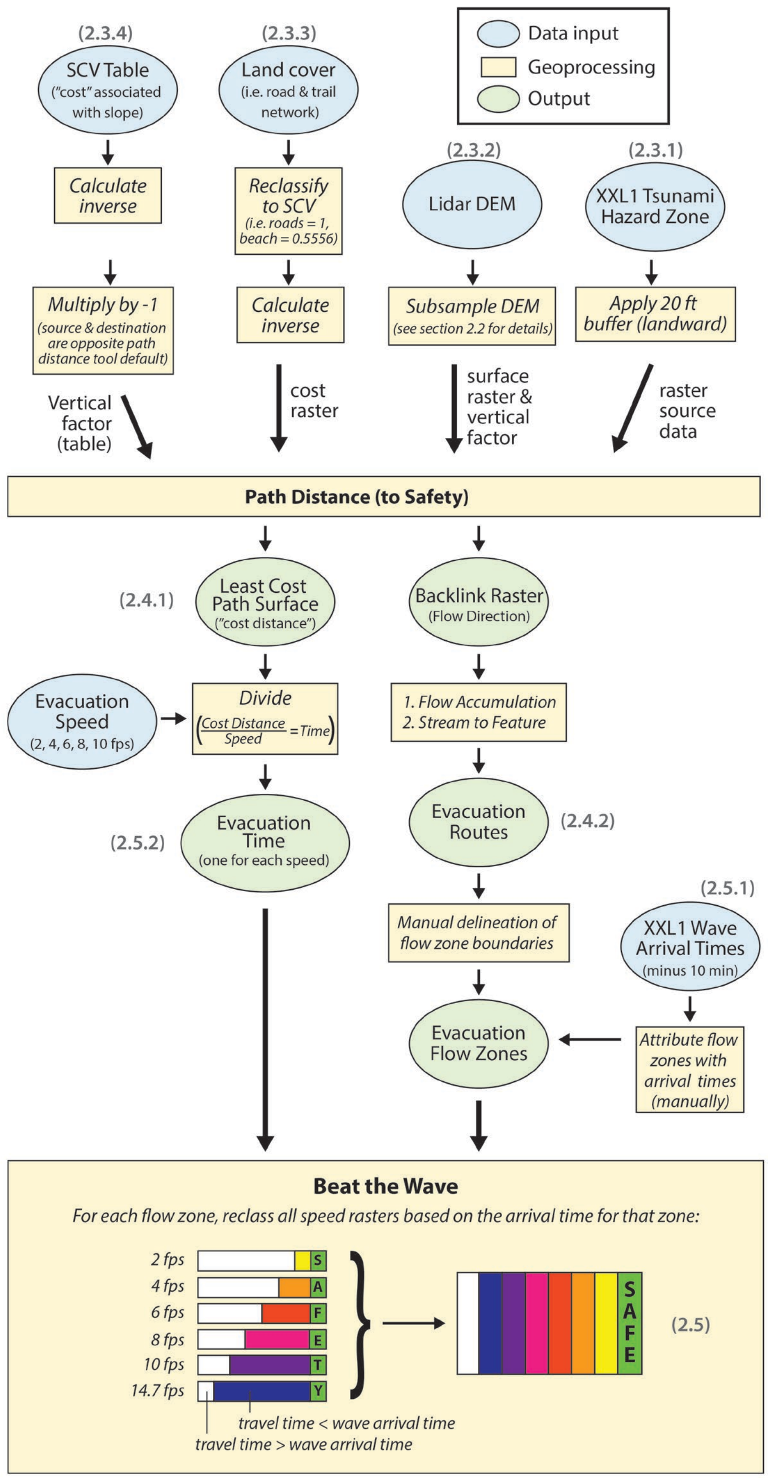
Regardless of infrastructure improvements considered for an area, wayfinding and outreach will always be an essential part of local tsunami evacuation planning.

2.3 LCD model inputs

Least-cost distance (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 meters) 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.

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 meters) 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-foot-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 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 accurately depict the curvatures. We then interpolated those points using an Esri Natural Neighbor function to produce a smoothed DEM (6-foot cell size) 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 case 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 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.

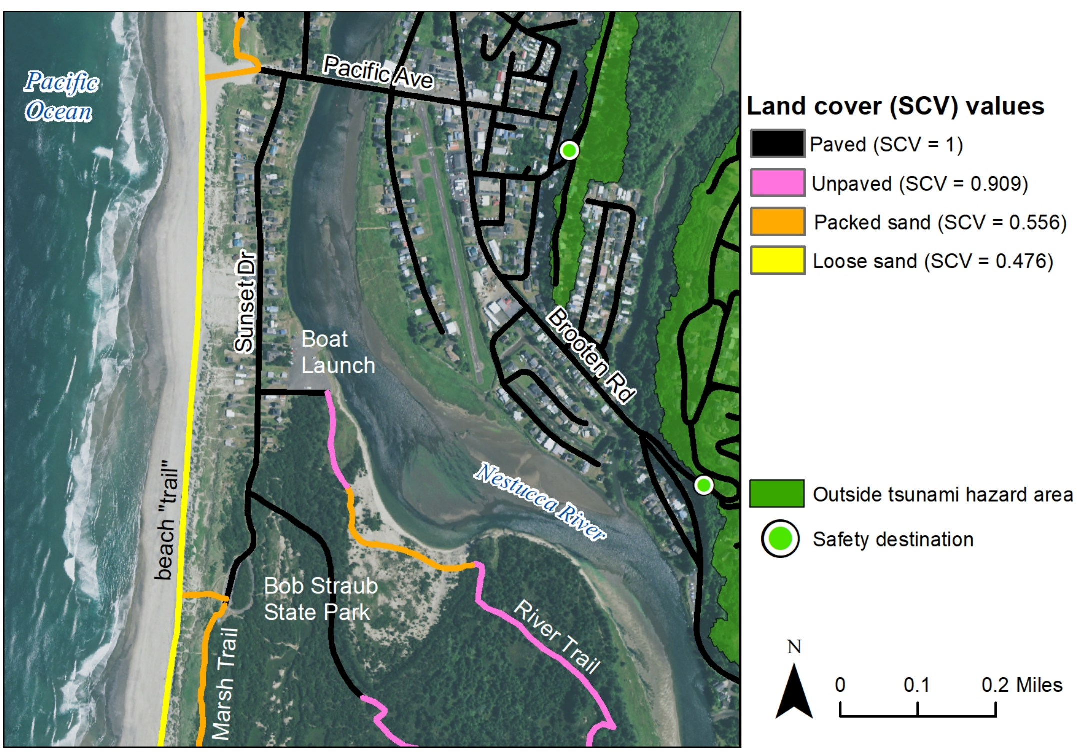
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

*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 (40 feet wide) 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-foot 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.

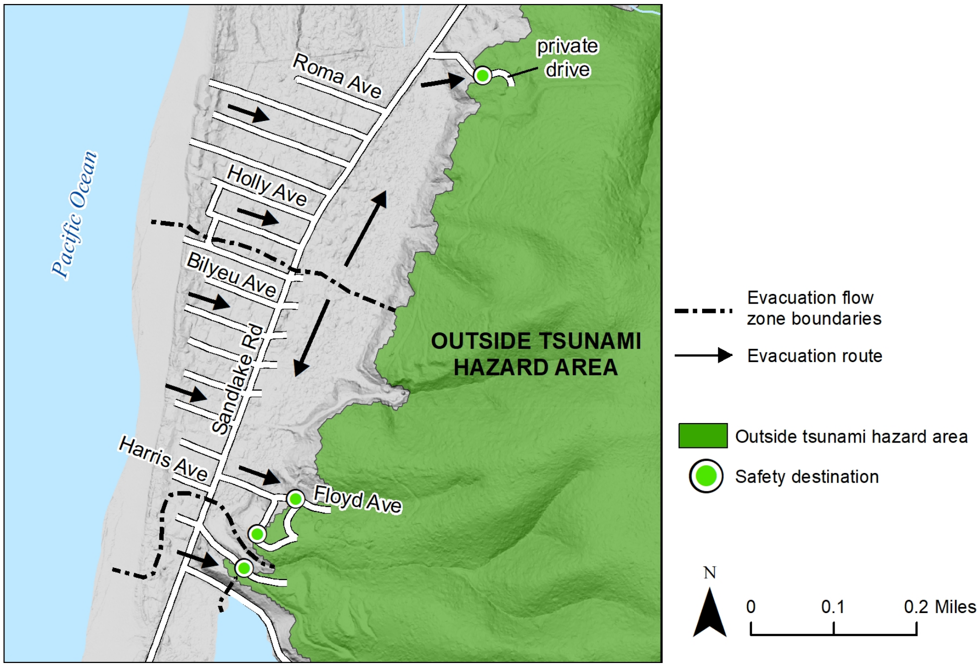
2.4 LCD model outputs

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 to 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.

We manually drew the flow zone polygons using the evacuation routes as a guide. Flow zone rasters can 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 specific locale. 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 more 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 half a foot at each computational grid point and interpolated those arrival data to create a continuous map showing wave arrival time.

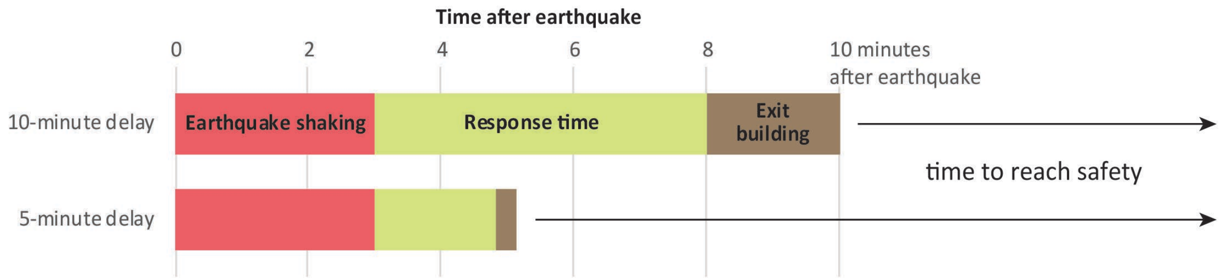
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted 10 minutes from the simulated tsunami arrival times to account for:

- the time in which earthquake shaking takes place,
- disorientation, shock and collecting family members, go-bags, et cetera, 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 due to 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. **Figure 2-5** graphically describes how the three components of evacuation delay are related in this study. It is important to appreciate that the values adopted are not explicitly known because there are uncertainties associated with the length of the earthquake shaking, the human response dimension (i.e., how quickly people respond and how organized they are [e.g., packing a bag, time spent searching for family members and pets]) and lastly, how easy it may be to leave a building (e.g., digging out of rubble) and get underway.

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. Results from the 5-minute evacuation delay also emphasize that the sooner one can begin evacuating, the more time one has to reach safety ahead of the tsunami.

Figure 2-5. Evacuation delays incorporated into BTW analyses undertaken in Oregon account for the earthquake shaking, human response, and building egress. The schematic shows that the less time spent in the response and exit phases, the sooner the evacuation phase can begin, thus giving an evacuee more time to reach safety.



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).

To explore an array of evacuation speeds appropriate for specific populations (e.g., the 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). These time maps were then "clipped"[1] 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 2-6** and in the final step of **Figure 2-2**. By integrating evacuation time maps with tsunami wave arrival data, we can produce Beat the Wave (BTW) maps that estimate the ***minimum speed*** needed to reach safety ahead of the wave.

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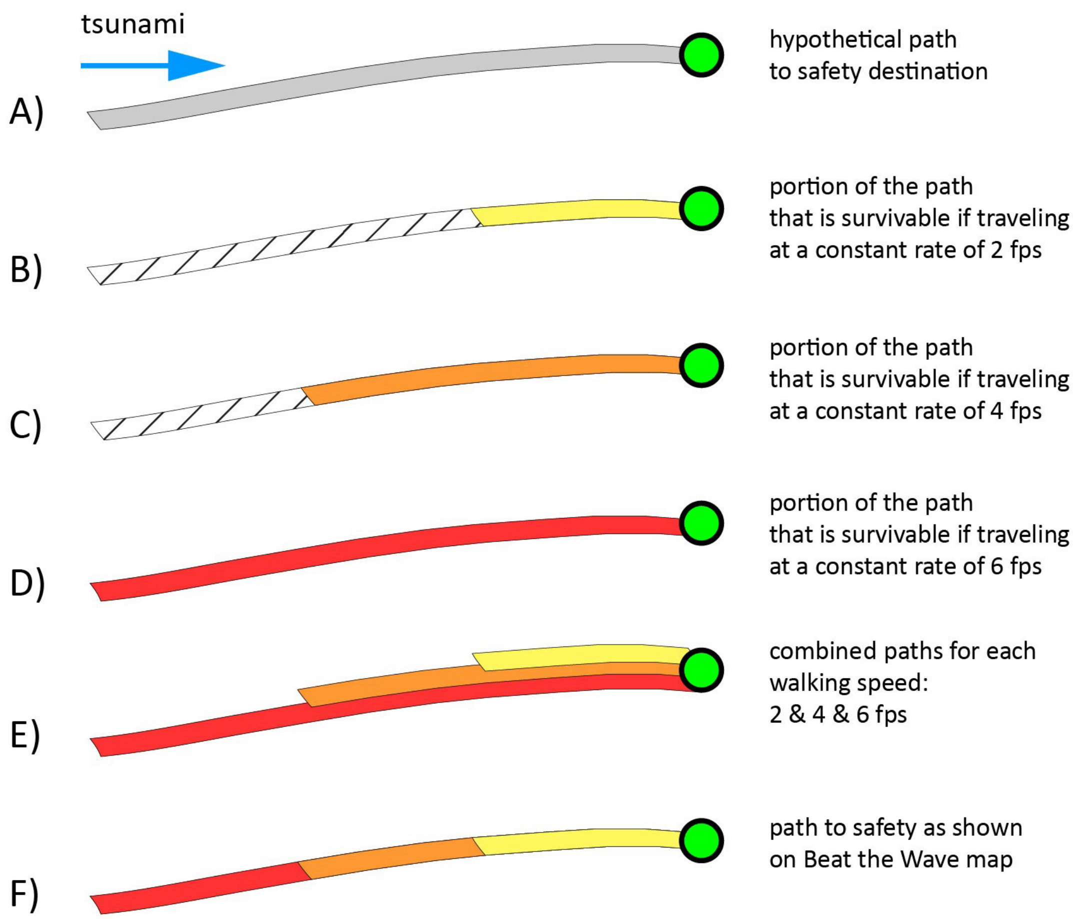
[1] "Clip" is a GIS software program command that "extracts features from one feature class that reside entirely within a boundary defined by features in another feature class" (https://support.esri.com/en/other-resources/gis-dictionary).

Figure 2-6. Illustration of 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 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. Speed categories in the map explanation were then given qualitative names such as “slow walking” and “running,” so the public could relate speed bins to their experience. Of particular interest are 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**). After examining the range of BTW speeds for Seaside (Priest and others, 2015) and reviewing a number of references describing speed categories (Paul, 2013; Margaria, 1968), we settled 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 at > 14.7 fps

A small experiment was conducted at Seaside, Oregon 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 <u>minimum</u> 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 a starting location all the way to safety. If an evacuee slows down for some portion of the route, the evacuee 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.

3.0 RESULTS AND DISCUSSION

This report covers the Nehalem Bay communities of Neahkahnie, Manzanita, Nehalem Bay State Park, Bayside Gardens, Nehalem, Wheeler, and Mohler/North Fork (**Figure 3-1**, **top**). Tsunami evacuation analyses (Beat the Wave) including detailed wave arrivals are presented separately for each community in sections 3.1 through 3.8. A brief examination of demographics follows in section 3.9. We evaluated a suite of scenarios, which included the following:

- A maximum considered XXL scenario that assumes “non-retrofitted bridges fail” due to earthquake ground motion and people evacuate within 10 minutes from the start of earthquake shaking. All subsequent scenarios assume these non-retrofitted bridges fail unless otherwise stated. GIS data for this scenario are found in the Nehalem_Bay_Tsunami_Evacuation_Modeling geodatabase.
- An XXL scenario that assumes liquefaction makes roads and trails significantly more difficult to walk on.
- An XXL scenario that assumes people evacuate within 5 minutes (i.e., 3 minutes of shaking, 2 minutes of delay instead of 7) from the start of earthquake shaking.
- Additionally, for Nehalem Bay State Park:
  - An XXL scenario that demonstrates the importance of Necarney Hill as the sole designated safety destination for the park at the time of this publication
  - An XXL scenario that assumes a “hypothetical trail” is constructed to safety at Airport Ridge, bringing high ground closer to those farther south on the spit
  - Three XXL scenarios that include “hypothetical vertical evacuation” structures
- Finally, two hypothetical mitigation options for Tohl Ranch Road by the mouth of the North Fork Nehalem River.

In general, we find a wide variety of evacuation speeds that the public must take in order to escape an XXL (maximum-considered) Cascadia tsunami that cover the spectrum from ***slow walk*** (2 fps, or 1.4 mph) to ***sprint*** (>15 fps, or >10 mph). Areas within Nehalem Bay State Park and Tohl Ranch Road will require evacuation travel speeds approaching a ***sprint*** to ensure survival. Because these areas are far from high ground, how quickly people respond and begin their evacuation will be the difference between life and death. To that end, tsunami wave arrival times will be presented first for each community. BTW evacuation modeling results will then be presented. Where applicable, hypothetical scenarios such as liquefaction, bridge retrofits, or the use of vertical evacuation structures will be evaluated in order to address potential mitigation options.

Unless otherwise noted, all scenarios include a 10-minute delay before starting evacuation to account for the expected disoriented state of people following severe earthquake shaking and 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.

Finally, it is inevitable that following the earthquake other factors may also contribute to impede travel times. This modeling does not account for these ancillary effects, which could include obstacles such as downed power lines or buildings. 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.***

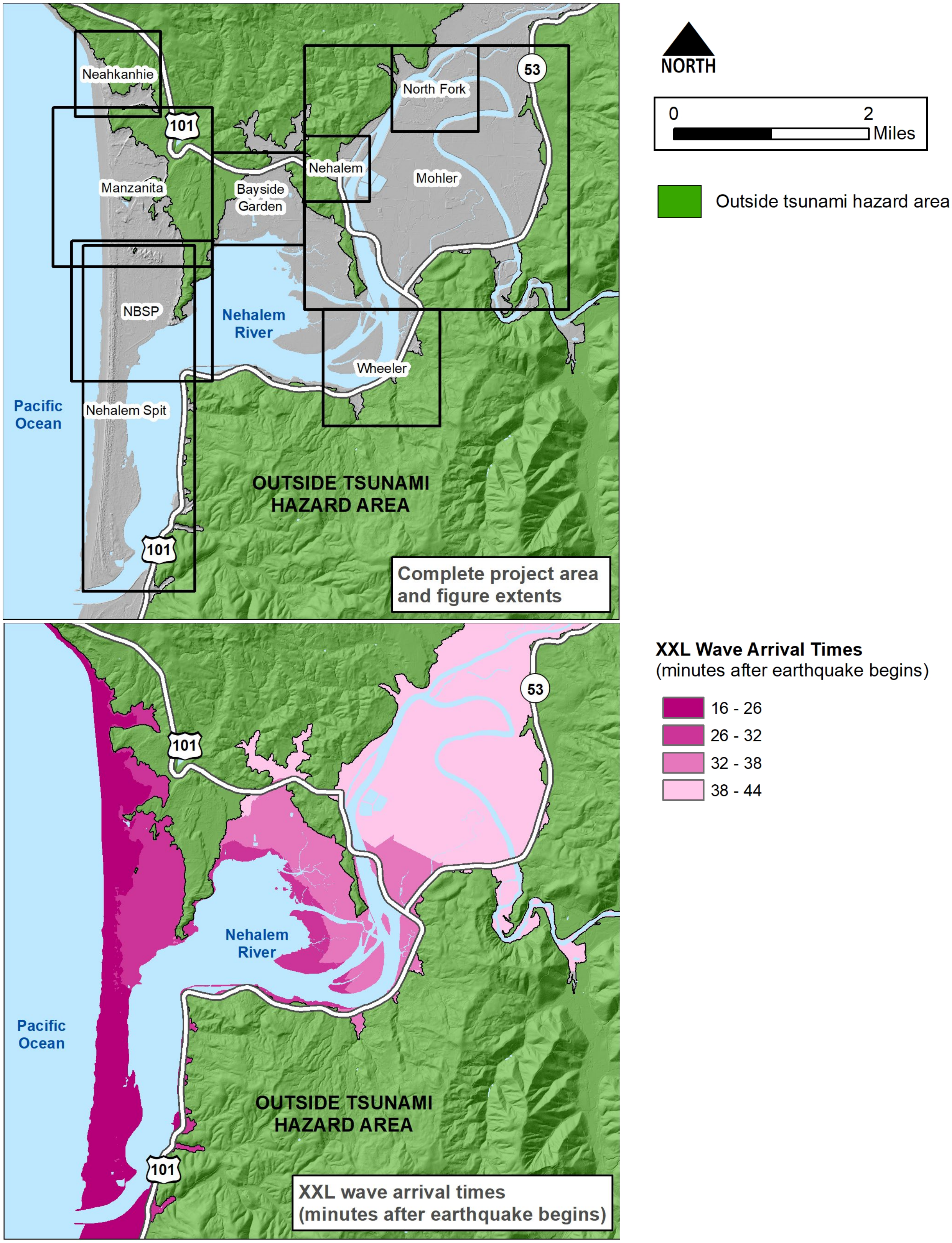
Table 3-1. Pedestrian evacuation speed categories and their conversions.

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).

Figure 3-1, **bottom** shows the arrival times for an XXL tsunami in the Nehalem Bay project area. The earliest wave arrivals are along the open coast; the tsunami reaches the beach ~16–18 minute after the start of the earthquake shaking. After 26 minutes Nehalem Spit has been inundated, and by 32 minutes Manzanita, Neahkahnie, Wheeler, and Bayside Gardens have been reached. The tsunami continues up the estuary, reaching Nehalem in ~38 minutes and Mohler in ~45 minutes. The tsunami reaches its farthest upriver extents ~1 hour after the earthquake, ~4-5 miles up the mainstem and North Fork of the Nehalem River (not shown in figure). Additional waves will continue to strike the coast and enter the estuaries, causing water levels to fluctuate for up to 12 hours after the earthquake. Tsunami wave arrival time data are found in the Nehalem_Bay_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

Figure 3-1. (top) Nehalem Bay project area map. Results will be discussed separately for each panel. (bottom) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake.



3.1 Neahkahnie

The Neahkahnie neighborhood sits on the open coast between the City of Manzanita and the base of Neahkahnie Mountain. Due to the steep landscape, much of the community is outside of the inundation zone. **Figure 3-2** shows the arrival times for an XXL tsunami in the Neahkahnie neighborhood. The tsunami reaches the beach ~16-20 minutes after the start of earthquake shaking and reaches maximum inundation extent within approximately 10 minutes. **Figure 3-3**, **top left** presents BTW results for a base scenario assuming the road and trail network remains intact. Nearly everyone can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. Evacuation flow zones for this scenario are presented in **Figure 3-3**, **bottom left**. The evacuation flow zones make clear which direction evacuees should choose based on their location.

As discussed in section 2.2, liquefaction is a very 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 Neahkahnie, all roads inside the XXL inundation zone are moderately to highly susceptible (Madin and Burns, 2013). The liquefaction scenario presented in **Figure 3-3**, **top right** illustrates the slight increase in minimum travel speeds necessary to reach high ground before the tsunami arrives. The overall similarity to the base scenario is due to the extremely short evacuation distances.

This area has short and relatively simple evacuation routes and no bridges or other key pieces of infrastructure that could compromise pedestrian evacuation; however, clear and visible signage as well as outreach are imperative to ensure evacuees do not walk the wrong direction after an earthquake. In addition to the public roads included in this study, there is a footpath connecting Beach Street to University Avenue, which will further reduce the distance to safety for those living on Beach Street (not shown in figure).

Figure 3-2. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Neahkahnie.

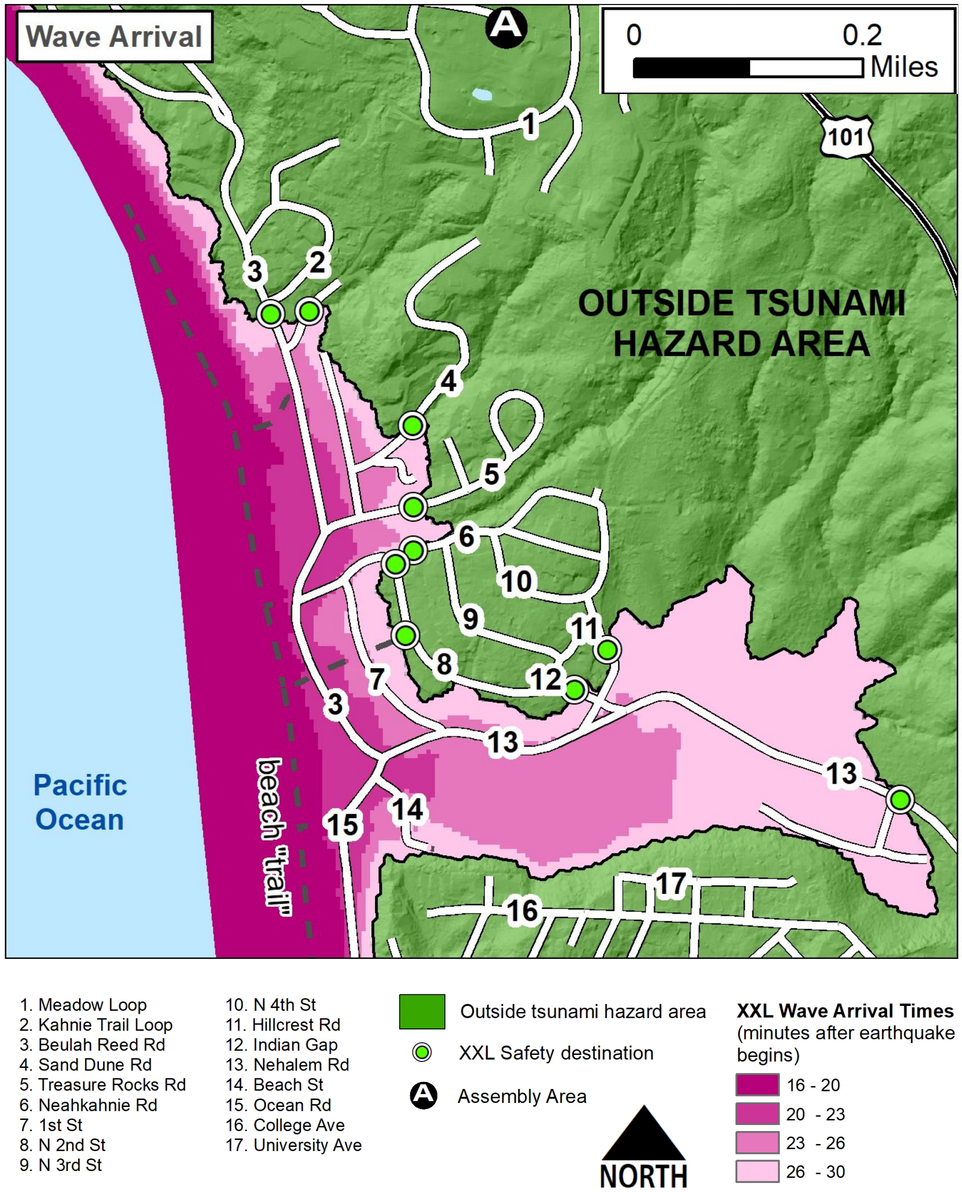
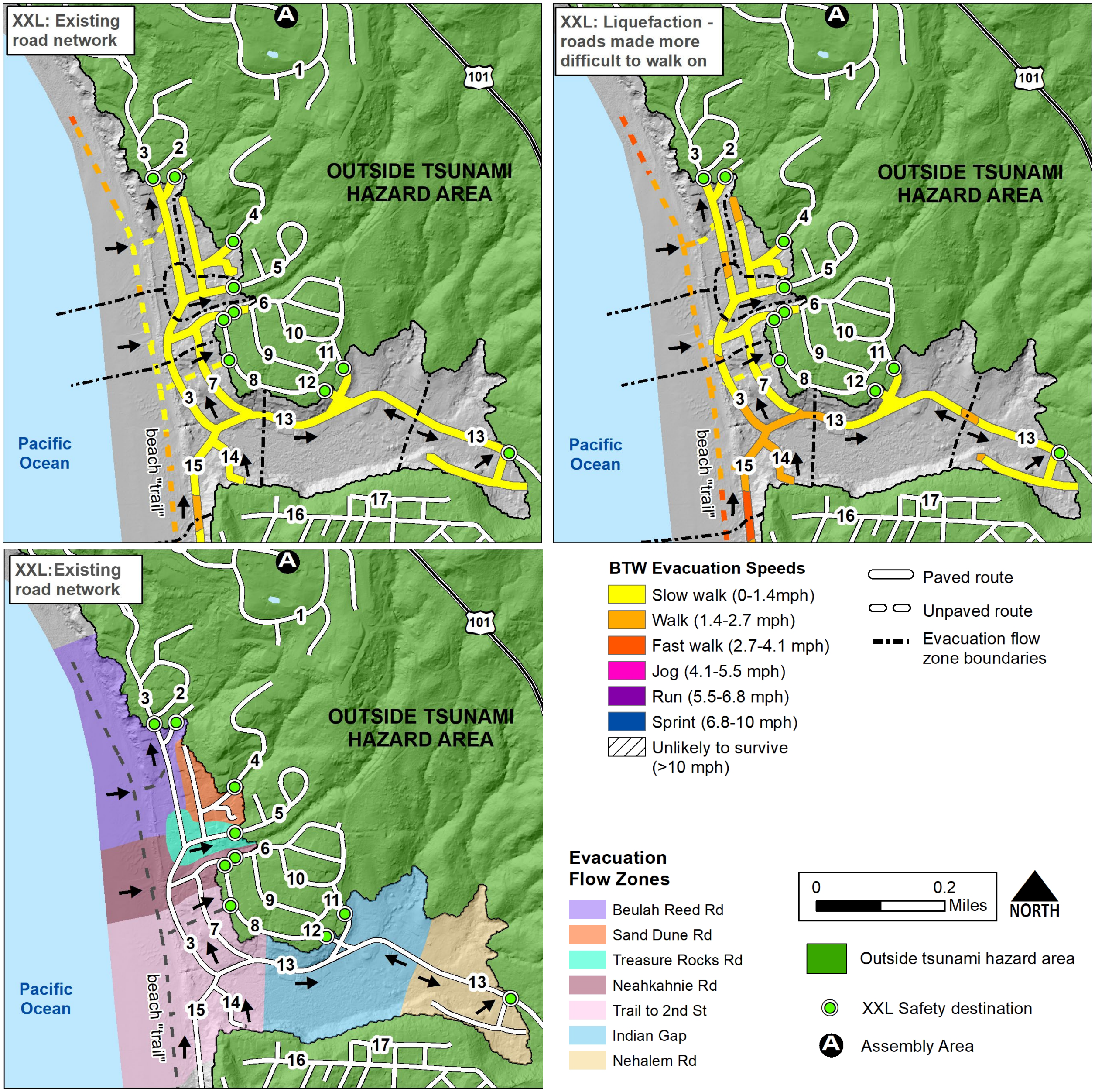


Figure 3-3. Beat the wave modeling in Neahkahnie for (top left) base scenario depicting the existing road and trail network and (top right) for liquefaction scenario. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. (bottom left) shows evacuation flow zones for base scenario. See Figure 3-2 for road labels.



3.2 Manzanita

The City of Manzanita lies on the open coast, and much of the community is inside the XXL tsunami inundation zone. City hall and the police department are also inside but near the inland edge of the inundation zone. In addition to its full-time residents, Manzanita is a popular tourist destination and second-home community. There are no bridges or other key pieces of infrastructure that would compromise pedestrian evacuation; therefore the only alternative BTW scenario considered is liquefaction.

The tsunami is expected to arrive in Manzanita ~20 minutes after the start of earthquake shaking (**Figure 3-4**) and takes approximately 10 minutes to reach its farthest inland extent. **Figure 3-5**, **top left** presents minimum BTW travel speeds for the base scenario, which assumes all roads and trails are passable after the earthquake. In this scenario, most people can reach safety at a ***slow walk*** (2 fps, or 1.4 mph) with a few streets near the beach requiring a ***walk*** (4 fps, or 2.7 mph) to survive. Evacuation flow zones are presented in **Figure 3-5**, **bottom left**. The evacuation flow zones make clear which direction evacuees should choose based on their location. The message for northern/downtown Manzanita is simple: head uphill (east) toward Highway 101. South of this area, evacuees must decide between several “islands” of high ground (Ridge Road, Bonny Lane, Necarney City Road, Manzanita Transfer Station, and Necarney Hill, which is discussed further in section 3.3).

Liquefaction poses a significant risk to this community due to its low-lying location adjacent to the Pacific Ocean and proximity to Nehalem Bay. **Figure 3-5**, **top right** presents minimum travel speeds for a liquefaction scenario. Travel speeds increase to ***walk*** for much of town, with a few small areas increasing to ***fast walk*** (6 fps, or 4.1 mph). People around the intersection of Necarney Boulevard and Sandpiper Lane) should be especially cognizant of their nearest safety destination because the high ground options are in different directions and no time can afford to be wasted debating which direction to head. As the evacuation flow zone boundaries in **Figure 3-5**, **bottom left** show, the best option for someone in this area may be north to Ridge Road, east toward the transfer station via Gary Street, or south to Necarney Hill. Evacuation flow zones remain unchanged between the base scenario and liquefaction.

Overall, this area has relatively short evacuation routes; however, clear and visible signage as well as outreach and evacuation drills are imperative to ensure evacuees waste no time before starting their evacuation and know which way to walk after an earthquake.

Figure 3-4. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Manzanita.

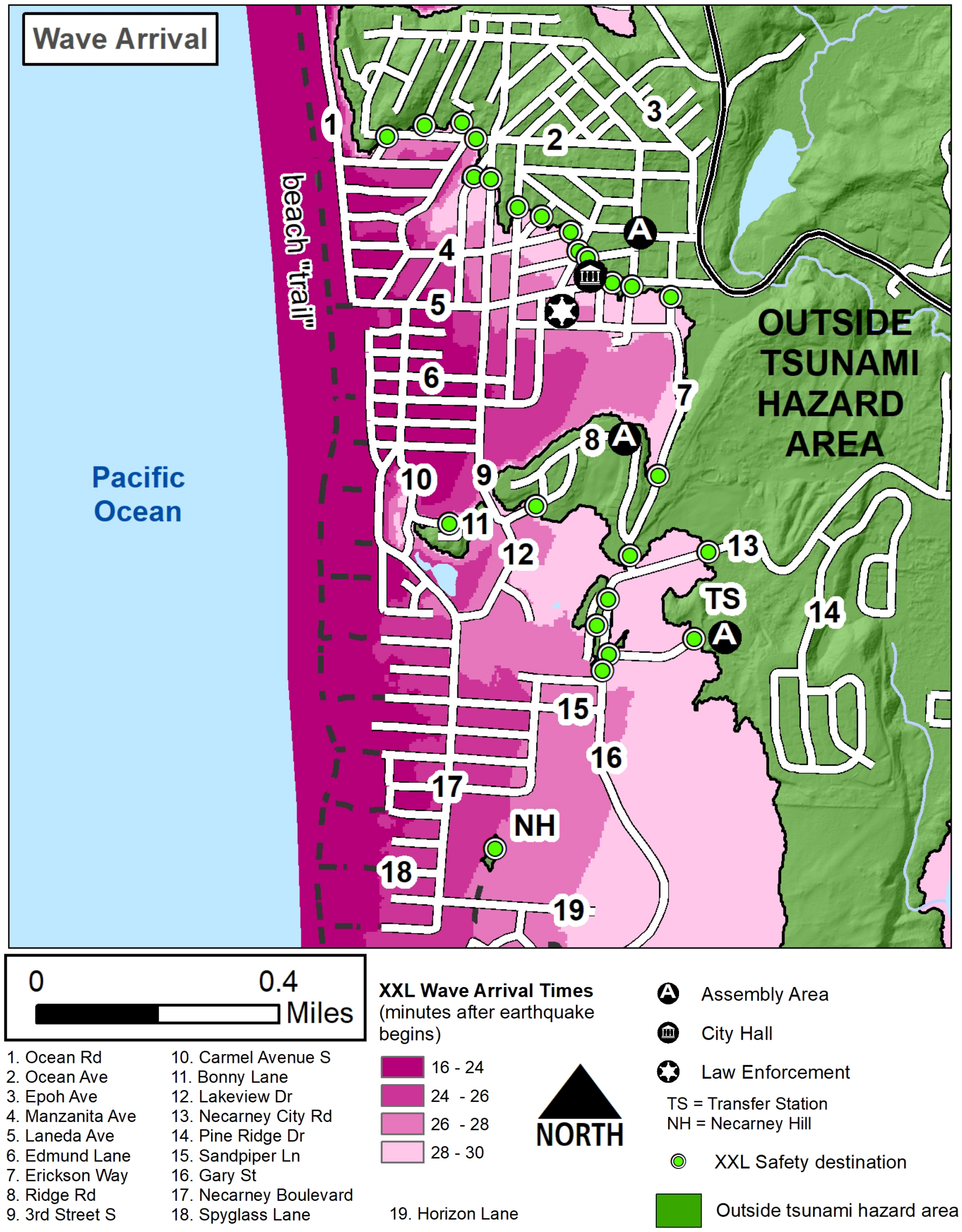
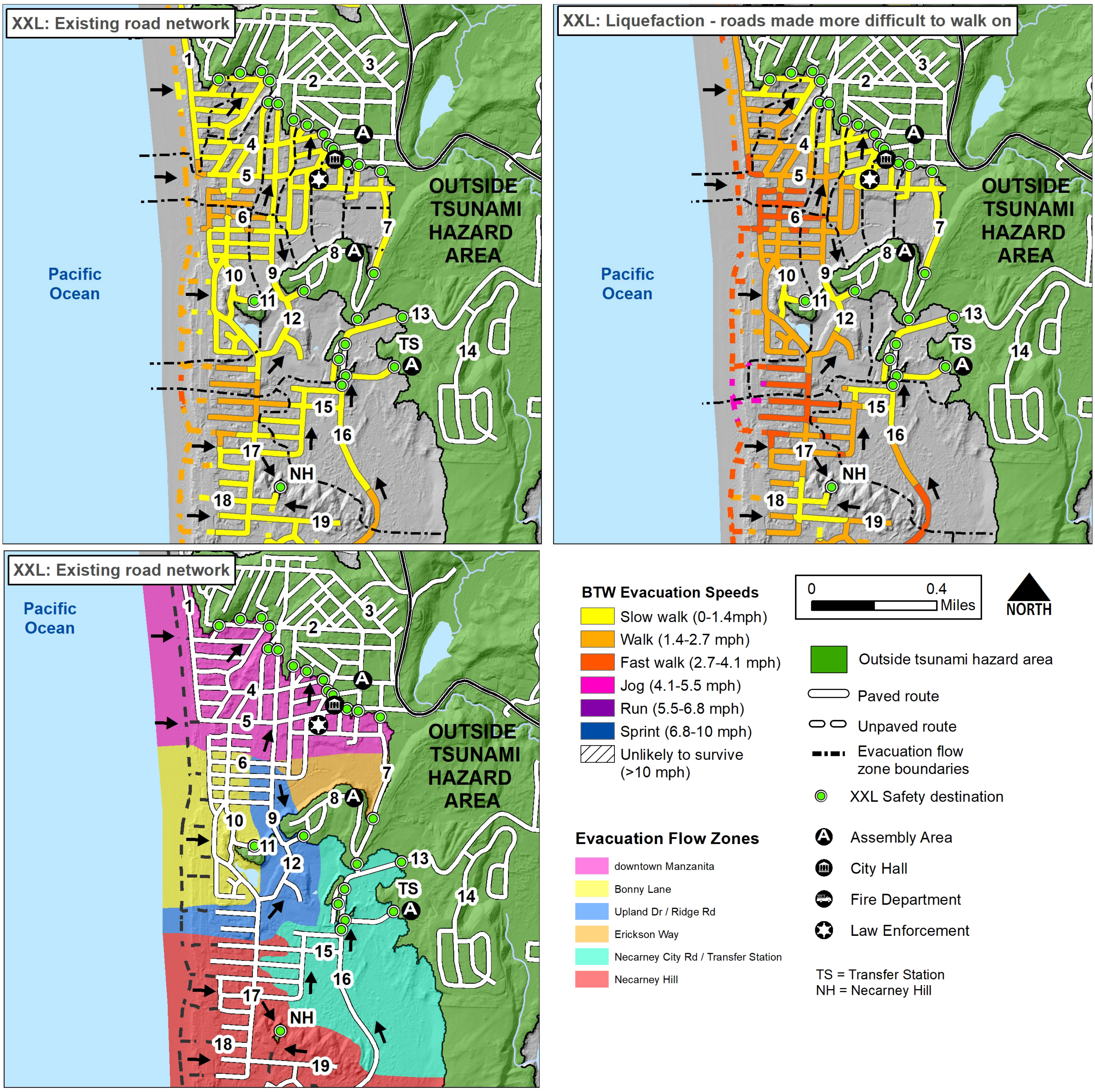


Figure 3-5. Beat the wave modeling in Manzanita for (top left) base scenario depicting the existing road and trail network and (top right) for liquefaction scenario. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. (bottom left) shows evacuation flow zones for base scenario. See Figure 3-4 for road labels.



3.3 Nehalem Bay State Park

Nehalem Bay State Park (NBSP) is one of the most visited state parks not only on the Oregon coast but in the entire state. NBSP is home to as many as 2,000 people on a summer weekend, with a maximum capacity of 3,000 people (Ben Cox, Oregon Parks and Recreation Department, oral communication, 2019). The visitor population is especially vulnerable given their probable lack of knowledge about geological hazards and local geography. The park is inside the XXL inundation zone; the nearest established high ground is north of the park on Gary Street, toward the Manzanita Transfer Station (not shown in campground figures; can be seen in **Figure 3-4**). There is a small island of high ground called Necarney Hill immediately northwest of the park entrance that OPRD is currently developing. Because this will be the official safety destination for NBSP as soon as next year, we include Necarney Hill as a safety destination for all BTW scenarios unless otherwise stated. There is also a ridge of high ground east of the airport; however, there are currently no trails to this destination. We will discuss the importance of Necarney Hill in scenario 1 and "Airport Ridge" in NBSP scenario 2.

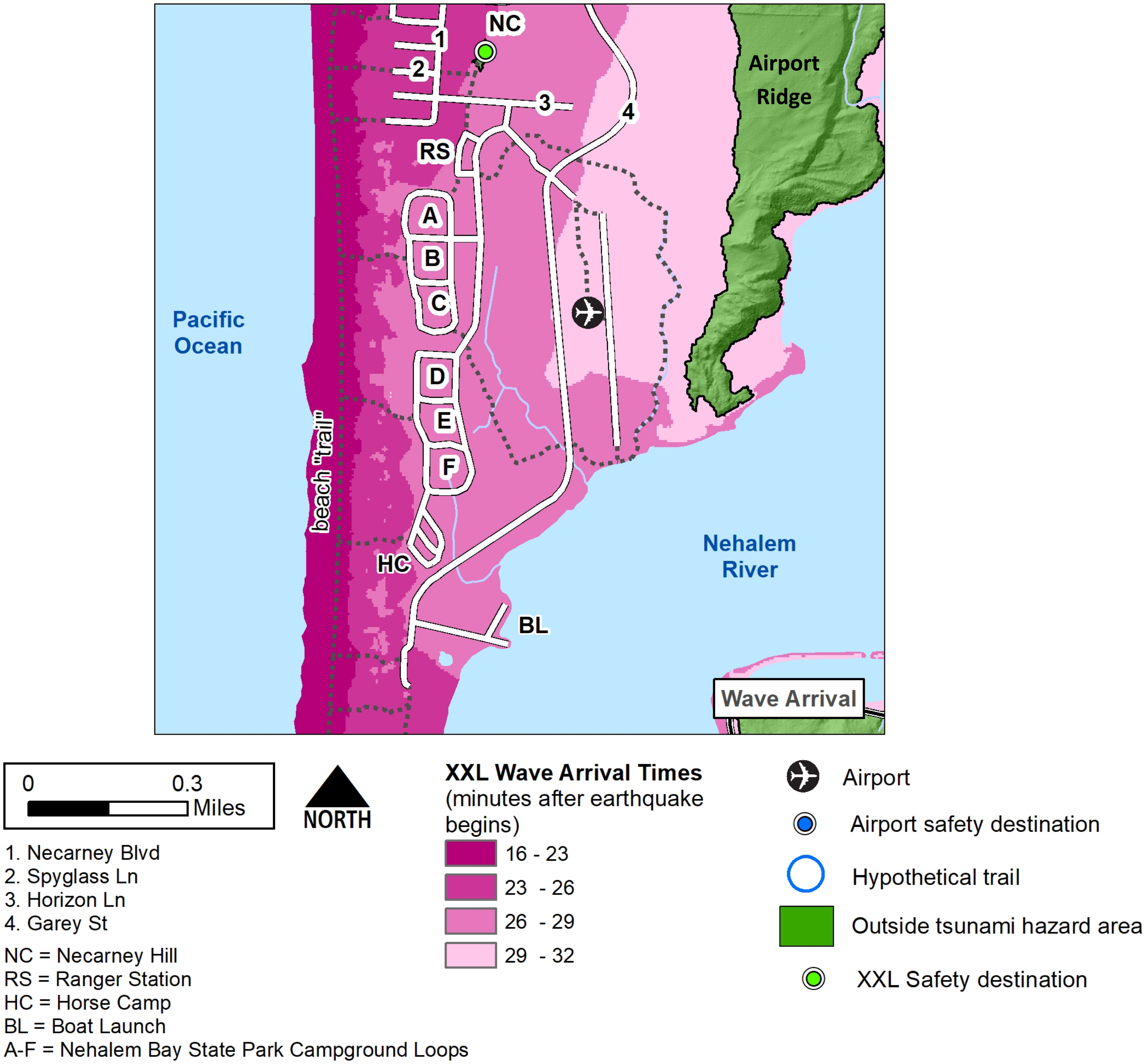
Approximately 85 percent of park visitors remain in the northern third of the park (Ben Cox, Oregon Parks and Recreation Department, personal communication, 2019), which contains the check-in booth and day-use parking lot (labeled as Ranger Station on figures), campground, airport, horse camp, and boat launch. The campground has ~300 tent, RV, and yurt sites distributed between six loops (A–F) and a horse camp site. South of the boat launch, Nehalem Spit continues another ~2 miles south to the mouth of the Nehalem River. This is a sparsely populated area with no overnight visitors; it can be reached only by foot or horse. Like most spits on the Oregon coast, there is no high ground outside the XXL tsunami inundation zone. The nearest designated high ground is Necarney Hill.

The first tsunami wave associated with an XXL event arrives at the beach ~18 minutes after the start of earthquake shaking (**Figure 3-6**). The tsunami reaches the campground in ~26 minutes and by ~29 minutes the entire park has been inundated. Overall, the XXL results for NBSP are similar to other remote coastal areas, namely, that faster travel speeds are required to reach safety, safety destinations are limited, and land cover conditions (i.e., loose sand and wetlands, as well as terrain) can make evacuation travel challenging.

The lack of high ground within NBSP means that mitigation options are limited to the building (and hardening) of evacuation trails to Necarney Hill (scenario 1) and/or Airport Ridge (scenario 2), as well as the construction of one or more vertical evacuation structures. In terms of the latter, we evaluate three separate vertical evacuation structure locations, two of which are in the campground while the third is by the boat launch (scenario 5).

We also consider the evacuation challenge introduced by liquefaction (scenario 3) and the improvement that comes from a reduction in evacuation response time (scenario 4). Because people in this area are more likely to be outdoors or in tents, their evacuation can generally start more quickly compared with people evacuating from buildings (see **Figure 2-5** for further explanation on delay time).

Figure 3-6. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Nehalem Bay State Park.



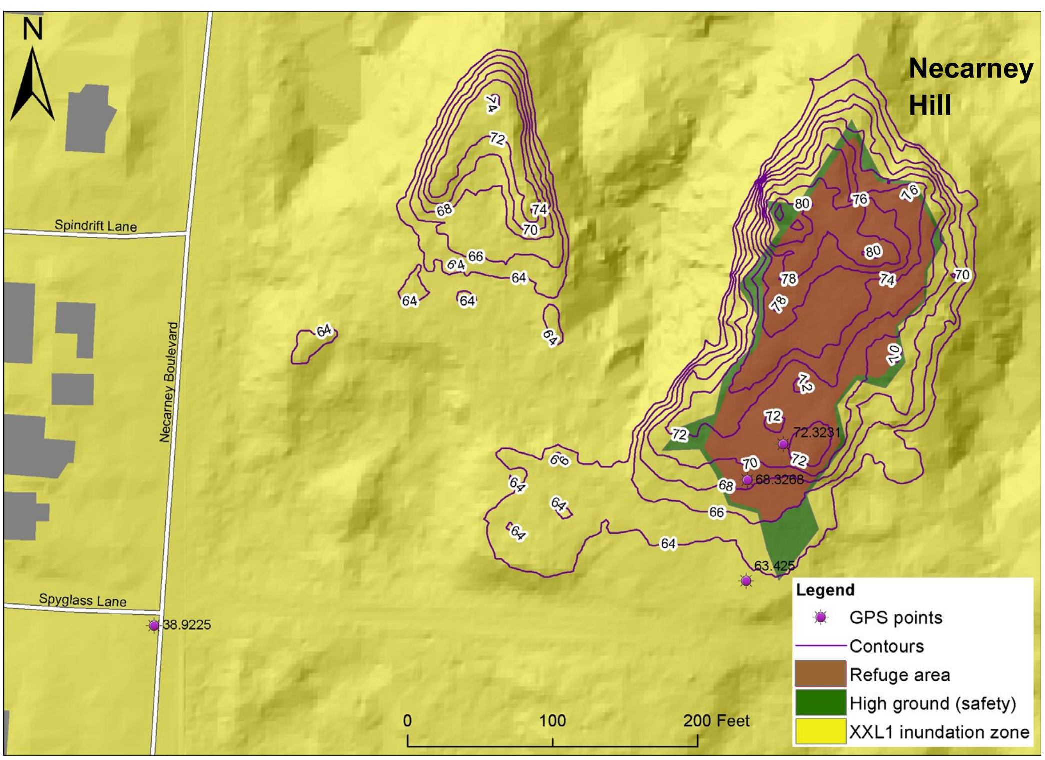
3.3.1 Scenario 1 – Necarney Hill

Currently, Nehalem Bay State Park directs all visitors to high ground on Gary Street toward the Manzanita Transfer Station, approximately 0.6 miles north of the park (station location can be seen in **Figure 3-4**). This safety destination is not ideal because it is so far from the park, especially the southern half of the campground. There is another piece of high ground closer to the park: Necarney Hill. It is a high point in a small east-west trending ridge of old vegetated dunes just north of the park. Despite its relatively small size, it is the best option for everyone in the park. OPRD recognizes Necarney Hill's evacuation potential and is currently developing it as the primary safety destination for the park.

Figure 3-7 provides detailed information on tsunami runup elevations at Necarney Hill. In addition to 2-foot lidar-derived elevation contours, we measured four elevations with a survey-grade GPS unit. Wave runup on the western side ranges from a low of 64 feet in the southwest to 81 feet in the northwest (there is no uniform runup elevation for this area).

The zone of safety on top of Necarney Hill is approximately 25,000 square feet (green + brown area in **Figure 3-7**), which we reduced to the area shown in brown to reflect a more realistic refuge area. This area is approximately 20,500 square feet. Given that an average person requires an area of ~10 square feet (this is what is used for defining space in vertical evacuation structures), ~2,000 people could potentially be squeezed into this area. Because it is unlikely that all 2,000 park visitors and ~100 south Manzanita residents (estimated using U.S. Census Bureau [2010] data) would evacuate to Necarney Hill in the event of a tsunami, the size of the refuge area is sufficient to hold the people who evacuate to Necarney Hill.

Figure 3-7. Necarney Hill area including elevation contours (64–80 feet above the NAVD88 vertical datum) and GPS-derived elevation values at key locations. The area outside the XXL tsunami zone and the slightly smaller area considered to be available as a refuge are shown in green and brown, respectively. Yellow zone represents the XXL tsunami inundation zone. Grey squares are building footprints. Elevation values are in feet.



Part of OPRD's plan for Necarney Hill is to build a trail connecting the day-use parking lot directly to the top of the hill. This creates a more direct route for those at the campground rather than having to travel via existing roads, which requires several left and right turns before reaching Necarney Hill via Spyglass Lane from the west (**Figure 3-8**). It also reduces the overall travel distance to the hill by roughly a quarter mile.

Figure 3-8. Map showing two routes for reaching Necarney Hill. The solid black line shows the existing route on paved park roads. The dashed black line shows the approximate route of a planned trail connecting the campground with safety via the day-use parking lot. Base map is 2018 National Agriculture Imagery Program (NAIP) imagery.

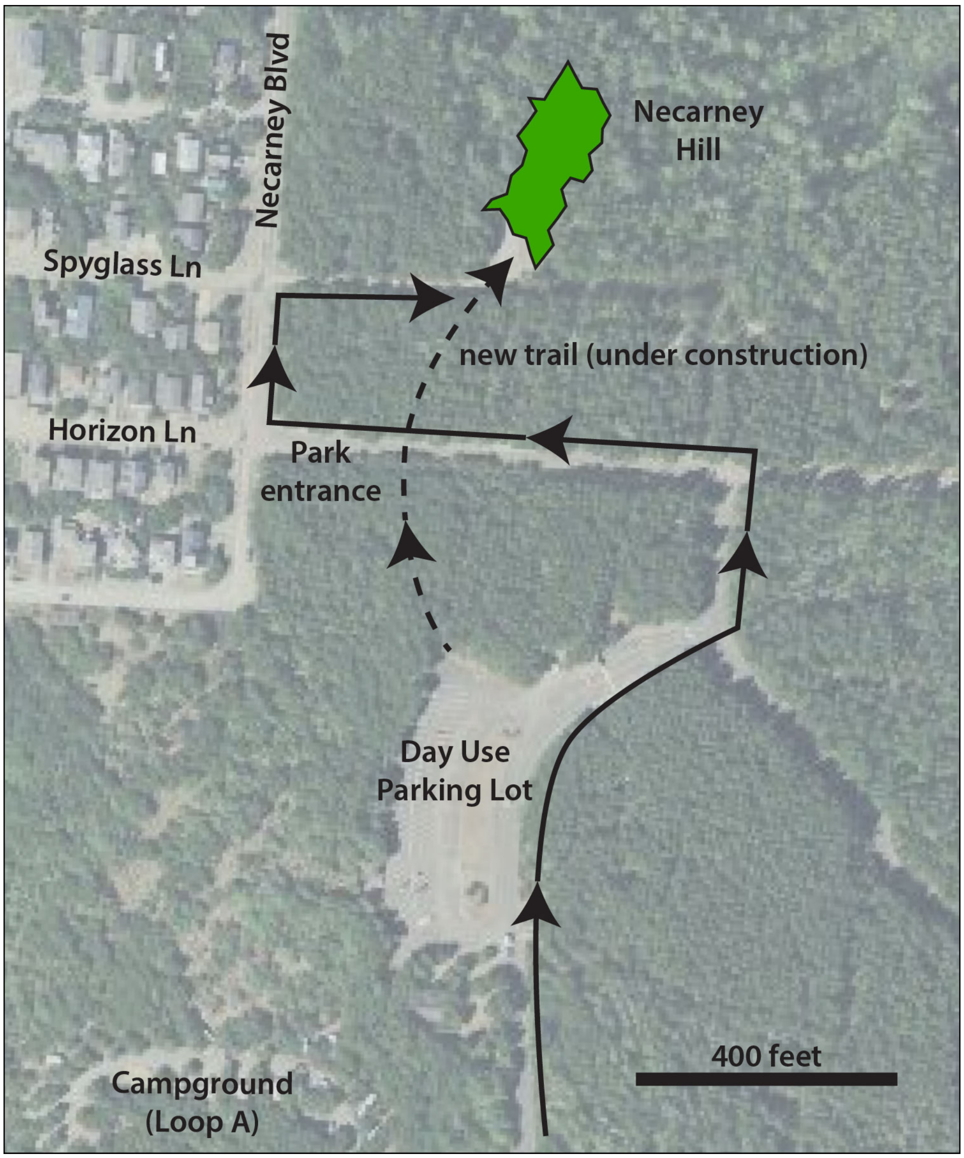


Figure 3-9, **left** presents BTW results in the campground for the NBSP base scenario, which assumes the road and trail network remains intact and Necarney Hill is a viable safety destination. Results for all of Nehalem Spit are shown in **Figure 3-10**, **left**. The new trail between Necarney Hill and the day-use parking lot (labeled as Ranger Station in figure) is also included. Camper in loops A–C can reach Necarney

Hill at a minimum speed of ***walk*** (4 fps, or 2.7 mph) and reach high ground ahead of the tsunami. Campers in Loops D–F must travel at a ***fast walk*** (6 fps, or 4.1 mph), and those in the horse camp must ***jog*** (8 fps, or 5.5 mph). Those at the boat launch must maintain a minimum speed of ***run*** (10 fps, or 6.8 mph) for 1.4 miles to reach Necarney Hill ahead of the tsunami. South of the boat launch, evacuation travel speeds on the trails increase to a ***sprint*** (15 fps, or 10 mph), while the individuals recreating in the southernmost mile of the spit are not expected to survive.

To further emphasize the importance of Necarney Hill, we modeled a scenario without it, forcing everyone in the park to evacuate to one of two safety destinations in south Manzanita (Bonny Lane or Necarney City Road/Gary Street) (**Figure 3-9**, **right**). This adds ~0.6 miles to what is already a long evacuation distance and BTW speeds reflect that, with camp loops B-E increasing to a ***jog***, Loop F and the horse camp increase to ***run***, and anyone at the boat launch must maintain a ***sprint*** (15 fps, or 10 mph) for over 2 miles to reach safety in time. Our results reinforce OPRD's plan to center their current evacuation planning around this safety destination in the near future.

Figure 3-9. Beat the Wave modeling in Nehalem Bay State Park showing the importance of Necarney Hill (scenario 1). (left) Necarney Hill as the closest safety destination and (right) without Necarney Hill, forcing everyone in the park to seek high ground in south Manzanita. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.

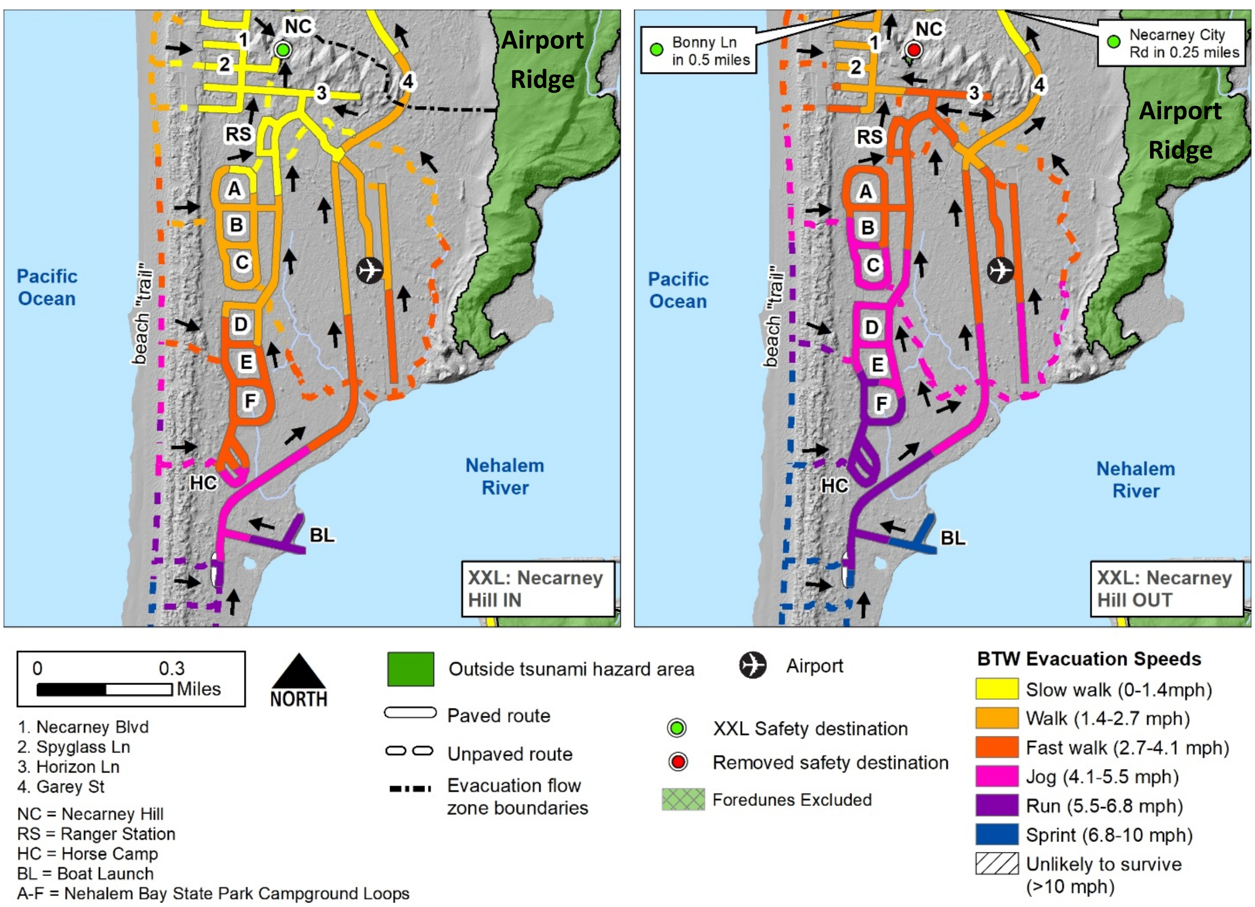
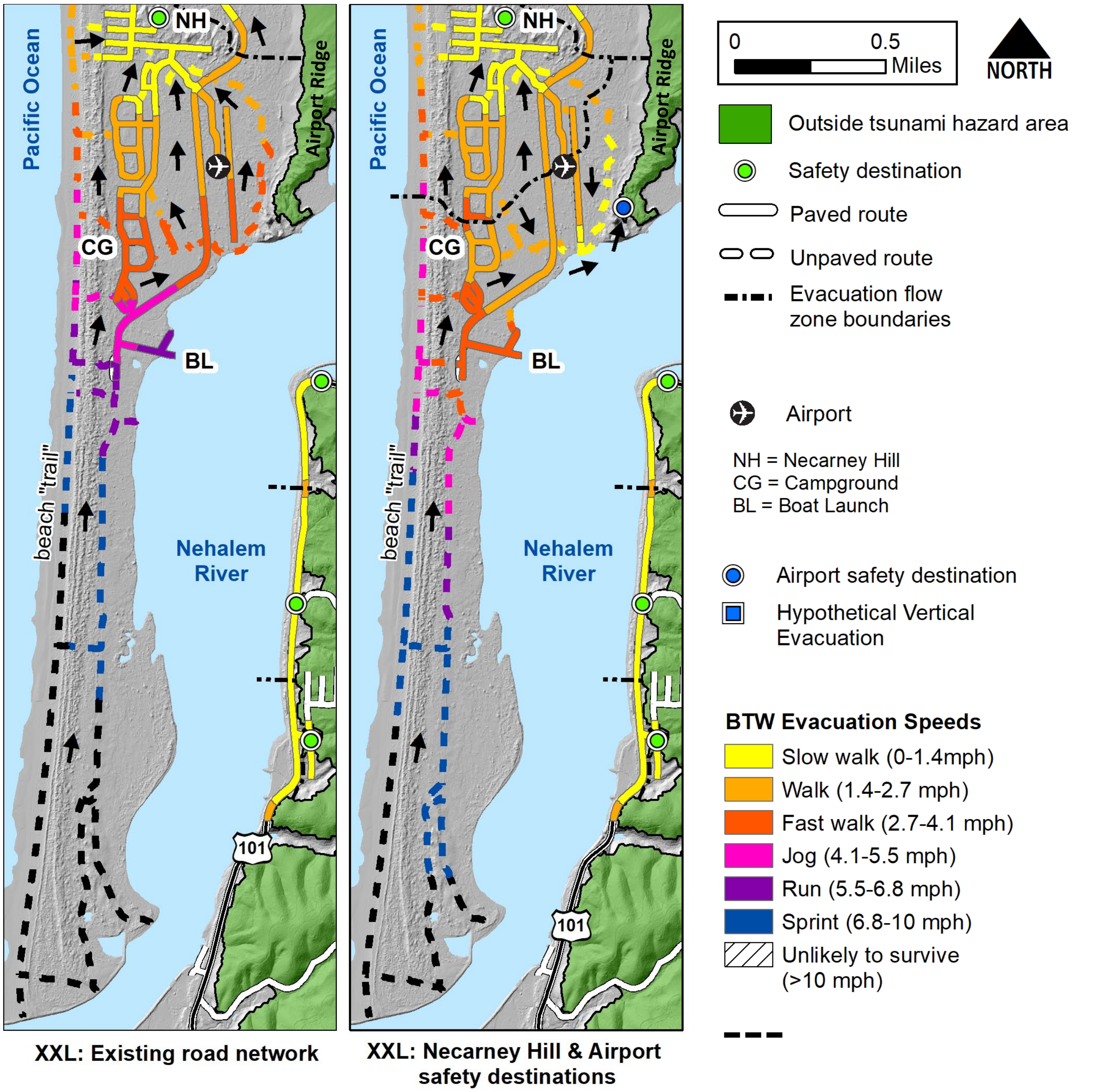


Figure 3-10. Beat the wave modeling in Nehalem Bay State Park showing results on Nehalem Spit for (left) Scenario 1: Necarney Hill and (right) Scenario 2: Airport Ridge. Colors on top of the road network reflect BTW minimum travel speeds, while black dash-dot lines define evacuation flow zone boundaries.

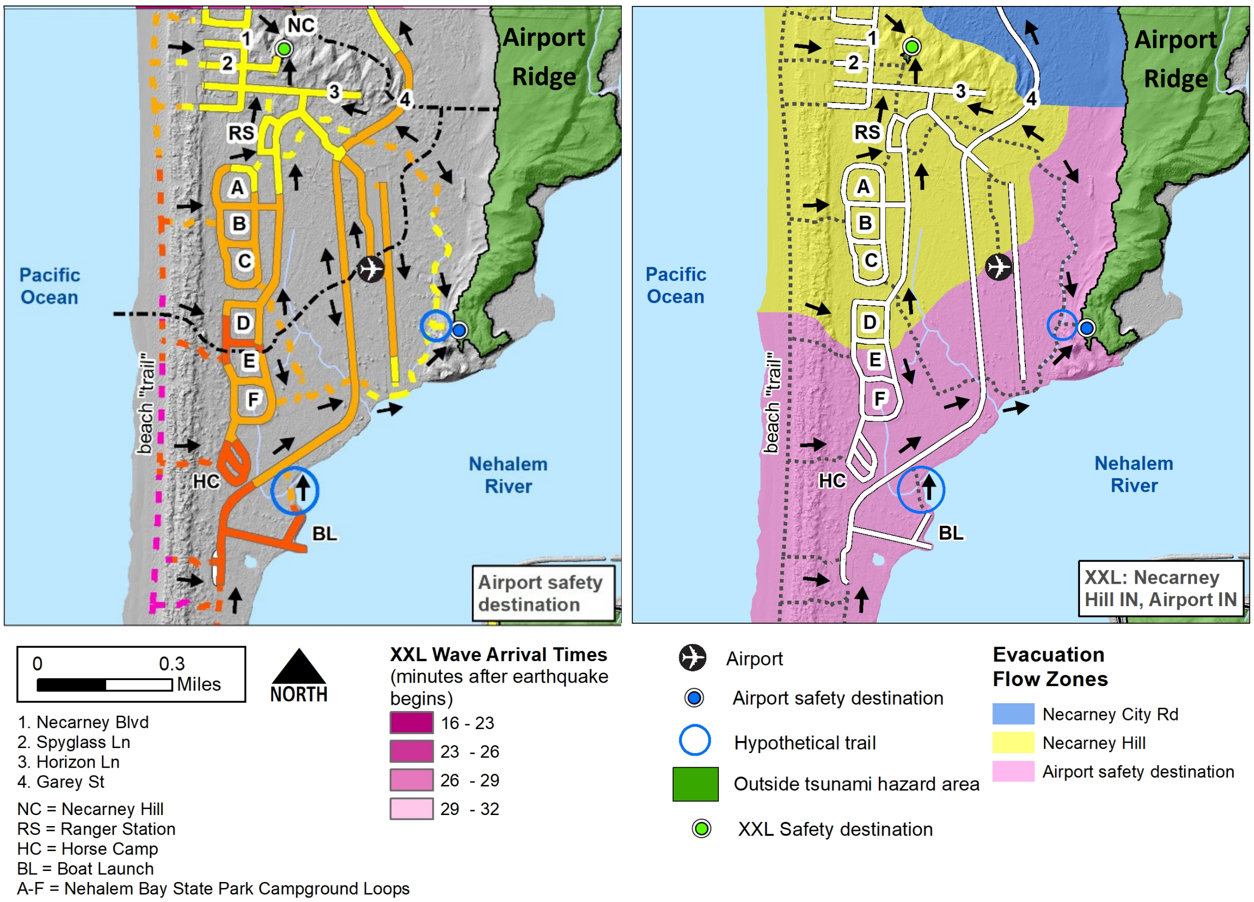


3.3.2 Scenario 2 – Airport Ridge

The addition of a second safety destination significantly improves evacuation for the southern part of NBSP. The 2-mile bike path that circumnavigates the airport and campground comes within ~400 feet of a north-south trending ridge of high ground that we refer to as "Airport Ridge." OPRD is aware of the potential of this location and has plans to construct a designated safety destination there once the Necarney Hill evacuation trail is complete. BTW results for this scenario are shown in **Figure 3-11** and **Figure 3-10**, **right** for the campground and spit, respectively. This new safety destination rather than

Necarney Hill becomes the best option for evacuees in the south end of the park including people in camp loops E and F, the horse camp, the boat launch, and the spit. The most dramatic change within the campground area is at the boat launch, which required a ***run*** to Necarney Hill but is reduced to a ***fast walk*** to Airport Ridge because the evacuation distance decreases from 1.4 miles to 1 mile. This scenario also results in a significant reduction in the area classified as ***unlikely to survive*** for the spit (a reduction from 1 mile to ~0.4 miles).

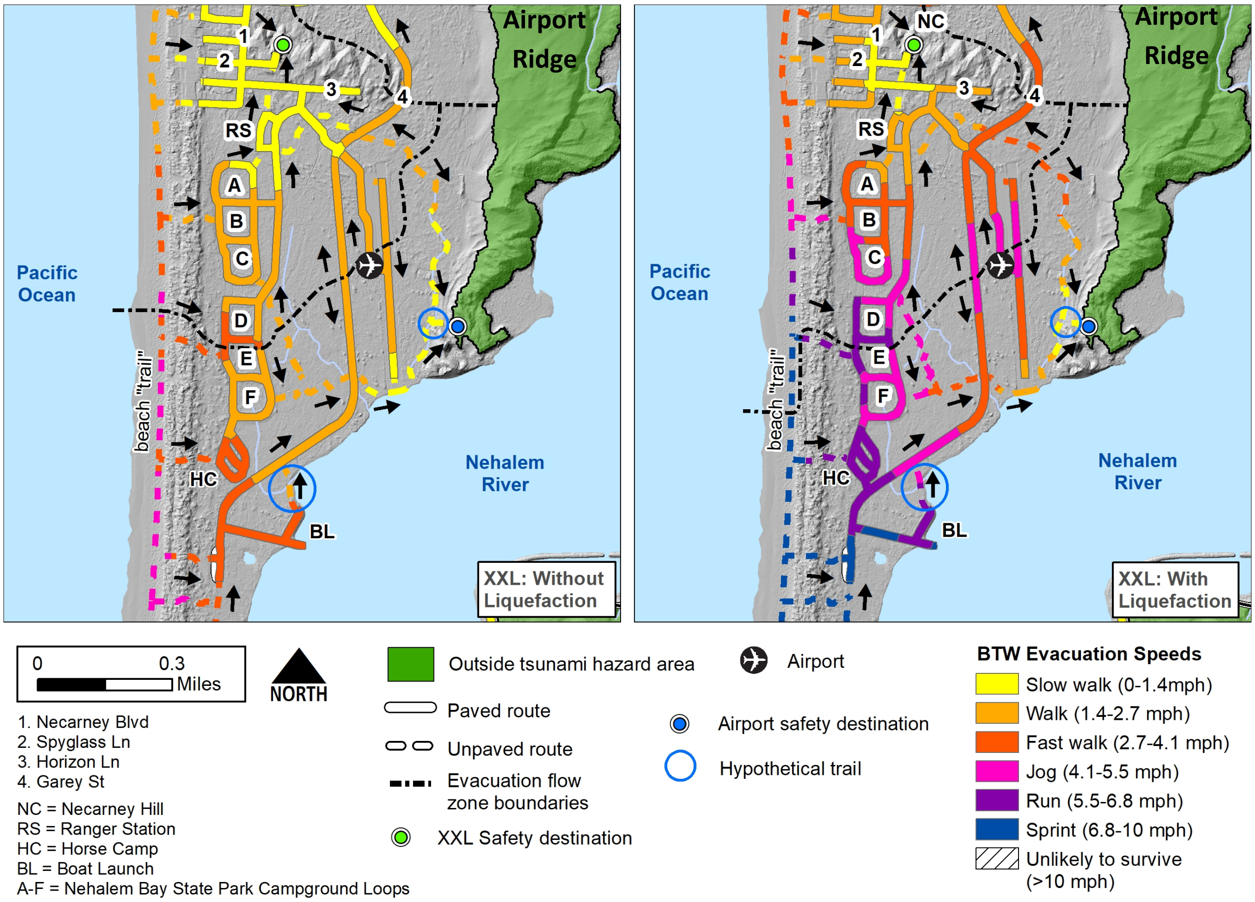
Figure 3-11. Beat the Wave modeling in Nehalem Bay State Park for scenario 2: Airport Ridge. (left) BTW minimum travel speeds. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones only.



3.3.3 Scenario 3 – Liquefaction

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. This includes all roads and trails within NBSP. The liquefaction scenario presented in **Figure 3-12, right** illustrates the dramatic increase in minimum travel speeds needed to reach high ground before the tsunami arrives, even with the inclusion of Airport Ridge. The most significant changes occur in the southern end of the campground and boat launch, where speeds increase to ***jog*** (8 fps, or 5.5 mph) and ***run*** (10 fps, or 6.8 mph). As a reminder, these speeds must be maintained for the duration of a person's evacuation.

Figure 3-12. Beat the Wave modeling in Nehalem Bay State Park for (left) Scenario 2: Airport Ridge and (right) Scenario 3: liquefaction (including Airport Ridge). Scenario 2 is shown for comparison. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.



3.3.4 Scenario 4 – Reduced evacuation delay

When exploring ways to reduce the potential for tsunami fatalities, any effort directed at reducing evacuation delay will save lives. Here we re-evaluate scenario 1 (Necarney Hill) and scenario 2 (Airport Ridge) with a 5-minute evacuation delay compared with the original 10-minute delay. For these scenarios, we assume the original ~3 minutes for the earthquake shaking and factor in a 2-minute rather than a 7-minute response time before getting underway (**Figure 2-5**). **Figure 3-13** shows side-by-side comparisons of both 5-minute delay results against scenario 1 for the campground. The entire spit is shown in **Figure 3-14**, **left**. Overall, we demonstrate that a reduction in response time results in a significant decrease in the required evacuation speed, which amounts to one speed category (evacuation flow zones remain unchanged). For example, people at the boat launch must travel at a ***run*** if they wait 10 minutes and head to Necarney Hill (**Figure 3-13**, **top left**). However, reducing the response time to 5 minutes results in a ***jog*** (**Figure 3-13**, **top right**) and if Airport Ridge is available as an alternative safety destination, minimum speed is further reduced to a ***walk*** (**Figure 3-13**, **bottom right**).

Given that people in the southern end of the campground or on the spit are anywhere from 1 to 3 miles from high ground and speeds must be maintained for the duration of the route, it would be extremely difficult for anyone to maintain the speeds required in scenario 1. By reducing individual response times and creating a closer safety destination (**Figure 3-13**, **bottom right** and **Figure 3-14**, **left**), the required evacuation speeds are reduced, enabling potentially many more people to reach safety in time. Admittedly, a 2-minute response time is optimistic for a population in an unfamiliar environment, especially if the event occurs at night. These results emphasize how important education and wayfinding signage will be to facilitate the shortest evacuation delay for park visitors.

Figure 3-13. Beat the Wave modeling in Nehalem Bay State Park for (top left) 10-minute evacuation delay (scenario 1, Necarney Hill safety destination), (top right) Scenario 4: 5-minute delay (with Necarney Hill safety destination only), and (bottom right) Scenario 4: 5-minute delay (with both Necarney Hill and Airport Ridge safety destinations). Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.

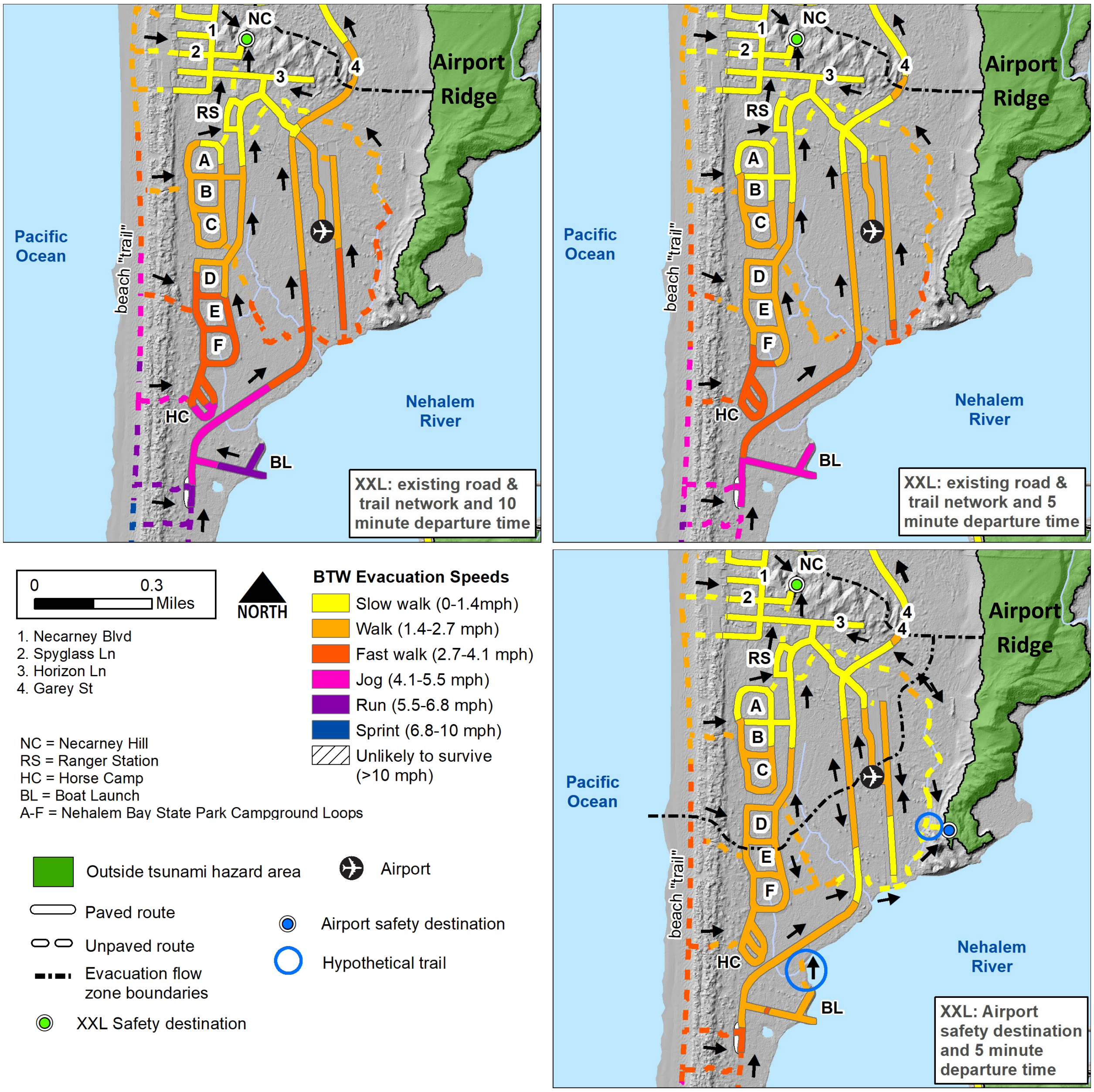
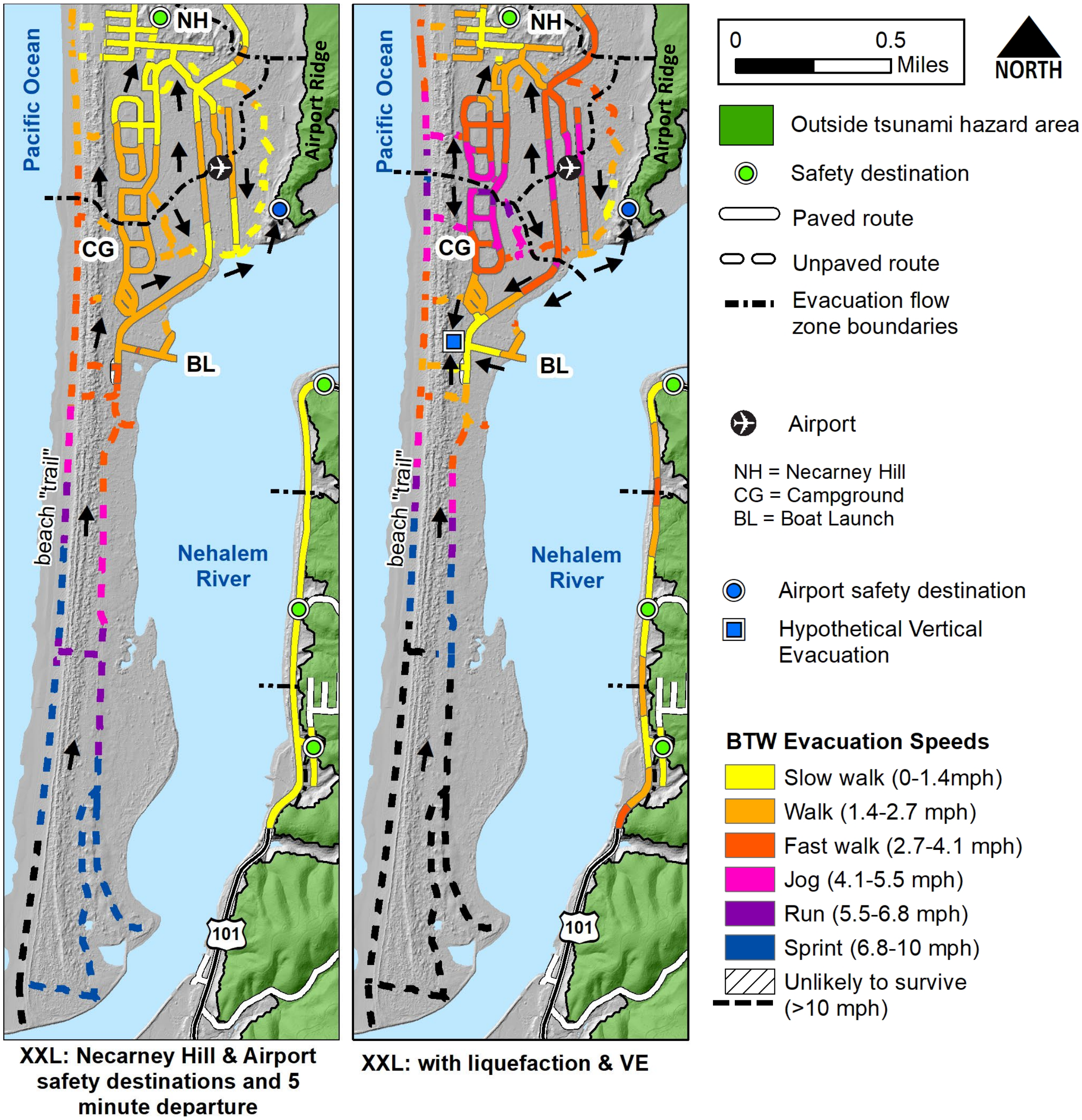


Figure 3-14. Beat the wave modeling in Nehalem Bay State Park showing results on Nehalem Spit for (left) Scenario 4: 5-minute departure time and (right) Scenario 5: vertical evacuation structure by the boat launch with liquefaction. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.



3.3.5 Scenario 5 – Vertical evacuation

The biggest challenge affecting evacuation potential at NBSP is the lack of high ground. As discussed in scenario 4, reducing a person's departure delay (i.e., response time) from 10 minutes to 5 minutes makes an enormous difference in that person's chance of surviving the tsunami by providing more time to reach high ground (**Figure 3-13**). Decreasing time to reach safety may also be accomplished by bringing high ground closer to visitors. This can be achieved through the construction of a tsunami vertical evacuation structure (TVES), which may be a building or berm. Such a structure, when built correctly and in targeted locations, could potentially save many lives. Although a TVES building would likely have a smaller footprint, a tall berm may be a better solution for this area, allowing it to be used for recreational purposes. In this scenario we evaluated three potential TVES sites:

- by the park amphitheater, between campground loops C and D
- between loop F and horse camp
- near the boat launch

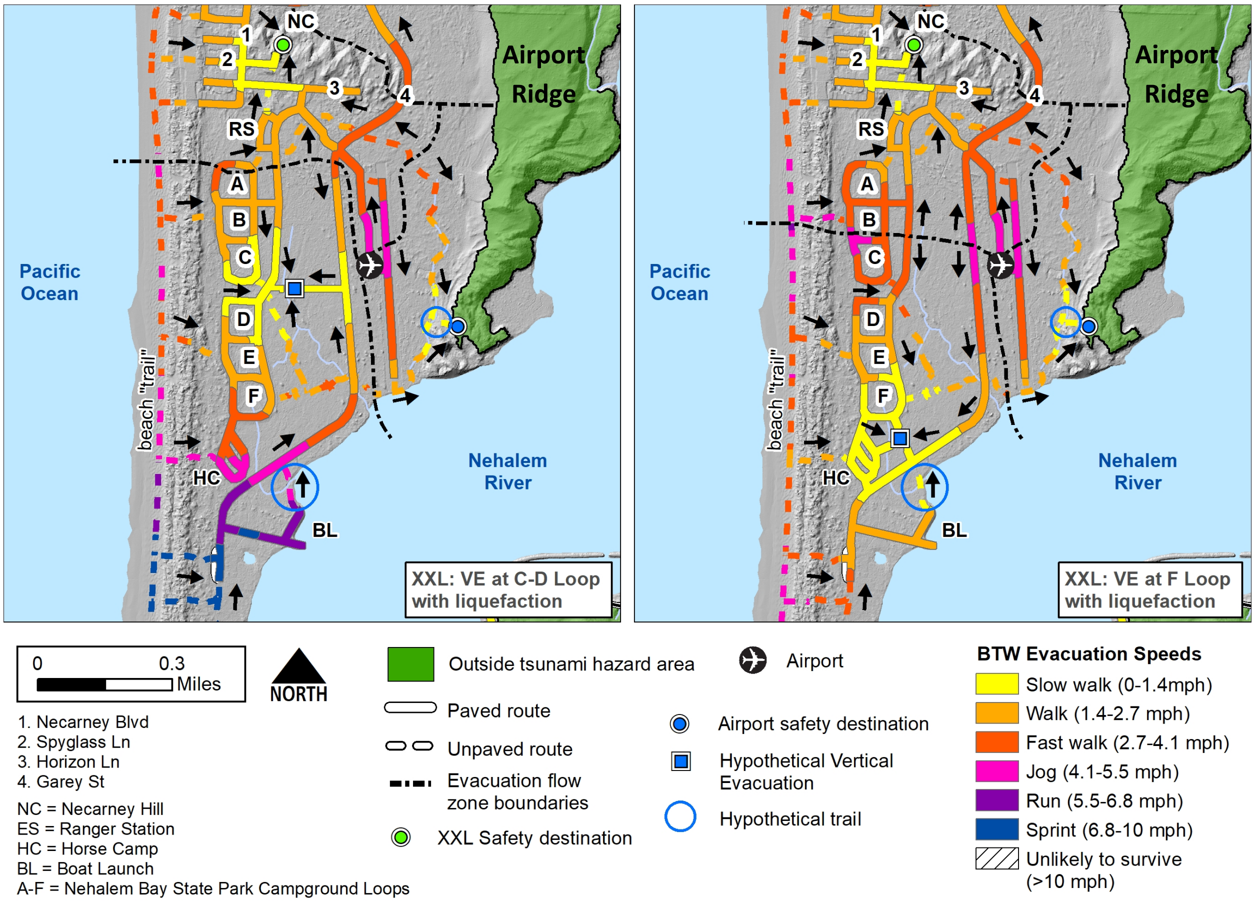
Results of our evacuation modeling for the two TVESs within the campground are presented in Figure 3-15. Results for the third TVES by the boat launch is presented in **Figure 3-14**, **right**. Note that TVES scenarios <u>include liquefaction</u>. This is to better reflect realistic minimum evacuation speeds needed to reach the structure, because smooth, clear roads are unlikely. There are noticeable improvements in evacuation speeds around the structures, but improvements are concentrated in a quarter-mile radius around the TVESs.

The amphitheater TVES is more centrally located between the day-use and overnight visitors, and in that sense, best serves the most people (**Figure 3-15**, **left**). It would also provide ample opportunities for awareness and other forms of education because the amphitheater is used regularly. Unfortunately, TVES is too far away from the boat launch and southern end of the campground to be of much use for those visitors.

A TVES constructed near Loop F/horse camp addresses this southern population better, greatly improving that area's evacuation potential. However, this site would serve fewer people and does not help those in the popular upper camp loops (**Figure 3-15**, **right**). The third TVES by the boat launch produces similar results (**Figure 3-14**, **right**), improving evacuation potential for the boat launch and horse camp but not elsewhere.

Overall, these results suggest that adding a TVES would be beneficial, but more than one is likely necessary to meet the needs of all park visitors. Further work is recommended to evaluate the cost-benefits of having such structures relative to other options.

Figure 3-15. Beat the wave modeling in Nehalem Bay State Park for two hypothetical vertical evacuation structures (scenario 6). (left) TVES located by the amphitheater between campground loops C and D, and (right) TVES located between loop F and horse camp. Both scenarios include liquefaction on all roads and trails. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.



3.4 Bayside Gardens

Bayside Gardens sits between the cities of Manzanita and Nehalem on the northern edge of Nehalem Bay. A significant portion of the community is inside the XXL inundation zone; however, the steep landscape results in short evacuation routes. **Figure 3-16** shows the arrival times for an XXL tsunami in Bayside Gardens. The tsunami reaches the bay shore ~30 minutes after the start of earthquake shaking and reaches maximum inundation extent within ~8 minutes. **Figure 3-17**, **top left** presents BTW results for a base scenario assuming the road and trail network remains intact. Nearly everyone can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. Evacuation flow zones for this scenario are presented in **Figure 3-17**, **bottom left**. The evacuation flow zones make clear which direction evacuees should choose based on their location.

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 Bayside Gardens, all roads inside the XXL inundation zone are moderately to highly susceptible. The liquefaction scenario presented in **Figure 3-17**, **top right** illustrates the increase in minimum travel speeds necessary to reach high ground before the tsunami arrives. Approximately half of the community must travel at a ***walk*** (4 fps, or 2.7 mph) in order to survive in this scenario.

This area has short and relatively simple evacuation routes and no bridges or other key pieces of infrastructure that could compromise pedestrian evacuation; however, clear and visible signage as well as outreach are imperative to ensure evacuees do not walk the wrong direction after an earthquake.

Figure 3-16. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Bayside Gardens.

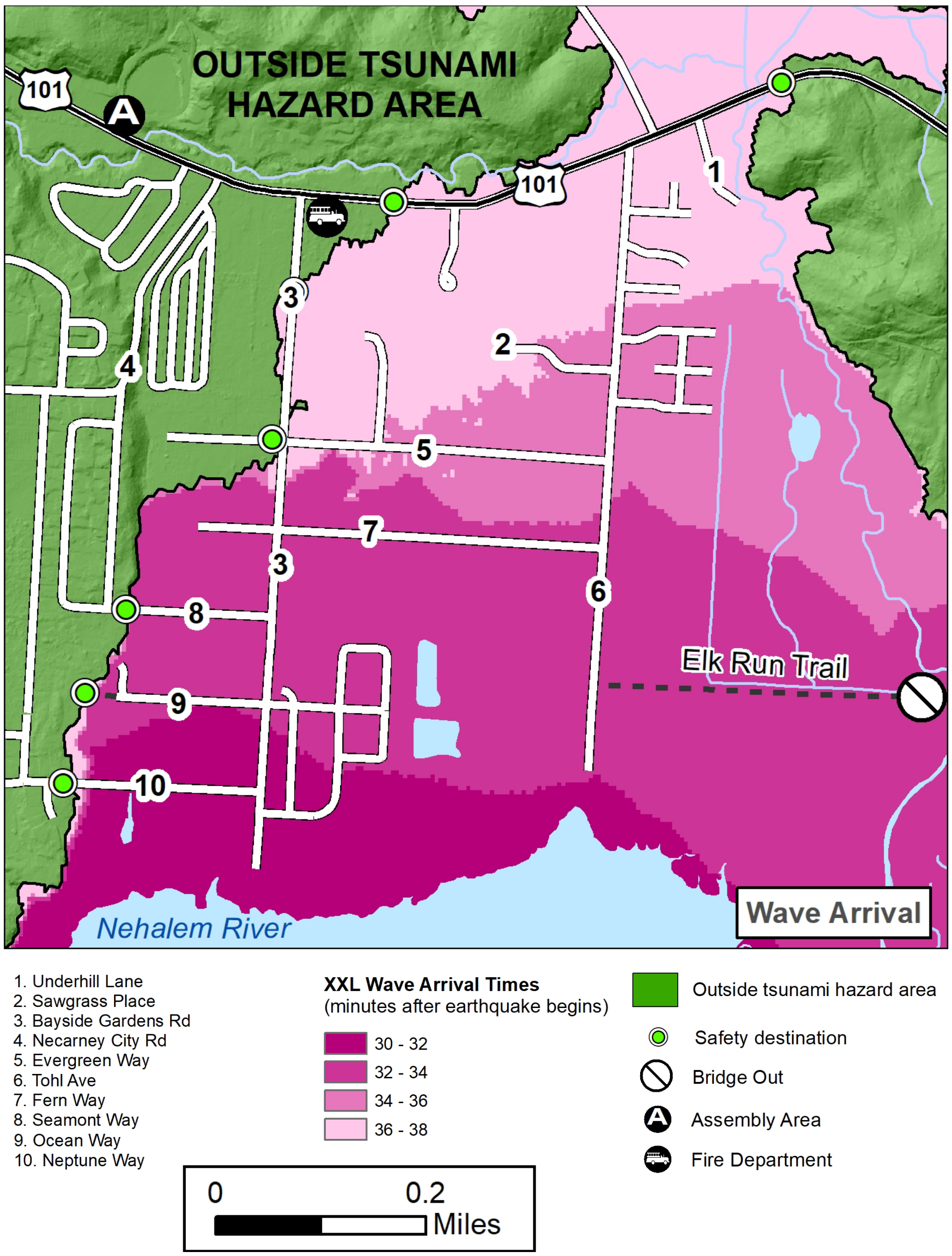
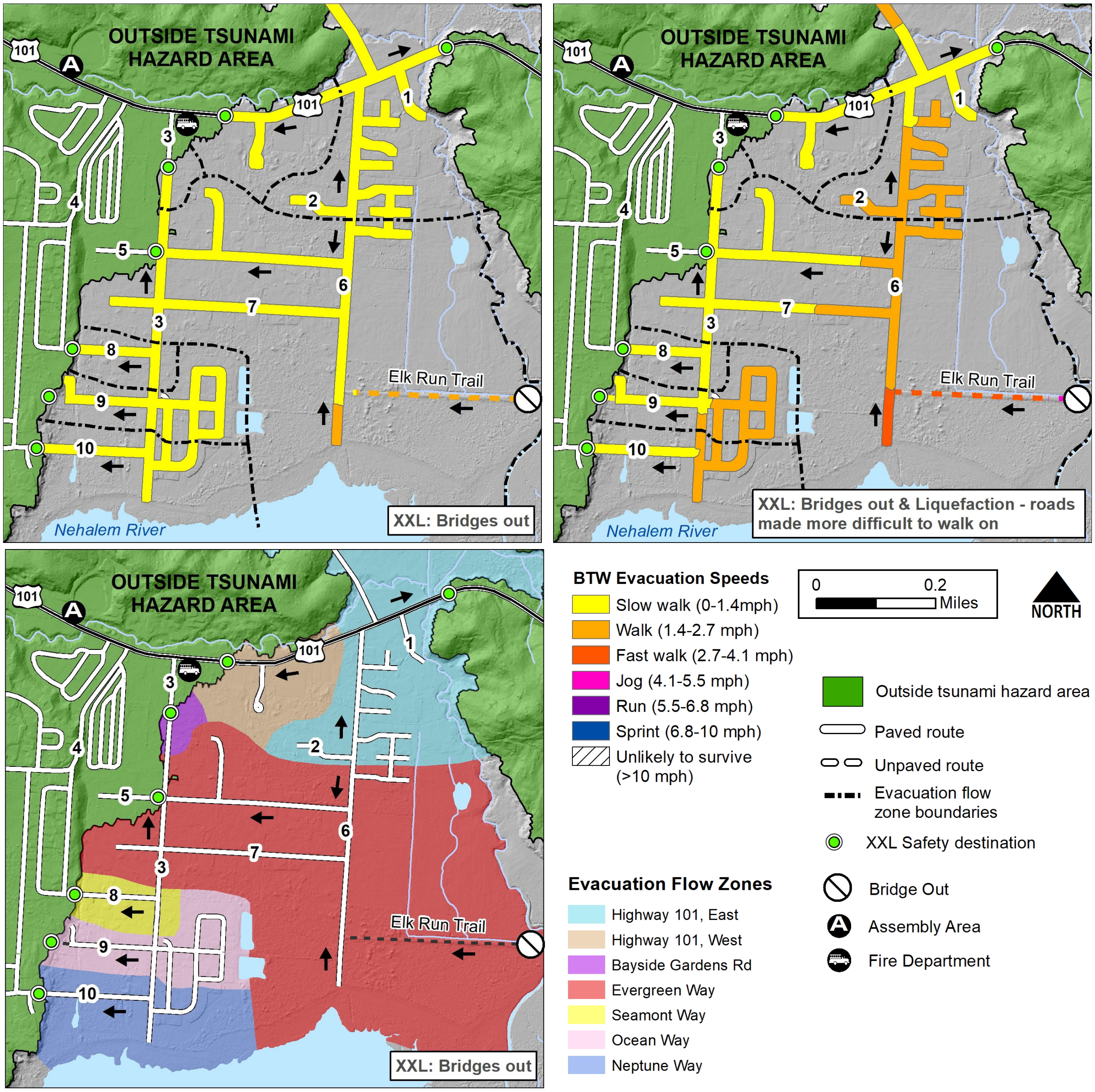


Figure 3-17. Beat the wave modeling in Bayside Gardens for (top left) base scenario depicting the existing road and trail network and (top right) for liquefaction scenario. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. (bottom left) shows evacuation flow zones for base scenario. See Figure 3-16 for road labels.



3.5 Nehalem

The City of Nehalem is adjacent to the Nehalem River, upstream from Bayside Gardens. Due to the steep landscape, nearly all of the community is outside of the inundation zone. Figure 3-18 shows the arrival times for an XXL tsunami in Nehalem. The tsunami reaches Highway 101 in the south part of town ~38 minutes after the start of earthquake shaking and reaches maximum inundation extent within ~2 minutes. Figure 3-19 presents BTW results for Nehalem. Because distances to safety are so short, a base scenario assuming the road and trail network remains intact is identical to a liquefaction scenario where roads are made more difficult to walk on. In both cases, all evacuees inside the inundation zone may reach safety at a ***slow walk*** (2 fps, or 1.4 mph) (**Figure 3-20**, **left**). Evacuation flow zones for this scenario are presented in **Figure 3-19**, **right**. The evacuation flow zones make clear which direction evacuees should choose based on their location.

This area has short and relatively simple evacuation routes and no bridges or other key pieces of infrastructure that could compromise pedestrian evacuation; however, clear and visible signage as well as outreach are imperative to ensure evacuees do not walk the wrong direction after an earthquake.

Figure 3-18. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Nehalem.

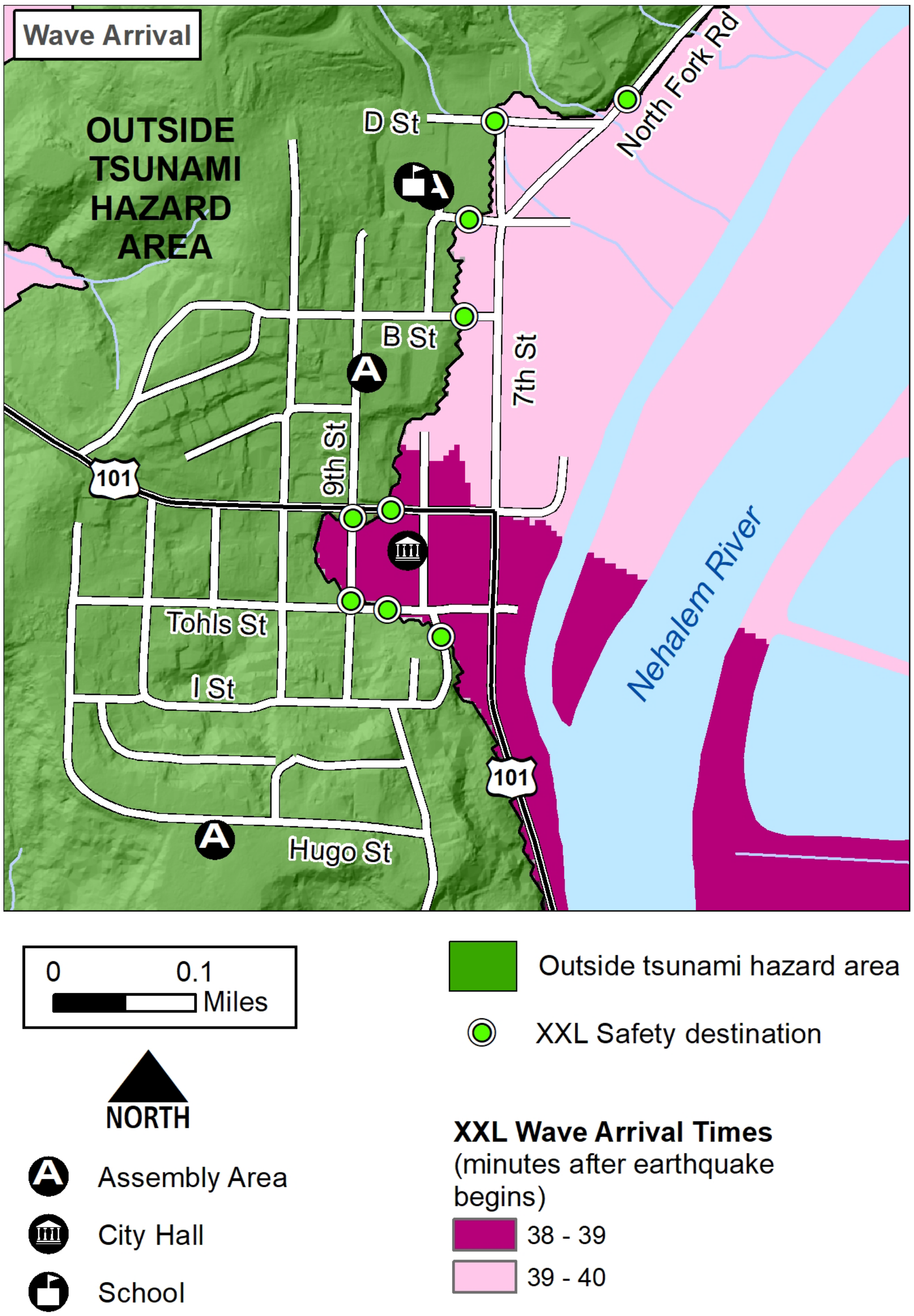
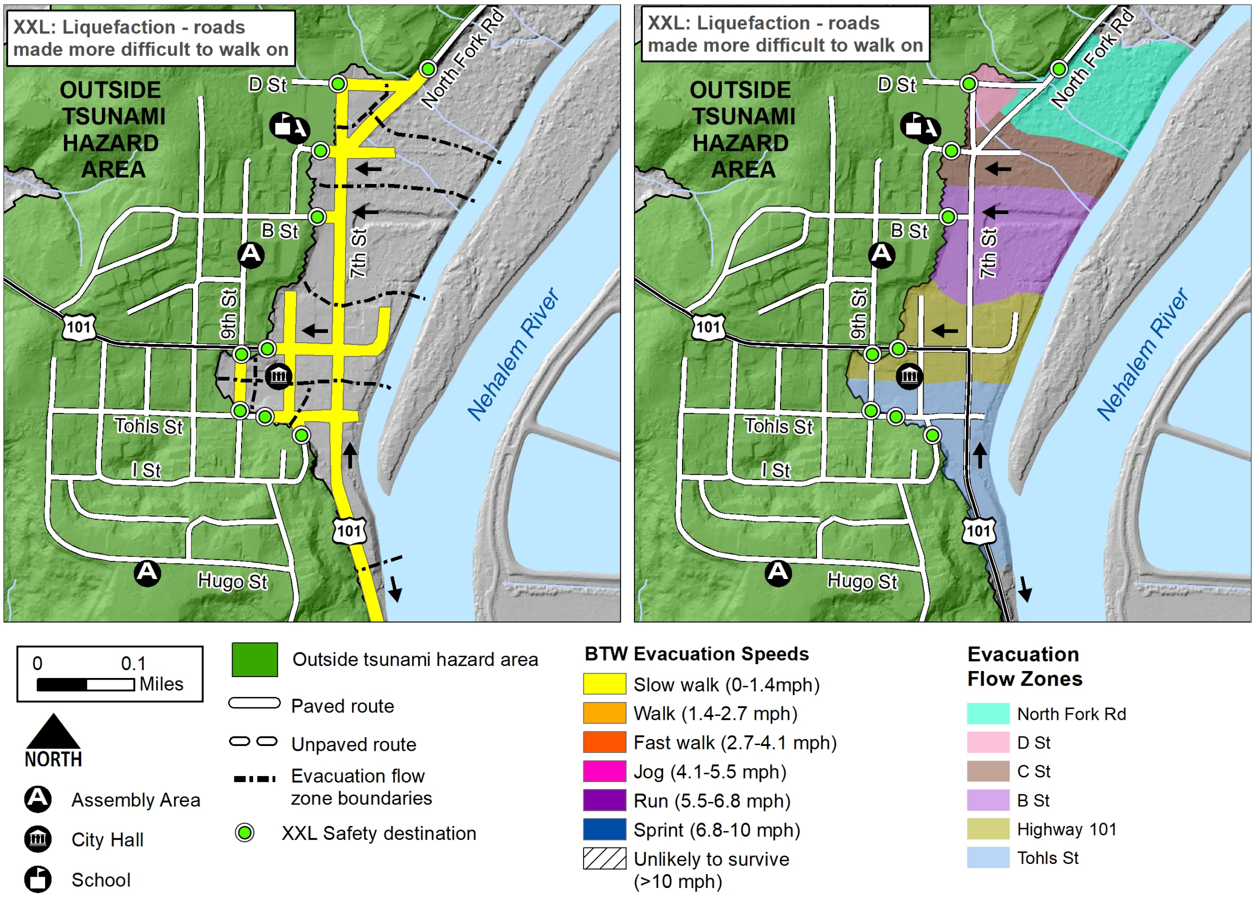


Figure 3-19. Beat the Wave modeling in Nehalem for base scenario and liquefaction scenario showing (left) minimum evacuation speeds and (right) evacuation flow zones. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.

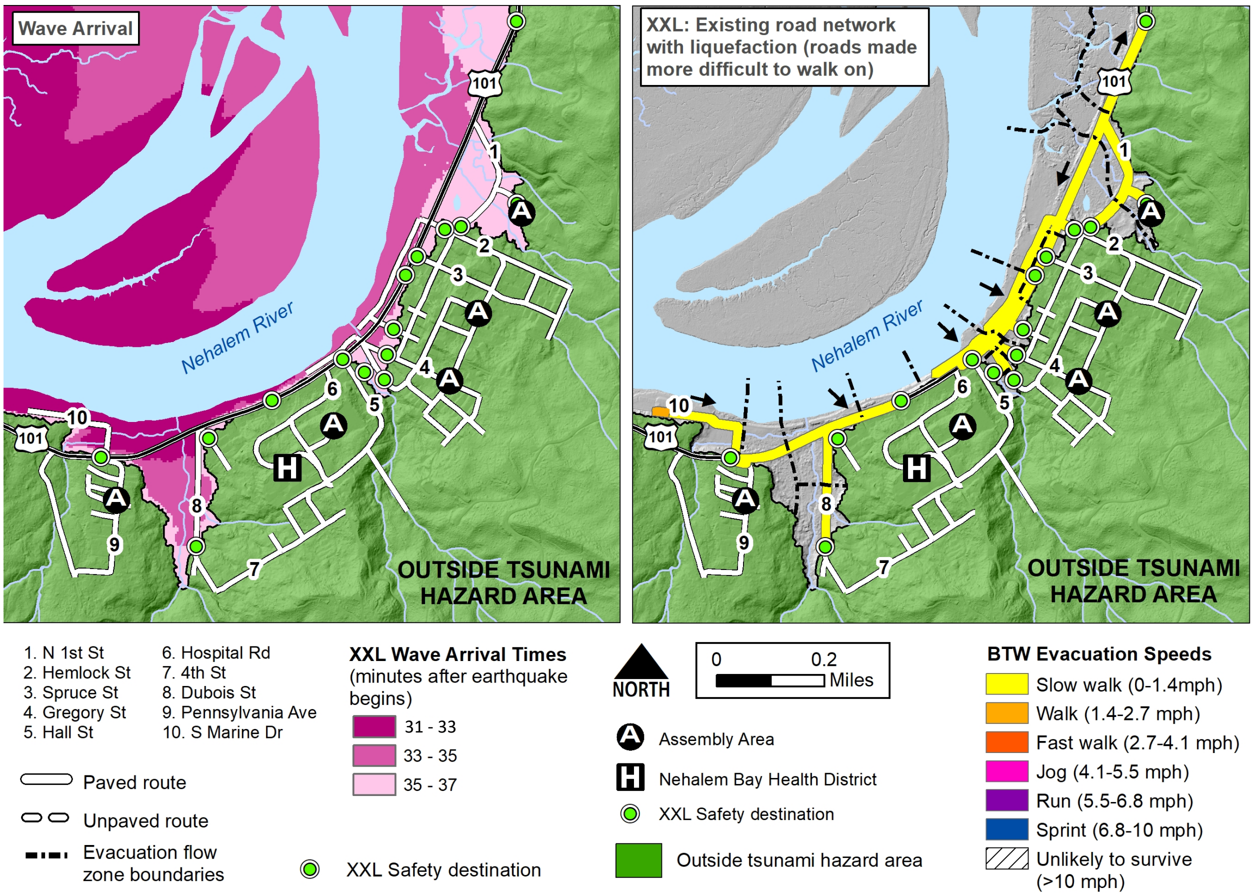


3.6 Wheeler

The City of Wheeler sits adjacent to the Nehalem River on the southern edge of Nehalem Bay. Due to the steep landscape, most of the community is outside of the inundation zone. **Figure 3-20, left** shows the arrival times for an XXL tsunami in Wheeler. The tsunami reaches Highway 101 ~31 minutes after the start of earthquake shaking and reaches maximum inundation extent within approximately 7 minutes. **Figure 3-20**, **right** presents BTW results for both a base scenario and a liquefaction scenario. As with Nehalem, because distances to safety are so short, the two scenarios are identical. In both cases, all evacuees inside the inundation zone may reach safety at a ***slow walk*** (2 fps, or 1.4 mph).

Highway 101 may be susceptible to lateral spreading because the seaward side of the road is so close to the bay. Lateral spreading can result in major failures to road infrastructure as the road slumps toward the bay. The Bayfront in Newport, Lincoln County, has a similar situation. In the Newport BTW study (Gabel and others, 2019), we considered a scenario where multiple safety destinations were blocked due to landslides or lateral spreading. There, liquefaction results were identical to the base scenario (***slow walk***) because of the prevalence of high ground via many different pathways. Wheeler also has multiple pathways to high ground, all of which are short. Therefore, we assume the same unchanging minimum evacuation travel speeds in Wheeler as for the base scenario (***slow walk***). The modeling does not account for all possibilities that come with these hazards (e.g., the complete removal of a section of Highway 101). Mitigation options include reinforcing Highway 101 against lateral spreading, as that would help to stabilize key routes.

Figure 3-20. (left) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Wheeler. (right) Beat the wave modeling in Wheeler for base scenario and liquefaction scenario. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.



3.7 Mohler

After the tsunami passes a constriction at Nehalem Point, Nehalem Bay widens, and the tsunami inundates the broad floodplains of the Nehalem River mainstem and North Fork. The communities of Mohler, Nehalem (discussed in section 3.5), and North Fork (discussed in section 3.8) as well as the Nehalem Bay boat launch are located here (**Figure 3-1**). Most of the inundation zone in this area is pastureland with most residents located along roads that skirt the edge of the inundation zone (Northfork Road and Highway 53). Some people, however, will be in the middle of the estuary at the time of the event, and they must be prepared to evacuate quickly due to the long distances to high ground.

Further challenging evacuation for this area are three bridges unlikely to survive the earthquake shaking: McDonald Road over the North Fork, Highway 101 over the Nehalem River, and Highway 101 over Gallagher Slough (near Wheeler). The McDonald Road bridge provides access to high ground for a small collection of homes across the river; the other two bridges provide access to nearby high ground for the Nehalem Bay boat launch. Two other bridges in the area are also unlikely to survive, but they are not essential for tsunami evacuation. They are the Highway 53 bridge over the Nehalem River and the Highway 101 bridge over the Port of Tillamook Bay Railroad. The former is nonessential for evacuation because the distance to safety is equidistant on both sides of the bridge. The latter is nonessential because there are no residences that rely on it to reach high ground. Nevertheless, these bridges will be critically important for post-tsunami recovery.

Figure 3-21 shows the arrival times for an XXL tsunami in this region of Nehalem Bay. The tsunami reaches Nehalem Point ~35 minutes after the start of earthquake shaking, the start of the North Fork Nehalem River after ~42 minutes, and Miami-Foley Road after ~46 minutes.

Figure 3-21. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for the Mohler–North Fork region of Nehalem Bay.

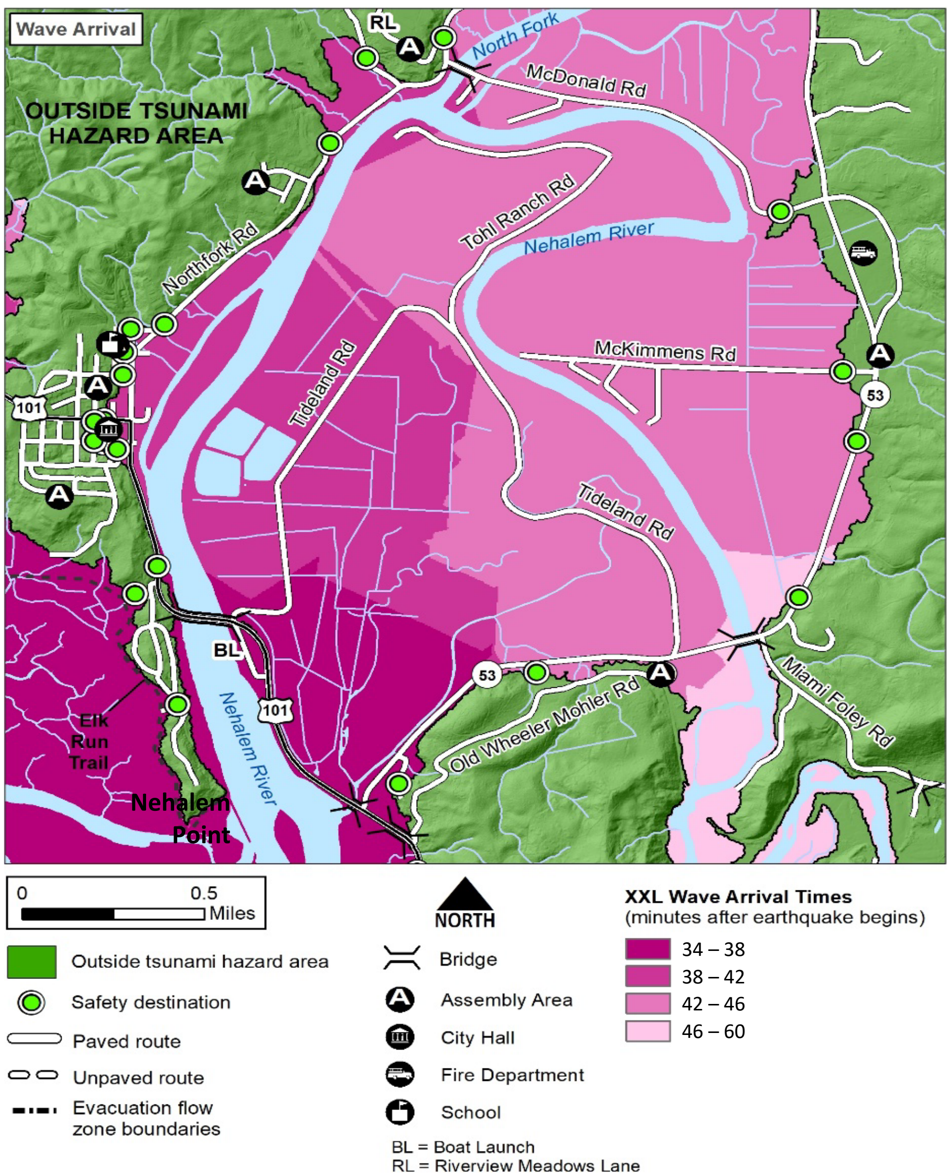


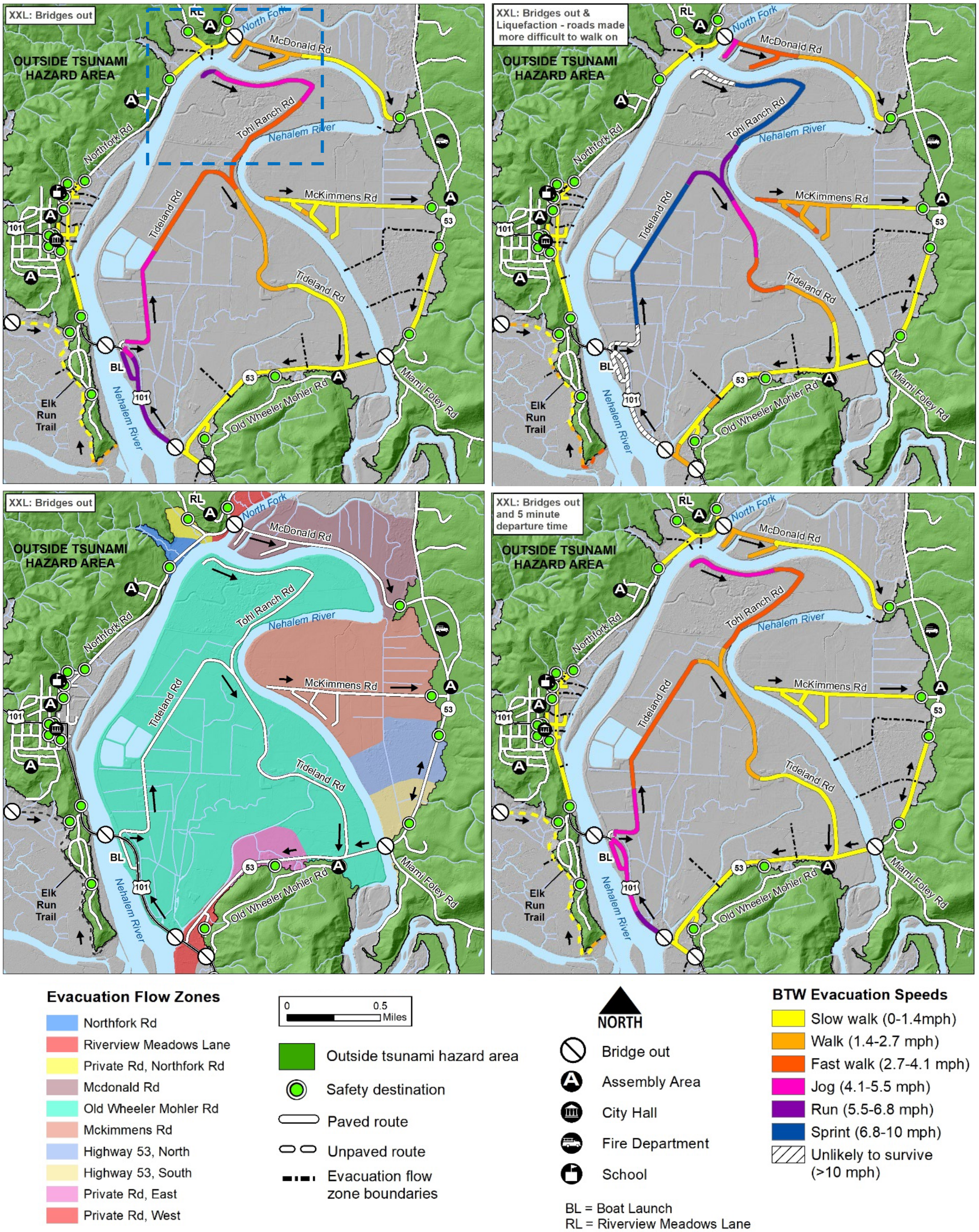
Figure 3-22, **top and bottom left** present minimum BTW travel speeds and evacuation flow zones for the base scenario, which assumes the aforementioned bridges fail but otherwise all roads and trails are passable after the earthquake. Travel speeds to reach safety in this area range from a ***slow walk*** (2 fps, or 1.4 mph) for everyone on Highway 53, Northfork Road, and McKimmens Road to ***jog*** (8 fps, or 5.5 mph) and ***run*** (10 fps, or 6.8 mph) for those at the end of Tohl Ranch Road, and ***run*** for the Nehalem Bay boat launch.

Minimum evacuation speeds for the boat launch would be significantly slower if the Highway 101 bridge over the Nehalem River remained available. It is a difference of traveling approximately 0.5 miles west toward the City of Nehalem versus traveling east on Highway 101 toward Wheeler and encountering two bridges that are likely impassable or, as our results show, taking the non-bridge route to high ground at Mohler via Tideland Road. Because this option requires maintaining a ***run*** (10 fps, or 6.8 mph) for approximately 3 miles, this scenario suggests there will be many fatalities in this location. The other two locations that merit a closer look, Tohl Ranch Road and McDonald Road, are examined in section **3.8**.

The inclusion of liquefaction dramatically increases the speed everyone in this area must travel (**Figure 3-22**, **top right**) with the most significant changes occurring at the same locations previously discussed: the boat launch and Tohl Ranch Road. Under these conditions the required evacuation speeds are unattainable on foot (***unlikely to survive***, >15 fps, or 10 mph).

Figure 3-22, **bottom right** presents results for a reduced evacuation delay scenario. Because people at the boat launch are more likely to be outdoors, their evacuation can generally start more quickly compared with people evacuating from buildings. This reduces the minimum evacuation speed for the boat launch to a ***jog*** (8 fps, or 5.5 mph). These scenarios further emphasize the need for additional evacuation planning at the Nehalem Bay boat launch.

Figure 3-22. Beat the Wave modeling in the Mohler–North Fork region of Nehalem Bay for (top left) bridges out scenario, (top right) liquefaction, and (bottom right) a reduced evacuation delay. Colors on top of the road network reflect minimum BTW travel speeds, and black dashed lines define evacuation flow zone boundaries. (bottom left) shows evacuation flow zones for bridges out scenario. Dashed blue square in top left panel outlines the North Fork area examined further in section 3.8.

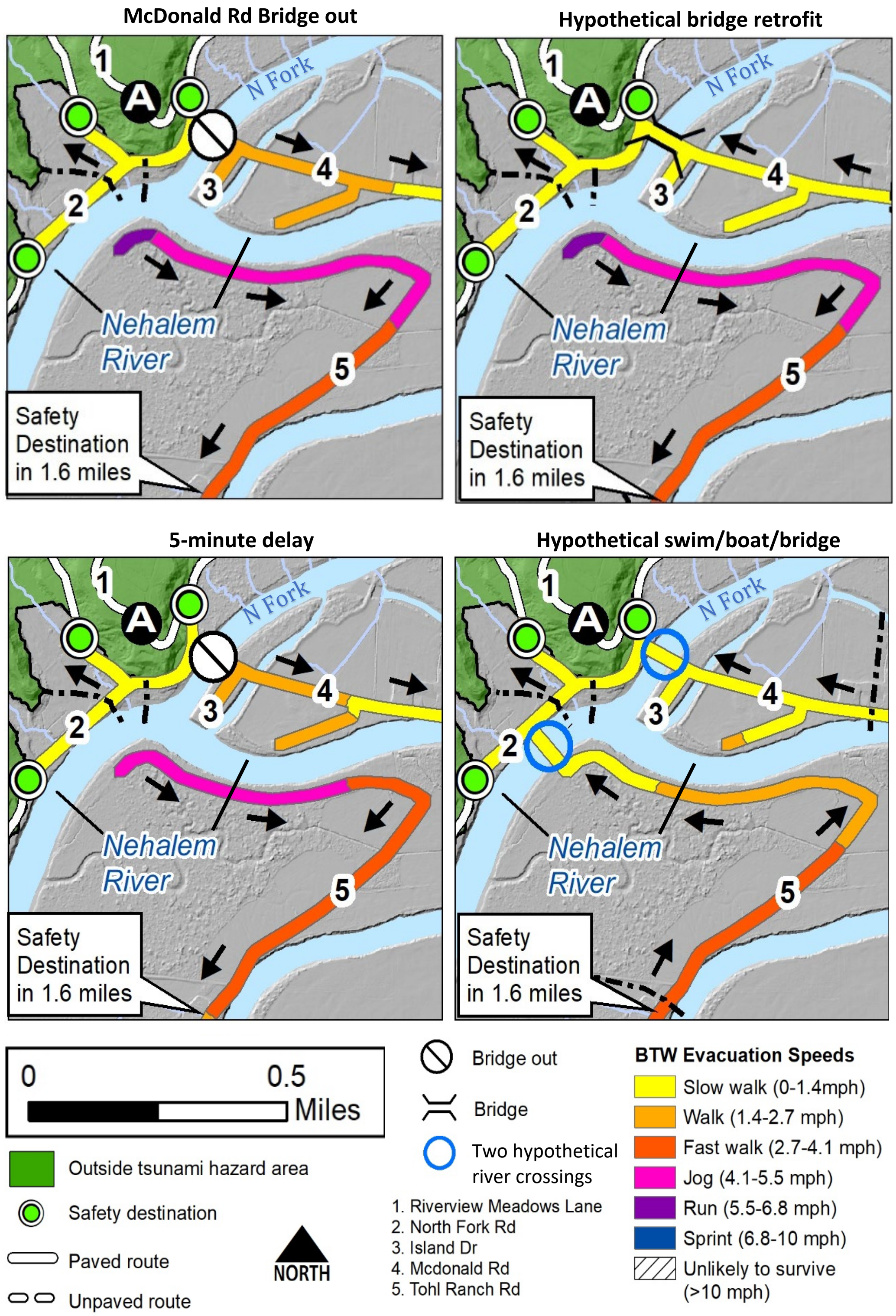


3.8 North Fork

The small communities on Tohl Ranch Road and McDonald Road at the confluence of the Nehalem River mainstem and North Fork face significant evacuation challenges. Although there is high ground on the north side of the river along Northfork Road, the McDonald Road community can only reach it via a bridge. Our analyses suggest that this bridge is unlikely to survive earthquake shaking, and there is no bridge access available for Tohl Ranch Road. Figure 3-23, **top left** reveals that if residents in this area must seek high ground, minimum travel speeds for McDonald Road and Tohl Ranch Road are a ***walk*** and ***jog/run***, respectively. Figure 3-23, **bottom left** presents minimum travel speeds assuming a 5-minute evacuation delay (compared to the default 10-minute delay). This scenario does very little to improve evacuation potential for Tohl Ranch Road, likely due to the long distance people must travel.

With these challenges in mind, we considered two hypothetical mitigation scenarios. Figure 3-23, **top right** presents a scenario where the McDonald Road bridge has been retrofitted to survive earthquake shaking. By allowing McDonald Road residents access to high ground on Northfork Road, travel speeds are reduced significantly to a ***slow walk***, while increasing the overall evacuation potential. However, such improvement does not help the Tohl Ranch Road community. A vertical evacuation structure in this community is unlikely to be considered, because there are so few permanent residents. However, given that nearly every house in this area has a dock and presumably a boat, we evaluated the option for residents to reach the Nork Fork Road via boat or even by swimming. While there are many dangers inherent to this evacuation plan, especially if it happens at night and/or during high river flow, in a life-or-death situation, it remains an option, especially if running 3 miles across roads toward high ground at Mohler is not feasible. To that end, Figure 3-23, **bottom right** presents BTW results for a scenario where evacuees from both McDonald Road and Tohl Ranch Road can reach Northfork Road by crossing the ~250-foot-wide river. To simulate the difficulty of swimming, we assigned the river "path" the same land cover cost value as liquefaction. As with the McDonald Bridge retrofit scenario, providing residents access to Northfork Road reduces minimum travel speeds to ***slow walk*** and ***walk*** for both communities. We fully acknowledge the inadequacy of this method to truly simulate a river evacuation. We simply hope to provoke further conversation about evacuation options for this community. These results could also provide a starting point for considering the construction of a new bridge crossing the North Fork at Tohl Ranch Road.

Figure 3-23. Beat the Wave modeling for the North Fork Nehalem River communities (top left) current conditions, which assumes the McDonald Road bridge fails, (top right) hypothetical earthquake retrofit of McDonald Road bridge, ensuring it remains a viable evacuation route, (bottom left) 5-minute evacuation delay (bridge out), (bottom right) hypothetical option to cross the Nehalem River at McDonald and Tohl Ranch Roads, either by boat, swimming, or constructing a new bridge.



3.9 Demographics

Table 3-2 provides demographic information for each of the five established communities discussed in this report. The total resident population for each community is provided as well as the total number of people who reside within the XXL tsunami inundation zone. This total is further differentiated by age group (< 65 and ≥ 65 years of age). The coast-wide population over 65 years of age makes up ~27 percent of the total population in the XXL tsunami zone (Bauer and others, 2020; Wood, 2007), although the actual number of people age ≥ 65 can vary significantly from one community to another. For example, **Table 3-2** indicates that Manzanita and Neahkahnie have higher numbers of people age 65 and over inside the XXL inundation zone, while Nehalem has a significantly smaller number (likely due to the fact that the inundation zone in Nehalem is mainly limited to the business district).

These results have an important bearing on the speed at which people may be able to travel to reach safety; Bauer and others (2020) reported that evacuation speed for those age ≥ 65 is reduced by a 0.8 walking speed reduction factor (based on recommendations from FEMA, 2017). Thus, communities with larger numbers of people age ≥ 65 years could evaluate where these people are situated with a focus toward developing community evacuation response plans specific to this population's needs (e.g., prioritizing mitigation such as constructing a vertical evacuation structure in one part of town over another because more elderly people live in that area).

Table 3-2. Permanent resident age demographics per tsunami inundation zone.

		Population within XXL Inundation Zone			
Community	**Permanent Population[1]**	**Total**	**< 65[2]**	**≥ 65[2]**	**Older Age Ratio[3]**
Neahkahnie	72	53	28	25	47 %
Manzanita	640	375	225	150	40 %
Bayside Gardens	739	404	294	110	27 %
Nehalem	280	65	57	8	12 %
Wheeler	400	58	46	12	21 %

Notes: XXL tsunami inundation zone defined from Priest and others (2013b). City and county total populations are from Portland State University 2018 certified population estimates (https://www.pdx.edu/prc/population-reports-estimates).

[1] Ignores the visitor (temporary) population visiting for the day or staying in hotels, second homes, vacation rentals, etc.

[2] Defines age in years.

[3] Denotes number of people ≥ 65 divided by the total community population within the XXL zone.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation provides a quantitative assessment of evacuation difficulty in the Nehalem Bay area including the communities of Neahkahnie, Manzanita, Nehalem Bay State Park (NBSP), Bayside Gardens, Nehalem, Wheeler, Mohler, and North Fork. The investigation implemented the Beat the Wave (BTW) approach to evacuation analysis developed by Priest and others (2015, 2016). 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 noted exceptions of Nehalem Bay State Park and Tohl Ranch Road in North Fork. Evacuation for NBSP will be challenging due to the scarcity of high ground combined with a high visitor population that will likely have little to no awareness of the hazard. However, if park visitors evacuate sooner (i.e., within 5 minutes from the start of the earthquake), then the chances of surviving a maximum considered XXL tsunami improve. Further improvements will come when the Airport Ridge safety destination is made available. Given the challenges facing people in the southern sections of campground as well as those recreating farther south on the spit, vertical evacuation becomes the only viable mitigation option. Such a scenario greatly improves the chances of achieving successful evacuation. 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. Further evaluation would be necessary to assess the cost/benefits of this option.

Without suitable mitigation efforts directed at developing safety destinations at Necarney Hill and Airport Ridge and/or constructing a vertical evacuation structure, evacuation on Nehalem Spit will be challenging, and the potential for significant loss of life is high. For residents living on Tohl Ranch Road, successful evacuation will also be difficult under existing conditions. We discuss improvements that would come from retrofitting the McDonald Road bridge, the construction of a new bridge on Tohl Ranch Road, and the extreme action of boating or swimming across the river as part of evacuation.

Regardless of walking speeds, physical limitations, and mitigation considerations, effective 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 routes 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).

5.0 ACKNOWLEDGMENTS

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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

Bauer, J. M., Allan, J. C., Gabel, L. L. S., O'Brien, F. E., and Roberts, J. T., 2020, Analysis of earthquake and tsunami impacts for people and structures inside the tsunami zone for five Oregon coastal communities: Gearhart, Rockaway Beach, Lincoln City, Newport, and Port Orford: Oregon Department of Geology and Mineral Industries Open-File Report O-20-03, 185 p. https://www.oregongeology.org/pubs/ofr/p-O-20-03.htm

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

Federal Emergency Management Agency, 2017, Hazus tsunami model technical guidance: Washington, D.C., Federal Emergency Management Agency, 111 p. https://www.fema.gov/medialibrary/assets/documents/24609

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., and Allan, J. C., 2019, Tsunami evacuation analysis of Newport, Lincoln County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-19-05, 61 p. https://www.oregongeology.org/pubs/ofr/p-O-19-05.htm

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, 2013, Tsunami evacuation map for Nehalem River Valley: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/ManzNehWheelEvacBrochure-4-17-12_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]

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. ftp://ftp2.census.gov/geo/tiger/TIGER2010BLKPOPHU/tabblock2010_41_pophu.zip

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., 2007, Variations in city exposure and sensitivity to tsunami hazards in Oregon: U.S. Geological Survey Scientific Investigations Report 2007-5283, 43 p. https://pubs.er.usgs.gov/usgspubs/sir/sir20075283

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.