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TSUNAMI EVACUATION ANALYSIS OF COMMUNITIES SURROUNDING THE COOS BAY ESTUARY: BUILDING COMMUNITY RESILIENCE ON THE OREGON COAST

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Coos_County_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) for the communities within the Coos Bay estuary including the cities of Coos Bay and North Bend, Charleston, Barview, Shore Acres, Sunset Bay, and the North Spit. Our analyses focused on a maximum-considered CSZ tsunami event covering 100% of potential variability, termed XXL and generated by a magnitude 9.1 earthquake. Evacuation paths were limited to established roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

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

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

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

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

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

1.0 INTRODUCTION

The objective of this study is to provide local government with a quantitative assessment of challenges affecting tsunami evacuation in the coastal communities of the Coos Bay estuary for the XXL scenario. These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, land use planning, and potential 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 ~Mw 9.0 (Priest and others, 2009; Witter and others, 2011), severely damaging bridges and other infrastructure that may be critical to evacuation. To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic scenarios, five of which are mapped statewide, each covering the following percentages of potential variability of Cascadia tsunami inundation (Priest and others, 2013b):

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

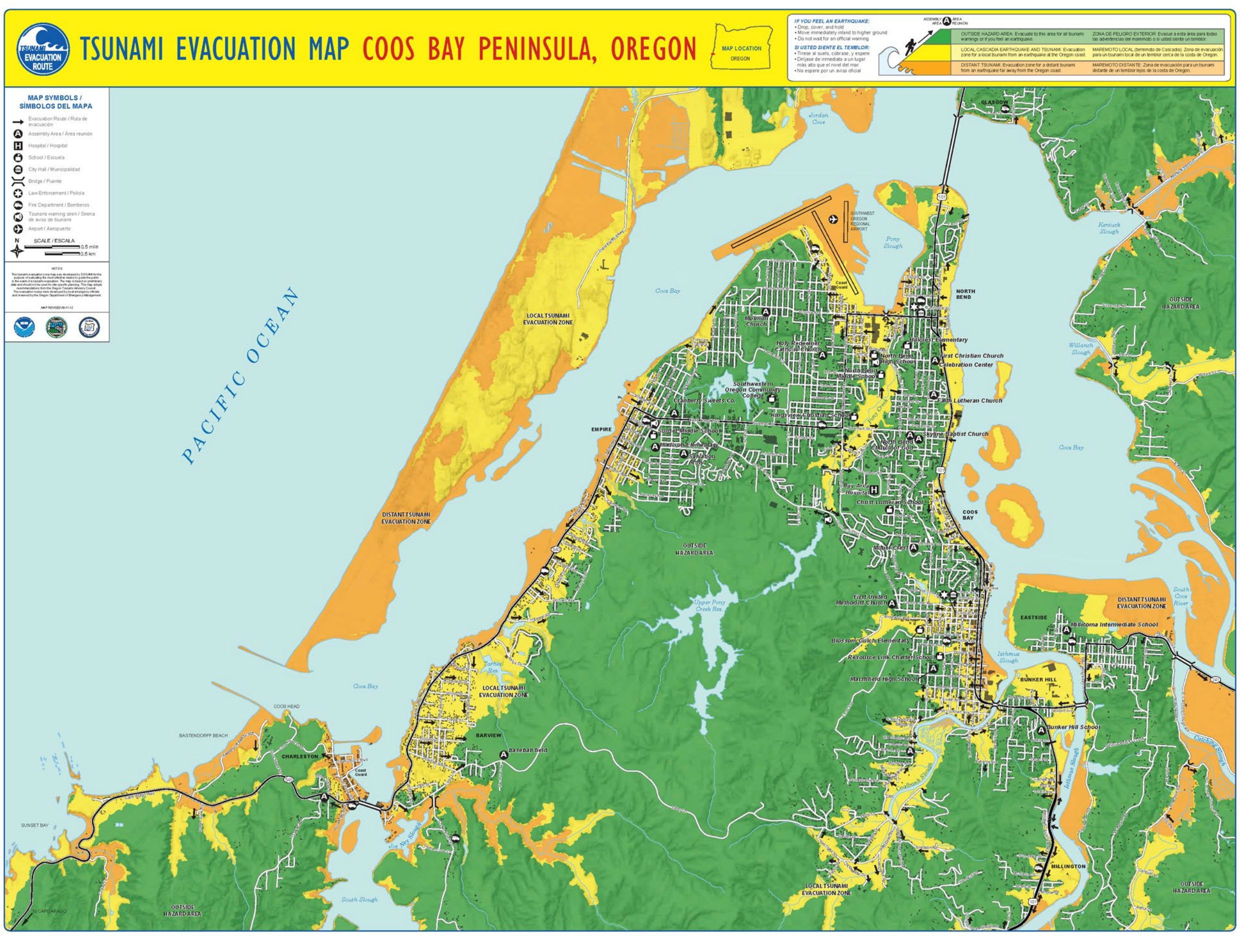
The maximum-considered CSZ tsunami (XXL1, referred to as "XXL" for much of the remainder of this report) inundates some portion of all low-lying communities within the Coos Bay estuary and in some cases, the entire community (**Figure 1-1**). The communities closest to the mouth of the estuary will be flooded within 20 minutes; 20 minutes later North Bend and Coos Bay on the east side of the estuary will be flooded.

A Note about Bridges and Tsunami Evacuation in the Coos Estuary

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 coastal communities in the Coos Bay estuary, modeling indicates area bridges are not essential for tsunami evacuation (i.e., safety can be reached without needing to cross bridges). Because "Bridges In" and "Bridges Out" Beat the Wave results are similar—and in most cases identical—only "Bridges Out" results are included in this report.

To further understand the evacuation landscape, we undertook a socioeconomic analysis to assess the numbers and types of people, businesses, and critical facilities (schools, hospitals, police, and fire) in the XXL, Large (L) and Medium (M) scenario tsunami zones. To date, socioeconomic exposure analyses have been completed for the Oregon coast using only the DOGAMI Large scenario (Wood and others, 2016), which covers ~95% of potential CSZ inundation variability. By performing similar analyses for XXL and Medium scenarios, we are now beginning to have a better understanding about the range of socioeconomic impacts the next CSZ tsunami is likely to have. To further improve our understanding of the likely socio-economic effects the next Cascadia earthquake and accompanying tsunami will have on coastal communities, DOGAMI has initiated a more comprehensive risk assessment project using the Federal Emergency Management Agency Hazus tool in order to determine more detailed exposure impact data (fatalities, injuries, buildings damaged, debris volumes etc.) for the Medium through XXL local tsunami scenarios. The timeline for these data becoming available for south coast communities is ~2-3 years.

Figure 1-1. DOGAMI (2012) tsunami evacuation map for the Coos Bay peninsula. 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.oregontsunami.org.



We evaluate tsunami evacuation difficulty by:

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

2.0 METHODS

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

2.1 Road and trail network

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

2.2 Hypothetical scenarios

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

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 conversation with local officials and on information about which bridges had been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. Our standard modeling process begins with a "base" run that includes all bridges, for comparison without them. This highlights which bridges are important for evacuation and can be important when prioritizing which bridges to retrofit or 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). 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. However, we did evaluate evacuation difficulty due to liquefaction in areas with high susceptibility (Madin and Burns, 2013). This was achieved by adjusting the land cover values to reflect loose sand instead of pavement for those roads potentially susceptible to liquefaction, thereby increasing the time it would take to evacuate along these roads; additional information describing land cover values is provided in section **2.3.3**. By identifying at-risk areas, a community can focus additional efforts on possible mitigation options like retaining walls, soil replacement, vibrocompaction, and construction of liquefaction-proof paths.

Figure 2-1. Water-saturated sand can turn to quicksand during strong shaking, forming sand boils, ponding, and sunken roads. In these examples, (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 remove completely an evacuation route, we created hypothetical scenarios to reflect that. There may be areas where landslide activity may make evacuation difficult but not impossible, and in those cases, we did not always model a landslide scenario. It is also likely that the area will be littered with smaller shallow slides (and possibly new deep-seated slides) after the earthquake, which will likely affect many roads; evaluating such landslides is beyond the scope of this study.

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

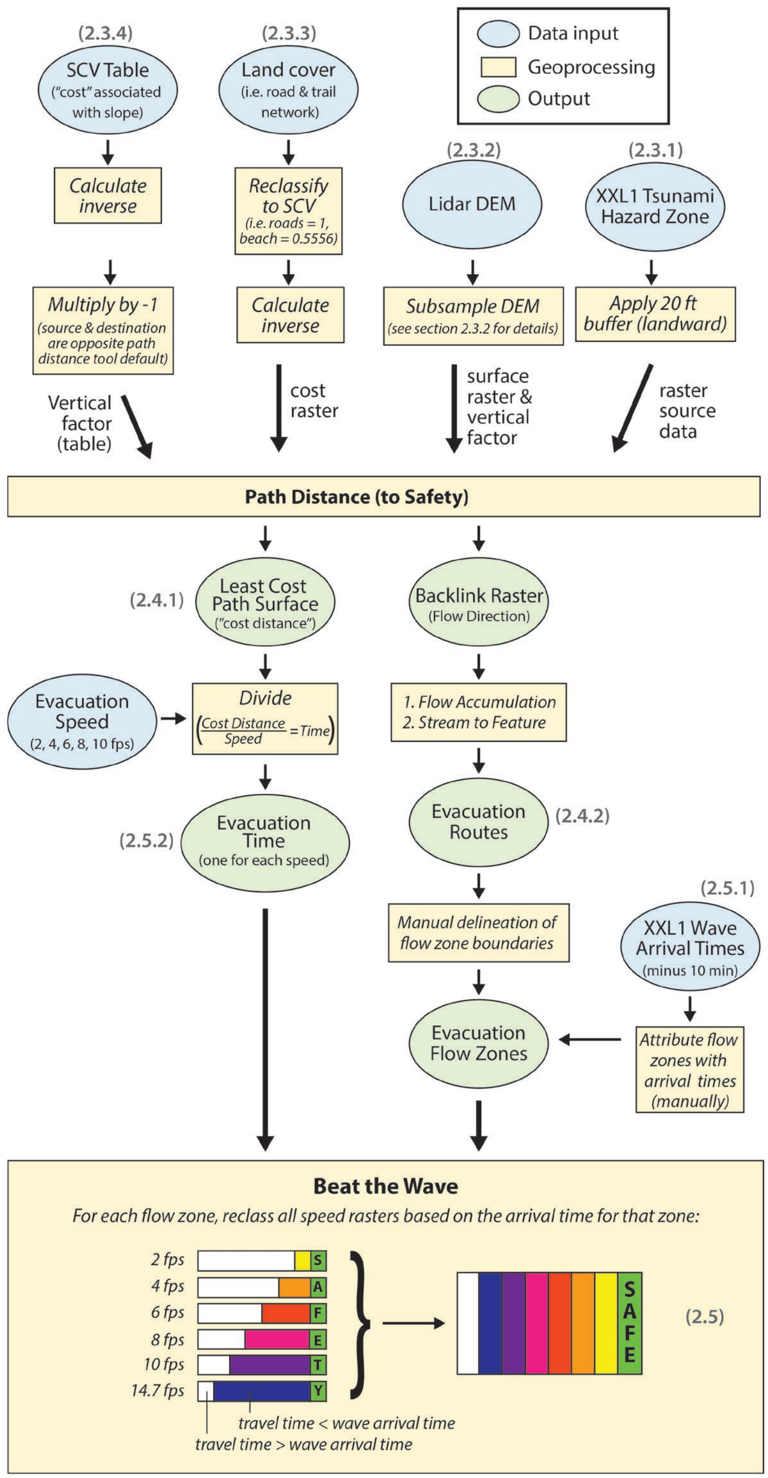
Regardless of infrastructure improvements considered for an area, wayfinding and outreach will always be an essential part of tsunami evacuation planning.

2.3 LCD model inputs

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

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

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



2.3.1 Tsunami hazard zone

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

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

2.3.2 DEM

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

2.3.3 Land cover raster

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

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

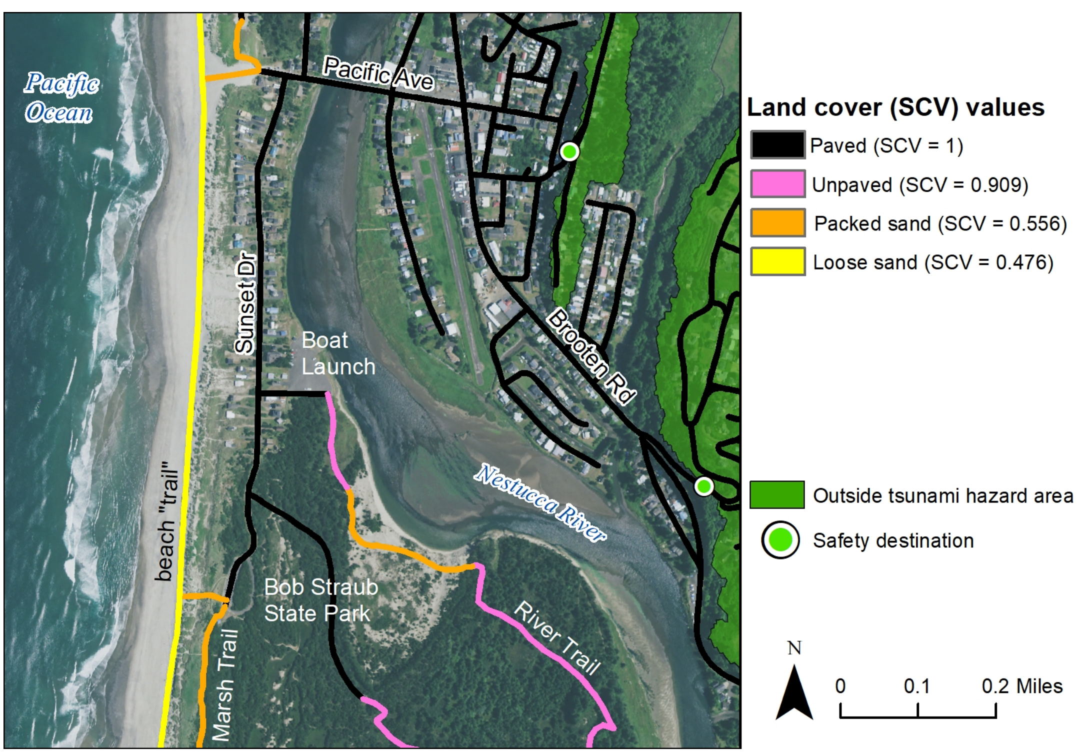
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

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

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

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

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



2.3.4 Speed conservation value (SCV) slope table

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

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

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

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

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

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

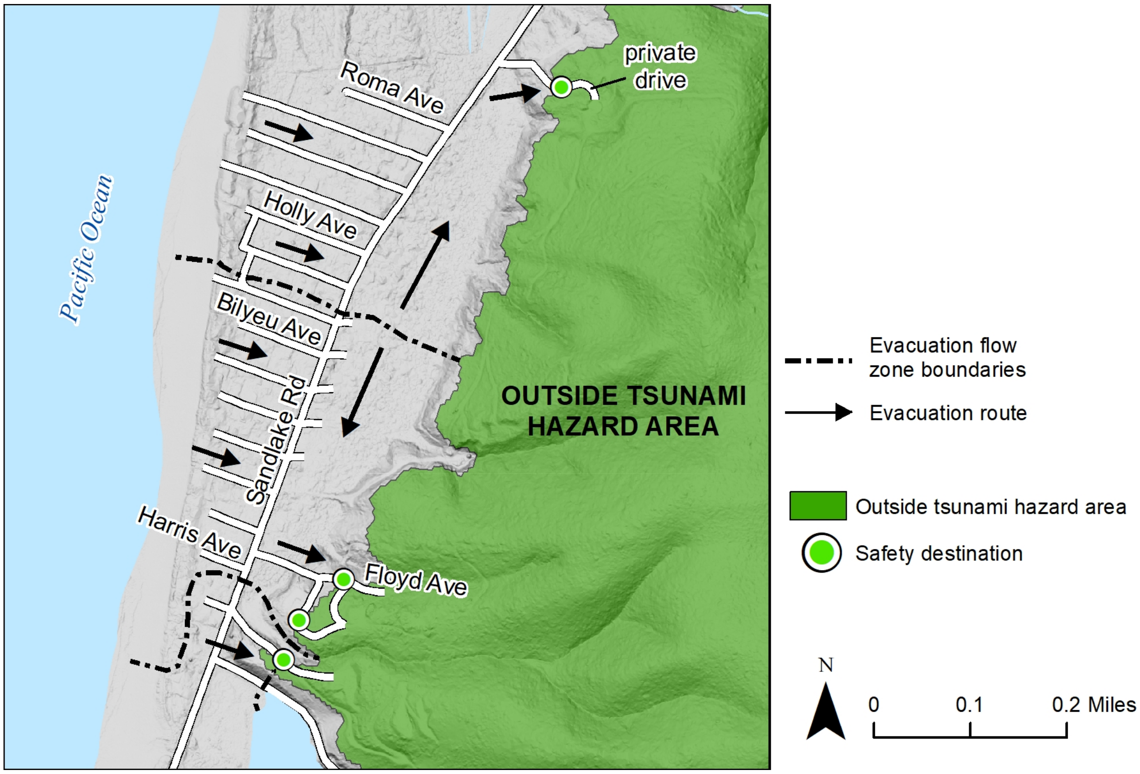
2.4 LCD model outputs

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

2.4.1 Path distance surface

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

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



2.4.2 Evacuation routes and flow zones

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

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

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

2.5 Beat the Wave (BTW) modeling

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

2.5.1 Wave arrival times

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

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

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

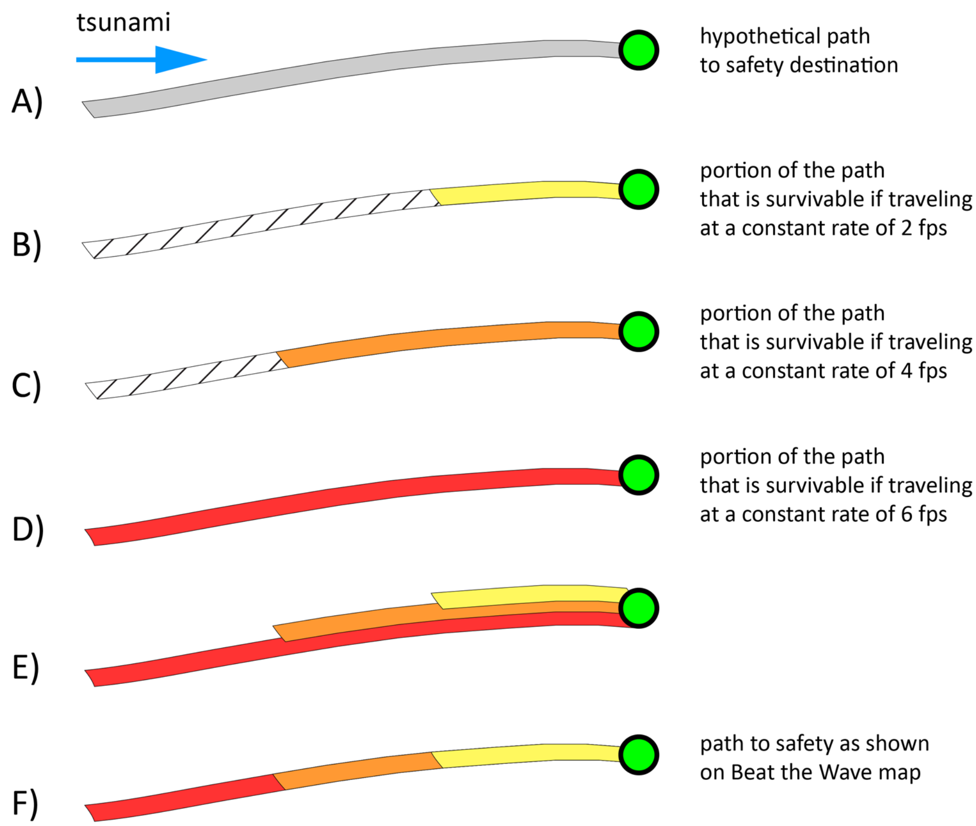
2.5.2 Evacuation time maps

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

As we constructed the 4 fps evacuation time maps, it became apparent that in order to explore fully an array of evacuation speeds appropriate for specific populations (e.g., elderly or small children versus able-bodied adults) we would have to make many more time maps using different speeds. 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 2-5** and in the final step of **Figure 2-2**. By integrating evacuation time maps with tsunami wave arrival data, we can now produce Beat the Wave (BTW) maps that estimate the ***minimum speed*** needed to reach safety ahead of the wave.

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

Figure 2-5. 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 at a constant rate to reach safety ahead of the tsunami. At 2 fps only a relatively small amount of the route is survivable (hashed areas denote unsurvivable sections of the path at given walking speed); however, at faster walking speeds, evacuees can cover more distance and reach safety if they maintain the initial walking speed. (E) displays how the different constant walking speeds are combined to create the (F) final BTW map. The BTW map shows minimum constant speeds necessary to reach safety ahead of the tsunami.



Evacuation speeds were initially grouped into five categories, which allow enough contrast in color choice that areas can be easily perceived on the map. A literature review of typical pedestrian speeds by Fraser and others (2014) found five travel speed groups: adult impaired, adult unimpaired, child, elderly, and running (**Table 2-3**). The ranges of speeds for these groups at one standard deviation (the last two rows of **Table 2-3**) provide some guidance for establishing bins that would be useful on the BTW map. 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 (must sprint at > 14.7 fps)

A small experiment was conducted at Seaside to evaluate the validity of the ***walk***, ***fast walk***, and ***slow jog*** BTW evacuation speed bins and to assess the difficulty in maintaining a constant minimum speed over the course of an entire evacuation route (Gabel and Allan, 2016). Five key routes were traversed by Gabel and Allan, who recorded their average speed along the route and the times when they reached critical locations (bridges, low areas, and safety). Overall, the tests indicated that when traveling at the speed specified by the BTW data, an evacuee will reach safety ahead of the tsunami. However, as speeds fall below the prescribed BTW speeds, the results of Gabel and Allan confirmed that the tsunami could overrun the individual. This limited test of BTW data suggests that the data are reasonable guides to <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 each location all the way to safety. If an evacuee slows down for some portion of the route, they must account for the time deficit by traveling faster than the required speed for the remainder of the route. We stress this point because the map can be misleading: as a route approaches safety the roads along which one travels show a slower BTW speed, but an evacuee cannot slow down. The slower speed is only relevant for someone starting evacuation from that closer location.

2.6 Socioeconomic analysis

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

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

We obtained data from American Community Survey (ACS) 2013–2017 5-year averaged estimates (https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2017/). ACS data are available at city and CDP levels. We note that ACS data are presented for the entire community and are not available by tsunami zone. Given that ACS relies on statistical sampling, we include the 90% uncertainty boundaries to emphasize the uncertainty present in each estimate. In general, smaller communities have a wider range of uncertainty for each estimate. The two primary community characteristics we obtained were the number of people with disabilities and the number of households in which Spanish is primarily spoken (American Community Survey Tables S1810 [Disability Characteristics], and S1602 [Limited English Speaking Households], respectively [U.S. Census Bureau, 2018]).

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

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

3.0 RESULTS AND DISCUSSION

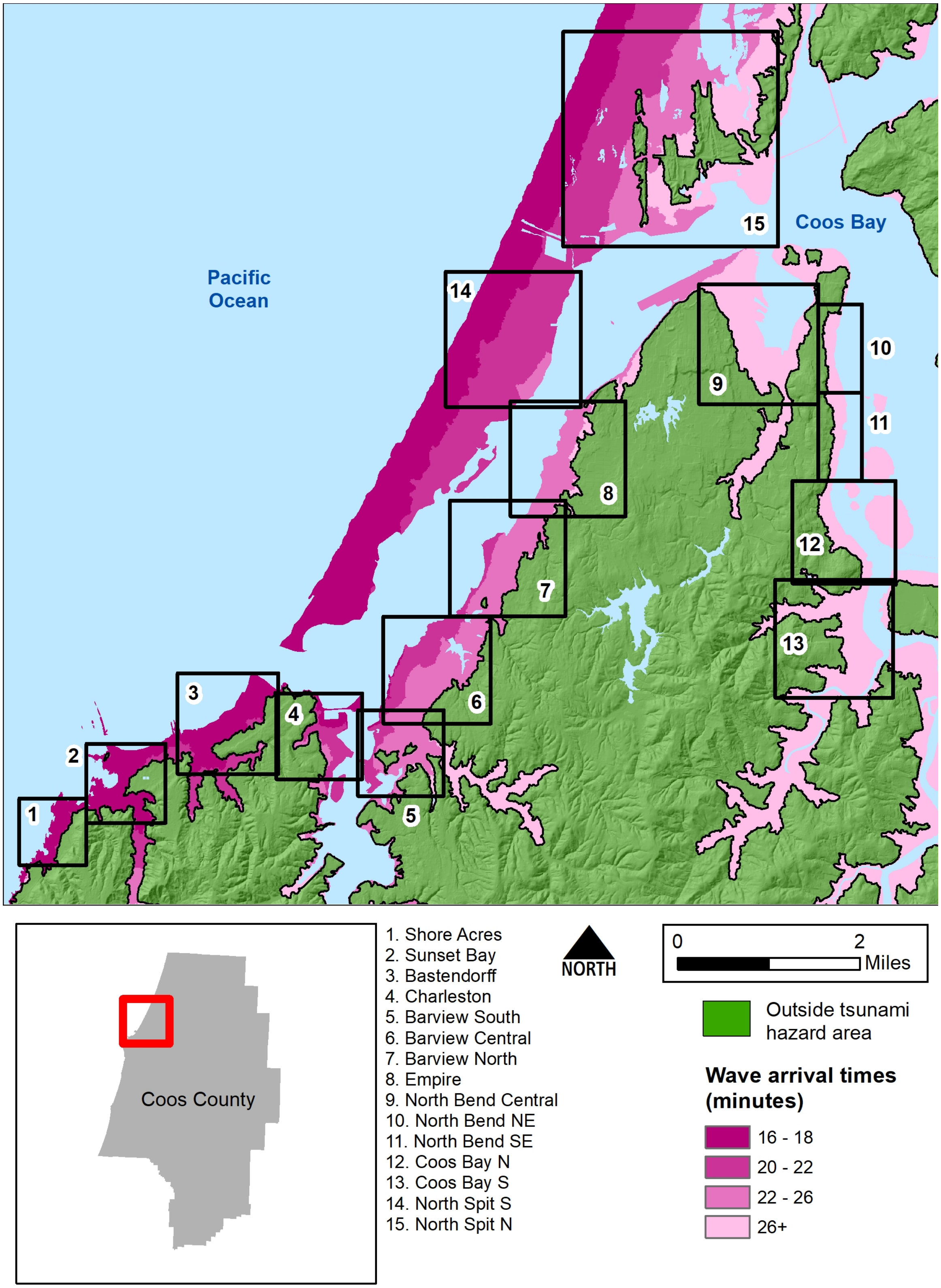
This report covers all communities affected by XXL in the Coos Bay peninsula region of Coos County, Oregon, including Charleston, Barview, Empire, North Bend, and Coos Bay. We also examine evacuation on the North Spit, Bastendorff Beach, Sunset Bay State Park, and Shore Acres State Park (**Figure 3-1**). Section 3.1 presents our tsunami evacuation analysis (Beat the Wave) including detailed wave arrivals; a brief socioeconomic analysis follows in section 3.2.

3.1 Beat the Wave

Overall, results for this area are positive due to the steep hills that back nearly every neighborhood. Coos Bay and North Bend can escape a maximum-considered Cascadia tsunami by walking at a minimum speed of 4 fps (***walk***). Charleston, Barview, Sunset Bay State Park, and the North Spit have farther to travel before reaching their nearest safety destinations and minimum walking speeds necessary to survive are higher.

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

Figure 3-1. Coos County area map and illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake. BTW results and detailed wave arrivals will be discussed separately for each area shown in the boxed figure extents. Note that wave arrival time group ranges are variable.



BTW results show the least-cost path distance modeling for a neighborhood, assuming the existing road network remains intact (referred to as the base scenario). Colors shading the road network denote minimum walking speeds required to reach safety ahead of the tsunami. Black dashed lines represent boundaries between evacuation flow zones that define the geographic extent of each safety destination. The purpose of this modeling is to identify and define detailed evacuation routes, which ultimately are used to define the evacuation flow zones in each sub-community. Each of the evacuation flow zones defines an area being evacuated and the associated nearest destination point(s) of safety (defined by bright green circles) located outside the inundation zone. The solid green color outside the tsunami inundation zone indicates "safety" in a maximum considered XXL local tsunami event.

A regional map of first tsunami wave arrival times can be seen in **Figure 3-1**. Detailed wave arrivals will also be presented for each community. BTW walking speeds on the roads and trails and evacuation flow zone data for the base scenario as well as tsunami arrival data for all areas discussed in this report are found in the Coos_County_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

All scenarios include a 10-minute delay before commencing 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. Tsunami wave arrival figures do not include this delay.

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

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

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

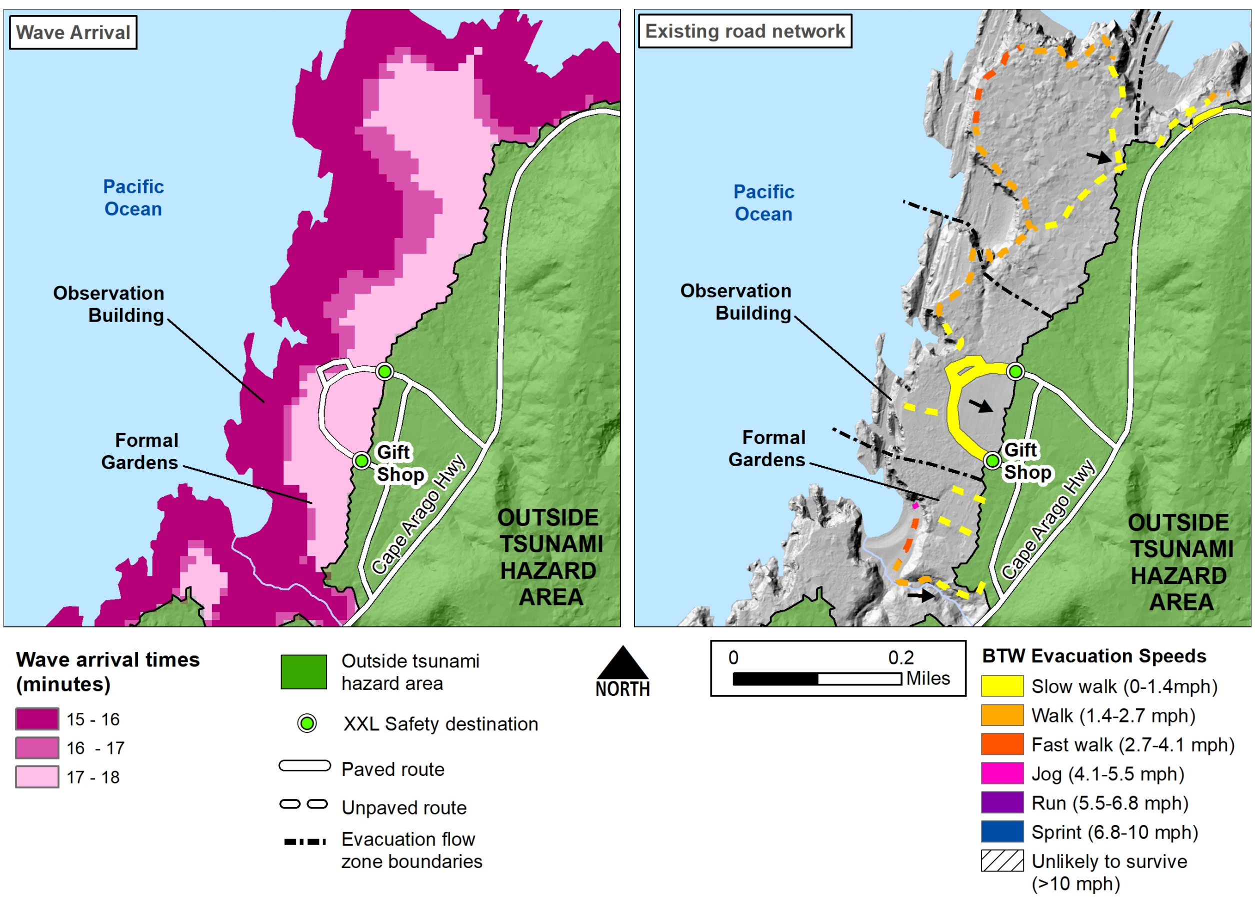
Note: walking at speeds of 2–4 fps is considered a reasonable measure for the elderly and for adults who may be mobility impaired (see Figure 6 of Fraser and others, 2014).

3.1.1 Shore Acres State Park

Shore Acres State Park is a part of a complex of State Parks with Cape Arago to the south and Sunset Bay to the north. Most of the region is perched on a bluff high above the ocean and is outside the XXL tsunami inundation zone, but the seaward edge of Shore Acres is inside the zone. This area includes the observation building and a portion of the formal gardens as well as some hiking trails. The gift shop lies exactly at the XXL inundation limit.

Figure 3-2, left demonstrates the arrival times for an XXL tsunami in the Shore Acres area. The tsunami reaches the base of the cliffs ~15 minutes after the start of the earthquake shaking and reaches its maximum inundation extent within just a few minutes. **Figure 3-2, right** presents BTW results for a base scenario assuming the road and trial network remains intact and relatively easy to use. Evacuees in the most populated areas within the park must travel at a minimum walking speed of ***slow walk*** (2 fps or 1.4 mph). This area has short and simple evacuation routes; however, clear and visible signage as well as outreach is imperative to ensure evacuees do not walk the wrong direction after an earthquake.

Figure 3-2. (left) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Shore Acres State Park and (right) Beat the Wave modeling for base scenario showing minimum BTW walking speeds (colors on top of road network) and evacuation flow zone boundaries (black dashed lines).



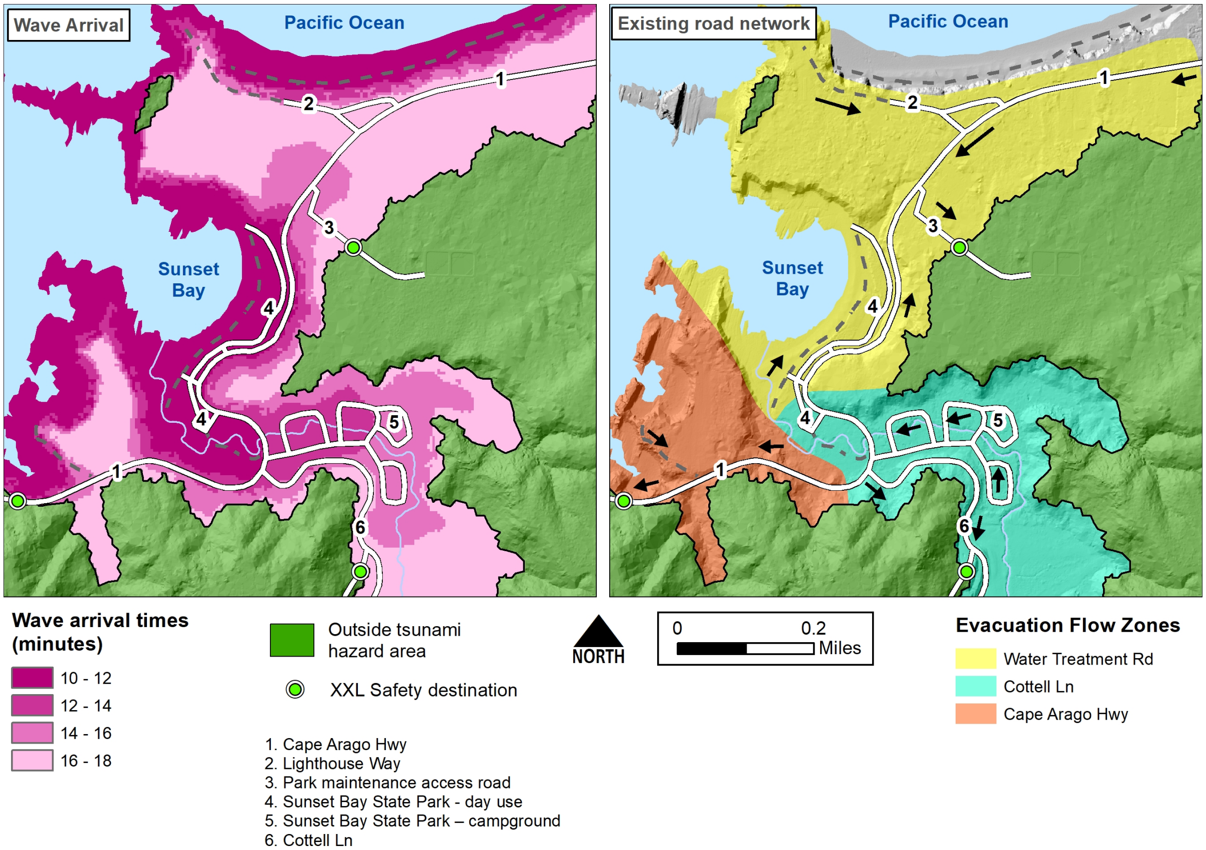
3.1.2 Sunset Bay State Park

Although there is a lot of high ground near Sunset Bay State Park, the areas where people recreate, stay overnight, and live are all inside the XXL tsunami inundation zone, so people must evacuate in the event of an earthquake. Areas of interest include the campground and two day-use parking lots for the state park, residences on Cape Arago Highway, and the Cape Arago lighthouse area west of Lighthouse Way.

None of the state park locations mentioned have simple evacuation routes. Evacuees in the parking lot immediately adjacent to Sunset Bay must travel north on Cape Arago Highway until they reach a park maintenance road leading to a water treatment facility. Evacuees in the day-use parking lot by the campground must travel south on Cape Arago Highway until they reach Cottell Lane. The campground itself is nestled in a low-lying valley, and confusion may arise when deciding which direction to evacuate. Campers, too, may choose to evacuate to high ground on Cottell Lane by walking out of the campground to Cape Arago Highway; however, during a meeting of local stakeholders in 2018 a State Parks ranger informed us that there is a trail off Loop B intended to provide a shorter evacuation route to high ground immediately north of the campground. Lighthouse Way and Cape Arago Highway residents in the northern extent of this region must also reach the park maintenance road via Cape Arago Highway in order to find high ground.

Knowing which direction to travel is crucial because of the early wave arrival times here; the entire area is expected to be inundated within 18 minutes after the start of earthquake shaking (**Figure 3-3, left**). These early wave arrivals result in higher BTW walking speeds than are seen for similar evacuation distances on the north coast of Oregon. Evacuation flow zones are presented in **Figure 3-3, right**.

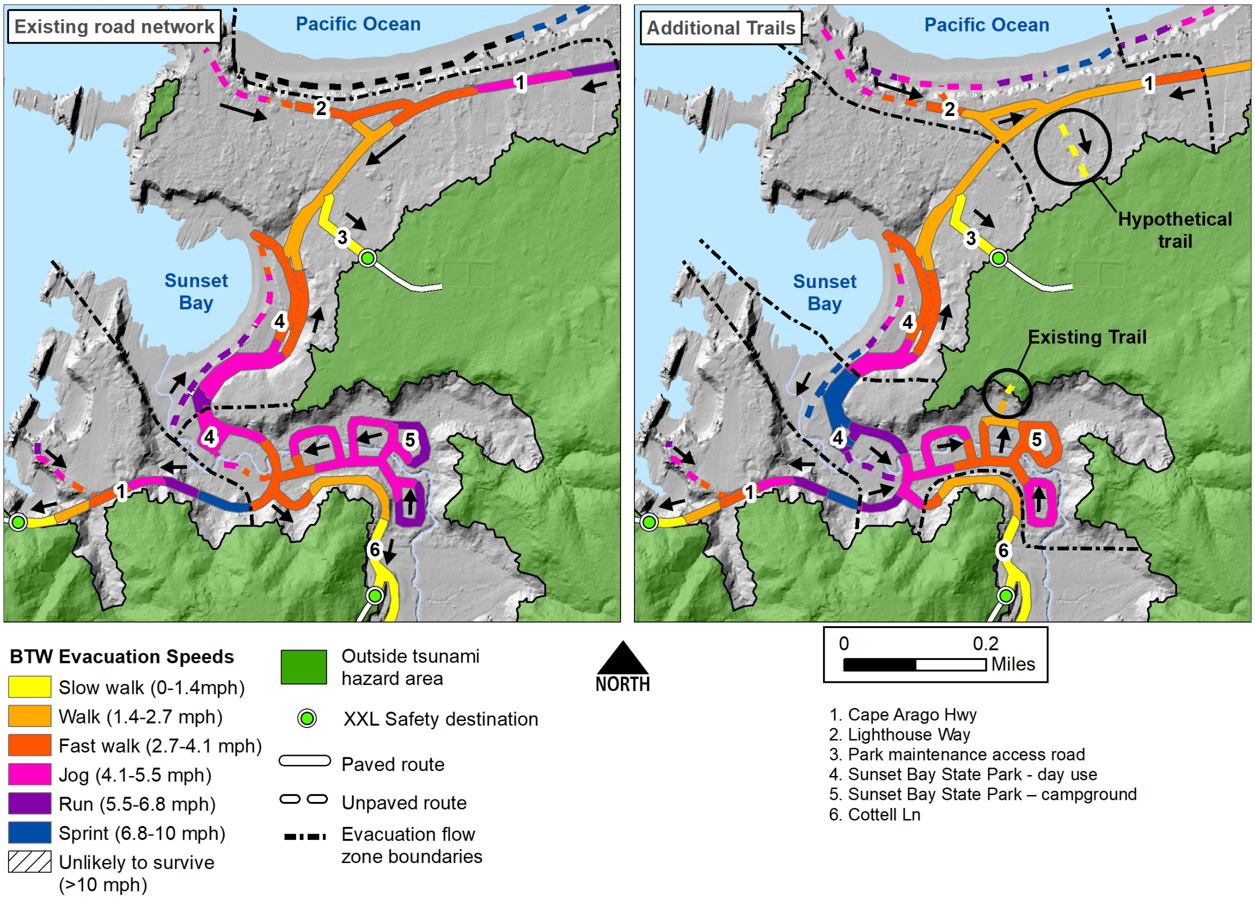
Figure 3-3. (left) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Sunset Bay State Park and (right) Beat the Wave modeling for base scenario showing evacuation flow zones only.



Minimum BTW walking speeds for the base scenario using existing roads and trails are shown in **Figure 3-4, left**. The campground trail was excluded from this scenario to understand results for evacuees who are not aware of the evacuation trail. Walking speeds range from ***fast walk*** (6 fps or 4.1 mph) on Lighthouse Way and at Sunset Bay to ***jog*** and ***run*** in the campground. **Figure 3-3, right** presents evacuation flow zones for the base scenario. These define the nearest safety destination for everyone in the region and may be useful for personal evacuation route planning as well as community-wide wayfinding efforts.

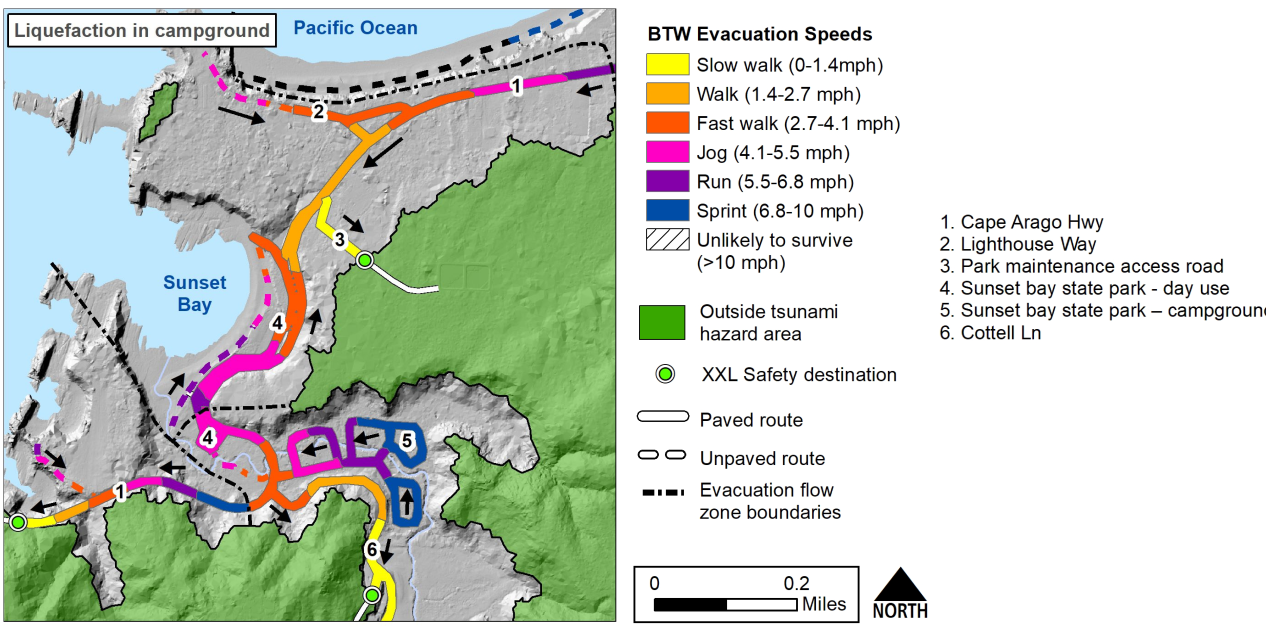
Due to the minimum walking speeds needed to survive, we considered the effects of additional trails to high ground in order to reduce evacuation distances. To do this, we added to our modeling a hypothetical trail at the intersection of Lighthouse Way and Cape Arago Highway as well as the existing evacuation trail inside the campground. **Figure 3-4, right** shows that walking speeds in the area of Lighthouse Way drop to ***walk***, and campground evacuation speeds are also significantly reduced.

Figure 3-4. Beat the Wave modeling in Sunset Bay State Park for (left) base scenario depicting the existing road and trail network and (right) including a hypothetical evacuation trail by Lighthouse Way and an existing trail at the campground.



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 this area, the land potentially at risk is confined to the campground. The liquefaction scenario presented in **Figure 3-5** illustrates the dramatic increase in minimum walking speeds necessary to reach high ground before the tsunami arrives, even with the evacuation trail. The highest speed in the campground increases to ***sprint*** (15 fps or 10 mph). As a reminder, these speeds must be maintained for the duration of a person's evacuation. These results may prompt decision makers to consider adding new evacuation trails as well as clear and visible signage to assist visitors. In any case, although our modeling is confined to roads, evacuees should find the nearest high ground accessible to them.

Figure 3-5. Beat the Wave modeling in Sunset Bay State Park for a scenario considering liquefaction.



3.1.3 Bastendorff Beach

The inundated areas of Bastendorff Beach have high ground nearby, resulting in straightforward evacuation routes. The tsunami arrives in ~14 minutes (**Figure 3-6**), which results in the need for faster minimum walking speeds than one may expect for such short distances. **Figure 3-7, left** presents BTW results for the base scenario. Evacuees in a small stretch of Bastendorff Beach Road must ***jog*** or ***run***; however, evacuees in most of the area must ***walk*** or ***fast walk*** (6 fps or 4.1 mph) to reach high ground ahead of the tsunami.

Figure 3-6. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Bastendorff Beach.

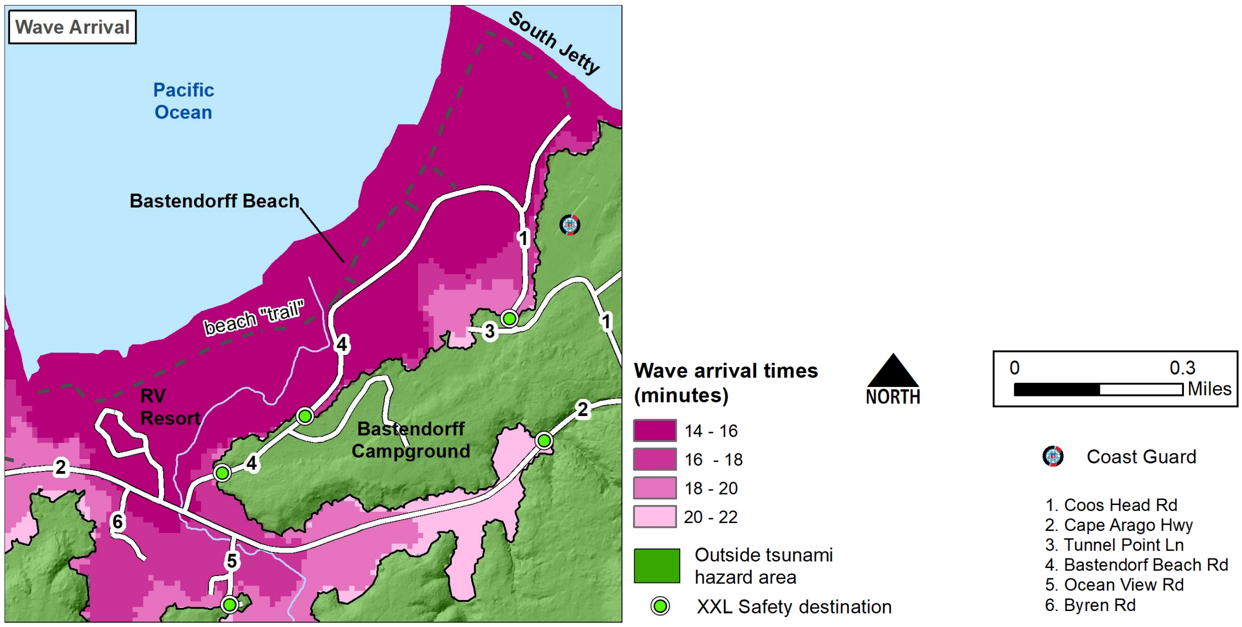
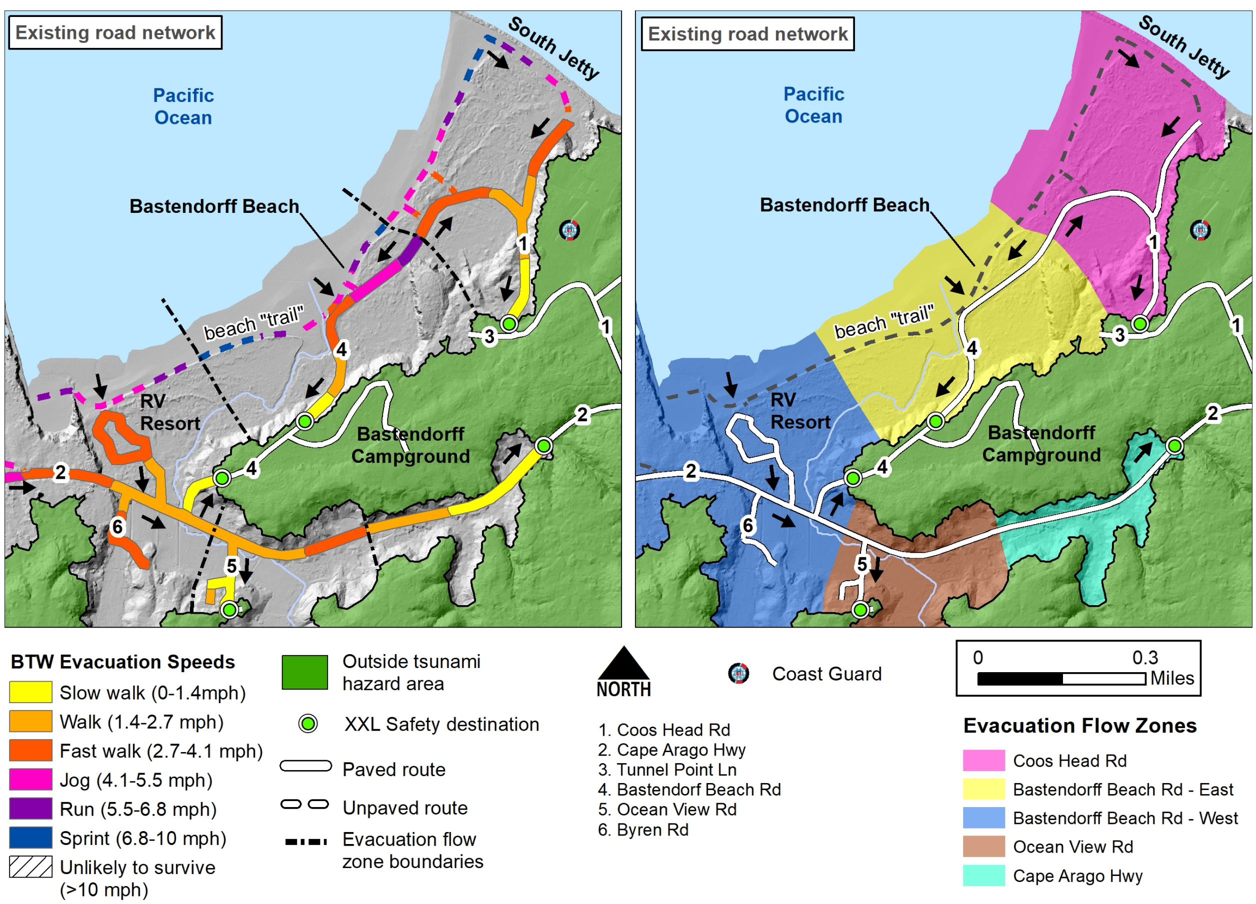


Figure 3-7. Beat the Wave modeling in Bastendorff Beach for base scenario (left) minimum speeds and (right) evacuation flow zones only.



3.1.4 Charleston

The community of Charleston lies just inside the mouth of Coos Bay. Most of town is inside the XXL tsunami inundation zone, but high ground is close by. In additional to its full-time residents, Charleston is home to a commercial fishing fleet, RV park, tourist destinations, and the Oregon Institute of Marine Biology (OIMB), a higher-education research facility with both employees and students, some of whom sleep there. The U.S. Coast Guard Coos Bay Station and Charleston Fire District Station 3 are also inside the inundation zone. High ground in Charleston can be accessed from the north via Coos Head Loop and from the south via Cape Arago Highway.

The Cape Arago Highway bridge over the entrance to South Slough is not expected to survive the earthquake shaking, so we did not include it in our BTW modeling. Although this bridge is clearly important for Charleston's connection with the greater Coos Bay area now and after an earthquake and tsunami, high ground on Charleston's side of the bridge means that the bridge is not necessary for evacuation purposes.

The tsunami is expected to arrive in Charleston ~16 minutes after the start of earthquake shaking (**Figure 3-8**). **Figure 3-9, left** presents minimum BTW walking speeds for the base scenario, which includes all roads but does not allow passage across the Cape Arago Highway bridge toward Barview. Most of town can reach safety at a ***walk*** or ***fast walk***, but evacuees in the marina area must ***jog*** (8 fps or 5.5 mph) in order to survive. Evacuation flow zones are presented in **Figure 3-8, right**. The evacuation flow zones make clear which direction evacuees should choose based on their locations. In Charleston, there is essentially one decision for an evacuee to make: to head north toward Coos Head Loop or south toward Cape Arago Highway.

Liquefaction poses a significant risk to this community due to its low-lying position adjacent to Coos Bay and South Slough. **Figure 3-9, right** presents minimum walking speeds when the model assumes navigating all roads will be extremely difficult. Travel speeds increase to ***sprint*** (10 fps or 15 mph) at the far ends of Alaska Packer Rd and the marina.

Figure 3-8. (left) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Charleston and (right) Beat the Wave modeling for base scenario showing evacuation flow zones only.

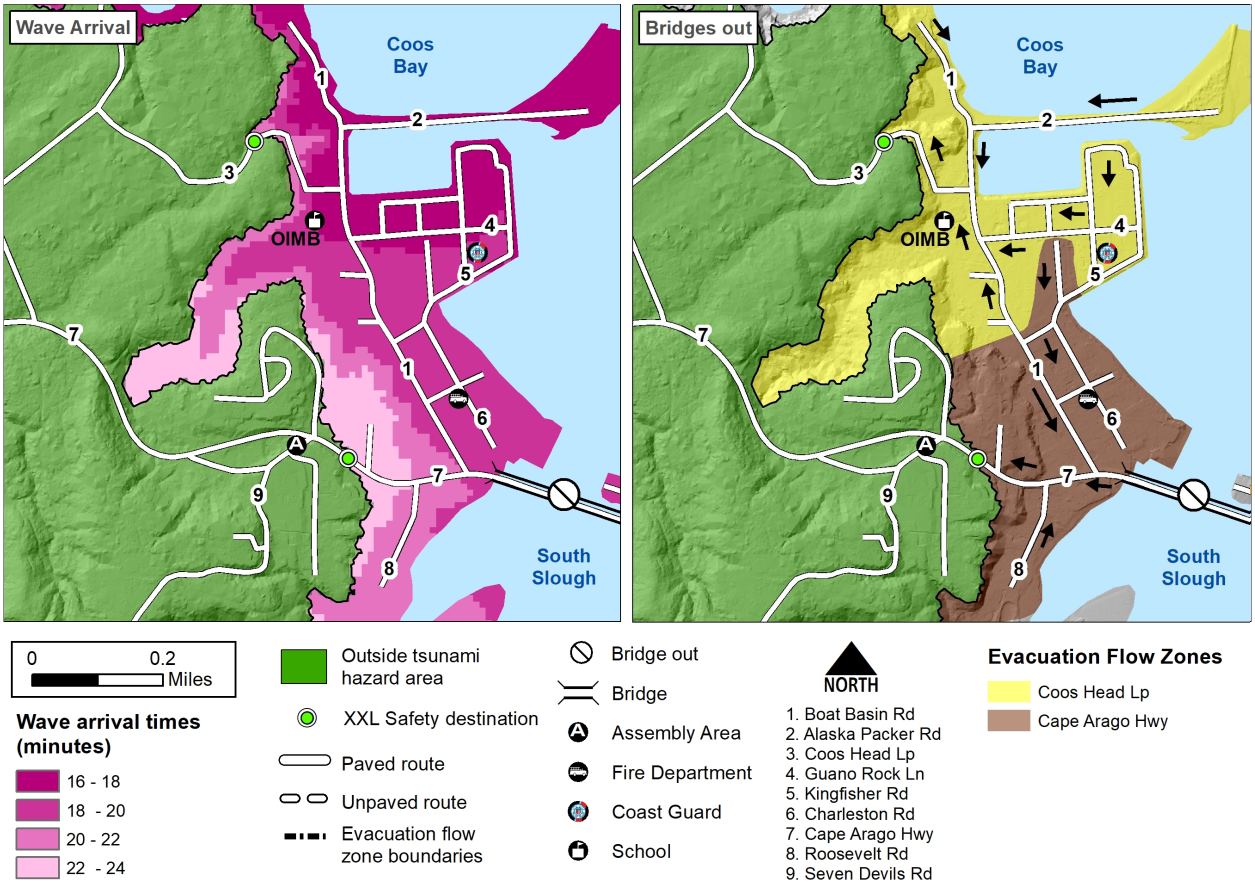
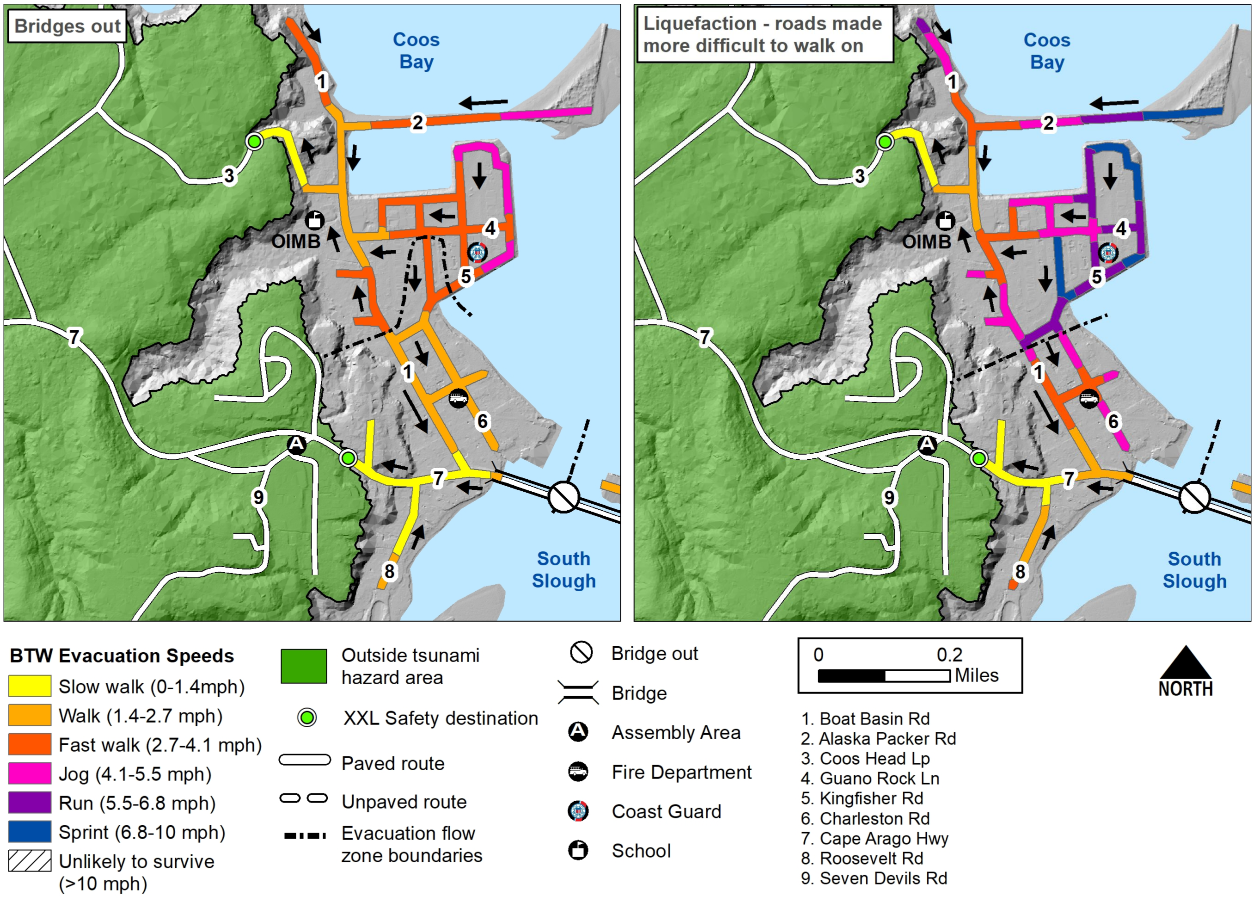


Figure 3-9. Beat the Wave modeling in Charleston for (left) base scenario depicting the existing road and trail network and (right) with liquefaction.



3.1.5 Barview to Empire

Barview and Empire are upriver from the mouth of Coos Bay. We have divided this area into four extents (Barview South, Barview Central, Barview North, and Empire) for the purpose of showing information in the figures, but we will discuss the results as a whole because of their similarities. The inundation area is a strip paralleling the path of the estuary, with the neighborhoods bordered by Coos Bay to the west and high ground to the east. Charleston Fire District Station 1 is inside the inundation zone. In much of this area, high ground is not very far away, evacuation routes are straightforward, and evacuation speeds are low. Liquefaction is not as likely as in other areas discussed in this report, so we do not present that BTW scenario for Barview and Empire.

We did not include in our modeling the two bridges in Barview because they have not been constructed to withstand the shaking of a Cascadia earthquake. The bridges are Cape Arago Highway over South Slough (connects Barview with Charleston to the west) and Crown Point Road over Joe Ney Slough (connects Barview with Charleston Fire District Station 2 to the south). Although these bridges will be vital for community connectivity after a Cascadia event, there is ample high ground on the Barview side of these bridges that they are not necessary for evacuation purposes.

The tsunami arrives in Barview ~18 minutes after the start of earthquake shaking and reaches Empire ~4 minutes later (**Figure 3-10**, **Figure 3-11**). Minimum walking speeds and evacuation flow zones are presented for this area in **Figure 3-12**, **Figure 3-13**, **Figure 3-14**, and **Figure 3-15**. With the exception of Barview Central, evacuees in this area can reach safety ahead of the tsunami by traveling at a ***walk*** (4 fps or 2.7 mph). The high density of roads leading to high ground means that there are a many safety destinations and evacuation flow zones. In many cases the routes are straightforward, especially in Empire (**Figure 3-15**). However, effective signage is always an important part of community preparedness, and in places like Barview South where routes are not as straightforward (**Figure 3-12**), signage will help to communicate the right direction to travel.

Barview Central has a wider inundation zone than elsewhere in the area, and evacuees must travel farther to reach safety, leading to higher minimum walking speeds (**Figure 3-13, left**). We considered possible mitigation options for this area, which is home to many people who may not be able to travel faster than a ***walk***. No options for hypothetical BTW scenarios with engineering solutions such as a vertical evacuation structure or a single earthquake-hardened road would not necessarily help enough people to justify the cost. This is because no single road emerges as a primary route; evacuation is somewhat evenly dispersed amongst several roads in the area. We encourage local decision makers to continue thinking about ways to assist this community in evacuation improvements and preparedness.

Figure 3-10. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) Barview South and (right) Barview Central.

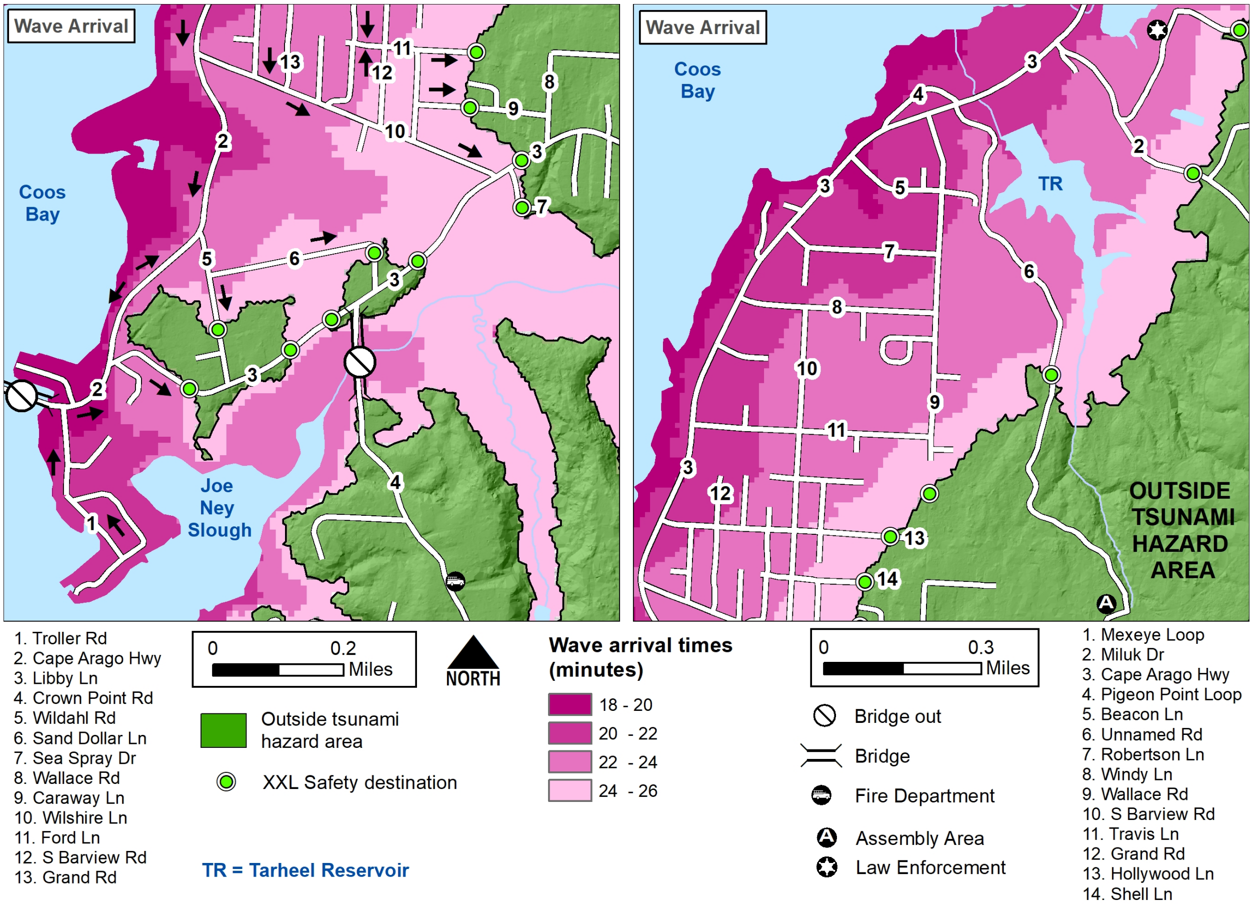


Figure 3-11. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) Barview North and (right) Empire. Note the wave arrival times are different for the two maps.

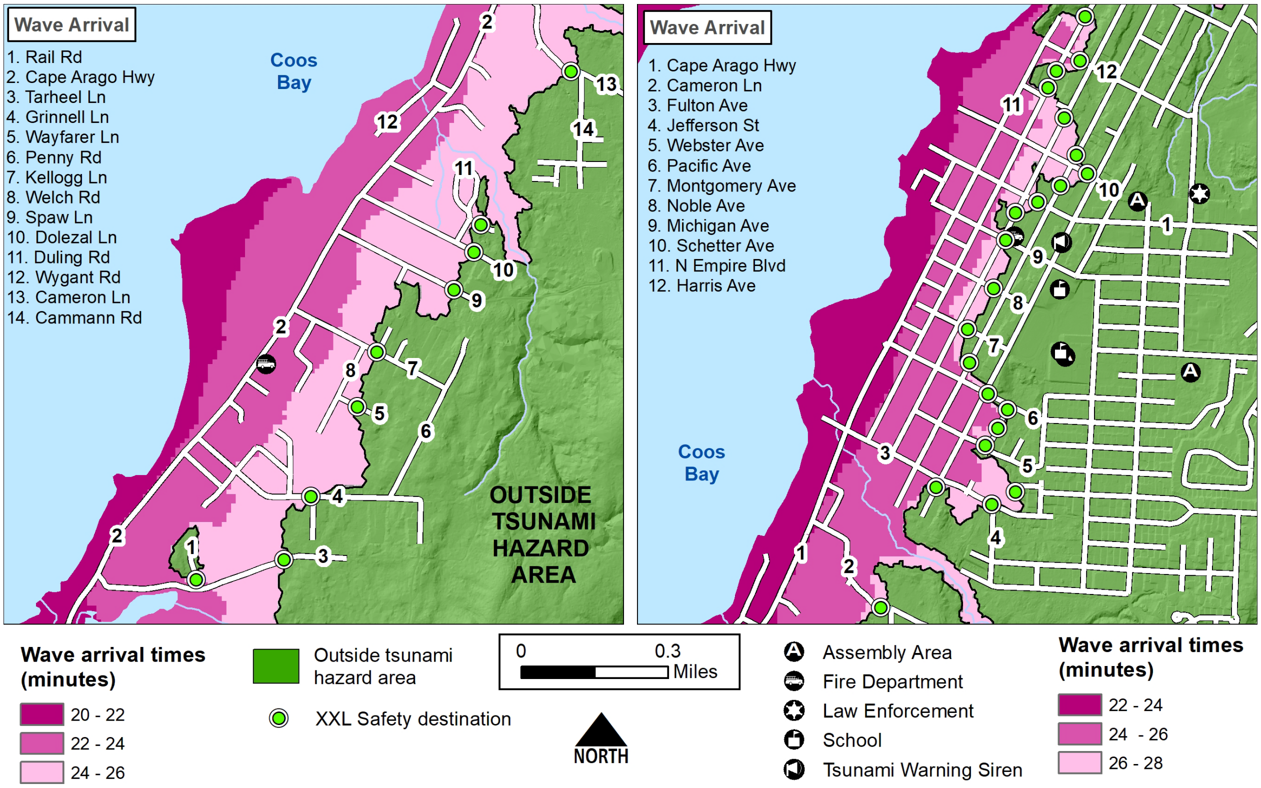


Figure 3-12. Beat the Wave modeling in Barview South for the base scenario depicting the existing road and trail network. (left) Colors on top of the road network reflect minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones shown as colored polygons instead of black dashed lines.

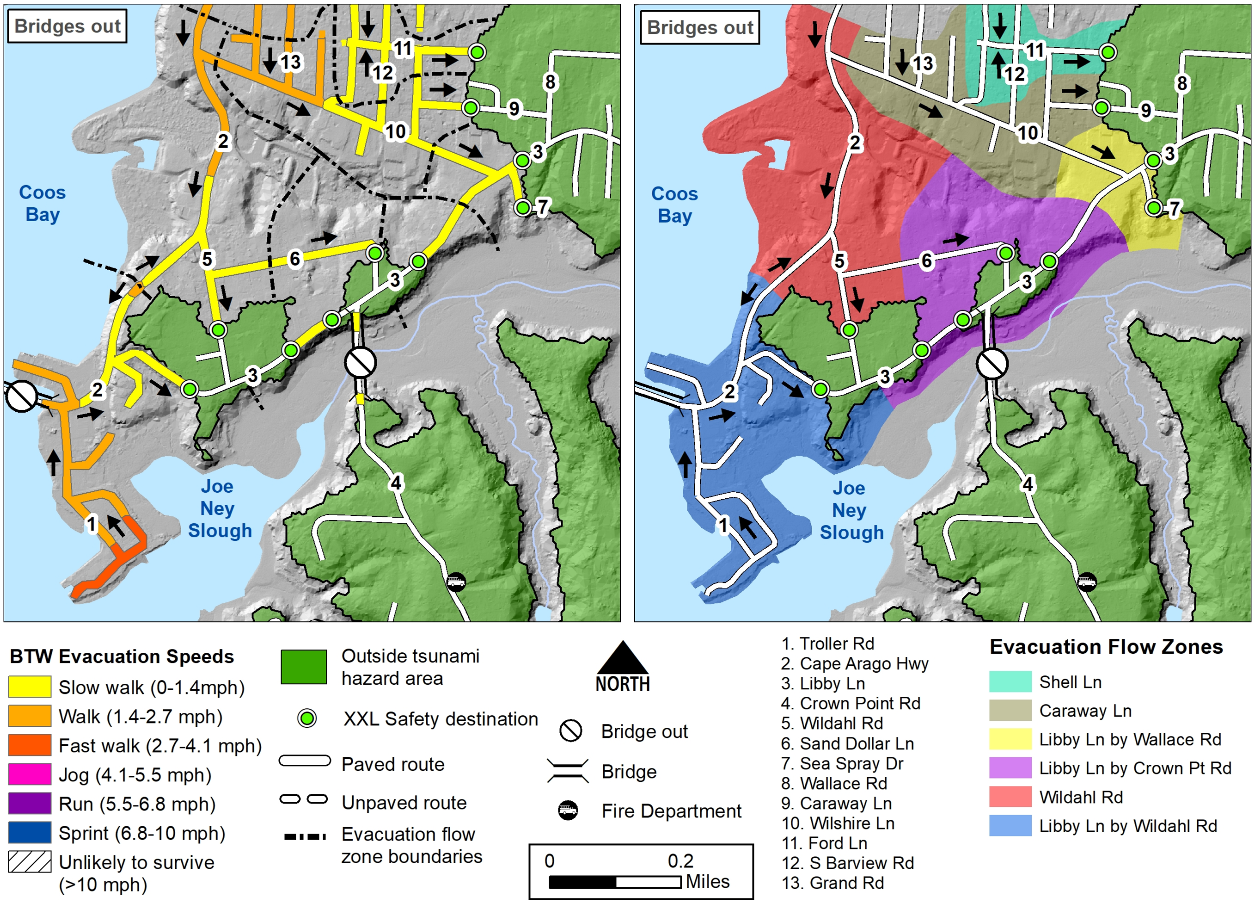


Figure 3-13. Beat the Wave modeling in Barview Central for the base scenario depicting the existing road and trail network. (left) Colors on top of the road network reflect minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones shown as colored polygons instead of black dashed lines.

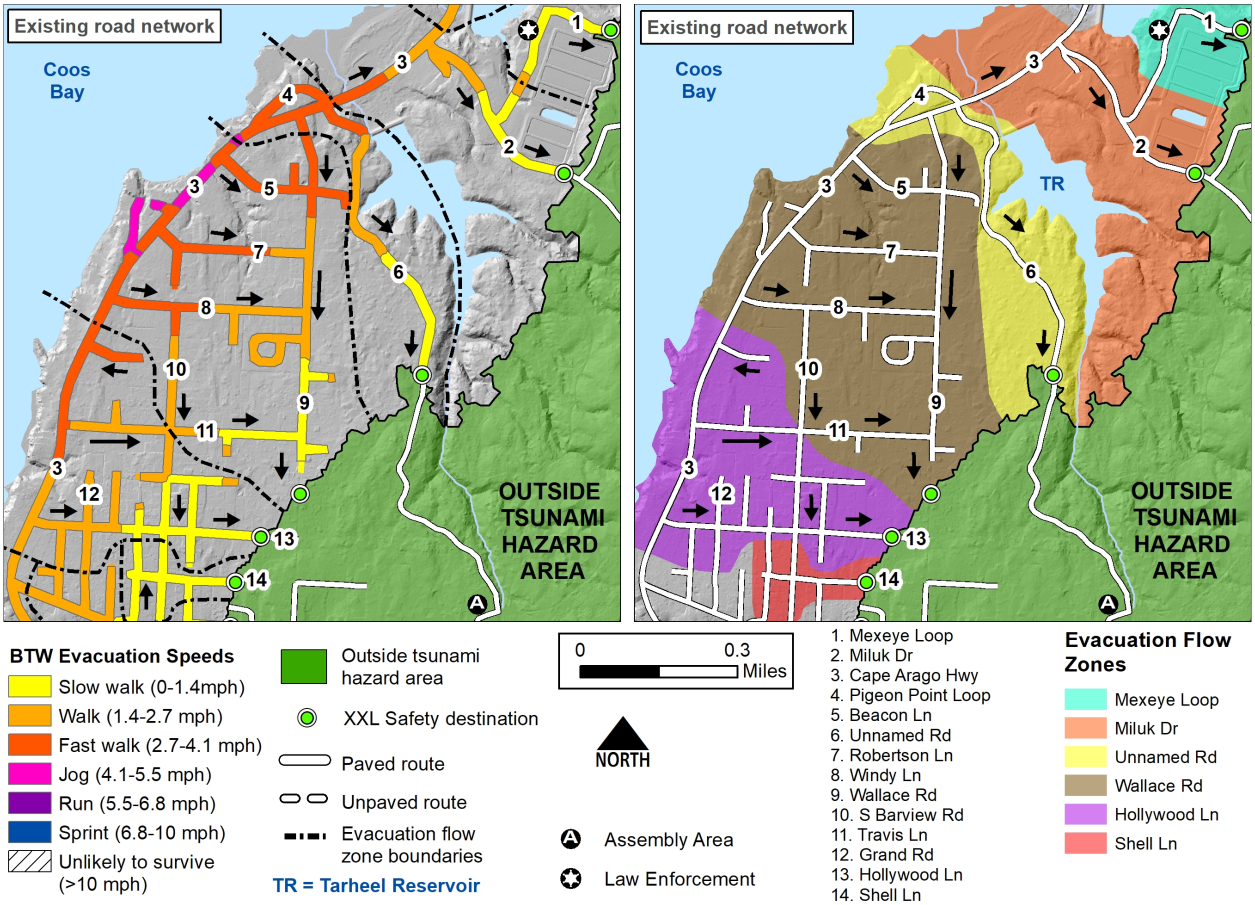


Figure 3-14. Beat the Wave modeling in Barview North for the base scenario depicting the existing road and trail network. (left) Colors on top of the road network reflect minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones shown as colored polygons instead of black dashed lines.

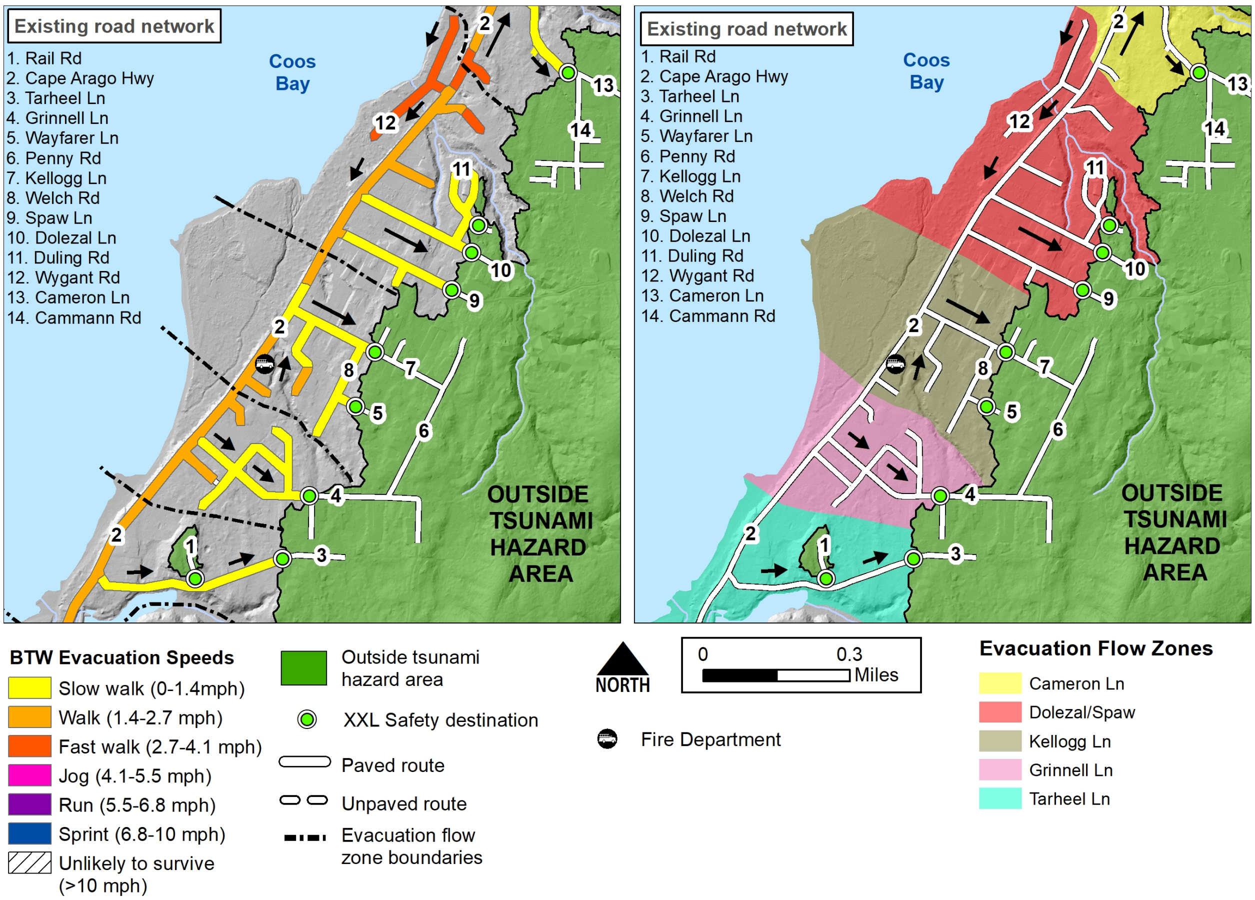
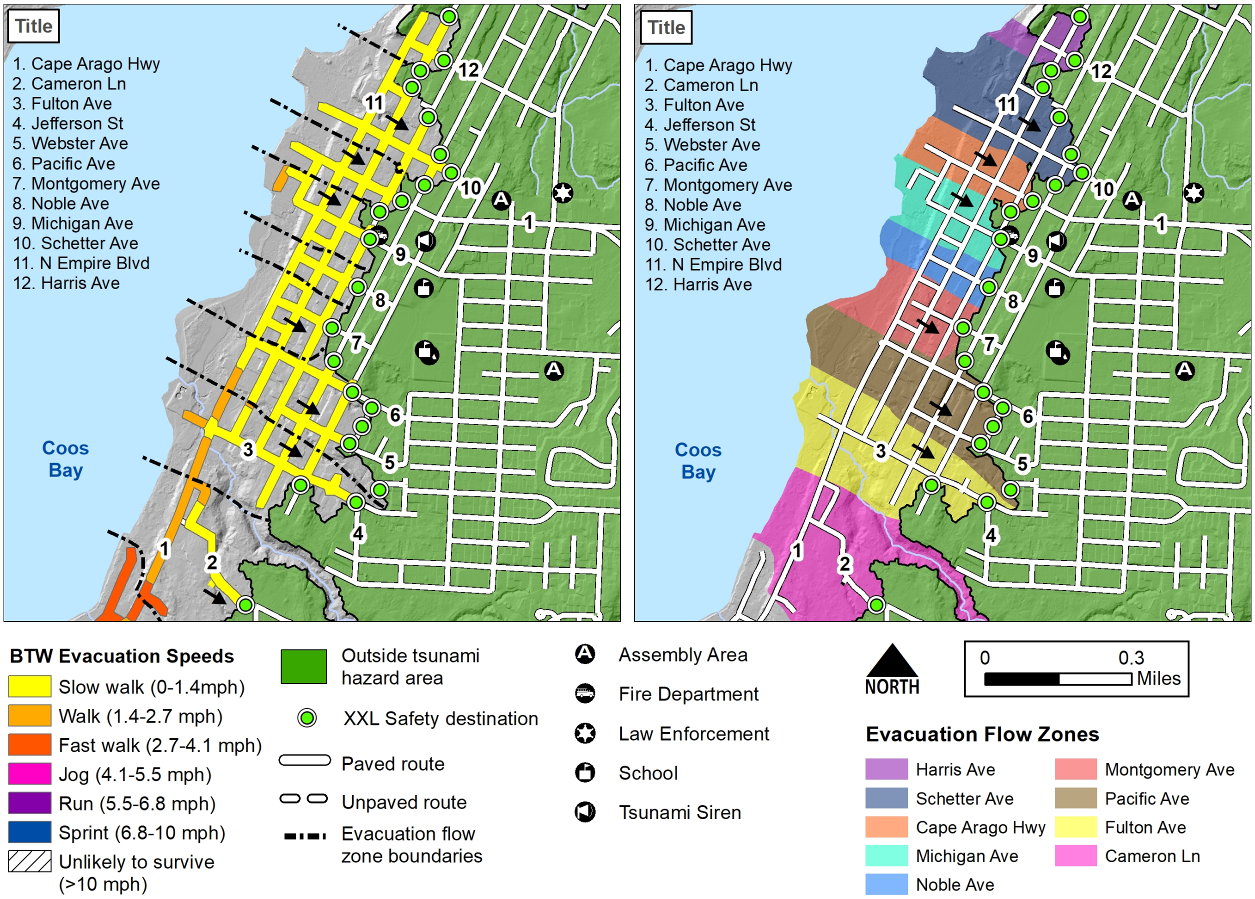


Figure 3-15. Beat the Wave modeling in Empire for the base scenario depicting the existing road and trail network. (left) Colors on top of the road network reflect minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries. (right) Evacuation flow zones shown as colored polygons instead of black dashed lines.



3.1.6 North Bend

We have divided the inundated areas of North Bend into three extents for the purpose of showing information in the figures. The "central" extent covers the northern tip of the Coos Bay peninsula and includes the airport and north end of Pony Slough. The "northeast" and "southeast" extents cover the strip of inundated land on the east side of the peninsula, from Bayview Avenue to Exchange Street, including the Mill Casino. The Virginia Avenue and Vermont Avenue bridges over Pony Creek are not expected to survive the earthquake and are not included in the base BTW scenario. A third bridge over Pony Creek (on Broadway Avenue) is also expected to fail. This area of North Bend is not shown in report figures but is included in the digital data.

The tsunami reaches the airport ~25 minutes after the start of earthquake shaking (**Figure 3-16, left**), Pony Slough is expected to be inundated after ~30–40 minutes, and the east side by ~40–45 minutes (**Figure 3-17**). BTW minimum walking speed for all North Bend is ***slow walk*** (2 fps or 1.4 mph) (**Figure 3-16, right**, **Figure 3-18**). Liquefaction is very likely; however, BTW results are unchanged due to the extremely short evacuation distances. This does not mean liquefaction will not be a challenge during evacuation; rather, the unchanged results indicate BTW modeling does not provide an effective means of conveying that difficulty.

Figure 3-16. (left) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for central North Bend and (right) Beat the Wave modeling for base scenario showing minimum BTW walking speeds (colors on top of road network) and evacuation flow zone boundaries (black dashed lines).

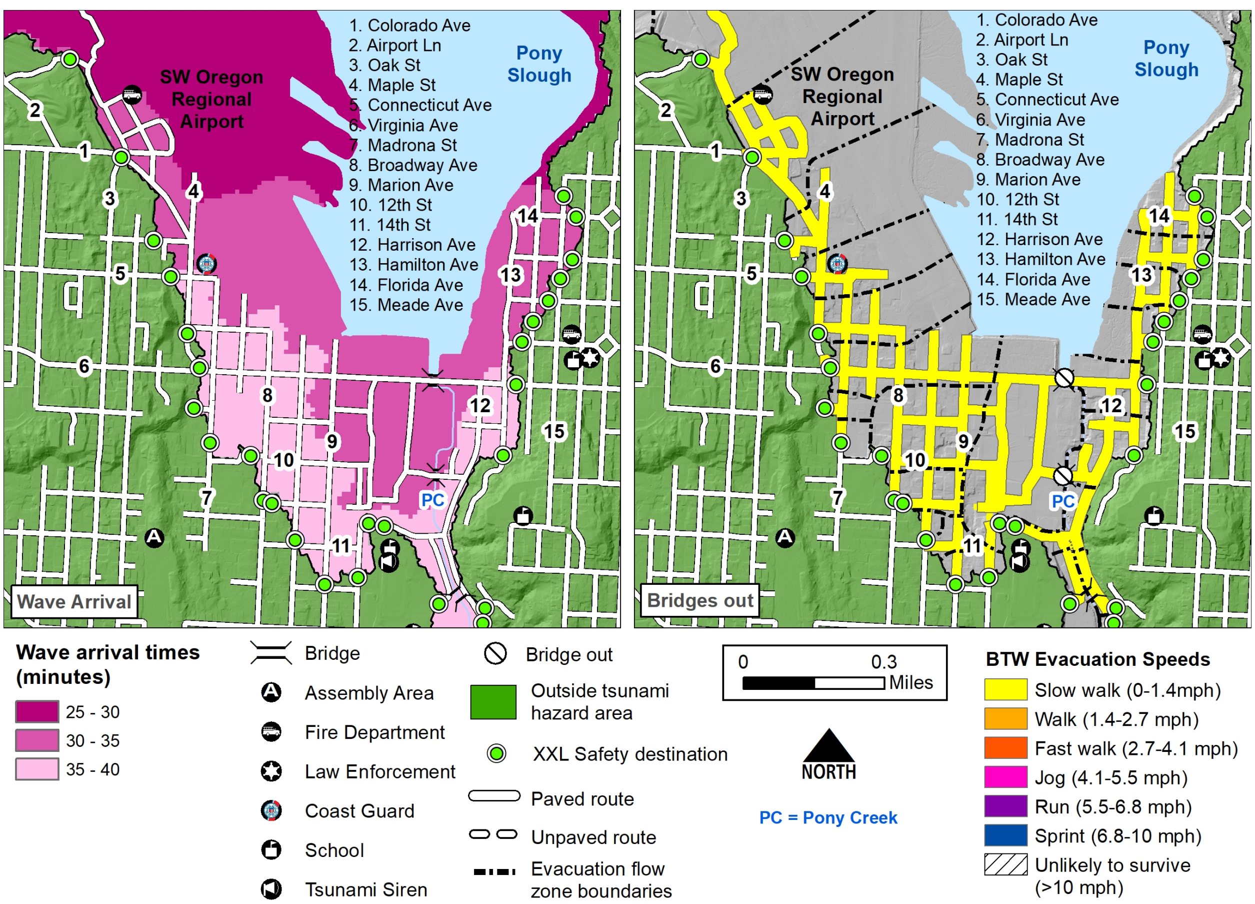


Figure 3-17. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) northeast and (right) southeast North Bend. Note different color ramp values for NE and SE.

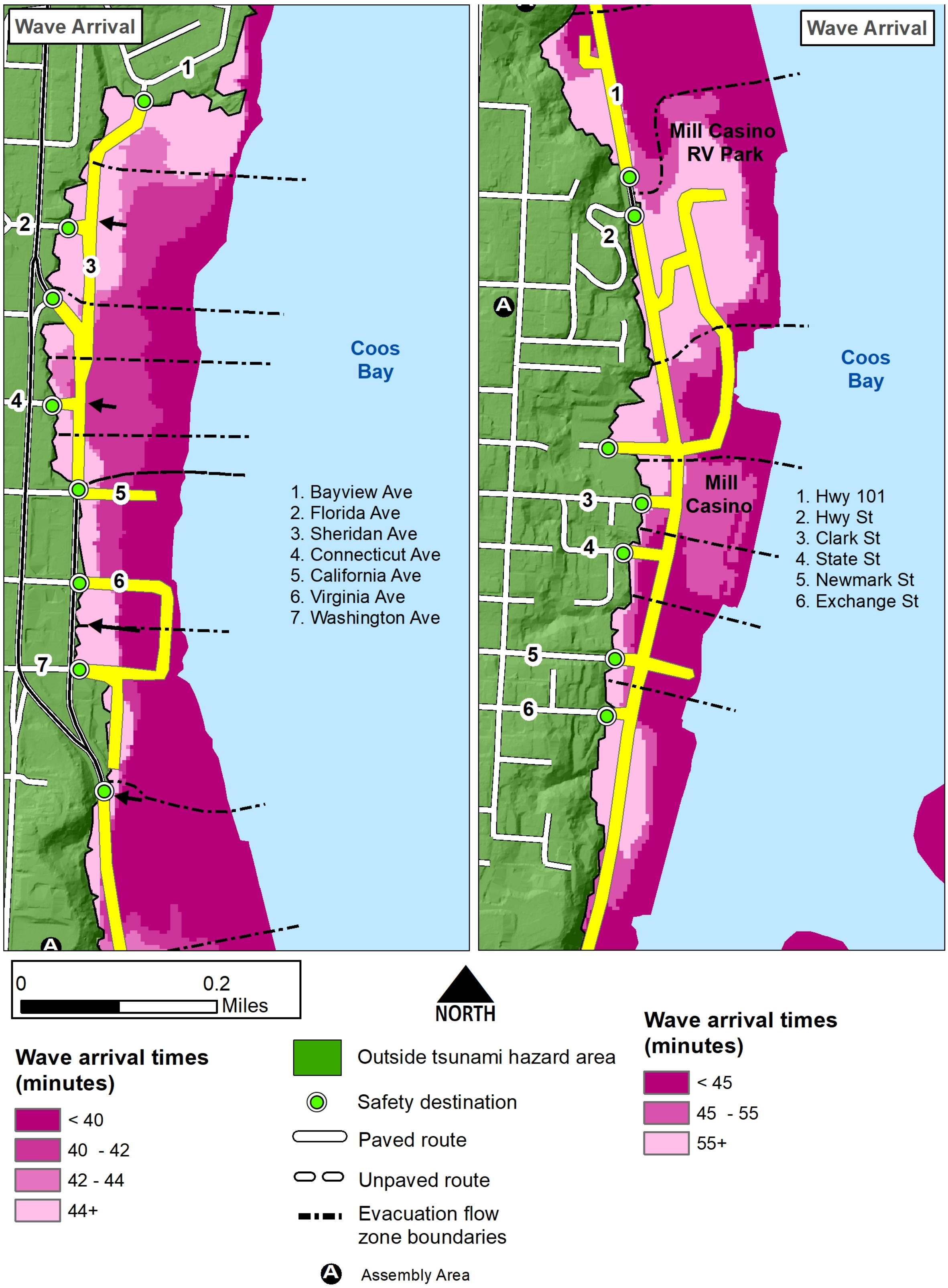
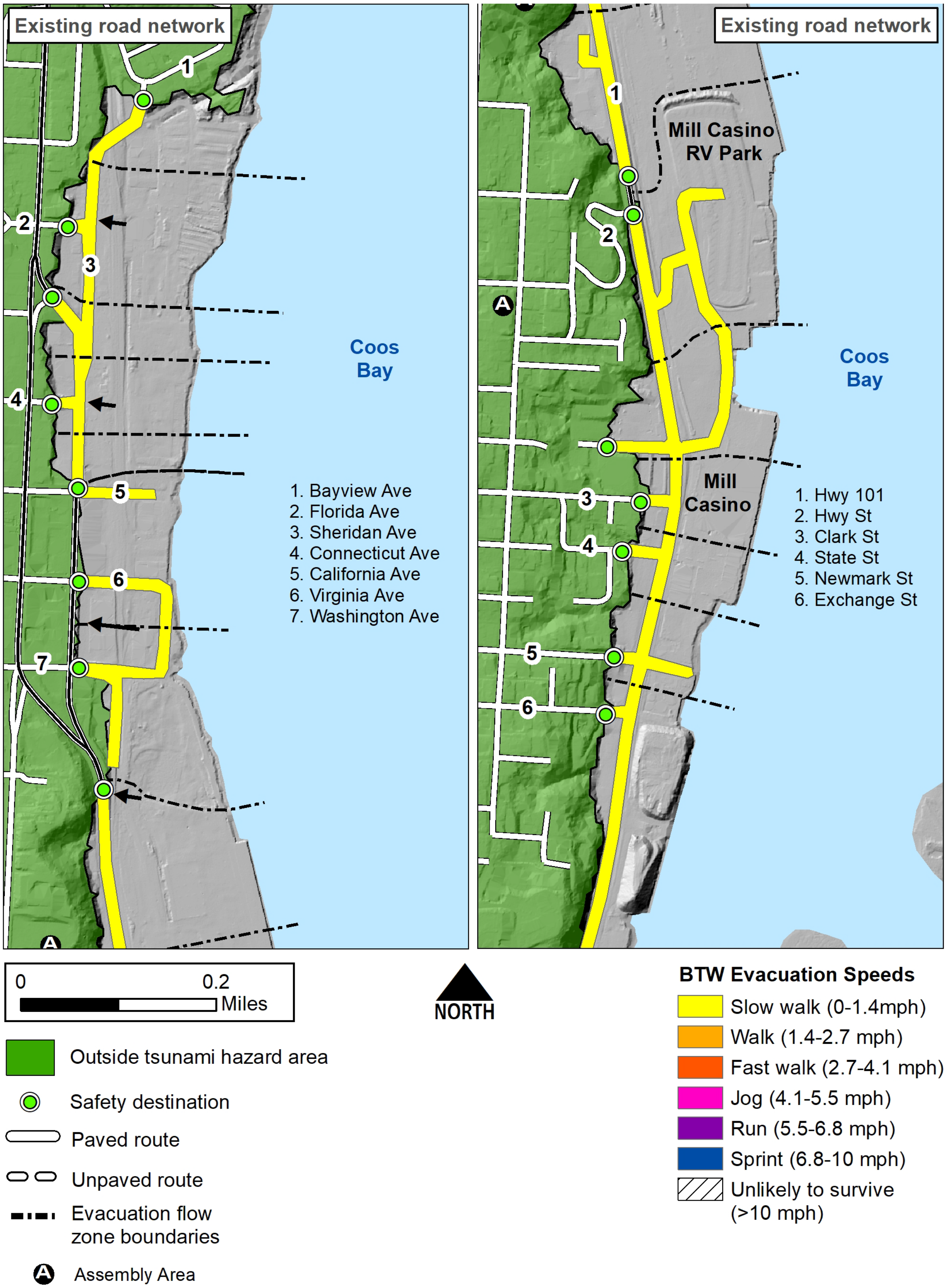


Figure 3-18. Beat the Wave modeling for base scenario showing minimum BTW walking speeds (colors on top of road network) and evacuation flow zone boundaries (black dashed lines) for (left) northeast and (right) southeast North Bend.



3.1.7 Coos Bay

The City of Coos Bay, upriver from North Bend, is reached by the tsunami ~45 minutes after the start of earthquake shaking (**Figure 3-19**). We separated results for Coos Bay into two figure extents. The northern extent covers the area from Teakwood Avenue to North Front Street; the inundated area is a narrow strip including Highway 101 and a few blocks inland. The southern extent covers the area from North Front Street to Coalbank Slough and has a significantly larger inundated area that includes Coos Bay police and fire stations as well as Blossom Gulch Elementary School.

The Highway 101 bridge over Coalbank Slough is not expected to survive and is therefore not included in the base BTW scenario. While high ground is immediately east of that bridge, this area of Coos Bay does not have far to travel in the other direction (to the west) to seek alternative high ground, therefore it is not a key bridge in terms of evacuation.

Figure 3-20 presents minimum BTW walking speeds for all of Coos Bay. The entire area can reach high ground at a ***slow walk*** (2 fps or 1.4 mph) thanks to the extremely high density of roads leading to high ground and long tsunami wave arrivals. As with most other communities within the estuary, liquefaction is a concern here however BTW results are nearly identical to the base scenario and do not illuminate areas that might require additional preparedness efforts.

Figure 3-19. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) north and (right) south Coos Bay.

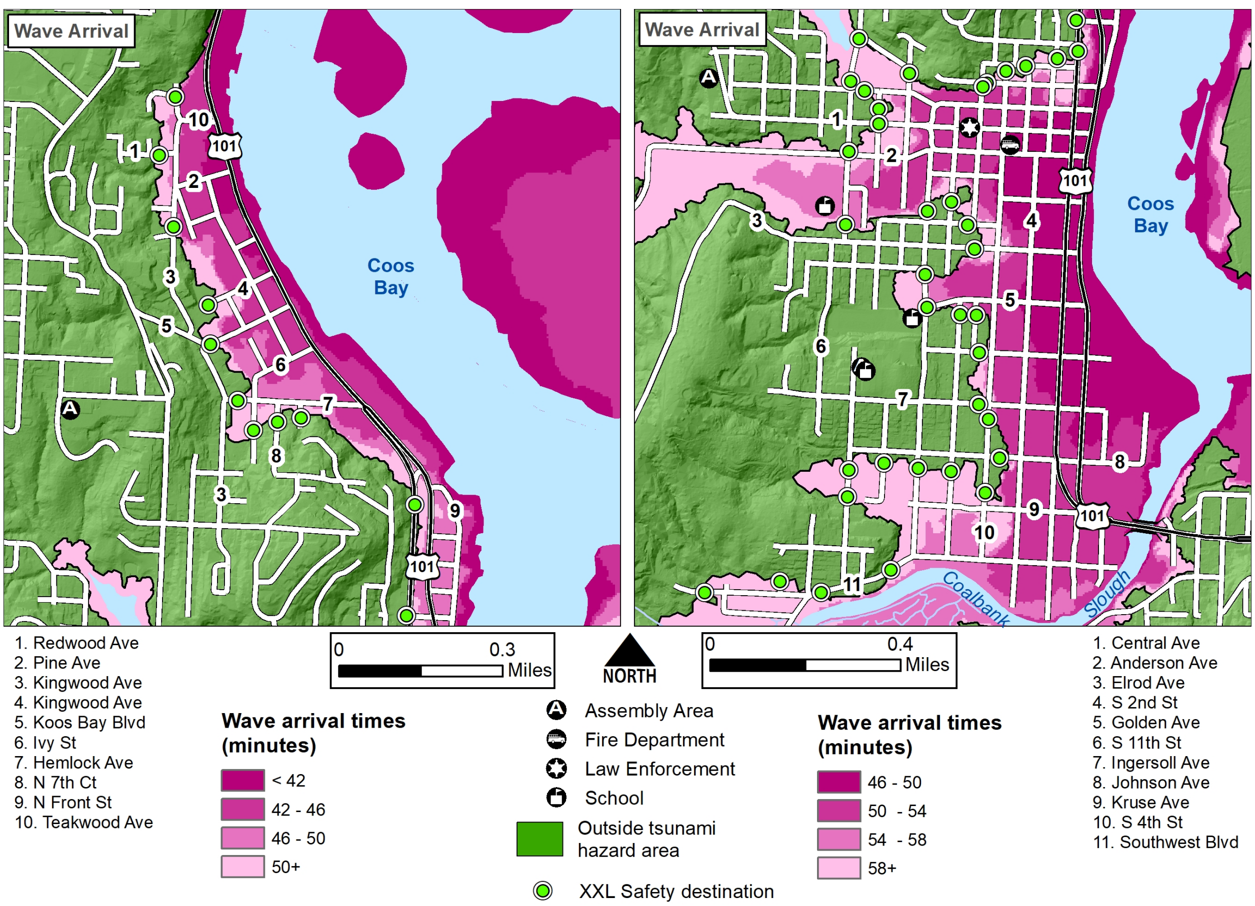
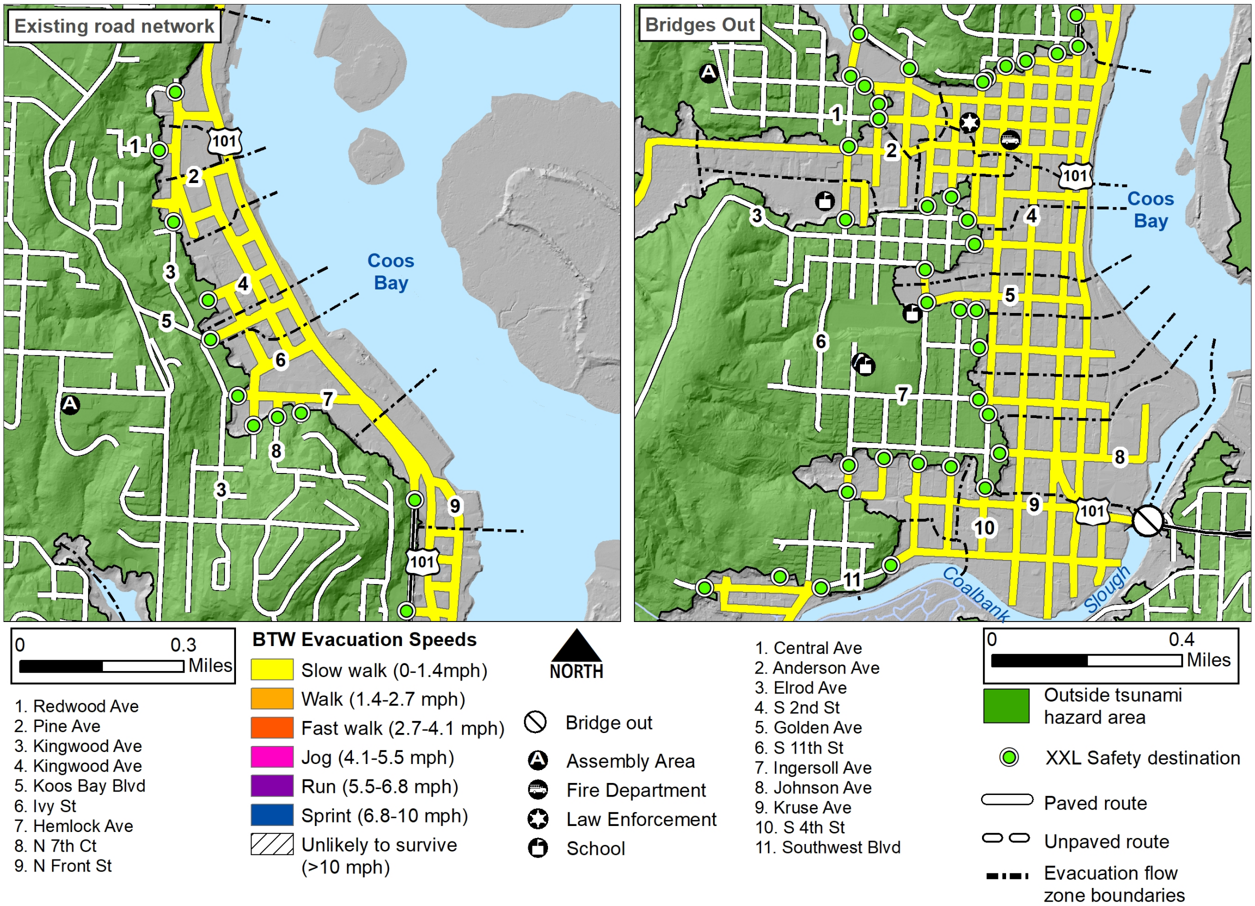


Figure 3-20. Beat the Wave modeling for base scenario showing minimum BTW walking speeds (colors on top of road network) and evacuation flow zone boundaries (black dashed lines) for (left) north and (right) south Coos Bay.

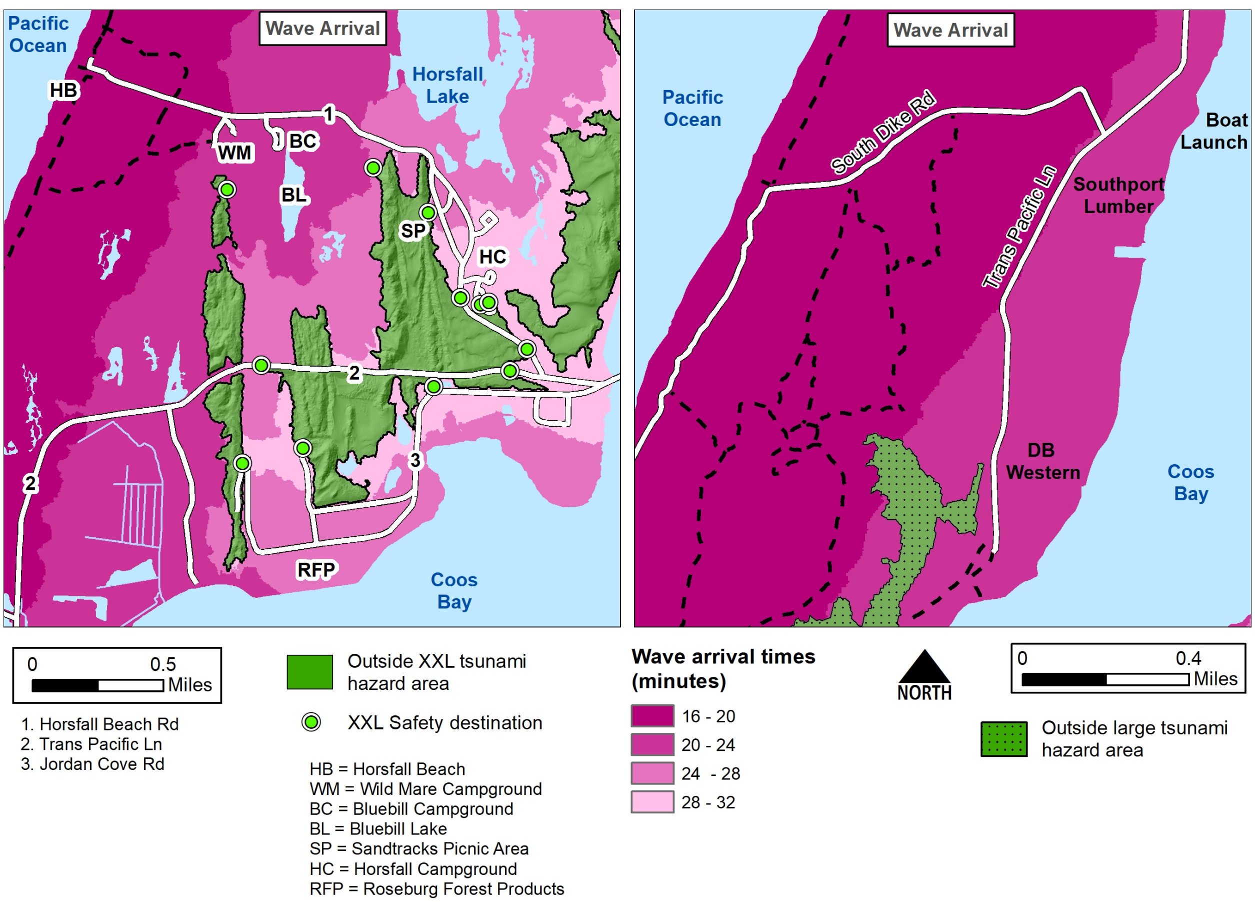


3.1.8 North Spit

Coos Bay North Spit is an isolated area separating Coos Bay from the Pacific Ocean. There are no permanent residents, but the area is home to a campground and numerous day-use recreational opportunities as well as several employers, primarily lumberyards. There is high ground outside XXL near the base of the spit, which is optimal because this area is the most populated on the spit. After Trans Pacific Lane turns south, there is no more XXL scenario high ground to be found; however, there are some dunes outside the Large (L) tsunami scenario.

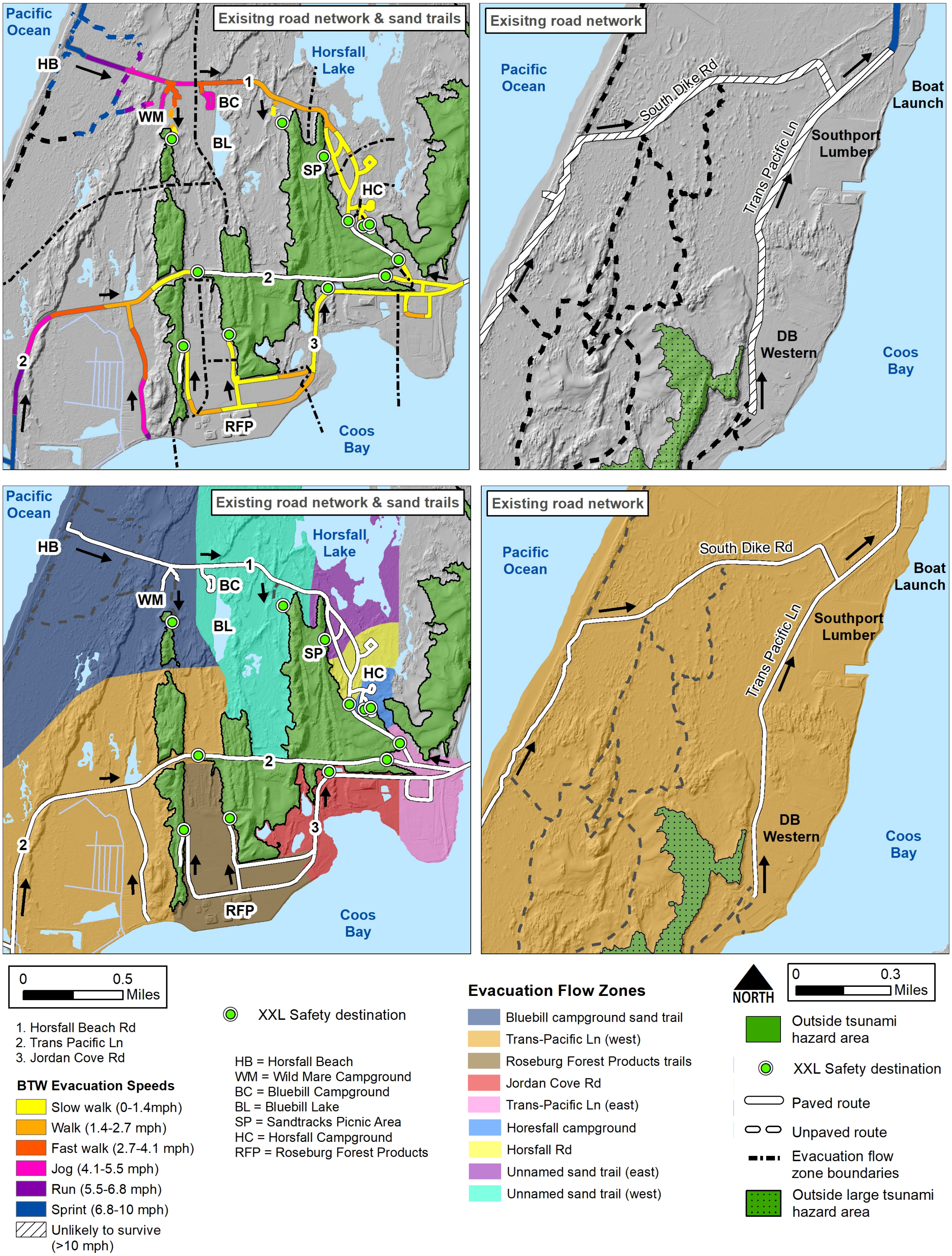
The first tsunami wave arrives on the beach of North Spit ~16 minutes after the start of earthquake shaking (**Figure 3-21**). The lumberyards and Bureau of Land Management (BLM) boat launch in Figure 3-21 and in subsequent figures) partway down the spit are expected to be inundated by 21 minutes. It will take between 16 and 32 minutes for the northern area to become fully inundated due the width of the spit. We do not see evidence of early wave arrivals inundating this area from the bay side; the wave advances in a relatively simple pattern from west to east.

Figure 3-21. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) north and (right) central North Spit.



Minimum BTW walking speeds and evacuation flow zones for a base scenario are presented in **Figure 3-22, top**. Evacuees from Horsfall Campground and Jordan Cove Rd can reach safety at a ***walk*** (4 fps or 2.2.7 mph) due to the many roads leading to high ground nearby. Required speeds from areas along Horsfall Beach Rd heading west toward the ocean are greater; evacuees at Horsfall Beach itself must ***sprint*** to reach high ground at Wild Mare Campground (also called Wild Mare Horse Camp) ahead of the tsunami (**Figure 3-22, top left**). This area is characterized by off-road vehicle recreation; these vehicles could be used to travel at speeds much faster than can be achieved on foot. Evacuees from the two lumberyards and anyone else recreating on the spit itself will have difficulty evacuating an XXL tsunami. We calculate a minimum walking speed of > 15 fps (>10 mph, ***unexpected to survive***) for this area (**Figure 3-22, top right**).

Figure 3-22. BTW modeling on the North Spit for the base scenario. (top) minimum BTW walking speeds and black dashed lines define evacuation flow zone boundaries for (left) north and (right) central North Spit. (bottom) Evacuation flow zones shown as colored polygons for (left) north and (right) central North Spit.



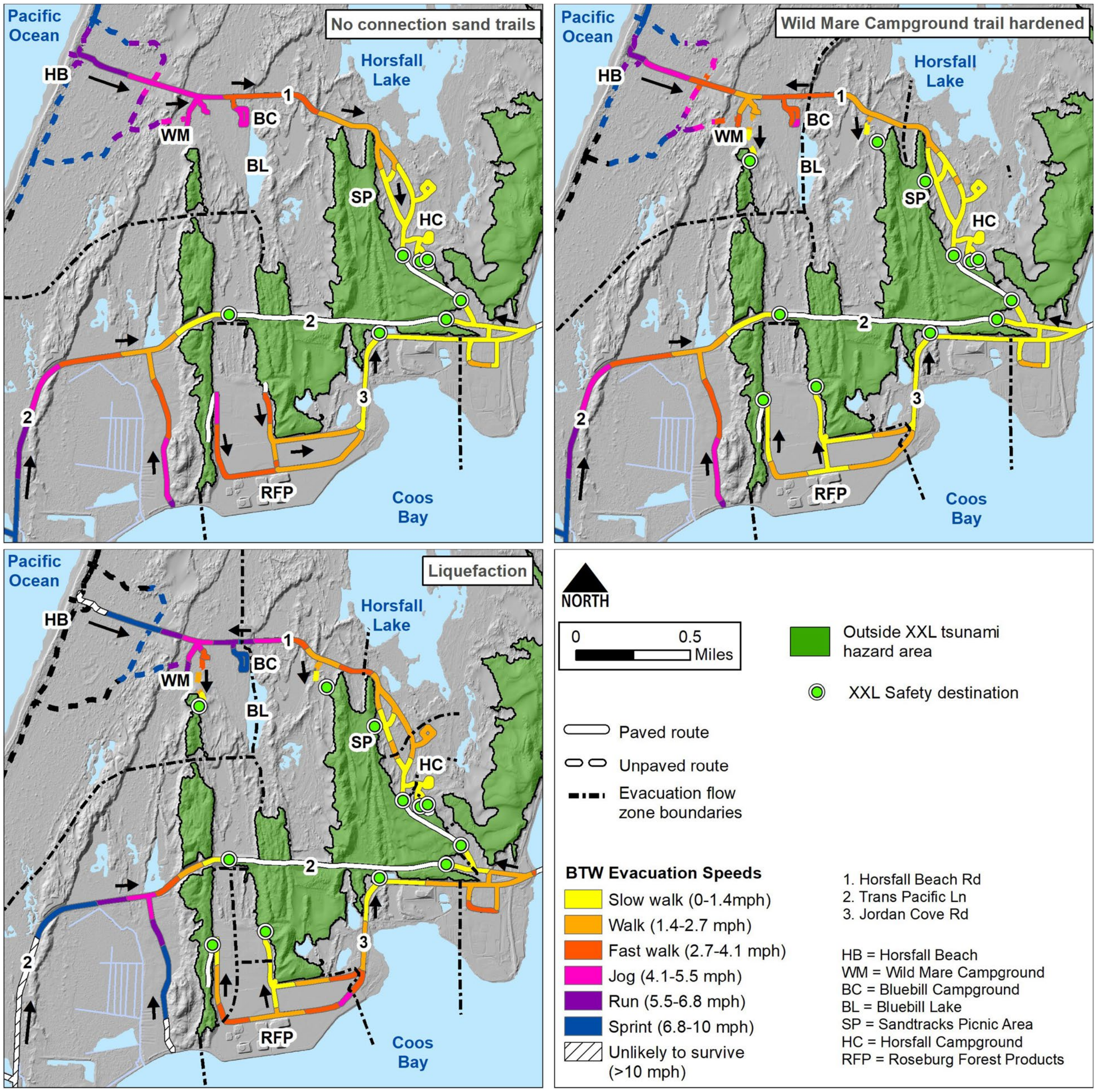
In the northern part of the spit, the base scenario includes a path from Wild Mare Campground to high ground up a dune 500 feet to the south. At the present time there is no signed evacuation route; however, the scarcity of high ground necessitates that people take advantage of this option. The extreme distances to safety and early tsunami wave arrivals require a plan for educating visitors on their options and easy-to-follow evacuation wayfinding. Because the route is not currently signed, we considered the alternative, which is for evacuees to travel on Horsfall Beach Road all the way to Horsfall Campground. **Figure 3-23, top left** demonstrates the unexpected results of this scenario: BTW speeds actually decrease at Horsfall Beach despite having to travel much farther. This is due to the significant difference in wave arrival times between Wild Mare Campground (~19 minutes) and Horsfall Beach (~29 minutes). Another cause for the unexpected reduction in BTW speeds is the difficulty walking up a steep dune in soft sand. This unexpected result reinforces the need for individuals to practice their routes, paying attention to details like where they choose to evacuate and how long it takes to get there. It also highlights areas where local decision makers may want to investigate and add signage directing people to the best safety available to them.

We also wanted to see what speed improvements could be gained by hardening the trail from Wild Mare Campground to safety on the high dune. Hardening the path would ensure easier and therefore faster passage than does the "soft sand" land cover used for the base run. **Figure 3-23, top right** presents minimum walking speeds for this scenario. This mitigation effort would reduce BTW walking speeds from ***sprint*** to ***run***.

Figure 3-23, bottom left presents results for the northern extent given the additional challenge of liquefaction due to the high susceptibility of the region. As expected, minimum walking speeds dramatically increase for this scenario. However, these results may be less meaningful for this area if evacuees can use off-road vehicles to evacuate.

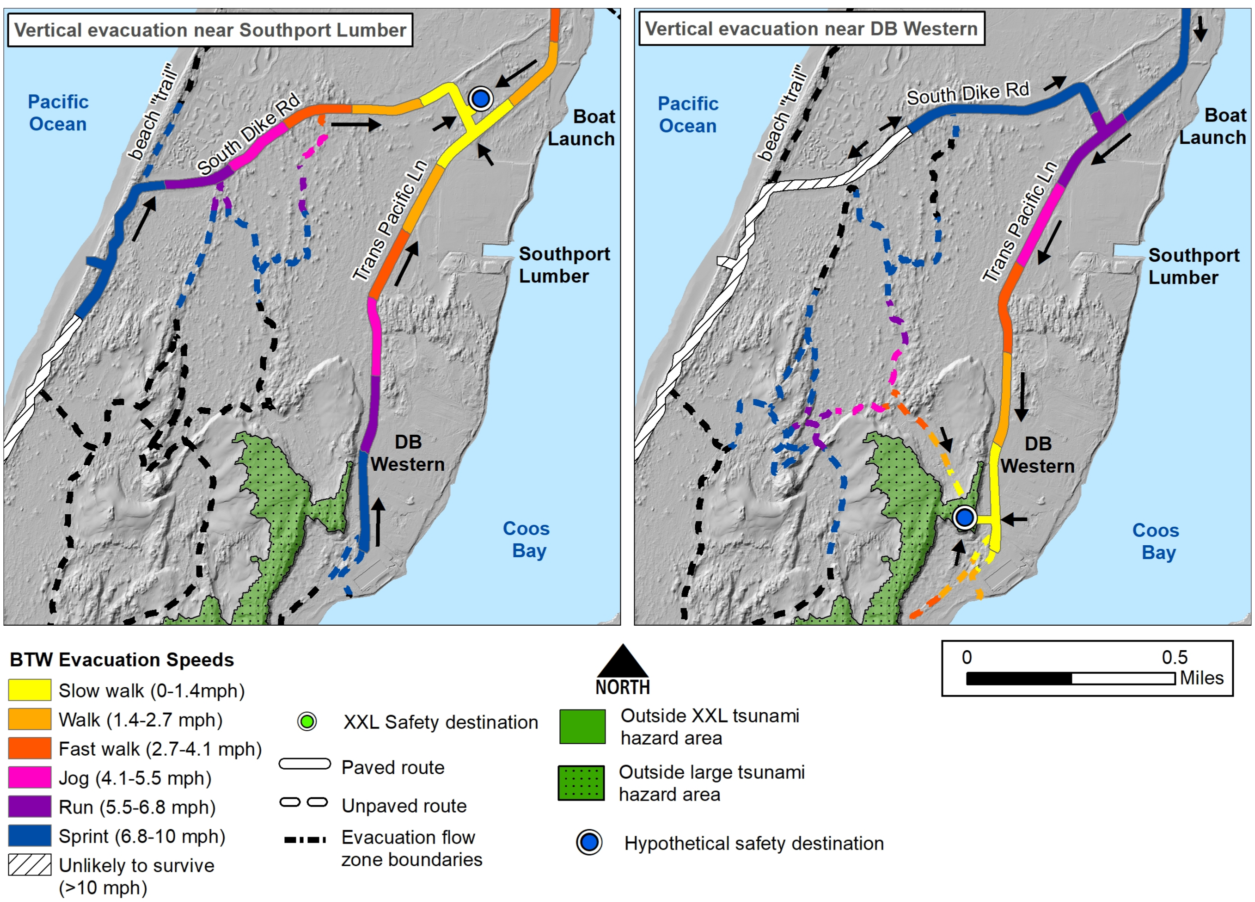
The situation farther south, in the vicinity of two lumberyards (Southport Lumber and DB Western) as well the BLM boat launch, is much more serious. XXL high ground is over 2 miles to the north and evacuees must travel well over 15 fps (10 mph) in order to survive (**Figure 3-22, top right**). Liquefaction is expected in this region and it will disrupt roads to the point that regular vehicles will have a difficult time driving over them. Off-road vehicles will likely fair better, but there is still no guarantee. We do not present results for liquefaction in the North Spit central area because minimum walking speeds are already at their maximum for the base run.

Figure 3-23. BTW modeling in the northern part of North Spit for three hypothetical scenarios. (top left) No trails available, everyone on Horsfall Beach Road must evacuate to Horsfall Campground. (top right) A trail between Wild Mare Campground and safety to the south is hardened and easier to use than a loose sand footpath. (bottom left) Base run with liquefaction.



The dangerous evacuation landscape on the spit presents a strong case for vertical evacuation. We modeled two hypothetical structures, one closer to Southport Lumber and the BLM boat launch (**Figure 3-24**, left) and the other closer to DB Western (**Figure 3-24**, right). The latter coincides with high ground considered safe for a Large (L) tsunami scenario. The L scenario covers 95% of the likely inundation (XXL covers 100%), meaning that there is only a 5% chance that high ground outside L will be inundated by a larger tsunami. In both cases, evacuees at the closer lumberyard can reach safety at a ***fast walk*** whereas evacuees from the other lumberyard must ***run*** or ***sprint***. At a ***fast walk*** and ***jog***, the construction of a vertical evacuation structure is most likely the optimal solution for those who are this far south on the spit (**Figure 3-24, right**).

Figure 3-24. BTW modeling in the central region of North Spit for two hypothetical scenarios. left) Vertical evacuation structure at the BLM information area between the boat ramp and Southport Lumber. (right) Vertical evacuation structure in the dunes west of DB Western. This scenario also reflects a Large (L) tsunami scenario, as the location of the man-made structure coincides with the area that is high enough to be outside this size tsunami.



3.2 Socioeconomic analysis

Several Coos County communities have a large percentage of buildings, residents, and jobs within the tsunami zone, which present evacuation, response, and recovery challenges. In this section we provide socioeconomic perspectives of four Coos County communities (the cities of Coos Bay and North Bend and the Bunker Hill and Barview U.S. Census Bureau census-designated places [CDPs]); **Figure 3-25**, **Figure 3-26**, and **Figure 3-27**). Bunker Hill CDP has very few roads inside the XXL inundation zone, so BTW results for this community are not presented in section 3.1.

Figure 3-25. Cities of Coos Bay and North Bend, and Bunker Hill, showing U.S. Census, census-designated places (CDPs), city boundaries, buildings and XXL tsunami zone. XXL tsunami zone from Priest and others (2013b). CDP and city boundaries from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).

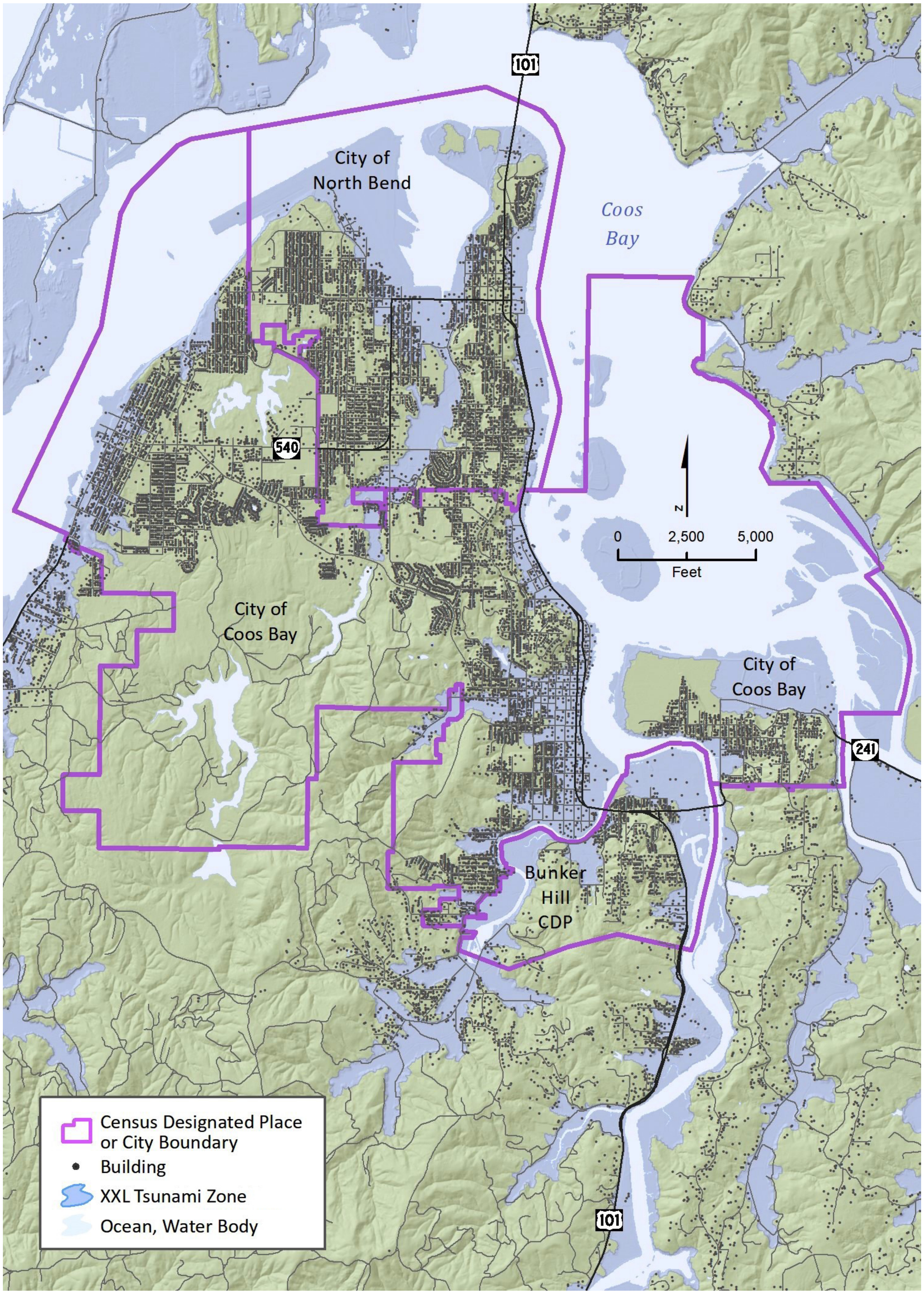


Figure 3-26. Bunker Hill U.S. Census Bureau census-designated place (CDP) and Coos Bay downtown, showing buildings, roads, and XXL tsunami zone. XXL tsunami zone from Priest and others (2013b). CDP and city boundaries from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).

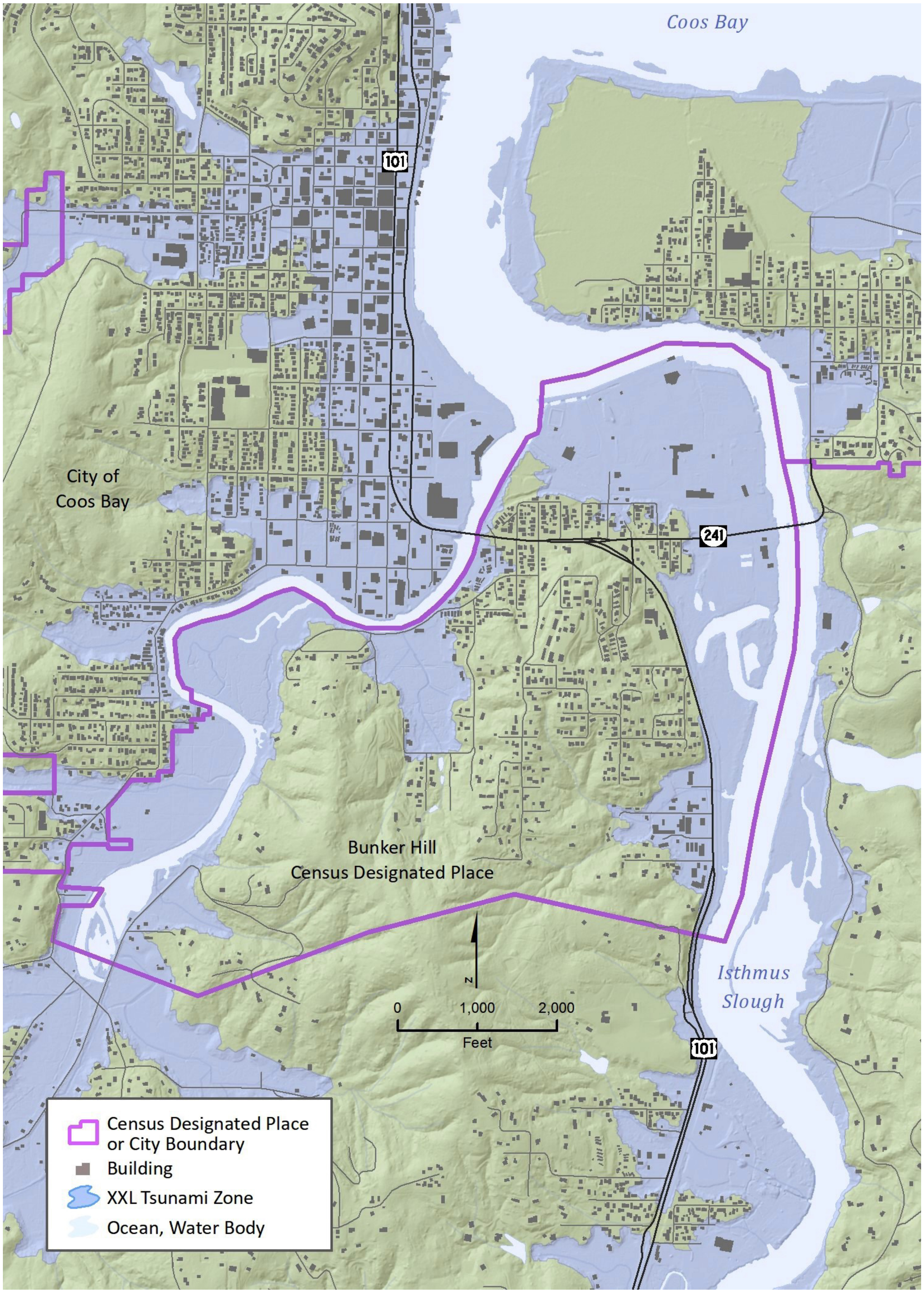
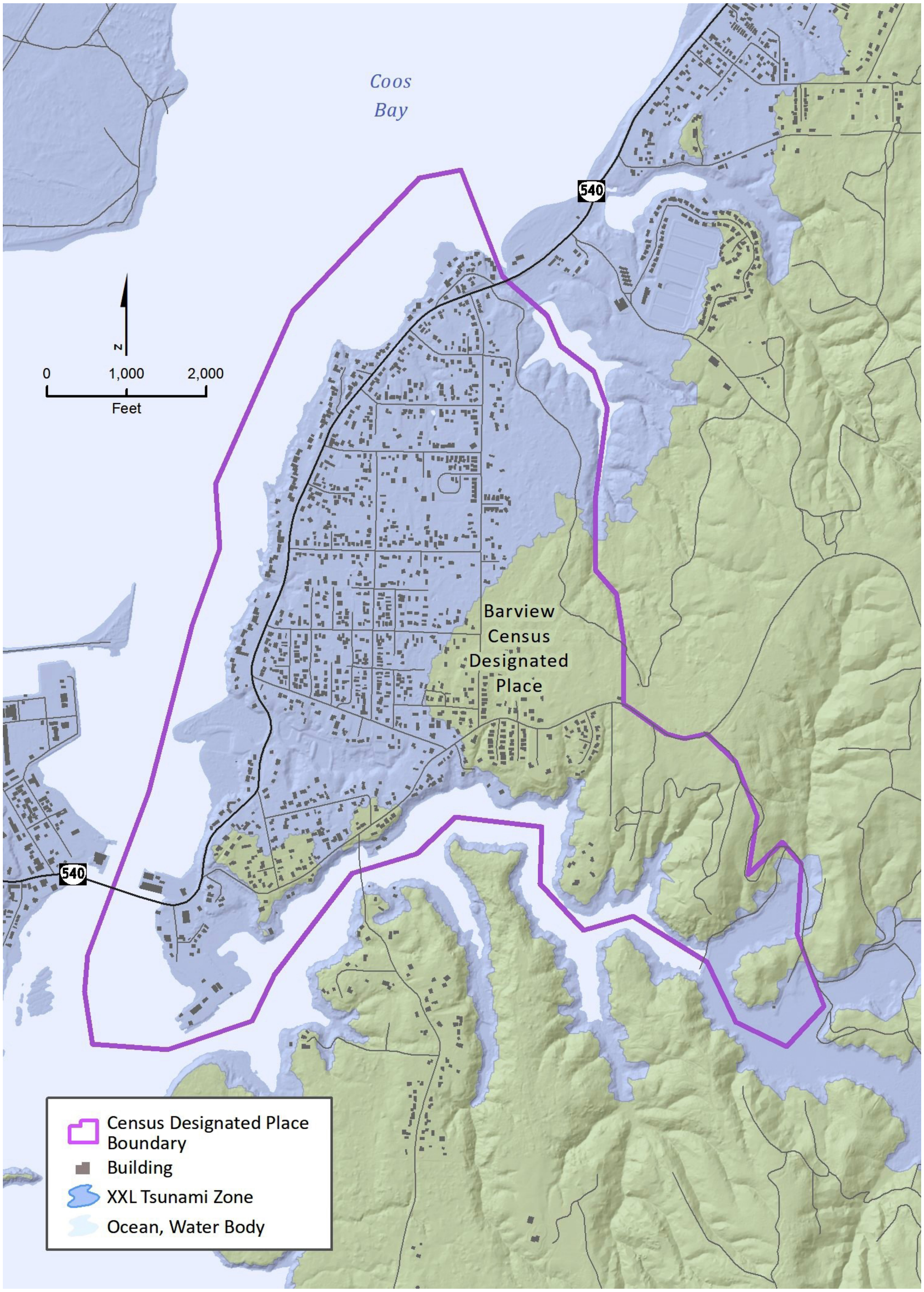


Figure 3-27. Barview U.S. Census Bureau census-designated place (CDP), showing buildings, roads, and XXL tsunami zone. XXL tsunami zone: from Priest and others (2013b). CDP boundary from U.S. Census Bureau (2010). Building footprints from Microsoft U.S. Building Footprints (https://github.com/microsoft/USBuildingFootprints).



In Oregon coastal communities, the percentage of a jurisdiction's permanent residents in the tsunami zone is often less than the percentage of building value in the tsunami zone (**Table 3-2**, **Figure 3-28**, **Figure 3-29**). The difference can be explained as follows: commercial and industrial development patterns with relatively expensive buildings are often concentrated around or adjacent to waterfronts and harbors, and large recreational-oriented facilities and motel-type housing are often concentrated near harbors and shorelines. In addition, real estate market dynamics in Oregon are such that many of the residential homes within the tsunami zone are second homes or vacation rentals that do not house permanent residents. Corresponding with commercial and industrial development patterns, the percentage of jobs in the tsunami zone is typically higher than the percentage of permanent residents within the tsunami zone (**Table 3-3**, **Figure 3-30**). A concentration of jobs within the tsunami zone can present additional disaster recovery challenges, as it is likely the place of employment will be extensively damaged or destroyed by a tsunami. Within many Oregon coastal communities, the Accommodation and Food Services sector (North American Industry Classification System Sector 72, https://www.census.gov/eos/www/naics/) is the largest employer by sector within the tsunami zone. Such is the case for Coos County overall and the City of North Bend (**Table 3-3**). The Accommodation and Food Services sector comprises establishments providing customers with lodging and/or preparing meals, snacks, and beverages for immediate consumption. The sector includes both accommodation and food services establishments because the two activities are often combined at the same establishment. (https://www.census.gov/eos/www/naics/).

The percentage of people speaking Spanish at home varies slightly by community (**Table 3-4**, **Figure 3-30**). Emergency planners can use the information to better understand the county and community diversity when creating tsunami preparation and evacuation messages.

Tsunami casualty models often assume all people within a tsunami zone can evacuate in a timely manner. **Table 3-5** quantifies the number and percentage of people within each community with a disability and who may have challenges mobilizing in a timely manner after an earthquake. In addition, family members or caretakers may be delayed while assisting a person with a disability. We emphasize that the percentages in **Table 3-5** are for the entire community and do not necessarily describe the population within the tsunami zone.

Figure 3-30 summarizes many of these data for the four communities being analyzed. Of note is Barview CDP, where most of the residents, building value, and jobs are within the tsunami zone. North Bend also has a disproportionately large percentage of jobs inside the inundation zone compared to the other communities.

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

		Tsunami Zone			
				XXL	
Community	Total Population	Medium	Large	Total	People 65 and Older
Barview CDP	2,021	99	323	1,376	326
Bunker Hill CDP	1,517	9	44	125	22
Coos Bay	16,680	1,200	1,561	3,385	861
North Bend	9,815	72	437	1,186	211
Uninc. Coos County*	21,073	337	920	2,279	361
Coos County Total	63,275	1,918	3,584	10,424	2,520

*People outside of city limits and CDP boundaries.

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

Figure 3-28. Percentage of permanent residents residing within selected tsunami zones for several Coos County communities, unincorporated Coos County (outside of all Coos County cities and CDPs), and overall Coos County. The tsunami zones are defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place. Data based on analysis of Oregon Department of Motor Vehicles records.

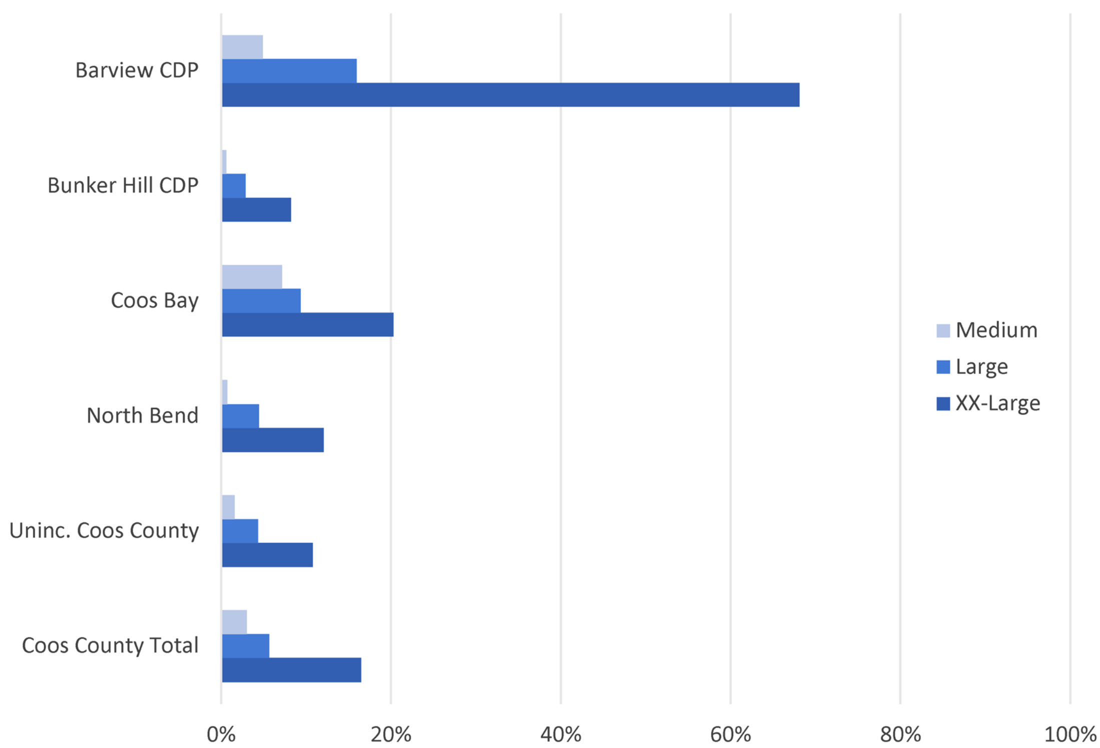


Figure 3-29. Percentage of a community's building replacement cost within selected tsunami zones for several Coos County communities, unincorporated Coos County (outside of all Coos County cities and CDPs), and overall Coos County (M. Williams, written communication, 2019). The tsunami zones are defined by Priest and others (2013b). CDP is U.S. Census Bureau census-designated place.

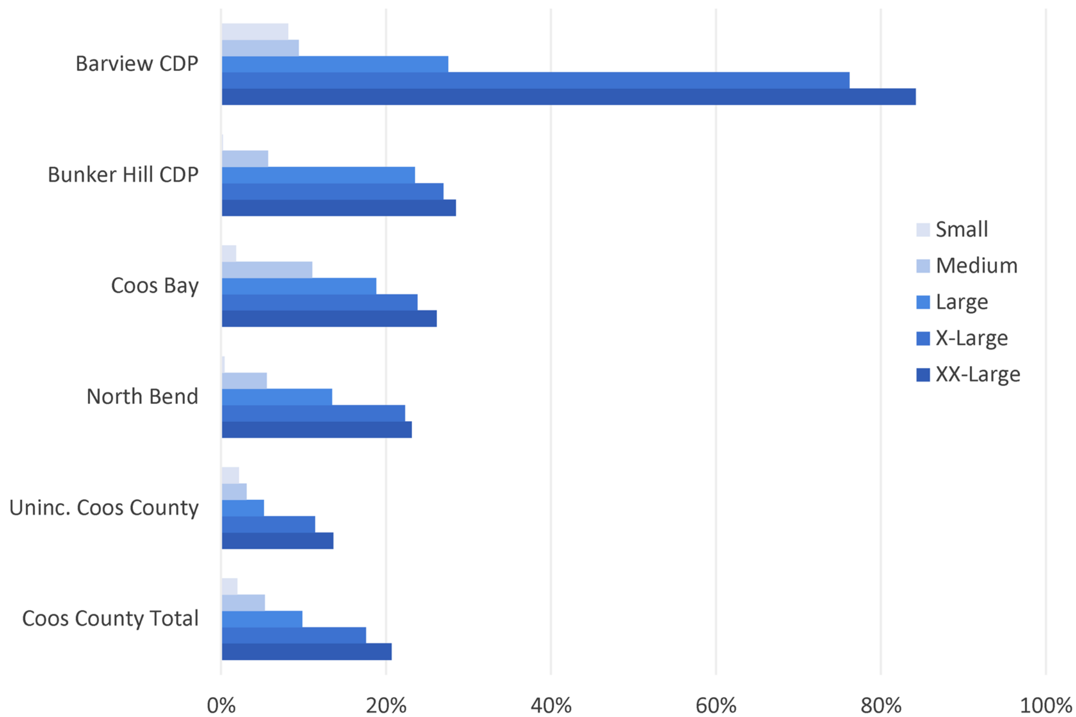
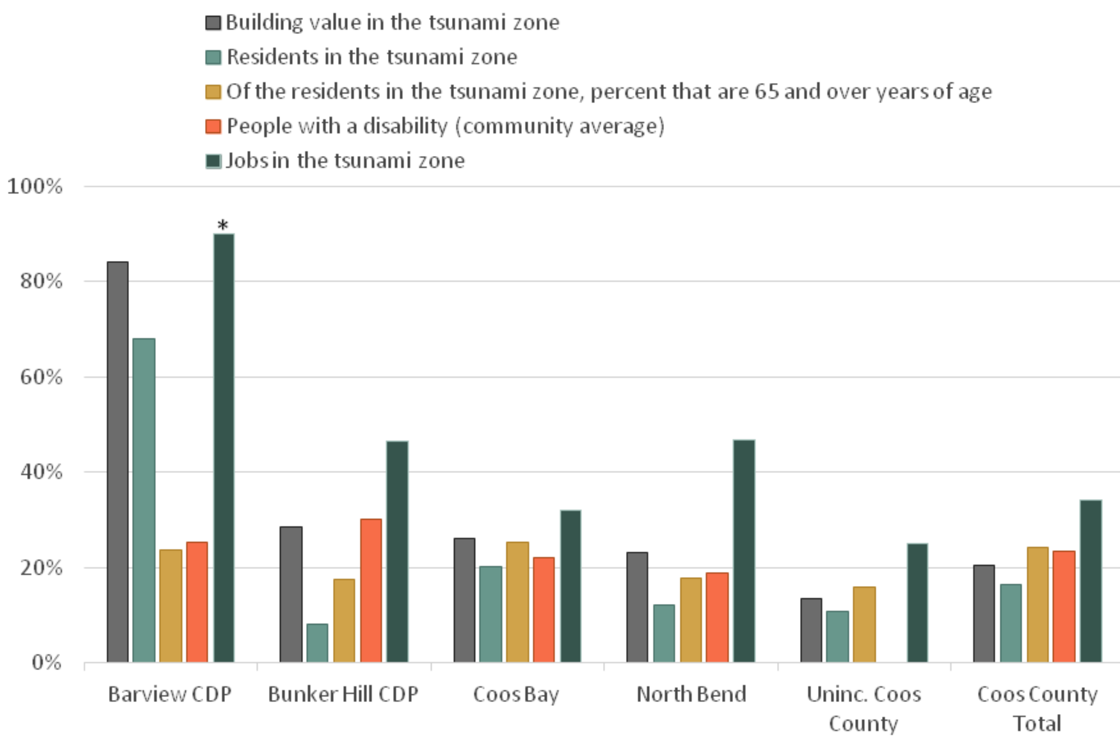


Table 3-3. Number of employers, employees, annual wages paid, and top employment sector for several Coos County communities, unincorporated Coos County (outside of all Coos County cities and CDPs [U.S. Census Bureau census-designated places]), and overall Coos County. The tsunami zone is the XXL scenario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

	Employers		Employees		Top Employment Sector in Tsunami Zone		
	Total	Tsunami Zone	Total	Tsunami Zone	% of Jobs in Tsunami Zone for Given Sector	NAICS Code	NAICS Category+
Barview CDP	24	23	100	—	—	—	—
Bunker Hill CDP	40	13	490	228	—	—	—
Coos Bay	685	351	14,145	4,520	20%	44	Retail Trade
North Bend	416	151	4,963	2,328	32%	72	Accommodation and Food Services
Uninc. Coos County*	593	116	5,201	1,309	11%	11	Agriculture, Forestry, Fishing and Hunting
Coos County Total	2,124	811	28,556	9,745	15%	72	Accommodation and Food Services

Employment data from Quarterly Census of Employment and Wages (second quarter, 2018; J. Mendez, Oregon Employment Division, written communication, September 28, 2018).
Symbol "—" indicates data not reported for employer confidentiality reasons.
*Employers outside of *all* Coos County CDPs and cities.
+North American Industrial Classification System.

Figure 3-30. Socioeconomic data for several Coos County communities, unincorporated Coos County (outside of all Coos County cities and CDPs [U.S. Census Bureau census-designated places]), and overall Coos County. Socioeconomic data sources are described in the text. The tsunami zone is defined by the XXL scenario (Priest and others, 2013b). Disability data are not available by tsunami zone but represent overall community percentage. Disability data are not available for unincorporated Coos County.



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

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

	Total Number of Households	Number of Households Speaking Spanish	Percent of Households with Margin of Error
Barview CDP	864	7	0.8% ± 1.4%
Bunker Hill CDP	587	53	9.0% ± 6.4%
Coos Bay	6,673	255	3.8% ± 1.5%
North Bend	3,863	122	3.2% ± 1.9%
Coos County	26,473	838	3.2% ± 0.7%

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

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

Difficulty Category	Estimate	Margin of Error
Barview CDP		
Individuals (estimate)	2,021	± 11.9%
Individuals with a disability	510	25.2% ± 6.7%
Hearing	240	11.9% ± 4.5%
Vision	135	6.7% ± 3.7%
Cognitive	134	6.7% ± 3.6%
Ambulatory	327	16.3% ± 6.2%
Self-care	69	3.4% ± 2.2%
Independent Living	168	9.7% ± 4.0%
Bunker Hill CDP		
Individuals (estimate)	1,501	± 32.0%
Individuals with a disability	453	30.2% ± 16.8%
Hearing	154	10.3% ± 8.4%
Vision	93	6.2% ± 5.1%
Cognitive	286	21.7% ± 17.5%
Ambulatory	163	12.3% ± 5.9%
Self-care	29	2.2% ± 2.6%
Independent Living	73	7.5% ± 6.6%
Coos Bay		
Individuals (estimate)	15,888	± 2.6%
Individuals with a disability	3,518	22.1% ± 2.6%
Hearing	769	4.8% ± 1.1%
Vision	216	3.9% ± 1.4%
Cognitive	1,637	11.1% ± 2.1%
Ambulatory	1,825	12.3% ± 1.9%
Self-care	754	5.1% ± 2.0%
Independent Living	310	12.0% ± 2.4%
North Bend		
Individuals (estimate)	9,468	± 1.1%
Individuals with a disability	1,798	19.0% ± 3.1%
Hearing	626	6.6% ± 1.6%
Vision	409	4.3% ± 1.7%
Cognitive	757	8.5% ± 1.9%
Ambulatory	894	10.0% ± 2.5%
Self-care	348	3.9% ± 1.4%
Independent Living	719	9.9% ± 2.4%
Coos County		
Individuals (estimate)	62,058	± 0.2%
Individuals with a disability	14,509	23.4% ± 1.5%
Hearing	4,747	7.6% ± 0.7%
Vision	2,551	4.1% ± 0.7%
Cognitive	5,831	9.9% ± 1.1%
Ambulatory	8,161	13.8% ± 1.1%
Self-care	3,038	5.2% ± 0.8%
Independent Living	5,292	10.5% ± 1.0%

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

4.0 CONCLUSIONS AND RECOMMENDATIONS

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

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

Another option is to consider the Large (L1) tsunami scenario instead of XXL. Natural high ground is available in the dunes, and the Large scenario covers 95% of the likely inundation (XXL covers 100%). The decision to direct evacuees to nearby L1 high ground versus directing them try to reach their nearest XXL safety destination must be done with care and deliberation because this scenario requires a completely different evacuation route and carries a different set of risks, primarily that the tsunami will overtop the dune.

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

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

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