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TSUNAMI EVACUATION ANALYSIS OF PACIFIC CITY, TILLAMOOK COUNTY, OREGON

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XXL1_BridgesIn feature dataset:

XXL1_BridgesIn_EvacuationFlowZones
XXL1_BridgesIn_EvacuationRoutes
XXL1_BridgesIn_WalkingSpeeds_Roads
XXL1_BridgesIn_WalkingSpeeds_Trails

XXL1_BridgesOut feature dataset:

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MaxTsunamiFlowDepth_XXL1
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Metadata in .xml file format:

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ABSTRACT

We evaluated pedestrian evacuation in the communities of Pacific City, Nestucca Spit, Woods, Tierra Del Mar, and Sand Lake, Tillamook County, in the event of a local tsunami generated by an earthquake on the Cascadia subduction zone (CSZ). Our analyses focused on a maximum-considered CSZ tsunami event covering 100% of potential variability, termed XXL1 and generated by a magnitude 9.1 earthquake. We determined ***minimum*** walking times to safety (defined as ~20 ft beyond the inundation limit) for a moderate walking speed of 4 fps (feet per second, 22 minutes/mile) using least-cost distance (LCD) routes determined by modification of the anisotropic path distance method of Wood and Schmidtlein (2012) and Wood and others (2016). Four feet per second is the standard speed for pedestrians to cross at signalized intersections (U.S. Department of Transportation, 2012). Evacuation paths were limited to roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

To estimate whether pedestrians can stay ahead of a tsunami along the evacuation routes, we produced maps of:

- Tsunami wave advance for an XXL1 event
- LCD walking time (at 4 fps)
- Detailed evacuation routes for the XXL1 scenario, and
- "Beat the Wave" (BTW) for the XXL1 scenario

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 primary scenario uses the existing road network and includes a 10-minute delay from start of earthquake before beginning evacuation. Additional challenges to evacuation are examined, including failure of non-retrofitted bridges and effects from liquefaction. In all cases, ***the identified minimum speeds must be maintained for the entire time it takes to evacuate from the inundation zone.*** Given the model limitations defined in the Methods section, results show that evacuation of the entire region is achievable at a moderate walking speed (4 fps) whether or not the bridge network remains viable. 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 within the community boundaries. Liquefaction, however, is shown to present a significant challenge to evacuation across the region. Finally, long distances to high ground and difficult walking conditions result in evacuation challenges for Nestucca Spit.

Possible mitigation options include increasing the number of evacuation routes by constructing more earthquake-hardened bridges (built or remodeled to withstand shaking from a major earthquake); adding new evacuation routes; and/or installing a tsunami refuge, otherwise known as a vertical evacuation structure, on Nestucca Spit.

1.0 INTRODUCTION

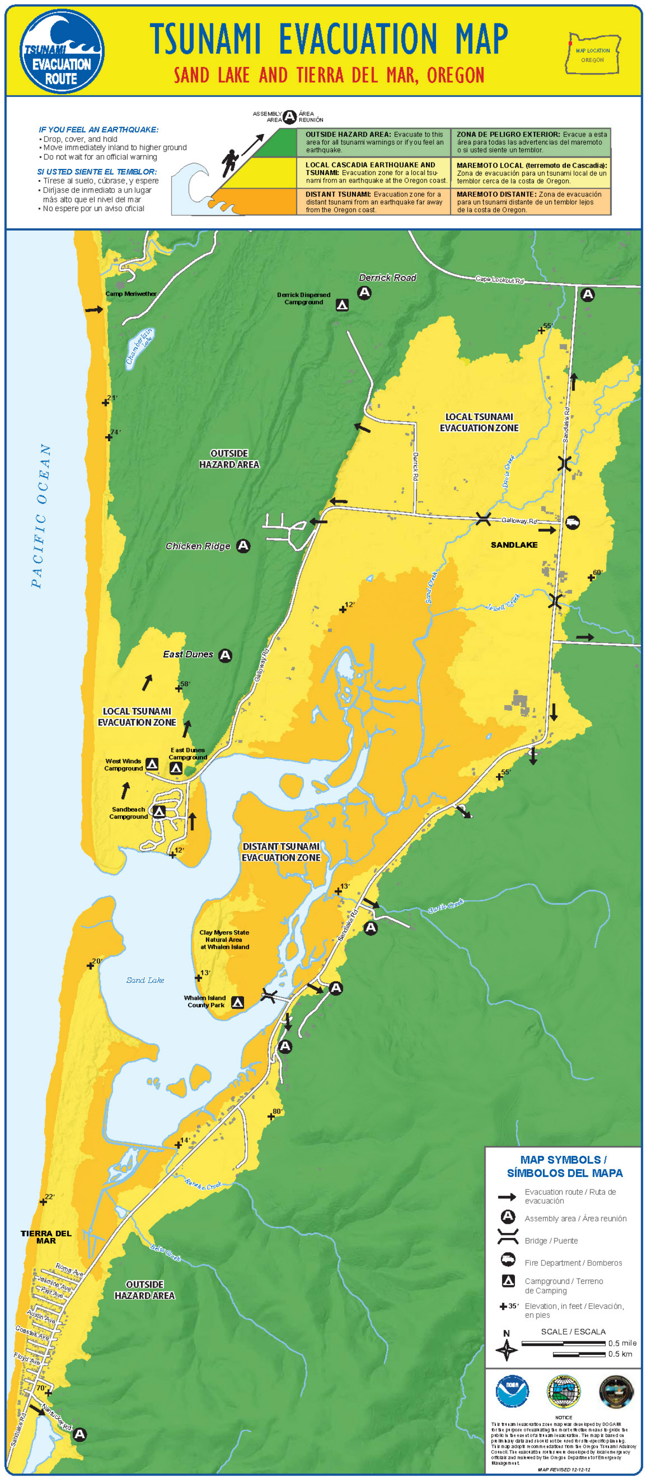
A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For the majority of the population, spontaneous evacuation on foot will be the only effective means of limiting loss of 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 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%)

In these scenarios a maximum-considered CSZ tsunami (XXL1, referred to as “XXL” for the remainder of this report) inundates virtually the entire Nestucca River and Sand Lake estuaries (**Figure 1-1** and **Figure 1-2**). Much of Pacific City and the other coastal communities will be flooded within 30 minutes of the start of earthquake shaking. Bridges can further complicate evacuation if they prove to be integral to a route and are not built to withstand the shaking from the earthquake. This does not turn out to be true for Pacific City and Woods: modeling indicates neither of the two major bridges is essential for evacuation (i.e., safety can be reached without needing to cross a bridge). The objective of this study is to provide local government with a quantitative assessment of the time, speed, and challenges affecting tsunami evacuation in Pacific City and nearby coastal communities 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.

Figure 1-1. DOGAMI (2013a) tsunami evacuation map for Pacific City, Woods, and Nestucca Spit showing geographic information. Inundation for a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL) is shown in yellow, while the maximum-considered distant tsunami scenario is shown in orange. (Note: the Cascadia scenario encompasses BOTH the yellow and orange zones.) High ground outside the XXL hazard area is green. See Witter and others (2011) for detailed explanations of the tsunami scenarios shown on this map. The full-scale version of this map is available at https://www.oregongeology.org/tsuclearinghouse/.

Figure 1-2. DOGAMI (2013b) tsunami evacuation map for the Sand Lake estuary showing geographic information. Inundation for a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL) is shown in yellow, while the maximum-considered distant tsunami scenario is shown in orange. (Note: the Cascadia scenario encompasses BOTH the yellow and orange zones.) High ground outside the XXL hazard area is green. See Witter and others (2011) for detailed explanations of the tsunami scenarios shown on this map. The full-scale version of this map is available at https://www.oregongeology.org/tsuclearinghouse/.



We evaluate tsunami evacuation difficulty by:

1. Using the least-cost distance (LCD) approach of Wood and Schmidtlein (2012) to provide estimates of walking times to safety for every place of origin adjacent to a road or trail in the community,
2. Illustrating how quickly the wave front of an XXL tsunami advances across the area after the earthquake,
3. Determining whether an evacuee can stay ahead of the tsunami all the way to safety on the routes defined by the LCD analysis, termed “beat the wave” (BTW), and
4. Running multiple BTW scenarios to investigate potential vulnerabilities and mitigation options.

2.0 METHODS

Agent-based and LCD modeling are the two most common approaches for simulating pedestrian evacuation difficulty. Agent-based modeling focuses on the individual and how travel would most likely 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) because we wanted to understand the spatial distributions of evacuation times in the greater Pacific City area without having to create a large number of scenarios for specific starting points required by agent-based models. BTW models integrate tsunami wave arrival data directly into the LCD analysis to produce map of ***minimum*** speeds that must be maintained to reach safety. Additional information on the methodology is given by Gabel and Allan (2017) and Priest and others (2015, 2016).

2.1 Road and trail network

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

2.2 Hypothetical scenarios

For each community, 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 were then designed with various hypothetical mitigation options 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. Multiple review sessions with community officials ensured local needs and concerns were addressed by the scenarios.

Evacuation time maps showing the time to reach safety at a constant walking speed of 4 ft/sec (fps) are provided for every community in **Appendix A**. Because BTW studies have only been done for a small number of communities along the Oregon coast, the evacuation time maps allow for direct comparison to other existing or future least-cost distance modeling studies for the region (e.g., Wood and others, 2016). Evacuation time maps are excluded from the main body of the report to avoid confusion with BTW results. This is because evacuation time maps assume a constant "slow" rate of evacuation, while ignoring the needed travel speed to safety in order to "beat" the tsunami. Detailed evacuation route maps can be found in **Appendix B**. A final BTW map for Pacific City and Woods is presented in **Appendix C**. These maps provide the same BTW data presented in this chapter, but they are presented in a manner fit for public use with instructions on how to read and interpret BTW data.

Bridge failure was simulated by removing that section of the road network, forcing the model to recalculate routes that originally relied on bridge connectivity. As of the date of this publication, none of the bridges have been designed to withstand significant seismic forces (Greg Cickavage, Tillamook County Public Works, oral commun., 2017). 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. Modeling indicates neither of the two major bridges is essential for evacuation because alternate high ground is roughly equidistant on either side of the bridge. This information can be important when prioritizing which bridges to retrofit or construct as part of a long-term resilience plan.

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

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

For landslide potential, we used the Statewide Landslide Information Database for Oregon (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). From these data we determined that there were no obvious situations where a landslide could completely remove an evacuation route, so we did not consider hypothetical scenarios involving landslides. However, it is 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, multi-story 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. 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.

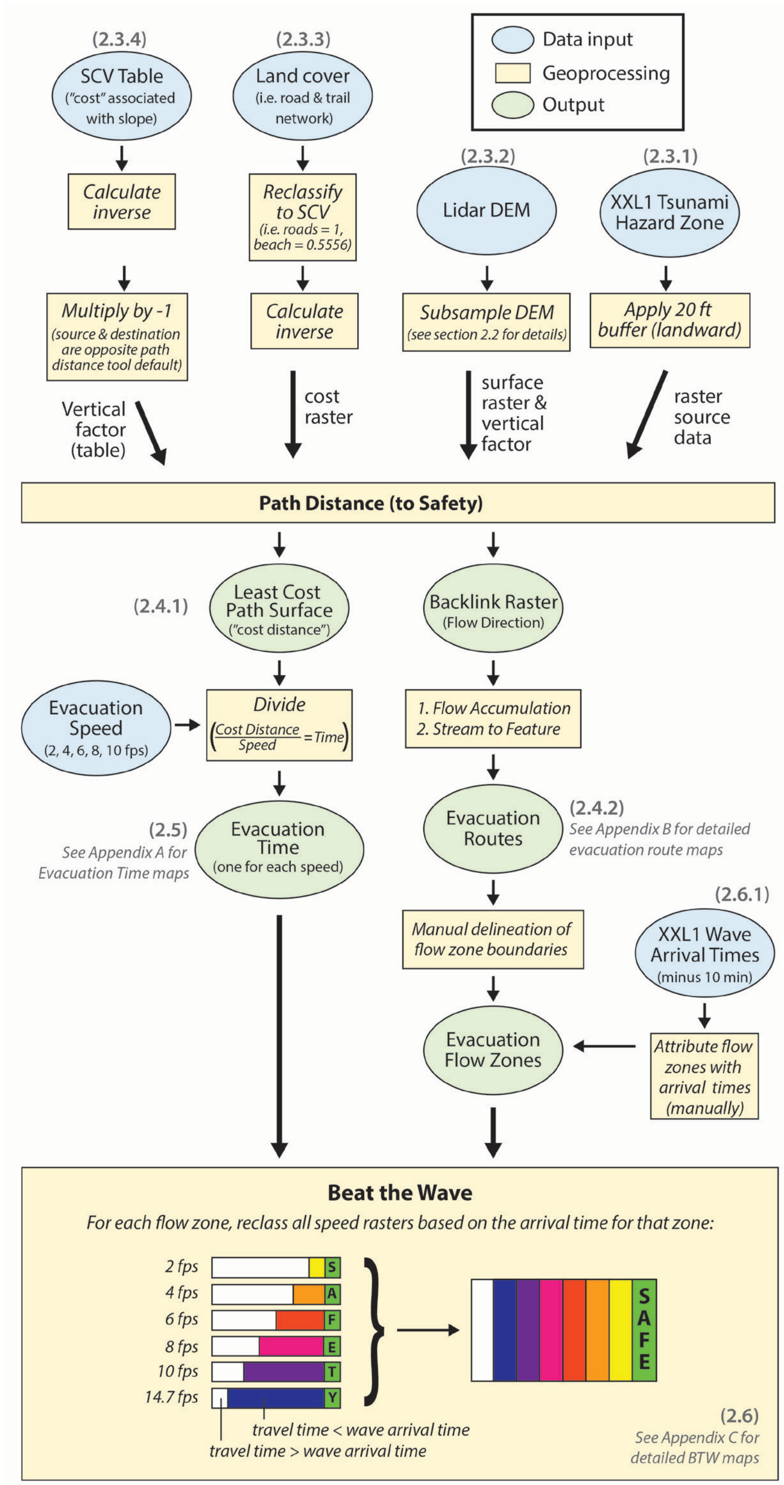
The only mitigation scenario considered for the Pacific City project areas is the construction of a vertical evacuation structure. Overall, the evacuation landscape is quite good, and wayfinding and outreach appear to be more important to survival than significant infrastructure improvements. As a reminder, we are referring to mitigation only in terms of life safety, meaning getting people out of the tsunami zone in the short amount of time between the earthquake and tsunami.

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 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 feet (6 m) beyond 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 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 community brochures (https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm) and online (http://nvs.nanoos.org/TsunamiEvac) for the entire Oregon coast.

For the purposes of this study, safety is reached when an evacuee has walked ~20 feet beyond the limit of tsunami inundation. Safety is also referred to as "high ground" throughout the remainder of this report. Safety *destinations* represent locations on the road and trail network that are ~20 feet beyond the limit of XXL inundation. 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 a sample land cover raster is shown in **Figure 2-3**.

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

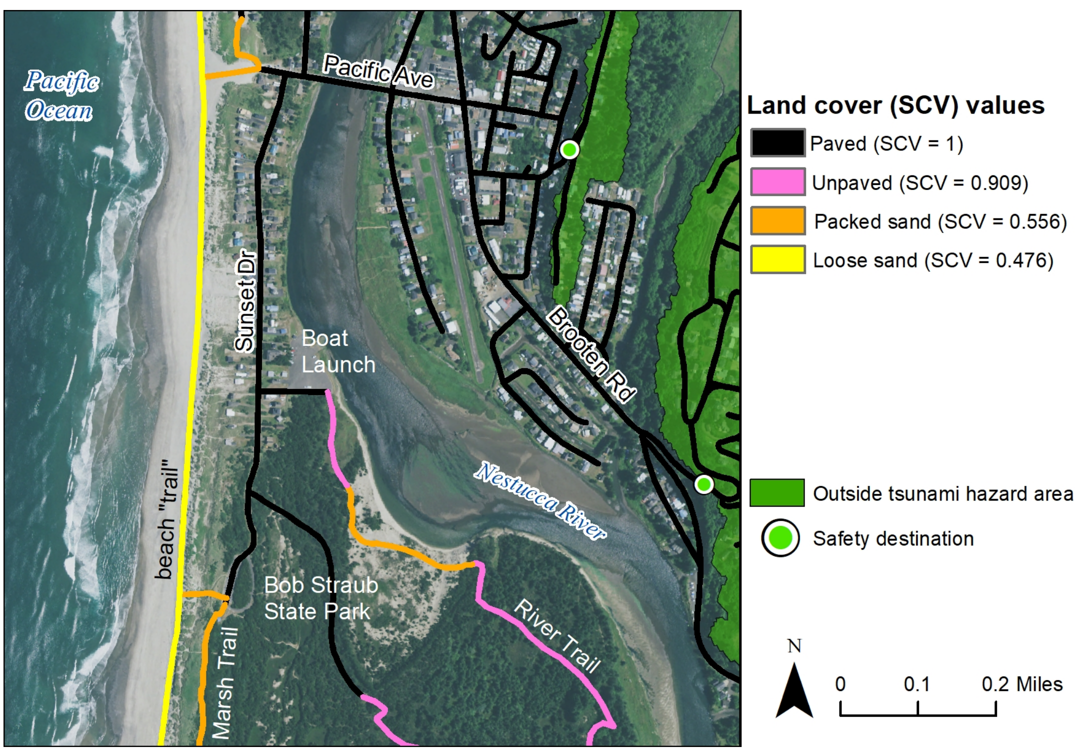
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

*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 land cover raster in Pacific City, 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.

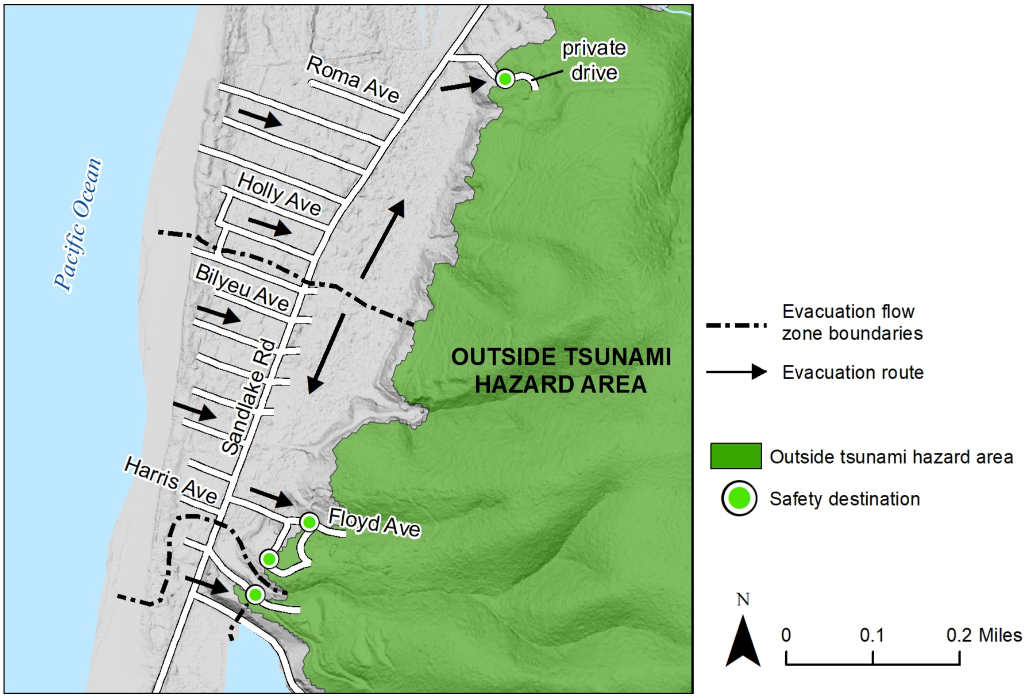
2.4 LCD model outputs

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 route, evacuation time, 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 1700 feet, while the least-cost path distance is 2700 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).



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 presented in **Appendix A**.

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

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

The importance of flow zone boundaries varies depending on the area. In some areas, everyone needs to head in the same general direction (e.g., Nestucca Spit; **Figure 3-6**), and the decision to take one road versus another is minor. In other locations such as the previous example in Tierra Del Mar, flow zone boundaries inform the decision to travel in potentially opposite directions (e.g., north to a private drive or south to Floyd Ave; **Figure 2-4**).

2.5 Evacuation time maps

The path distance surfaces were converted to walking times to compare tsunami arrival times to pedestrian arrival at various critical junctures. This was done by dividing the path distance surface raster by a constant speed (distance ÷ speed = time). We assumed 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 fully explore 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. This is explored further in the next section where we discuss the development of tsunami wave front advance maps and integrating tsunami wave arrival data directly into the LCD analysis to produce beat the wave (BTW) maps that estimate the ***minimum speed*** needed to reach safety ahead of the wave.

2.6 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 they must travel.

2.6.1 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.

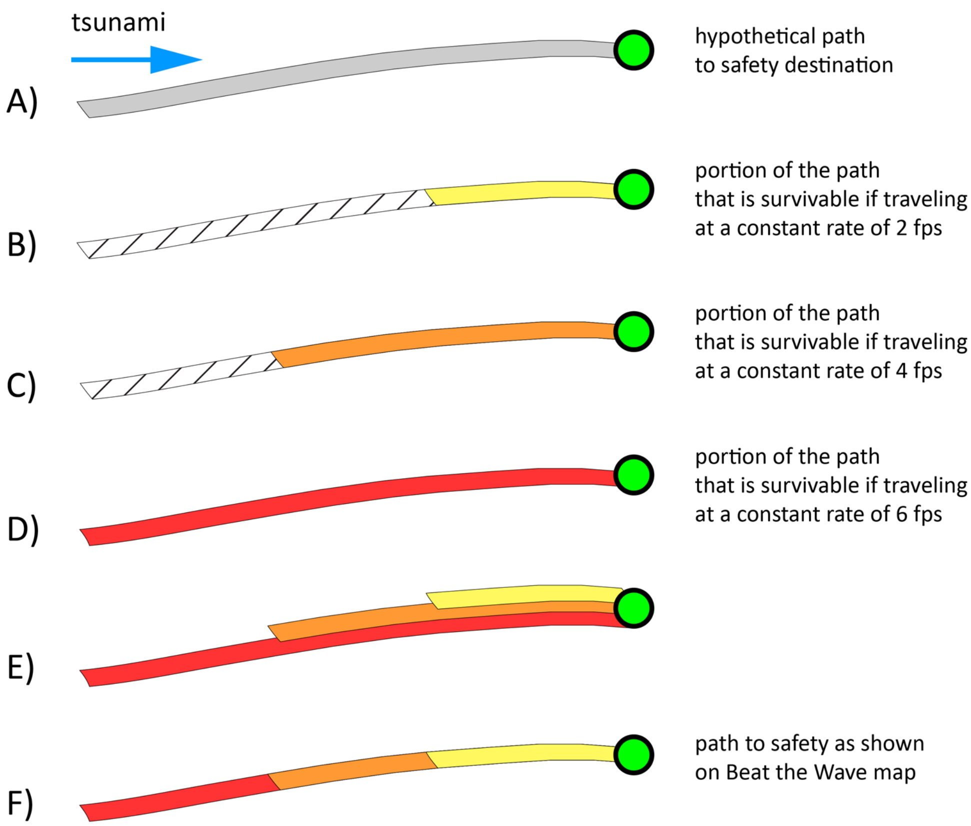
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted 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 (USGS, 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 Nestucca Spit and Sand Lake Recreation Area, we reduced the delay from 10 minutes to 5 minutes to reflect the likelihood of people being outside (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.

2.6.2 Reclassifying evacuation time maps into BTW

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 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**.

Figure 2-5. Illustration of Beat the Wave 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.



Binning of evacuation speeds was initially limited to 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

2.6.3 Reading a BTW map

A BTW map for Pacific City and Woods is provided in **Appendix C**. 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, he/she must account for the time deficit by traveling faster than the required speed for the remainder of the route. We stress this point because the map can be misleading: as a route approaches safety the roads along which one travels show a slower BTW speed, but an evacuee cannot slow down. The slower speed is only relevant for someone starting evacuation from that closer location.

3.0 RESULTS AND DISCUSSION

Results from our tsunami evacuation and BTW analyses are presented separately for each community. The Pacific City project area includes Pacific City, Woods, Nestucca Spit, Tierra Del Mar, and the Sand Lake estuary including Sand Lake Road and the Sand Lake Recreation ("Rec") Area (**Figure 3-1**). In general, we find that the public can escape a maximum-considered Cascadia tsunami from all major population areas with most locations requiring minimum walking speeds of 4 fps (***walk***). The exception is Nestucca Spit, where evacuees must travel a significant distance to reach the nearest safety destination. Although the spit has few permanent residents, Bob Straub State Park has many visitors on busy summer weekends.

Tsunami wave arrivals will be presented first for the entire region. BTW evacuation modeling results will then be presented separately for each community. When applicable, hypothetical scenarios such as bridges failures and liquefaction will be included.

Unless otherwise noted, all scenarios include a 10-minute delay before commencing evacuation to account for the expected disorientated state of people following severe earthquake shaking, and the time required to exit buildings. This delay was reduced to 5 minutes for Nestucca Spit and the Sand Lake Rec Area because people in these locations will be outdoors when the earthquake strikes. Although they may remain in place for the 3–5 minutes of earthquake shaking before beginning their evacuation, the additional ~5 minute delay to exit a building is not necessary. **Table 3-1** represents a summary of the range of speeds and their conversions that will be used throughout the remainder of this report.

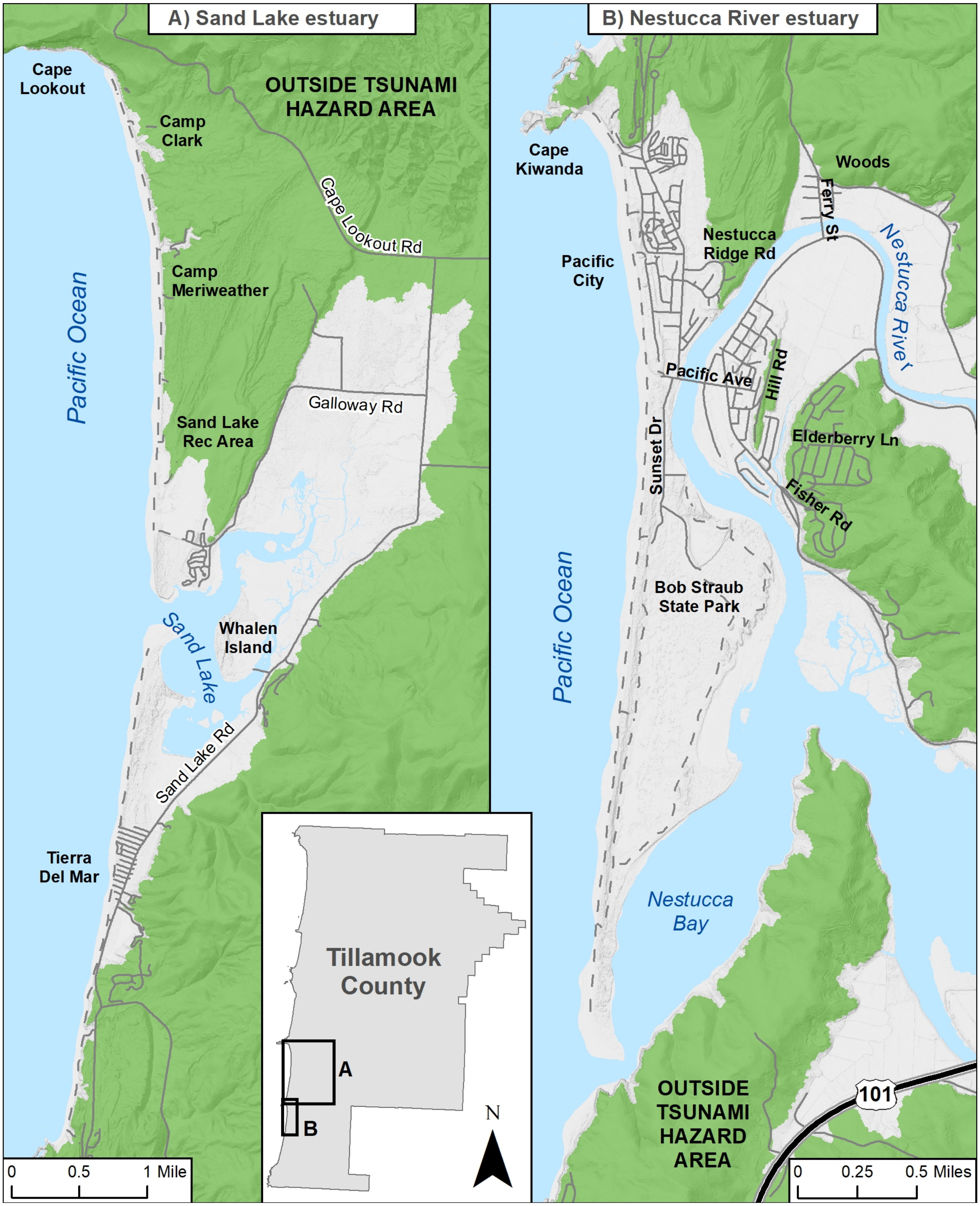
One important note—it is inevitable that following a disaster other factors will contribute to impede travel times. This modeling does not account for these ancillary effects. As a result, ***the public should maintain the overarching goal of immediately evacuating after the earthquake and moving as 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).

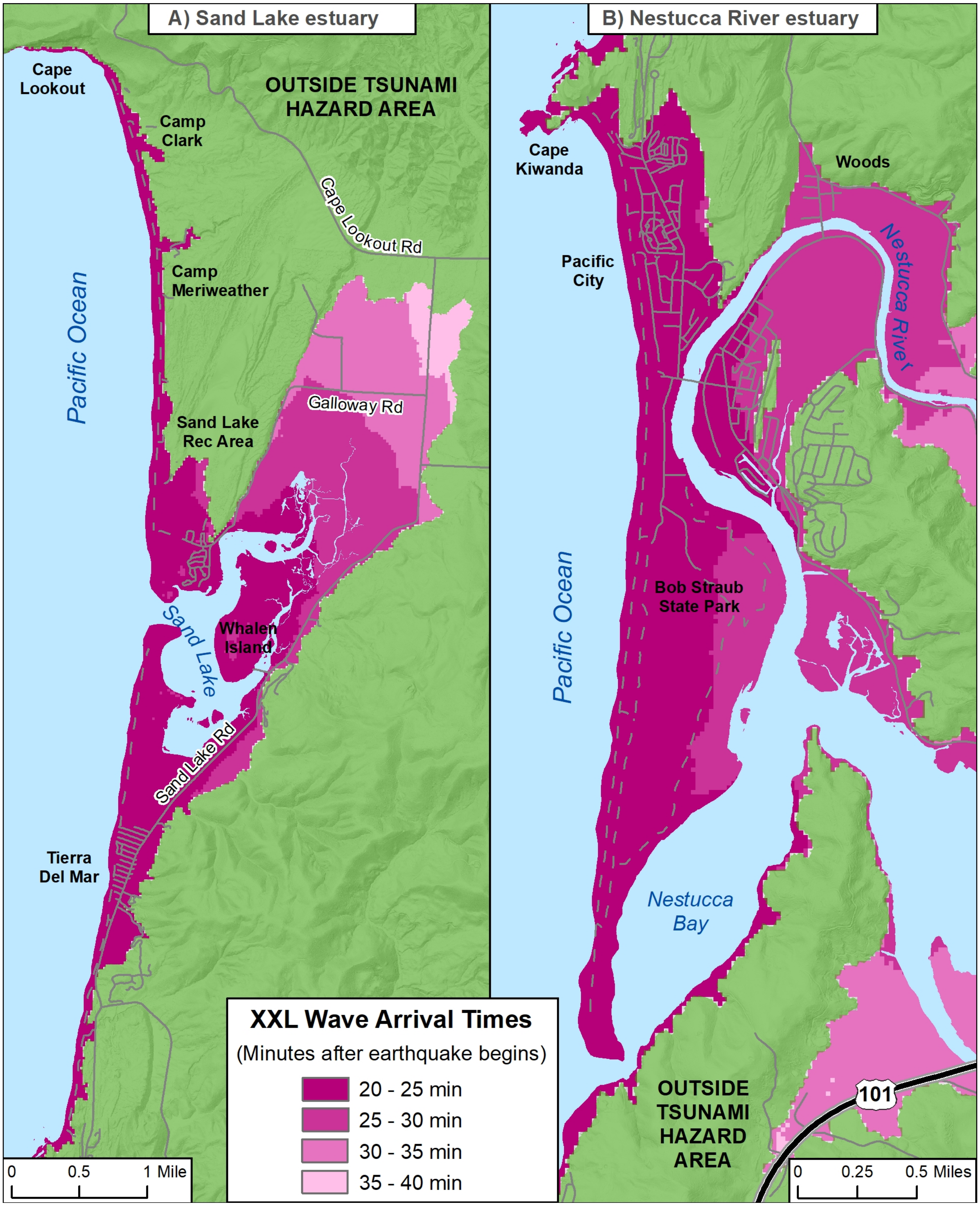
Figure 3-1. Project area map including the communities of Pacific City, Woods, Nestucca Spit, Tierra Del Mar, and Sand Lake. Green is outside the tsunami hazard area.



3.1 Tsunami wave arrivals

Figure 3-2 demonstrates the arrival times for an XXL tsunami in the Pacific City project area. The earliest wave arrivals are along the open coast; the tsunami reaches the beach ~18–20 minutes after the start of the earthquake shaking. By 25 minutes, nearly the entire study area is expected to be inundated with the exception of east Pacific City by Hill Road and Woods, which are inundated by 27 minutes after the earthquake. The tsunami continues up the Nestucca River past Woods, reaching its farthest upriver extent after about 1 hour at river mile 8, about 1 mile upstream from Cloverdale (not shown in figure). The tsunami travels up the Little Nestucca River approximately 3 miles, reaching its farthest extent near the town of Meda after ~50 minutes. The entire Sand Lake estuary is inundated by 40 minutes, reaching its furthest extent ~0.2 miles south of the Sand Lake Road/Cape Lookout Road intersection. Additional waves will continue to strike the coast and enter the estuary, causing water levels to fluctuate for up to 12 hours after the earthquake. Tsunami wave arrival time data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

Figure 3-2. Illustration of XXL tsunami wave arrivals after a Cascadia subduction zone earthquake for the (A) Sand Lake and (B) Nestucca River estuaries.



3.2 Pacific City

The community of Pacific City can be divided in two parts separated by the Nestucca River. Everything west of the Pacific Avenue bridge ("Beachy Bridge") over the Nestucca River is inundated in the XXL tsunami scenario, with high ground to the north (Cape Kiwanda) and to the east (Nestucca Ridge Road). The low-lying areas on the east side of the river are also inundated, with Hill Road and the Elderberry Lane community providing high ground (**Figure 3-1**). The Nestucca Rural Fire and Rescue Station #82 and the Pacific City state airport are within the inundated area; no other critical facilities (i.e., schools or hospitals) are present in Pacific City. *For the remainder of the report, we will refer to Pacific City "West" and "East" to differentiate between the inundated areas of Pacific City on either side of the Nestucca River.*

Overall, results for Pacific City are positive due to the community's proximity to high ground. Our modeling indicates the following:

1. Several evacuation routes are available to the public. This means evacuation to high ground can be achieved in a timely manner; however, knowing which direction to travel is important.
2. Beachy Bridge is not crucial to evacuation.
3. Modeled BTW pedestrian evacuation speeds for much of the community were determined to be low (***walk***), regardless of the potential for bridge failure. Because of this, no mitigation options were evaluated for Pacific City (i.e. no hypothetical new evacuation trails or vertical evacuation structures). As noted previously, these are minimum recommended speeds, and the public should endeavor to evacuate as rapidly as possible.
4. Liquefaction will make evacuation more difficult; however, mitigation options for this hazard are beyond the scope of this study.

3.2.1 Scenario 1 — Existing road network

Figure 3-3A and **Figure 3-4**A show the least-cost (path) distance modeling for Pacific City West and East, respectively, assuming the existing road network including bridges remains intact. Colors on top of the road network reflect 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. Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesIn feature dataset.

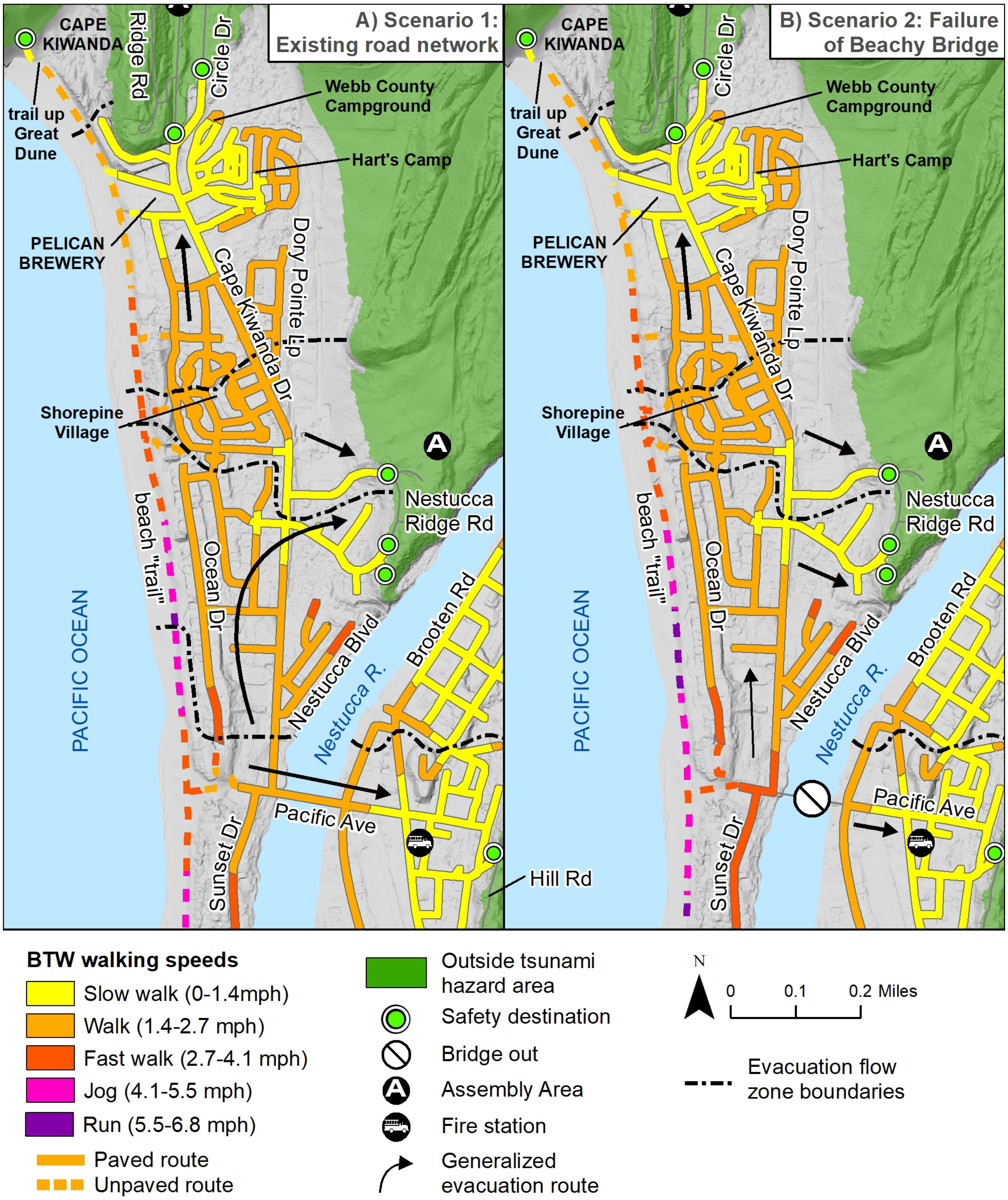
3.2.1.1 Pacific City West

Figure 3-3A shows that evacuation in Pacific City West looks extremely positive. Even though tsunami arrival times for the neighborhood are on the order of ~20–25 minutes (**Figure 3-2**), most locations are relatively close to evacuation destinations (i.e., safety). The entire area is characterized with **minimum** evacuation speeds of ***slow walk*** and ***walk*** except for 300-400 feet of ***fast walk*** at the end of Ocean Drive, Nestucca Boulevard, and Ray Avenue (adjacent to Nestucca Boulevard).

The area is characterized by five evacuation community flow zones (corridors). For anyone on the beach itself, high ground can be found up Cape Kiwanda by following the heavily-used footpath to the top of the dune. The northern half of town including Pelican Brewery and the campgrounds has high ground to the north via Cape Kiwanda Drive. The campgrounds can access this same high ground via Circle Drive.

The third and final piece of high ground west of the river is on Nestucca Ridge Road, which can be accessed from its northern or southern connection with Cape Kiwanda Drive. This road is also the nearest safety destination for the southern half of Pacific City West (including Sunset Drive and Nestucca Spit). The nearest safety destination for the area immediately west of Beachy Bridge is on Hill Road, in the neighborhood of Pacific City East.

Figure 3-3. Beat the Wave modeling in Pacific City West for (A) Scenario 1: Existing road network, and (B) Scenario 2: Failure of Beachy Bridge. Colors on top of the road network reflect BTW minimum walking speeds and black dashed lines define evacuation flow zone boundaries.

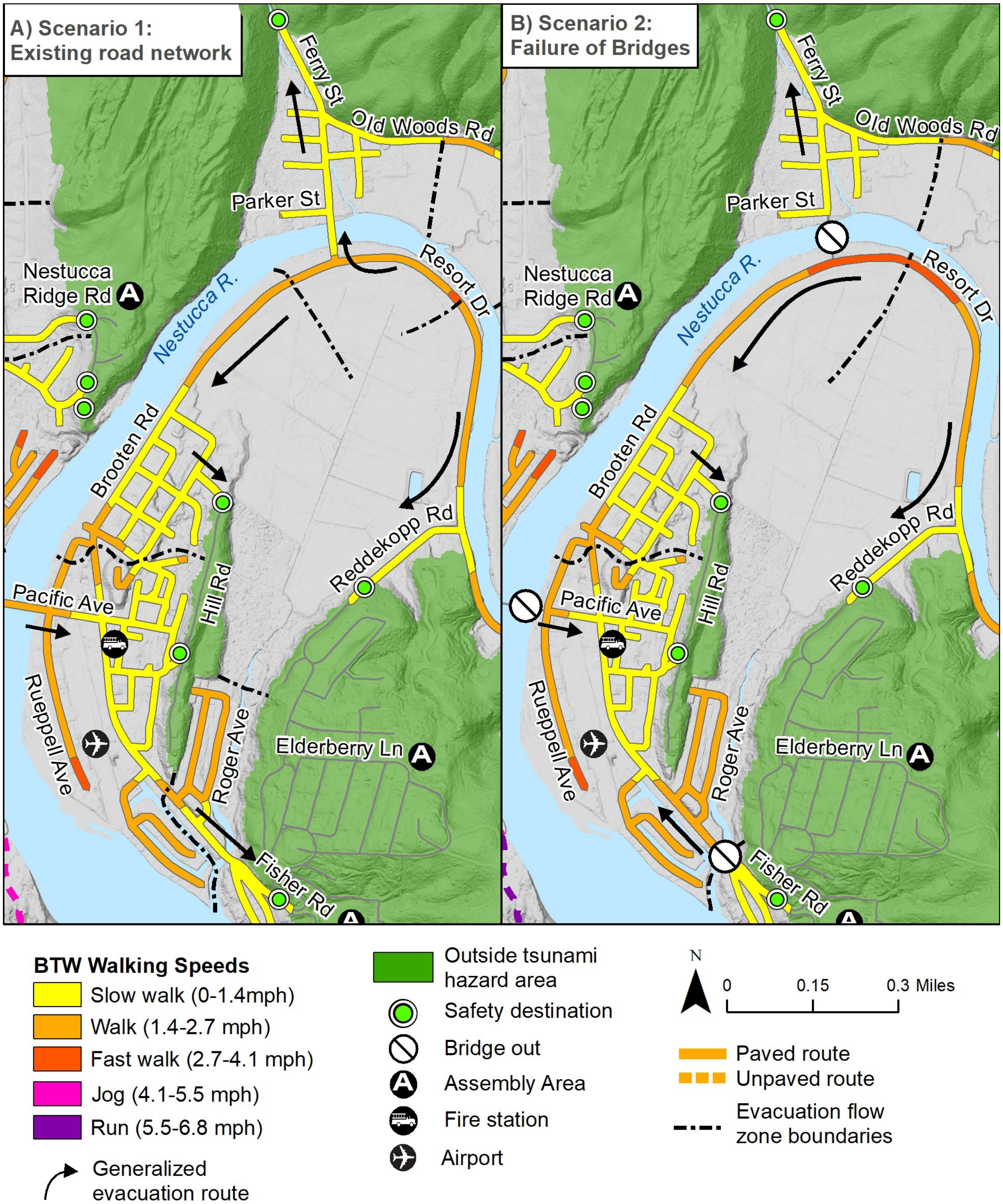


3.2.1.2 Pacific City East

Figure 3-4A shows that evacuation in Pacific City East also looks extremely positive. It takes the tsunami about 5 additional minutes to reach high ground by Hill Road (**Figure 3-2**). Most locations are relatively close to evacuation destinations (i.e., safety), and nearly the entire area is characterized with a **minimum** evacuation speed of ***slow walk*** with a few blocks of ***walk***.

The area is characterized by three evacuation community flow zones. All of Pacific City East evacuates to Hill Road, which can be accessed from the north or south end. The southern portion evacuates across the Brooten Creek Bridge to Fisher Road. The community of Woods evacuates to the north via Ferry Street. This community will be discussed in detail in the following section.

Figure 3-4. Beat the Wave modeling in Pacific City East and Woods for (A) Scenario 1: Existing road network, and (B) Scenario 2: Failure of Beachy Bridge. Colors on top of the road network reflect BTW minimum walking speeds, and black dashed lines define evacuation flow zone boundaries.



3.2.2 Scenario 2 — Failure of bridges

Figure 3-3B and **Figure 3-4**B show the least-cost (path) distance modeling for Pacific City West and East, respectively, assuming Beachy Bridge, Brooten Creek Bridge, and Woods Bridge fail during earthquake shaking. Detailed evacuation routes, 4-fps evacuation times, and a final BTW map for this scenario can be found in the appendix (**Figure B-1**, **Figure A-1**, and **Figure C-1**, respectively). **Appendix D** presents evacuation flow zones for this scenario (without BTW speed data). Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

3.2.2.1 Pacific City West

Beachy Bridge over the Nestucca River is likely to fail during earthquake shaking. Although it may be possible for some to swim across the river and reach high ground on Hill Road, as shown in scenario 1, (**Figure 3-3**A), we considered a scenario restricting evacuation to the road network. **Figure 3-3**B shows that the evacuation landscape is virtually unchanged when the Beachy Bridge is unavailable for evacuation. A side-by-side comparison of the bridge "in" and "out" (**Figure 3-3**) shows that the bridge is only used by a small stretch of road immediately west of the bridge. The extra distance for those evacuees who now have to walk to reach Nestucca Ridge Road is so small to not make a significant impact on minimum walking speeds. There is a slightly larger impact on evacuation from the spit, which can be seen at the bottom of the figure; BTW speeds on Sunset Drive increase from ***walk*** to ***fast walk***. This will be discussed further in section 3.4.

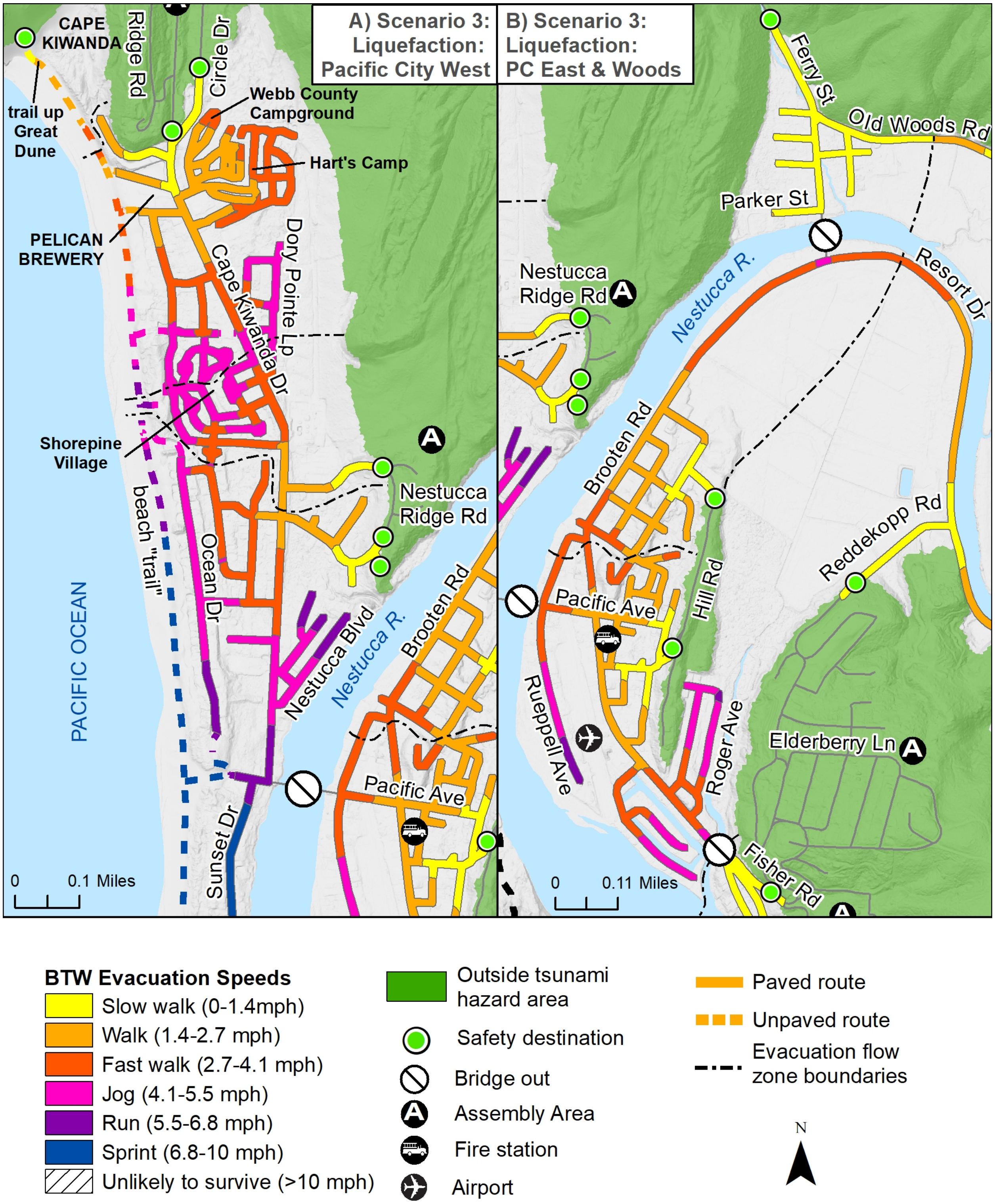
3.2.2.2 Pacific City East

The bridge over Brooten Creek (Brooten Creek Road) is small but crosses a significant ravine that will be difficult for many to scramble across after the earthquake. Because this bridge is also likely to fail during the earthquake, we examined the evacuation landscape were this route to be cut off (**Figure 3-4**B). Results show a slight increase in walking speeds for those nearest the bridge on the west side (Stephen and Roger Avenues), who are now blocked from their original safety destination on Fisher Road. No change is observed on the east side because Fisher Road remains available.

3.2.3 Scenario 3 — Liquefaction

Because Pacific City is surrounded by the Pacific Ocean and the Nestucca River and sits on mostly unconsolidated sand, liquefaction is likely to influence evacuation travel to high ground. To that end, we considered a scenario where all roads and trails were modeled with a loose sand land cover value. This approach slows modeled pedestrian evacuation speed, simulating the difficulty evacuees might encounter when trying to walk across roads covered with sand and mud from sand boils and other liquefaction features (e.g., **Figure 2-1**). No routes were blocked. **Figure 3-5** shows a significant increase in modeled BTW speeds throughout the area, with even those closest to high ground increasing from ***slow walk*** to ***walk***. A large portion of the community increases from ***walk*** and ***fast walk*** to ***jog*** including the Shorepine and Dory Pointe communities. Sections of Ocean Drive, Nestucca Boulevard, Ray Avenue, and Rueppell Avenue increase to ***run***. Evacuation flow zones are virtually unchanged from scenario 2 (we chose to not include bridges in this scenario due to their likely failure). Although this is only a basic look at how liquefaction could impact evacuation, these results suggest that evacuation challenges could have a significant impact on survivability and that additional mitigation should be considered.

Figure 3-5. Beat the Wave modeling in Pacific City and Woods for Scenario 3: Liquefaction. Colors on top of the road network reflect BTW minimum walking speeds, and dashed black lines define boundaries between evacuation flow zones. (A) Pacific City West and (B) Pacific City (PC) East and Woods.



3.2.4 Discussion

Overall, the evacuation landscape in Pacific City is very positive. The prevalence of high ground to the north (Cape Kiwanda) and east (Nestucca Ridge Road in Pacific City West and Hill Road in Pacific City East) results in minimum evacuation speeds categorized no higher than a ***walk*** for nearly all of town. Although Beachy Bridge and Brooten Creek Bridge are unlikely to survive the earthquake shaking, our results show that there is no need to use them for evacuation purposes. This does not discount their importance for post-event recovery and community connectivity.

Incorporating liquefaction into the model does significantly alter BTW evacuation results. Although not much can be done to directly mitigate for liquefaction, wayfinding efforts will help reduce evacuation delays due to route confusion and will provide additional time to deal with the difficulty due to walking across liquefied terrain.

No landslide scenarios were considered for this area, but there may be some slope failures in the vicinity of Cape Kiwanda, Cape Kiwanda Drive, and Circle Drive. We do not anticipate the loss of every option for reaching high ground; rather, it is likely that at most one or two routes will be blocked but adjacent roads or clear ground could be used to reach safety in a comparable distance.

Finally, we recognize that high ground in Pacific City East (Hill Road) can be accessed from additional directions via unmarked roads, driveways, and backyards. We encourage everyone to consider their best route.

3.3 Woods

The community of Woods sits on a narrow strip of land between the Nestucca River and the Oregon Coast Range (**Figure 3-1**). Although the entire community is within the XXL inundation zone, there is high ground to the north via Ferry Street. The Woods Bridge over the Nestucca River on Ferry Street connects Woods with Pacific City via Brooten Road. The Woods County Campground and a small collection of homes reside along Brooten Road and Resort Drive adjacent to the south end of the bridge.

The tsunami reaches Woods ~26 minutes following the start of earthquake shaking. We considered vulnerabilities due to bridge failure and liquefaction. No mitigation options were evaluated although it is possible that some landsliding could impede evacuation on Sand Lake Road, which is technically the only evacuation route for the community. The hardening of this road or the construction of new evacuation trails may be desirable for long-term resilience.

3.3.1 Scenario 1 — Existing road network

Because the tsunami arrives in ~30 minutes (**Figure 3-2**) and most locations are relatively close to evacuation destinations, the entire area is characterized with a **minimum** evacuation speed of ***slow walk*** (**Figure 3-4**A). There is one evacuation flow zone for the area, via Ferry Street. Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_ Evacuation_Modeling geodatabase, XXL1_BridgesIn feature dataset.

3.3.2 Scenario 2 — Failure of Ferry Street Bridge

The Woods Bridge is likely to fail during earthquake shaking. Although it may be possible for some to swim across the river and reach high ground up Ferry Street, as shown in scenario 1 (**Figure 3-4**A), we considered a scenario restricting evacuation to the road network. **Figure 3-4**B shows that the evacuation landscape is virtually unchanged when the Woods Bridge is unavailable for evacuation. A side-by-side comparison of the bridge "in" and "out" (**Figure 3-4**) shows that the bridge is used by only a small stretch of road immediately south of the bridge. This does result in an increase in walking speed from ***slow walk*** to ***walk*** for Woods County Campground and a few residences. See **Figure B-1**, **Figure A-1**, and **Figure C-1** for detailed evacuation routes, 4-fps evacuation times, and a final BTW map for this scenario. **Appendix D** presents evacuation flow zones for this scenario (without BTW speed data). Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_ Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

3.3.3 Scenario 3 — Liquefaction

As with Pacific City, the river-level location of Woods suggests a high probability that its roads will be affected by liquefaction. Results are shown in **Figure 3-5**B. Due to the close proximity of high ground, results are unchanged from **Figure 3-4**B.

3.3.4 Discussion

As expected, Woods has extremely low evacuation difficulty due to its close proximity to high ground. There is no reliance on bridges and even the added complication of liquefaction does not significantly alter the modeled results. Nevertheless, wayfinding is still essential to survival. The modeling assumes an evacuee does not take a wrong turn, which increases route distance and time and increases the possibility of being overcome by the tsunami. Landslides may be an issue in this area because of the steep slopes along Ferry Street as it heads north; however, high ground is still attainable via off-road paths as well as an unmarked private path off Parker Road heading west.

3.4 Nestucca Spit

For this project, Nestucca Spit is defined as the region south of Pacific Avenue including Sunset Drive, Bob Straub State Park, and the trail network on the spit (**Figure 3-1**). In total, this area extends over 2 miles between Beachy Bridge and the mouth of the Nestucca River. The first 0.5 miles south of Beachy Bridge contains Sunset Drive, which is a paved road containing the only housing in the area (a mix of permanent and transient), and a popular boat launch for the Nestucca River. Sunset Drive ends in the Bob Straub State Park day-use parking lot. A trail network extends all the down to the tip of the spit, about 2.3 miles south of Beachy Bridge. No overnight camping is allowed on the spit. High ground for everyone on the spit is Nestucca Ridge Road, 0.6 miles north of Beachy Bridge. This destination becomes increasingly difficult to achieve farther down the spit.

The first tsunami wave arrives on the beach in 20 minutes, similar to the beach in Pacific City; however, arrival times within the spit are slightly more complicated because the tsunami comes up the river simultaneously as it overtops the foredune. Bob Straub parking lot and the boat launch are inundated 22 minutes after the earthquake, and the tsunami reaches Beachy Bridge 1 minute later (**Figure 3-2**).

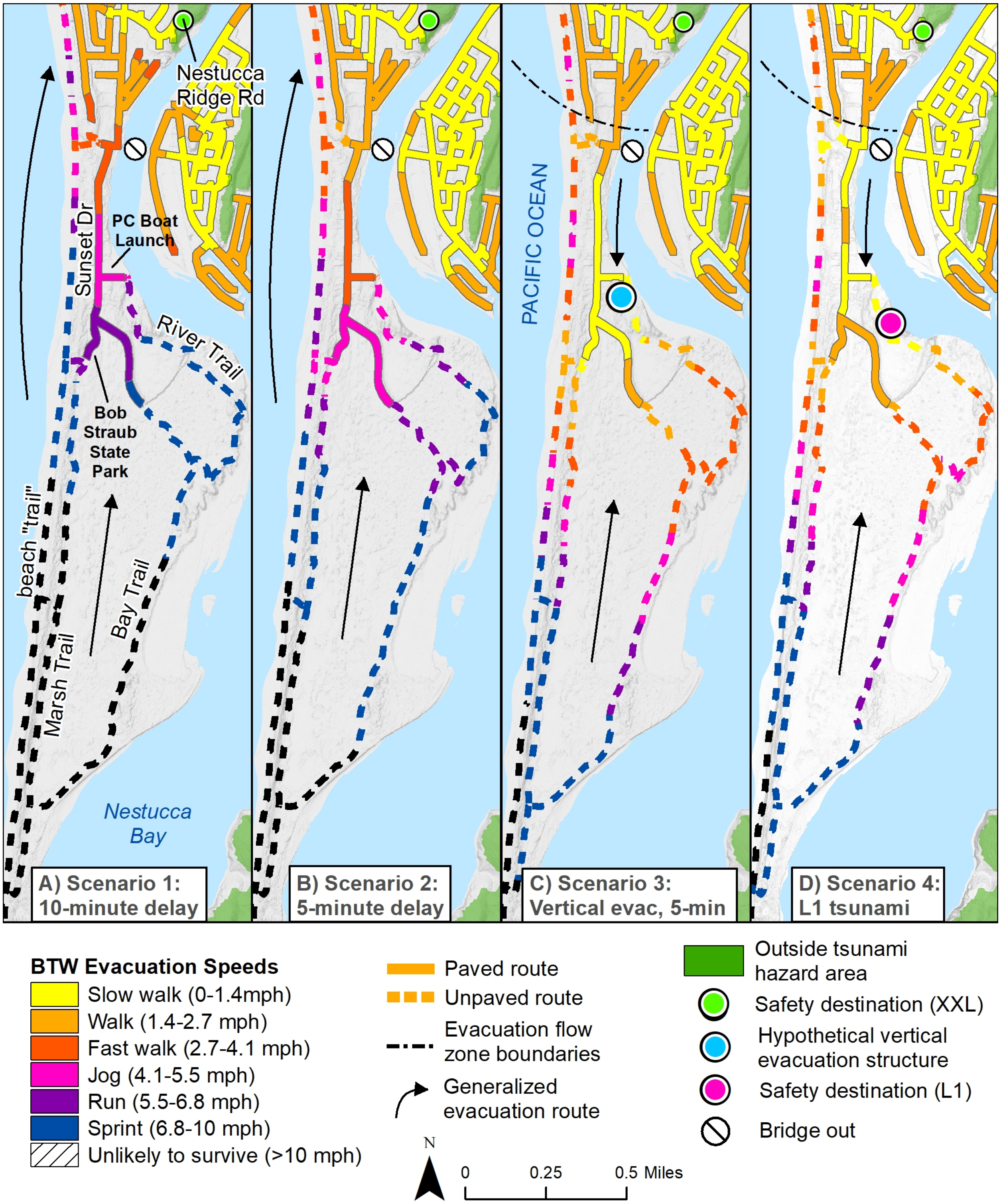
Overall, results are similar to what we have seen in other remote coastal areas, namely that much faster travel speeds are needed to reach safety, safety destinations are limited, and land cover conditions (i.e., loose sand and wetlands) can make evacuation difficult. The lack of high ground on the spit means there are not a lot of options for mitigation aside from a vertical evacuation structure, which is considered in scenario 3, below. Although there is no safe ground on the spit in the case of an XXL tsunami, there are a few dunes near Bob Straub that are high enough to be considered safe in a Large (L1) tsunami scenario. Because the modeling shows that an XXL scenario is unsurvivable for virtually everyone on the spit, we present results for a Large tsunami in scenario 4. With the BTW results for a Large scenario, Oregon Parks and Recreation, the community of Pacific City, Tillamook County, and the public can consider an alternative evacuation solution (e.g., head to a large dune on the spit that may be high enough depending on the size of the actual tsunami).

We also model a reduction from the 10-minute delay to a 5-minute delay because people in this area are more likely to be outside or in a tent, which means their evacuation can generally start more quickly compared with people evacuating from buildings. Due to the lack of infrastructure, the only vulnerability considered was liquefaction.

3.4.1 Scenario 1 — Failure of Beachy Bridge

The nearest high ground for the spit is on Hill Road in Pacific City East, across Beachy Bridge; however, as discussed in section 3.2.2, Beachy Bridge is expected to fail during earthquake shaking. This means the nearest high ground for the spit is Nestucca Ridge Road. **Figure 3-6**A shows an increasingly difficult evacuation landscape at the south end of Pacific City. Evacuees on Sunset Drive must travel at a ***fast walk*** or ***jog***, those at Bob Straub parking lot must ***jog***, those ~0.5 miles south of that must ***sprint***, and those located in the last ~1 mile of trails are ***unlikely to survive***. See **Figure A-2** for 4-fps evacuation times for Nestucca Spit. Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

Figure 3-6. Beat the Wave modeling on Nestucca Spit for (A) Scenario 1: Failure of Beachy Bridge, (B) Scenario 2: 5-minute evacuation delay, (C) Scenario 3: hypothetical vertical evacuation structure, and (D) Scenario 4: L1 (rather than XXL) tsunami. Colors on top of the road network reflect BTW minimum walking speeds, and dashed black lines define boundaries between evacuation flow zones. PC is Pacific City.



3.4.2 Scenario 2 — 5-minute delay

To better understand the effects of evacuation delay, we reduced the 10-minute evacuation departure delay to 5 minutes for areas where people are already outside, either in a tent or RV. Such an approach allows for a faster transition from waiting out the earthquake shaking to evacuating and is relevant for Bob Straub State Park and anyone recreating on the spit. **Figure 3-6**B demonstrates the resulting minimum walking speeds associated with a 5-minute evacuation delay. Bob Straub parking lot decreases to ***fast walk*** and the area ***unlikely to survive*** is pushed ~0.5 miles south. These results confirm the importance of evacuating as soon as possible after earthquake shaking begins.

3.4.3 Scenario 3 — Vertical evacuation structure

Because people recreating out on the spit are *unlikely to survive* a CSZ event, due to the required fast travel speeds needed to beat the wave (even with a shorter evacuation delay), we evaluated the effect of constructing a vertical evacuation structure at the Pacific City Boat Launch. This location was chosen because it is a well-known and popular location centrally located between the homes on Sunset Drive and Bob Straub parking lot with the highest concentration of people on the beach and trails. As expected, BTW speeds are dramatically reduced by this hypothetical structure with a further reduction in the area classified as ***sprint*** and only a tiny section of beach classified as ***unlikely to survive*** (**Figure 3-6**C).

3.4.4 Scenario 4 — Large tsunami scenario

The unfortunate reality is that surviving the XXL tsunami on Nestucca Spit, especially at the southern end, is going to be extremely difficult and for many impossible. Another option is to consider the Large (L1) tsunami scenario instead of XXL. Because it is a smaller tsunami, one dune on the spit is considered safe. The L1 scenario still covers 95% of the likely inundation (XXL covers 100%), meaning that there is only a 5% chance that high ground outside L1 will be inundated by a larger tsunami.

Figure 3-6D shows that minimum walking speeds reduce dramatically when high ground can be found on the spit rather than having to walk to Nestucca Ridge Road. Results are quite similar to scenario 3 (**Figure 3-6**C), the hypothetical vertical evacuation structure, because the naturally high dune is ~800 feet south of the boat launch. Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, L1_BridgesOut feature dataset.

3.4.5 Discussion

Nestucca Spit has significant evacuation challenges, as is typical of spits along the Oregon coast. There is only one safety destination for the entire ~2.5 mile stretch: Nestucca Ridge Road in Pacific City West. Although reducing the initial evacuation delay from 10 minutes to 5 minutes does improve the situation, evacuees south of the Bob Straub parking lot must maintain a ***sprint*** to reach safety with those the last ~0.5 miles of trail adjacent to the mouth of the Nestucca River ***unlikely to survive***. The only mitigation option is to construct a vertical evacuation structure. Our modeling shows the improvement such a structure would have: the highest density of people – evacuees from homes on Sunset Drive and the parking lot for Bob Straub – could reach the structure at a ***slow walk***; evacuees on nearby trails would need to maintain ***walk*** speed. Farther down the spit evacuation remains difficult; however, we chose not to place the vertical evacuation structure farther south because of the relative paucity of people. A second structure farther south on the spit would likely remove the worst walking speed categories (***sprint*** and ***unlikely to survive***).

These analyses presuppose that any vertical evacuation structure have adequate capacity for the population served and is designed and constructed to remain intact and accessible after the earthquake shaking while also resisting tsunami forces and scour. The significant height of the structure, potential large footprint, and large cost are likely to be a deterrent. Costs versus benefits must be carefully evaluated among all these options, including the possibility of designing a structure built to withstand a smaller tsunami, such as that modeled in the L1 scenario, characterized by significantly shallower flow depths.

One alternative to constructing a vertical evacuation structure is to direct people to a vegetated dune near the boat launch, which is high enough to be outside the L1 tsunami zone (but not high enough to withstand XXL1). Without suitable mitigation efforts directed at constructing a vertical evacuation structure or establishing signage directing people to L1 high dunes, we anticipate some loss of life because the time required to "beat the wave" to safety in this area is too long relative to the arrival time of the tsunami.

3.5 Tierra Del Mar

The community of Tierra Del Mar (TDM) sits on a narrow strip of land between the Pacific Ocean and the Oregon Coast Range (**Figure 3-1**). Although the entire community is within the XXL inundation zone, there are several roads leading to high ground.

The tsunami reaches TDM ~20 minutes after the start of earthquake shaking. We considered the added evacuation difficulty due to liquefaction in scenario 2. No mitigation options were evaluated, although it is possible that some landsliding could impede evacuation on one or more evacuation routes. The hardening of these roads may be desirable for long-term resilience.

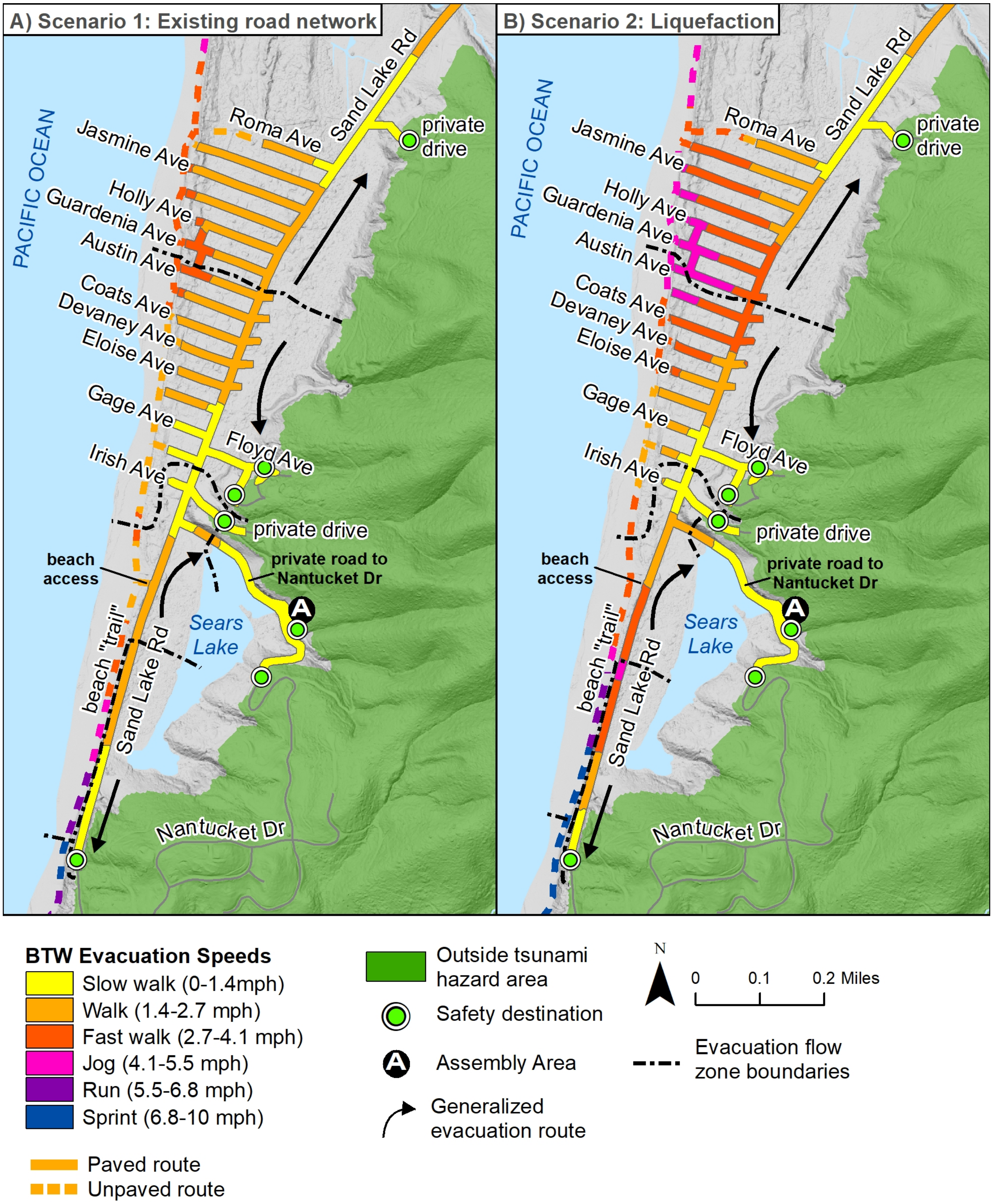
3.5.1 Scenario 1 — Existing road network

Despite proximity of Tierra Del Mar to the ocean and the somewhat early tsunami wave arrivals, high ground is near enough to result in BTW minimum walking speeds of ***walk*** for all of town with a few small blocks of ***fast walk*** by Austin Avenue. The area is characterized by five evacuation flow zones. A private drive (marked with an evacuation sign) provides the nearest high ground for the north end of town, from Guardenia Avenue to Roma Avenue. The central part of town evacuates up Floyd Avenue, while the southern area evacuates up Nantucket Road or an adjacent private drive (unmarked). The very southern portion of Sand Lake Road evacuates south along Sand Lake Road toward Cape Kiwanda, although there are no residences or beach access parking lots in this evacuation flow zone. **Figure B-2** and **Figure A-3** provide detailed evacuation routes and 4-fps evacuation times for this scenario. **Appendix D** presents evacuation flow zones for this scenario (without BTW speed data). Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesIn feature dataset.

3.5.2 Scenario 2 — Liquefaction

As with the other communities already discussed, liquefaction will likely increase evacuation difficulty for Tierra Del Mar. **Figure 3-7**B shows higher minimum BTW walking speeds than in scenario 1 (**Figure 3-7**A); however, the increases are not nearly as great as observed for Pacific City (**Figure 3-5**). The area from Devaney Avenue to the north end of town increases to a ***fast walk*** with a small area by Austin avenue increasing to ***jog***.

Figure 3-7. Beat the Wave modeling in Tierra Del Mar for (A) Scenario 1: Existing road network, and (B) Scenario 2: Liquefaction. Colors on top of the road network reflect BTW minimum walking speeds, and black dashed lines define evacuation flow zone boundaries.



3.5.3 Discussion

Overall, Tierra Del Mar has relatively low evacuation difficulty due to its close proximity to high ground. There is no reliance on bridges, but liquefaction would likely make evacuation more difficult. As always, wayfinding is essential to survival. The modeling assumes an evacuee does not take a wrong turn, which increases route distance and time and increases the possibility of being overcome by the tsunami.

A low-lying marsh between the community and high ground to the east prevents the construction of an additional evacuation route in the middle of town (between a private drive north of town and Floyd Avenue in the south), which would reduce the one section of town that has slightly higher walking speeds. That marsh, however, does not appear to affect the evacuation routes that currently exist, and as long as evacuees know which direction to walk, safety is attainable.

Sand Lake Road heading south toward Pacific City contains a well-known landslide that may impede evacuation in that area. Fortunately, no one lives in that evacuation flow zone, and Nantucket Road provides an alternative source of high ground for anyone who happens to be in that area.

3.6 Sand Lake

The final region included in the Pacific City study encompasses the entirety of the Sand Lake estuary including Whalen Island, the Sand Lake convenience store, and the Sand Lake Rec Area (**Figure 3-1**), a part of the Siuslaw National Forest. The modeled XXL tsunami inundates most of Sand Lake Road and reaching its farthest extent ~0.5 miles south of Cape Lookout Road. Modeling was done on the open beach as far north as the base of Cape Lookout, although the figures shown in the text do not include the northernmost extent (results can be found in the digital data).

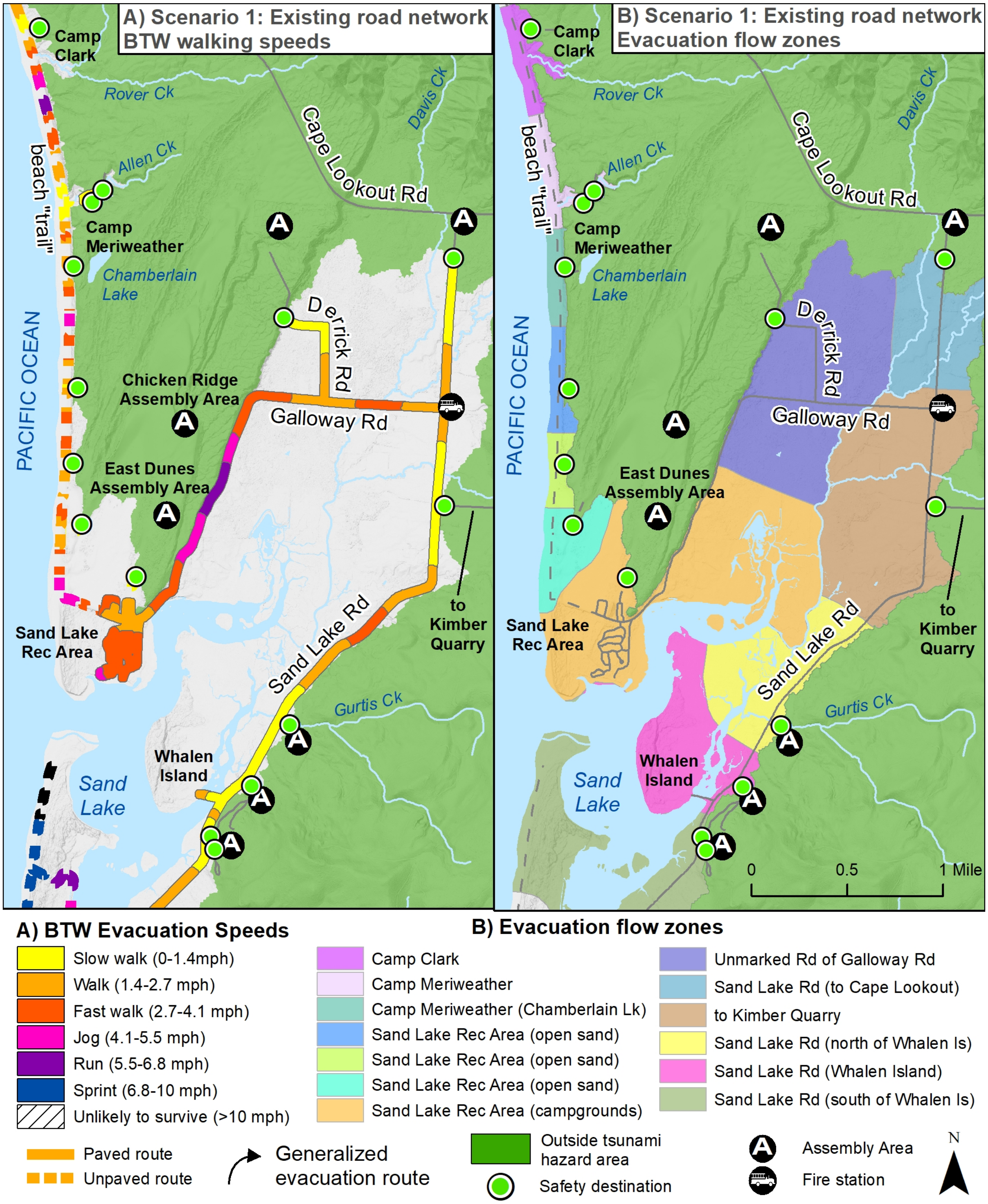
Open coast wave arrivals are on par with Pacific City and Nestucca Spit, ~20 minutes after the earthquake (**Figure 3-2**). The tsunami arrives at Whalen Island and the Sand lake campgrounds in 24 minutes, and the convenience store in 34 minutes.

Overall, results show that evacuees can reach safety with reasonable BTW walking speeds. High ground is very close for evacuees in some areas, while others must travel slightly farther and know which way to go. We model a reduction in the 10-minute delay for the high concentration of people in the Sand Lake Rec Area because people in this area are more likely to be outside or in a tent, which means their evacuation can generally start more quickly compared with people evacuating from buildings. We also consider liquefaction for this area.

3.6.1 Scenario 1 — Existing road network

Overall, **Figure 3-8** reflects a positive evacuation landscape for the Sand Lake estuary. BTW speeds shown in **Figure 3-8**A show that almost all of Sand Lake Road including Whalen Island can reach high ground at a ***slow walk*** or ***walk*** with ~0.2 miles of ***fast walk***. One notable exception to this pattern is the portion of Galloway Road heading south toward the Sand Lake Rec Area parking lot and campgrounds. This area is categorized with minimum walking speeds of ***fast walk*** through ***run***; however, the modeling does not acknowledge the fact that high ground is present immediately adjacent to the road and one would need only to scramble up the hill beside the road to reach high ground in a matter of a few minutes. There are also a few unmarked roads in this stretch that would help reduce the distance to high ground. **Figure 3-8**B summarizes the evacuation flow zones for the region. See **Figure B-2** and **Figure A-4** for detailed evacuation routes and 4-fps evacuation times for this scenario. Walking speeds on the roads and trails as well as evacuation flow zone data are found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset.

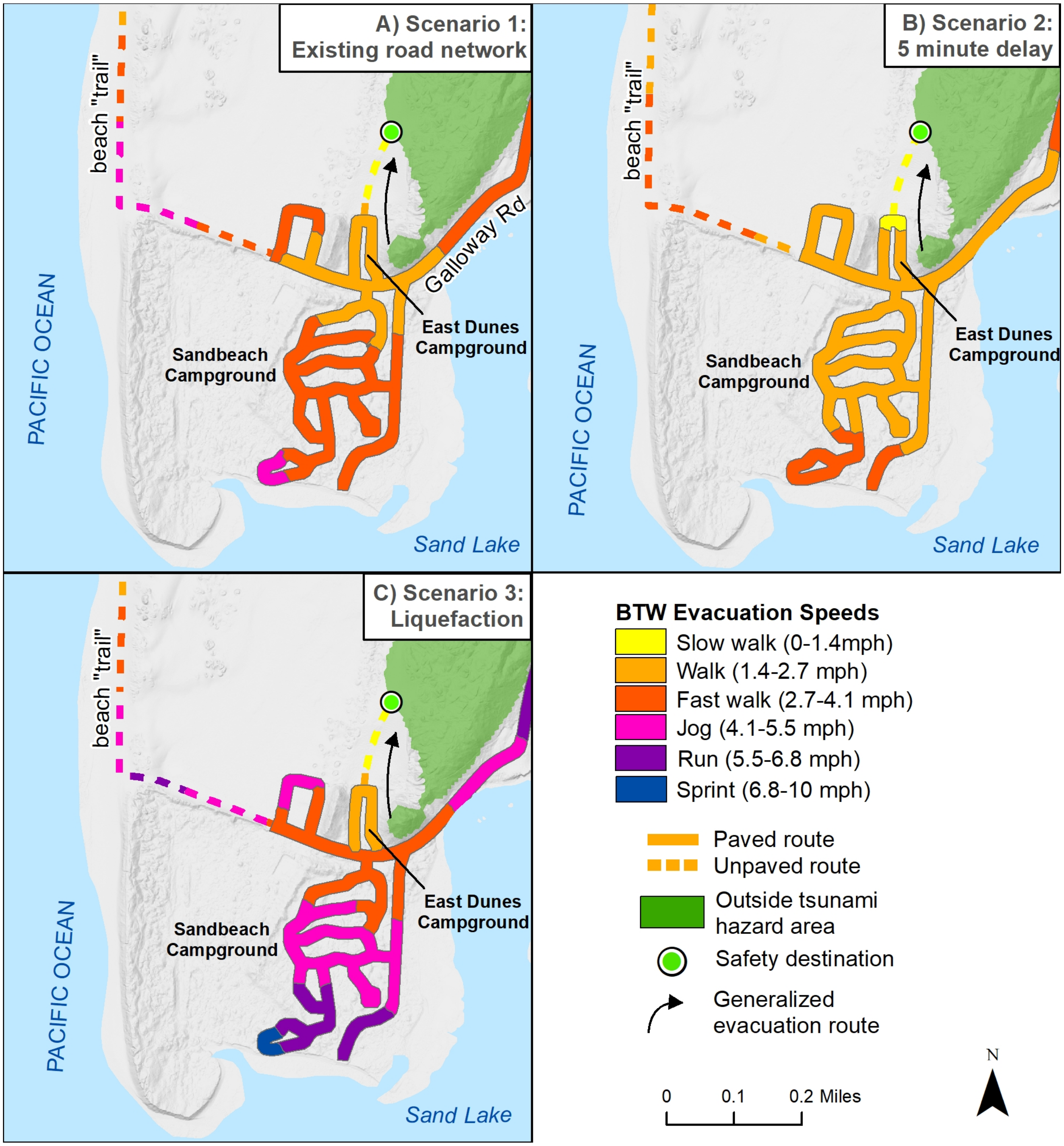
Figure 3-8. Beat the Wave modeling in Sand Lake for Scenario 1: Existing road network. A) BTW minimum walking speeds and B) evacuation flow zones only.



3.6.2 Scenario 2 — 5-minute delay

For Nestucca Spit (Section 3.4.2), we ran a simulation using a 5-minute evacuation delay to reflect the likelihood that evacuees can travel sooner because they will be outside at the time of the earthquake. For Sand Lake, we focus our discussion on the Sand Lake Rec Area day-use parking lot and campgrounds because that is likely where the most people will be; however, full results are included in the digital data. As can be seen in **Figure 3-9**B, the resulting BTW speeds are almost identical to scenario 1 (**Figure 3-9**A). The one improvement is at the southern end of Sandbeach Campground, where the BTW speed is reduced from ***jog*** to ***fast walk***. All evacuees in this area head north across the open sand to high ground.

Figure 3-9. Beat the Wave modeling of the Sand Lake Recreation Area for (A) Scenario 1: Existing road network, (B) Scenario 2: 5-minute evacuation delay, and (C) Scenario 3: Liquefaction. Colors on top of the road network reflect BTW minimum walking speeds. No evacuation flow zones are shown because there is only one for the area (high ground on the open dunes north of East Dunes Campground and day-use parking lot).



3.6.3 Scenario 3 — Liquefaction

As expected, the added complication of liquefaction dramatically increases minimum walking speeds needed to survive the tsunami. For the campground this results in ***jog*** to ***run*** for most of the campground (**Figure 3-9**C). This scenario reinforces the need for preparation and immediate evacuation.

3.6.4 Discussion

Results show that much of the Sand Lake estuary is sufficiently close to high ground to ensure safe evacuation for most people assuming a prompt departure and an understanding of which route to take. The single exception to this is the campground at the Sand Lake Rec Area, which may be difficult to evacuate if liquefaction slows down travel across what are, normally, paved roads. We encourage further consideration for mitigation in this area including additional signage and outreach and hardening a trail up to high ground.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation accomplished the primary objective: to provide a quantitative assessment of evacuation difficulty in Pacific City and surrounding coastal communities including Woods, Tierra Del Mar, Nestucca Spit, and Sand Lake. 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 Nestucca Spit, where very high evacuation speeds are needed to survive. In this location, a vertical evacuation structure is the only viable mitigation option because there is no other natural high ground (outside XXL) in the area. 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, and the Large scenario covers 95% of the likely inundation (XXL covers 100%). The decision to direct people to nearby L1 high ground versus Nestucca Ridge Road (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.

Without suitable mitigation efforts directed at constructing a vertical evacuation structure or establishing signage directing people to the L1 high dune, we anticipate potential loss of life because the time required to “beat the wave” to safety in this area is too long relative to the arrival time of the tsunami.

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).

5.0 ACKNOWLEDGMENTS

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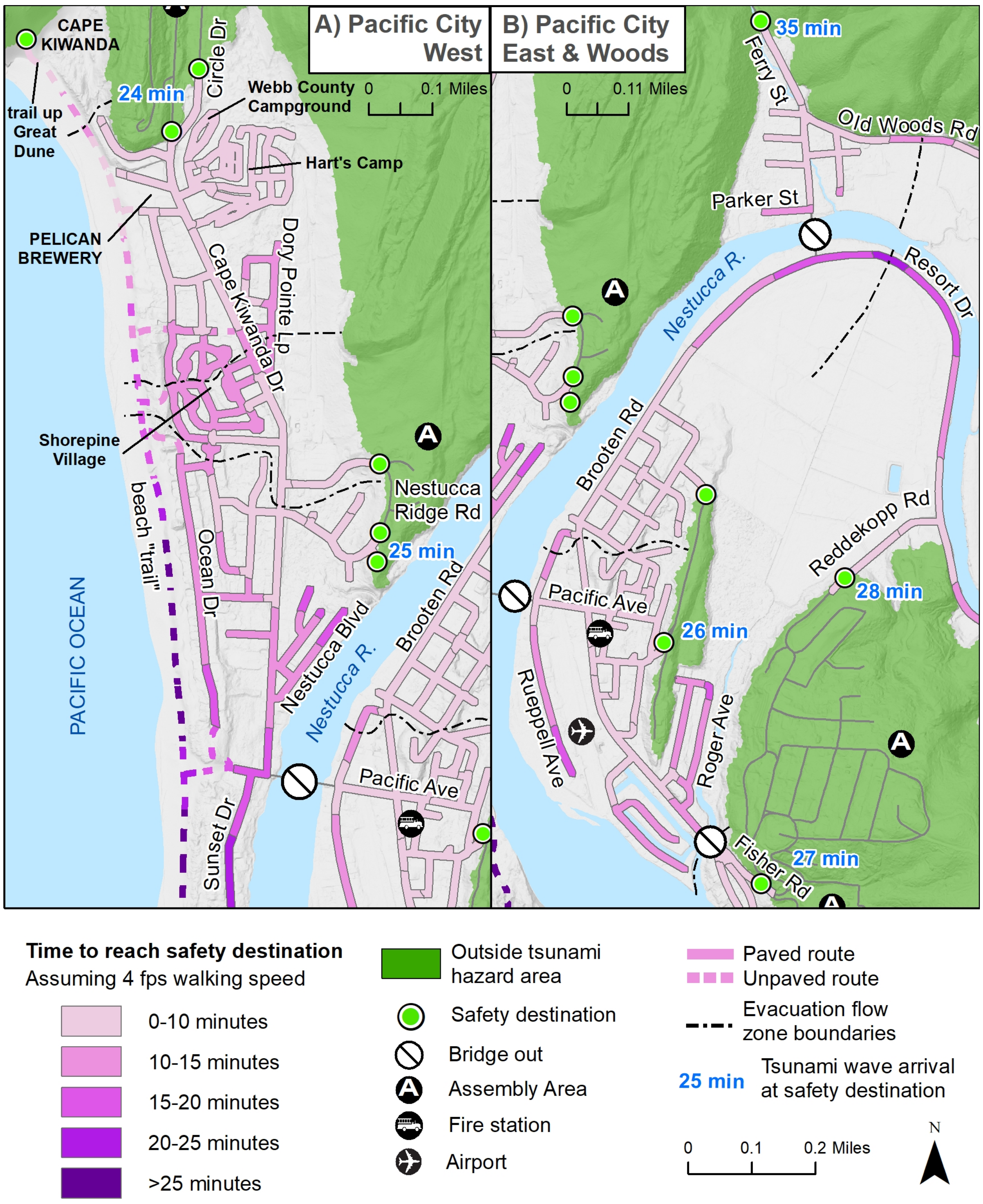
APPENDIX A. EVACUATION TIME MAPS

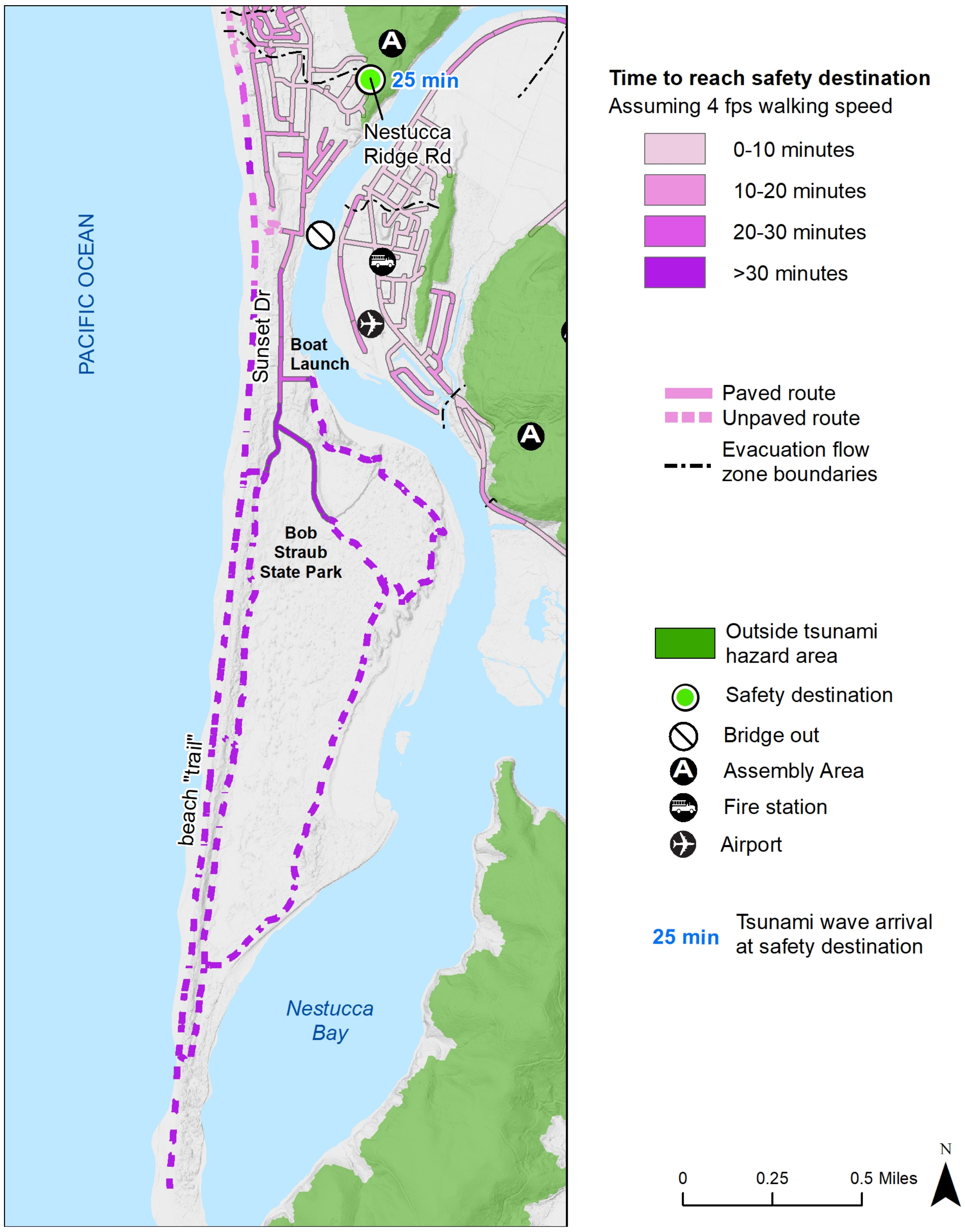
A.1 Pacific City and Woods

Figure A-1. Evacuation time map based on a standard 4-fps speed for the communities of Pacific City and Woods using Scenario 2: Failure of bridges. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationTime feature classes.



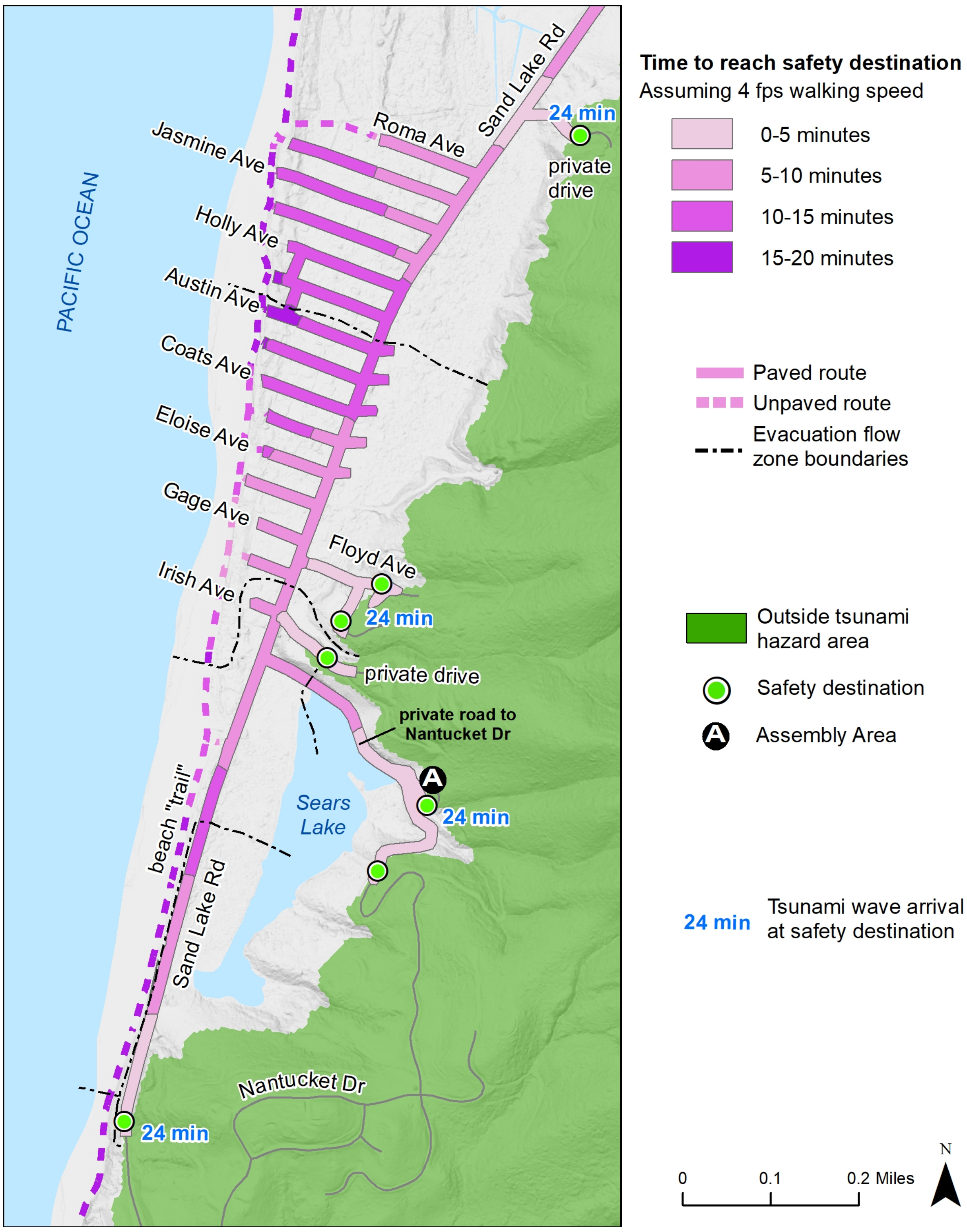
A.2 Nestucca Spit

Figure A-2. Evacuation time map based on a standard 4-fps speed for Nestucca Spit using Scenario 1: Failure of Beachy Bridge. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationTime feature classes.



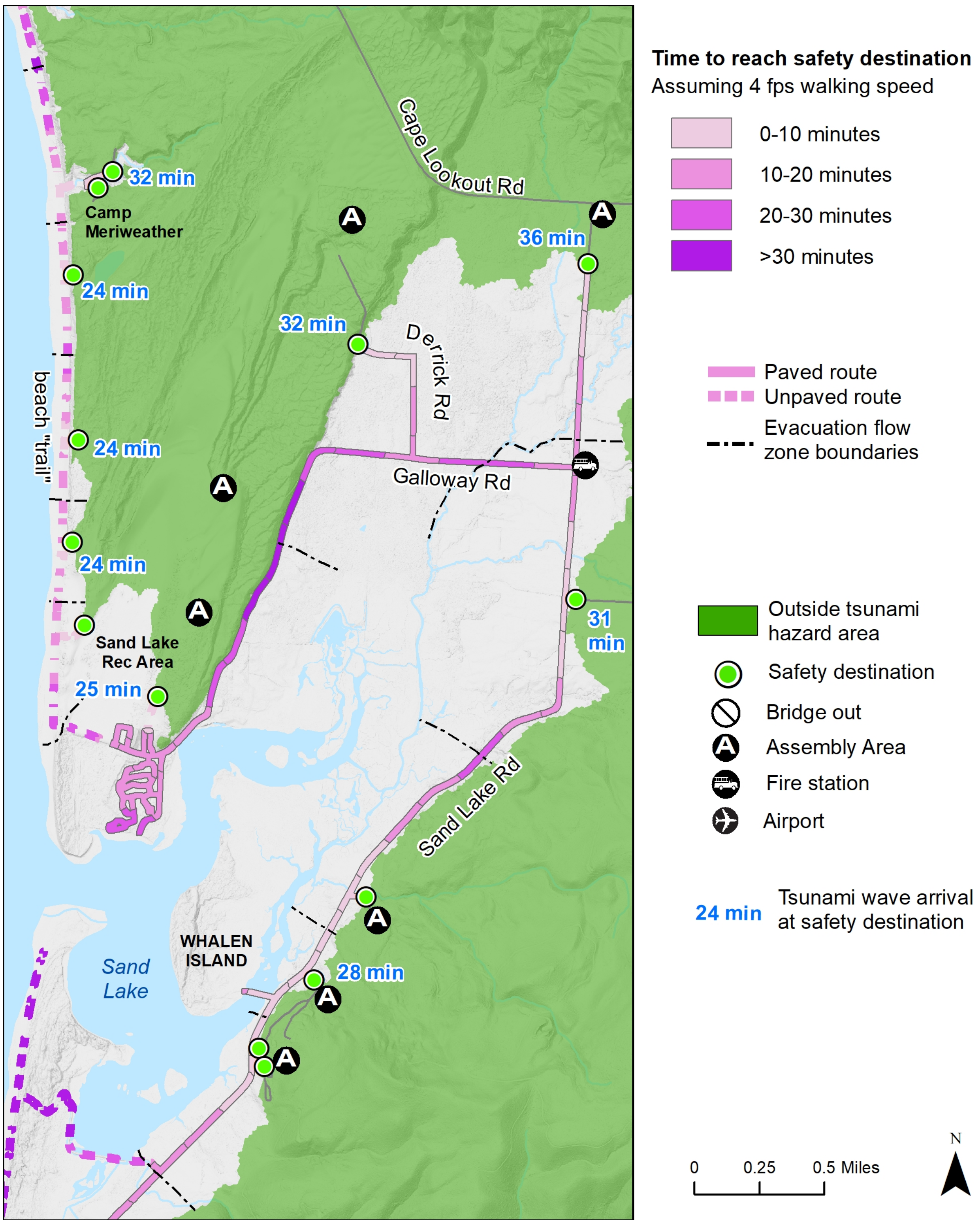
A.3 Tierra Del Mar

Figure A-3. Evacuation time map based on a standard 4-fps speed for Tierra Del Mar using Scenario 1: existing road network. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature datasets, EvacuationTime feature classes.



A.4 Sand Lake

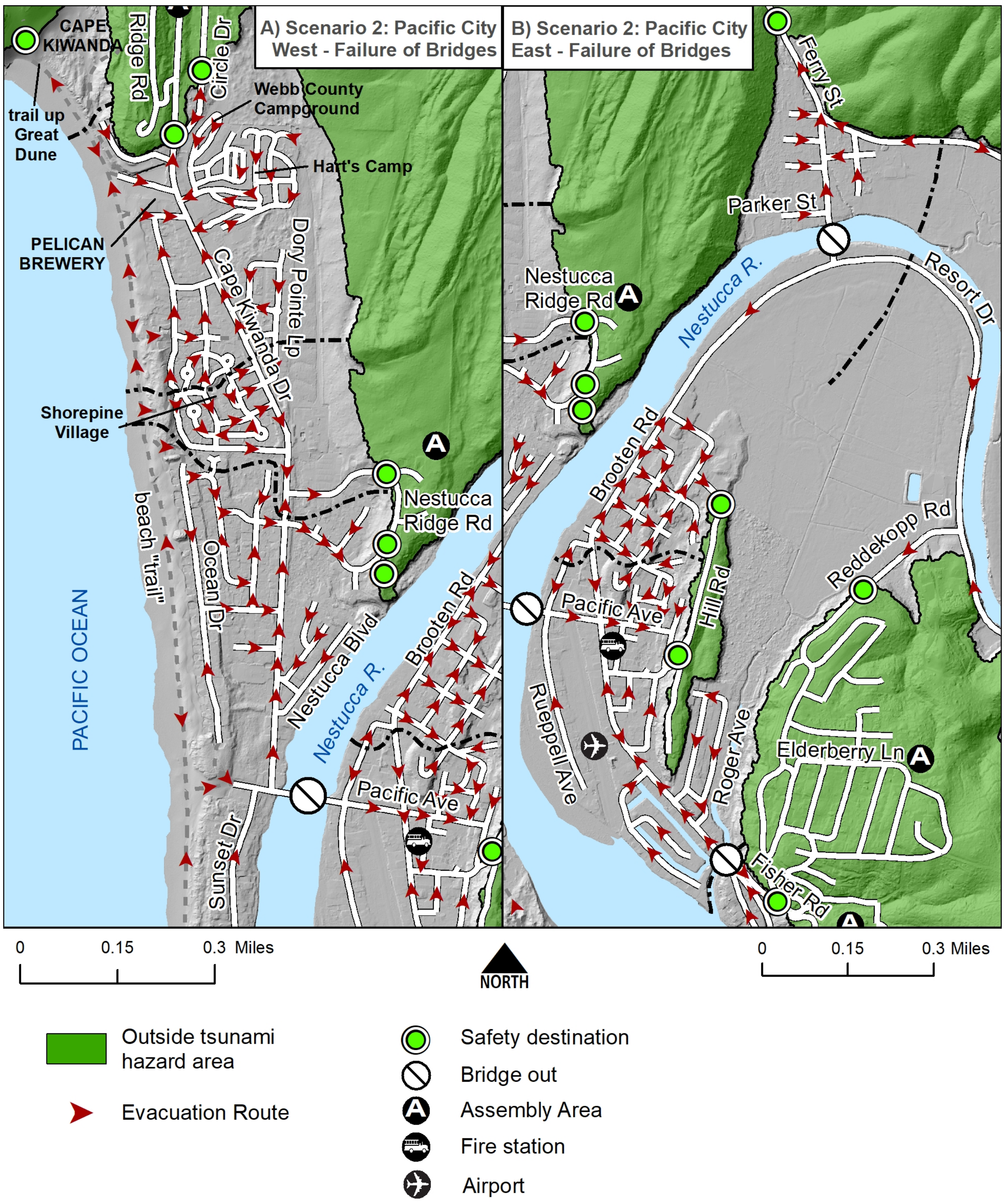
Figure A-4. Evacuation time map based on a standard 4-fps speed for Sand Lake using Scenario 1: existing road network. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationTime feature classes.



APPENDIX B. DETAILED EVACUATION ROUTE MAPS

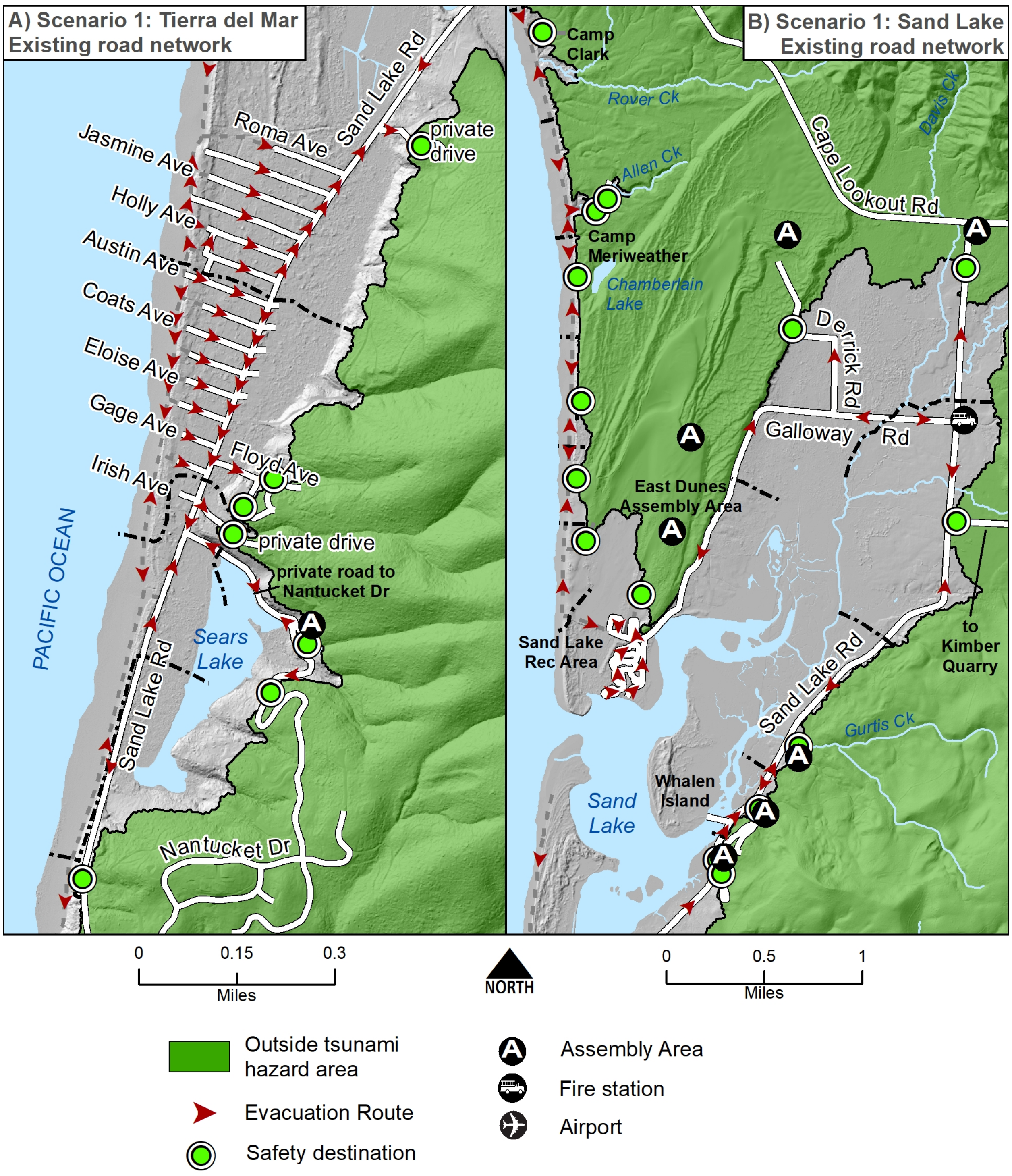
B.1 Pacific City and Woods

Figure B-1. Detailed evacuation routes for Pacific City (A) and Woods (B) using Scenario 2: Failure of bridges. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationRoutes and EvacuationFlowZones feature classes.



B.2 Tierra Del Mar and Sand Lake

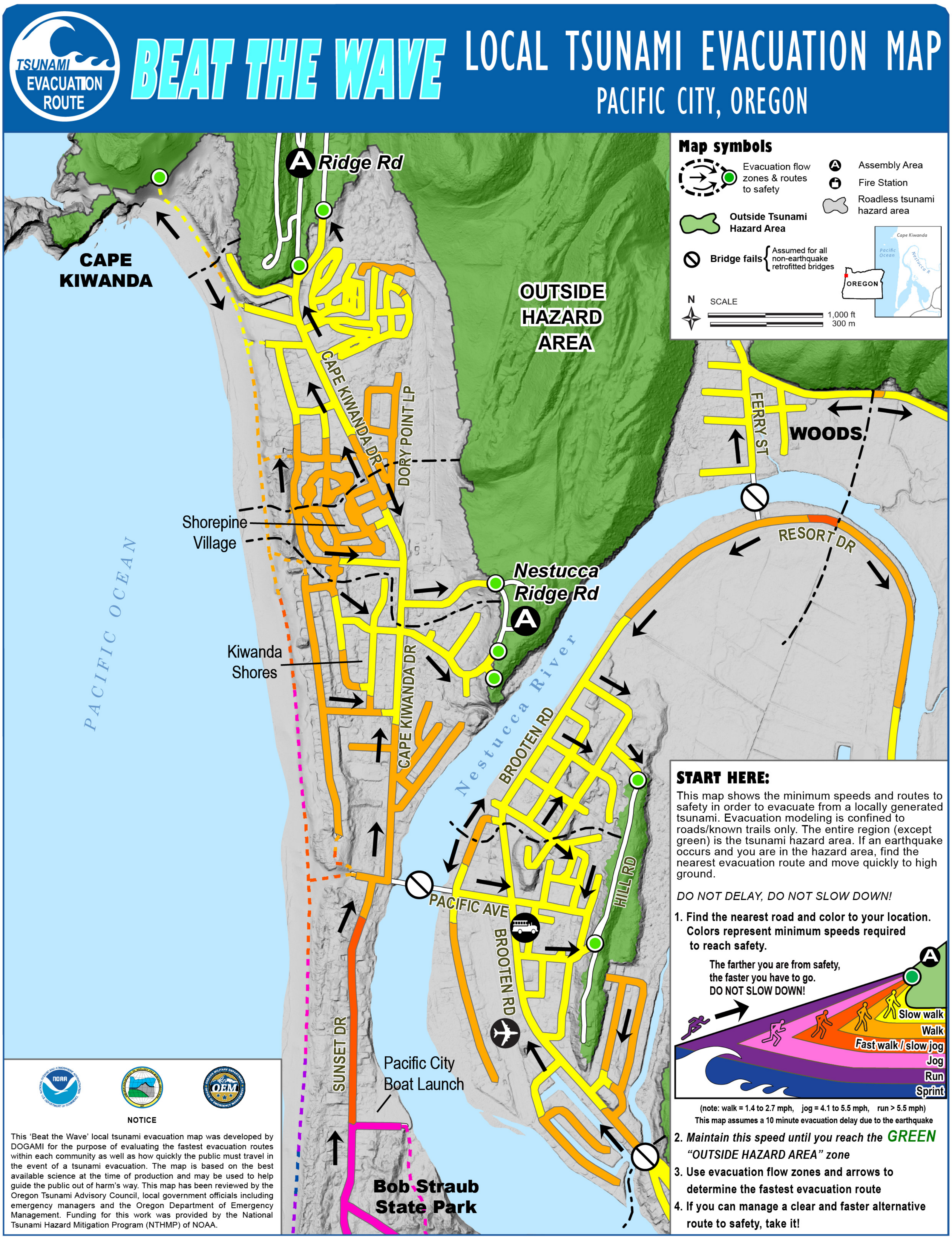
Figure B-2. Detailed evacuation routes for Tierra Del Mar and Sand Lake using Scenario 1: existing road network. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationRoutes and EvacuationFlowZones feature classes.



APPENDIX C. BEAT THE WAVE MAP

C.1 Pacific City and Woods

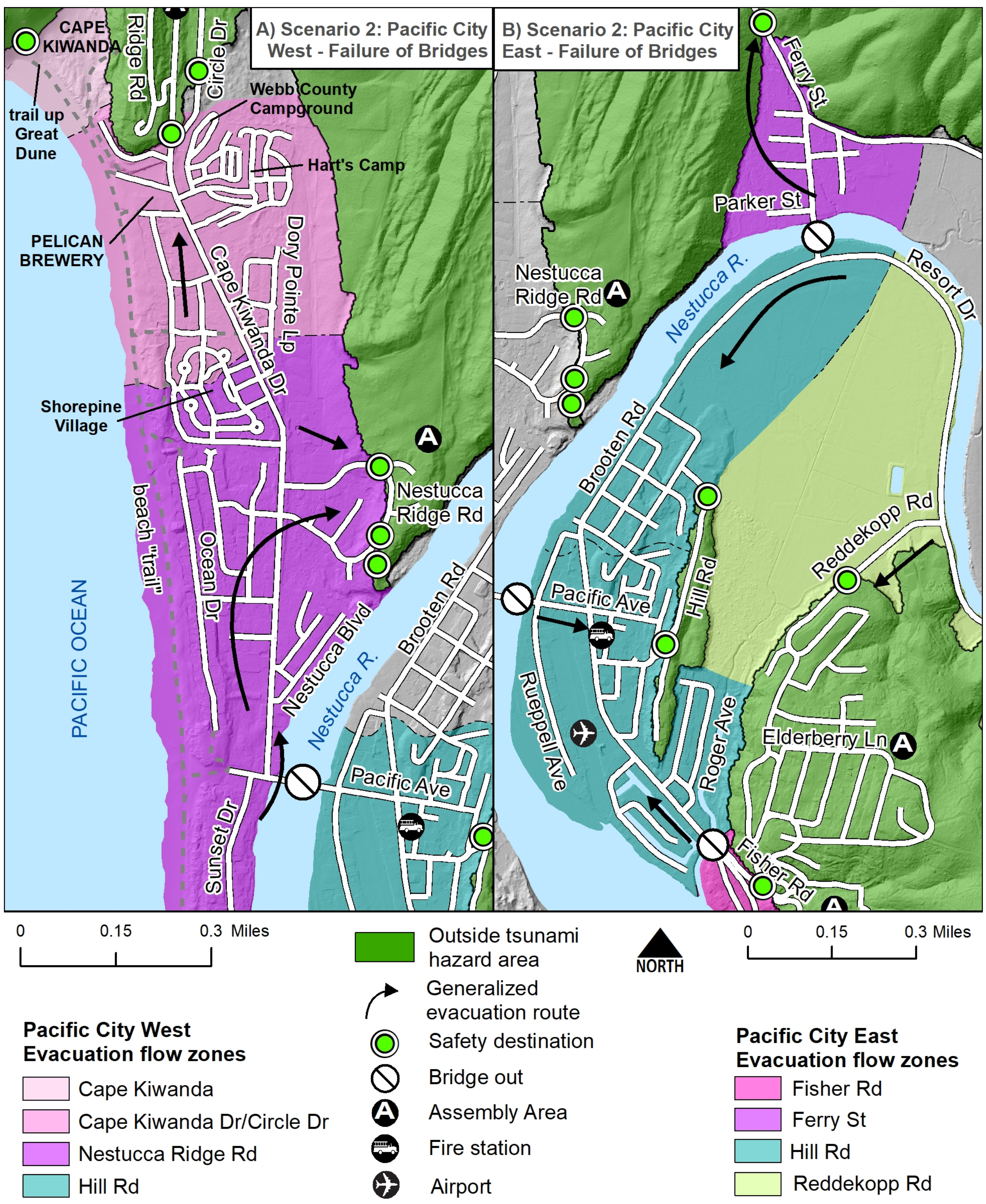
Figure C-1. Final Beat the Wave map for Pacific City and Woods. Colors on top of the road and trail network reflect BTW minimum walking speeds; solid lines represent roads and dashed lines represent trails. Black dash-dot lines define evacuation flow zone boundaries.



APPENDIX D. WATERSHED-ONLY MAPS

D.1 Pacific City and Woods

Figure D-1. Evacuation flow zones for Pacific City and Woods using Scenario 2: Failure of bridges. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.



D.2 Tierra Del Mar and Sand Lake

Figure D-2. Evacuation flow zones for Tierra Del Mar and Sand Lake using Scenario 1: existing road network. These data can also be found in the Pacific_City_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.