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TSUNAMI EVACUATION ANALYSIS OF NEWPORT, LINCOLN COUNTY, OREGON

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ABSTRACT

We evaluated pedestrian evacuation in the city of Newport and surrounding areas, including Agate Beach, Nye Beach, the Bayfront, South Beach, and Ona Beach, Lincoln 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. Evacuation paths were limited to roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

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

- Tsunami wave advance for an XXL1 event,
- Detailed "Beat the Wave" (BTW) results for the XXL1 scenario, including evacuation routes, minimum walking speeds, and evacuation flow zones,
- Detailed BTW results for the L1 scenario for select locations, and
- BTW results for multiple hypothetical scenarios.

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 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 of north Newport is achievable at a moderate walking speed (4 fps). 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. Results for south Newport vary widely. The vertical evacuation structure currently under construction at the Oregon State University (OSU) Hatfield Marine Science Center will greatly improve survivability from a local tsunami, enabling staff, students, and the public to more easily reach high ground. For example, evacuation at a moderate walking speed (4 fps) is achieved for the entire Hatfield peninsula given the presence of this structure. It is the first of its kind to be built on the Oregon coast and only the second in the United States. The highest minimum walking speeds are found in South Beach State Park (6 fps without liquefaction). Liquefaction is not expected to present a significant challenge to evacuation in north Newport. However, in south Newport liquefaction could present a significant challenge to evacuation across the region.

Possible mitigation options include adding new evacuation routes; constructing more earthquake-hardened roads (built or remodeled to withstand shaking from a major earthquake and liquefaction); and/or installing a tsunami refuge, otherwise known as a vertical evacuation structure, at South Beach State Park.

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 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%)

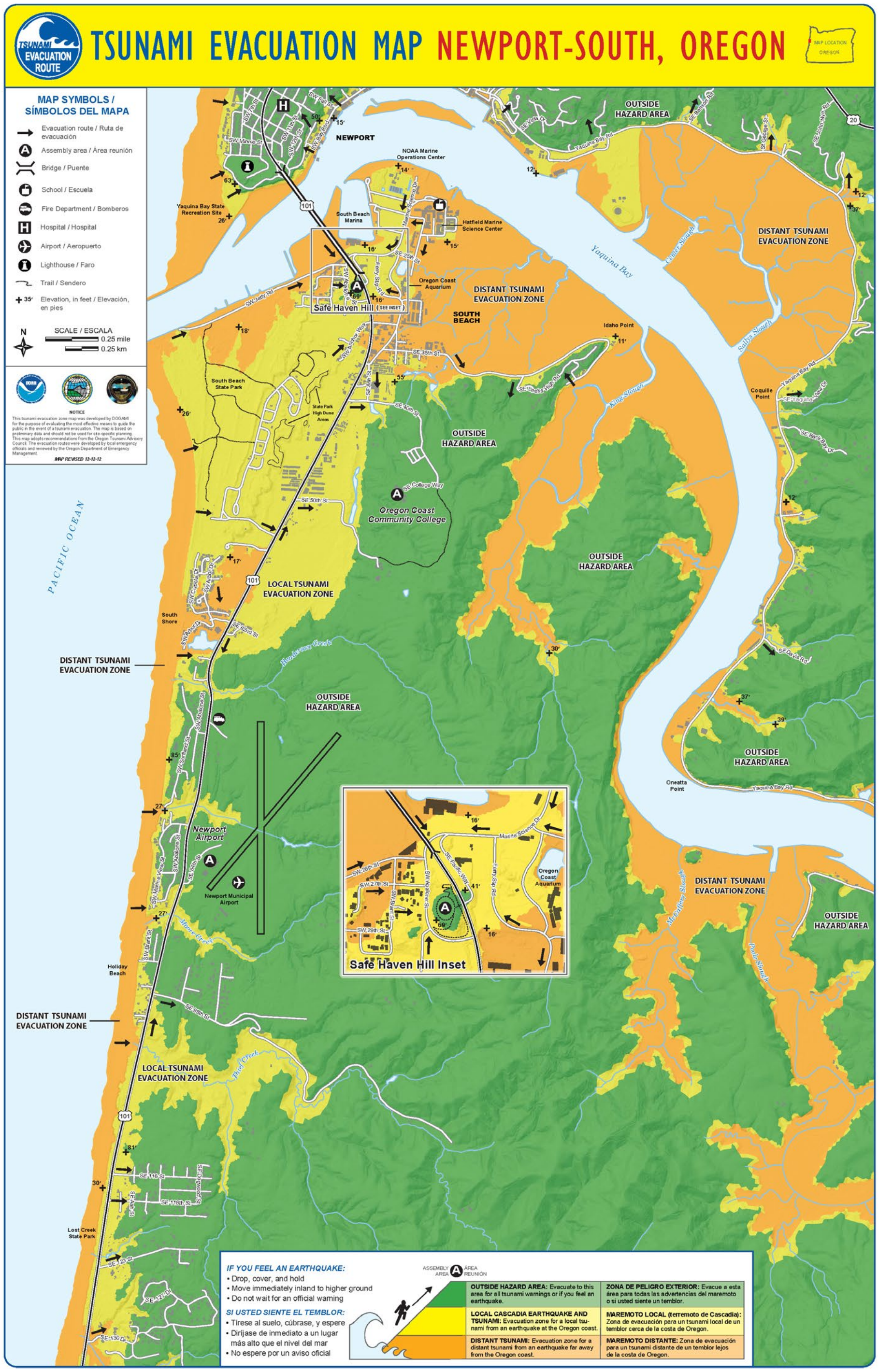
In these scenarios a maximum-considered CSZ tsunami (XXL1, referred to as “XXL” for the remainder of this report) inundates small, isolated sections of Newport north of Yaquina Bay (“north Newport”) and a significant portion of Newport south of Yaquina Bay (“south Newport”) (**Figure 1-1** and **Figure 1-2**). Much of Newport and the surrounding area will be flooded within 30 minutes of the start of earthquake shaking. The objective of this study is to provide local government with a quantitative assessment of the time, speed, and challenges affecting tsunami evacuation in Newport and nearby coastal communities for the XXL scenario. The Large (L1) tsunami scenario is also discussed for South Beach State Park due to its additional evacuation challenges. These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, land use planning, and potential vertical evacuation options.

A Note about Bridges and Tsunami Evacuation in the Newport Area

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” scenario modeling. For Newport, modeling indicates the Yaquina Bay Bridge and other smaller bridges in the area are not essential for tsunami evacuation (i.e., safety can be reached without needing to cross bridges). Because “Bridges In” and “Bridges Out” Beat the Wave results are similar—and in most cases identical—only “Bridges Out” results are included in this report.

Figure 1-1. DOGAMI (2012a) tsunami evacuation map for north Newport 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.oregontsunami.org.

Figure 1-2. DOGAMI (2012b) tsunami evacuation map for south Newport 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.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 here as "Beat the Wave" (BTW), and
3. 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 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 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. The decision to remove certain bridges in the study area was decided after conversation with local officials and based on whether they had been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. We always begin with a 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.

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

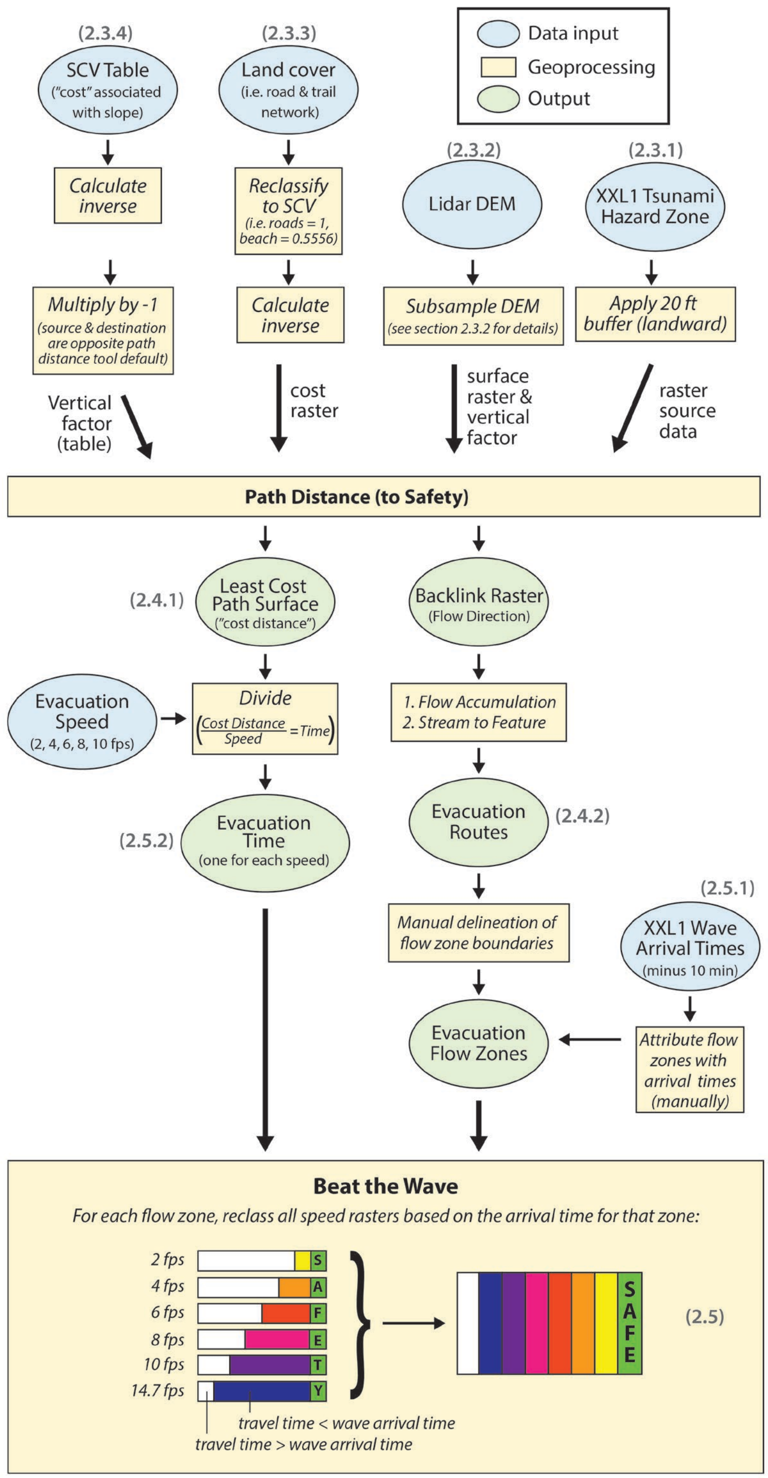
In conclusion, regardless of the infrastructure improvements considered for an area, wayfinding and outreach are essential parts of tsunami evacuation planning. As a reminder, in this report we refer to mitigation only in terms of life safety, meaning getting people out of the tsunami zone in the short 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 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.

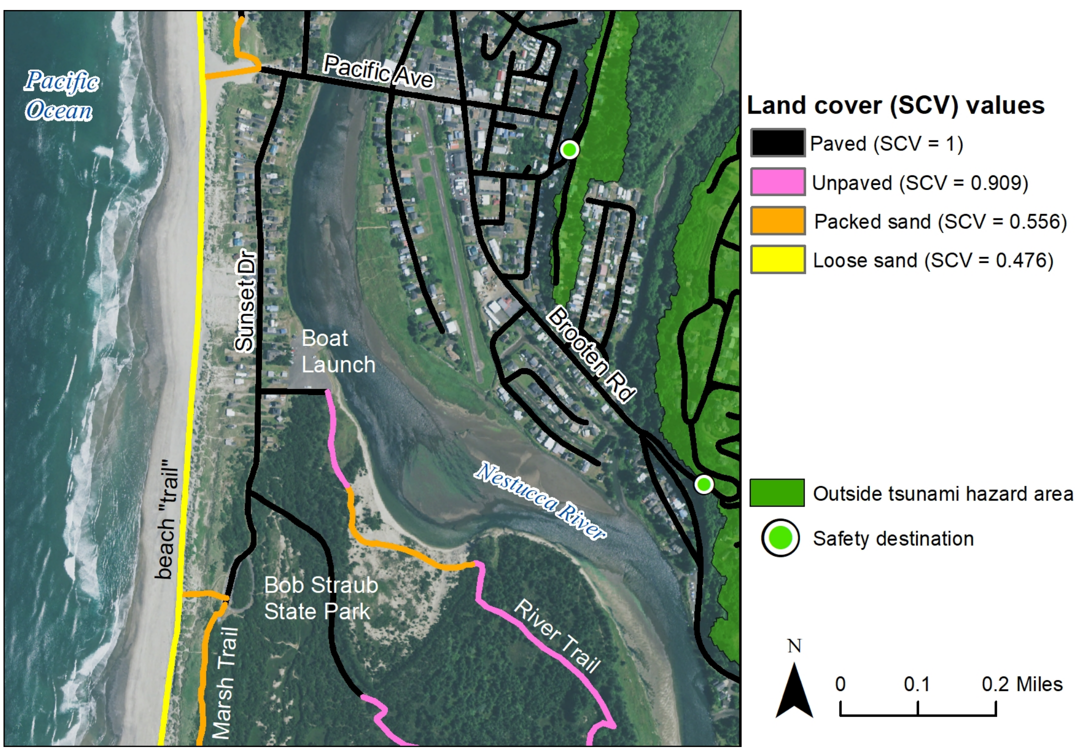
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

*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.

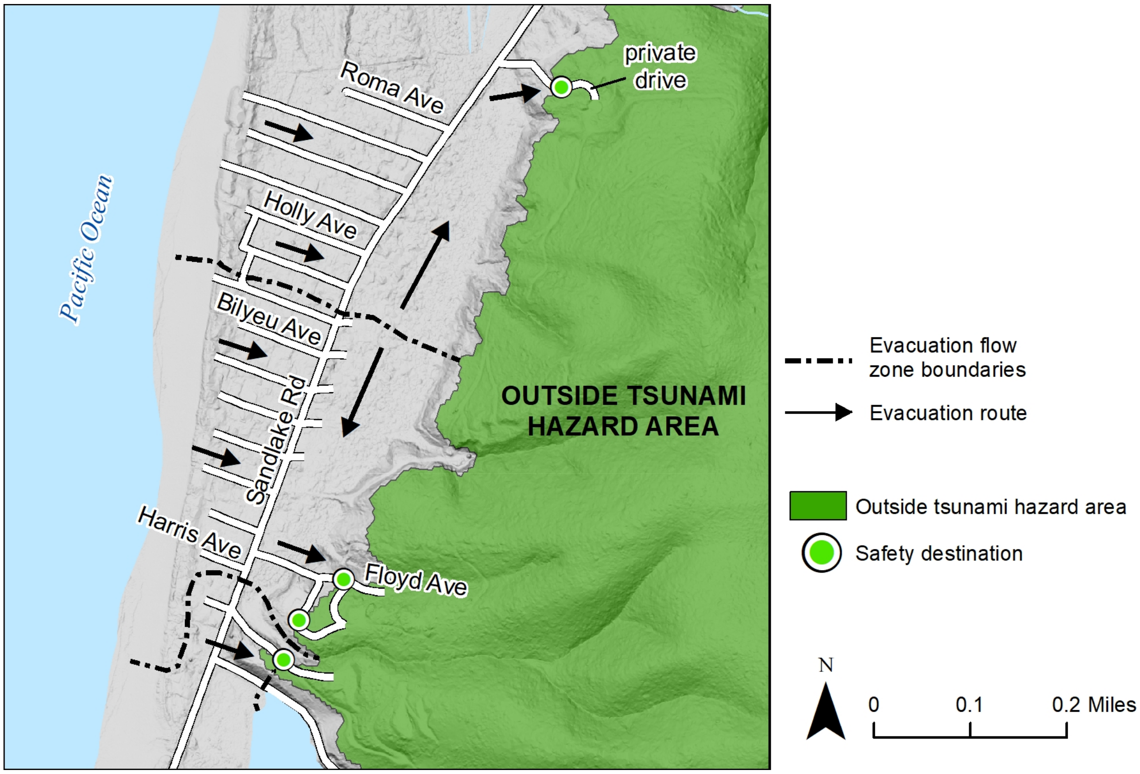
2.4 LCD model outputs

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 land cover 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 destinations and are referred to as evacuation routes. **Figure 2-4** shows what we call “generalized evacuation routes,” meaning the arrows illustrate the overall direction of travel toward a safety destination and are not turn-by-turn directions. Detailed evacuation routes are found in the digital data.

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

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

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

2.5 Beat the Wave (BTW) modeling

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

2.5.1 Wave arrival times

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

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

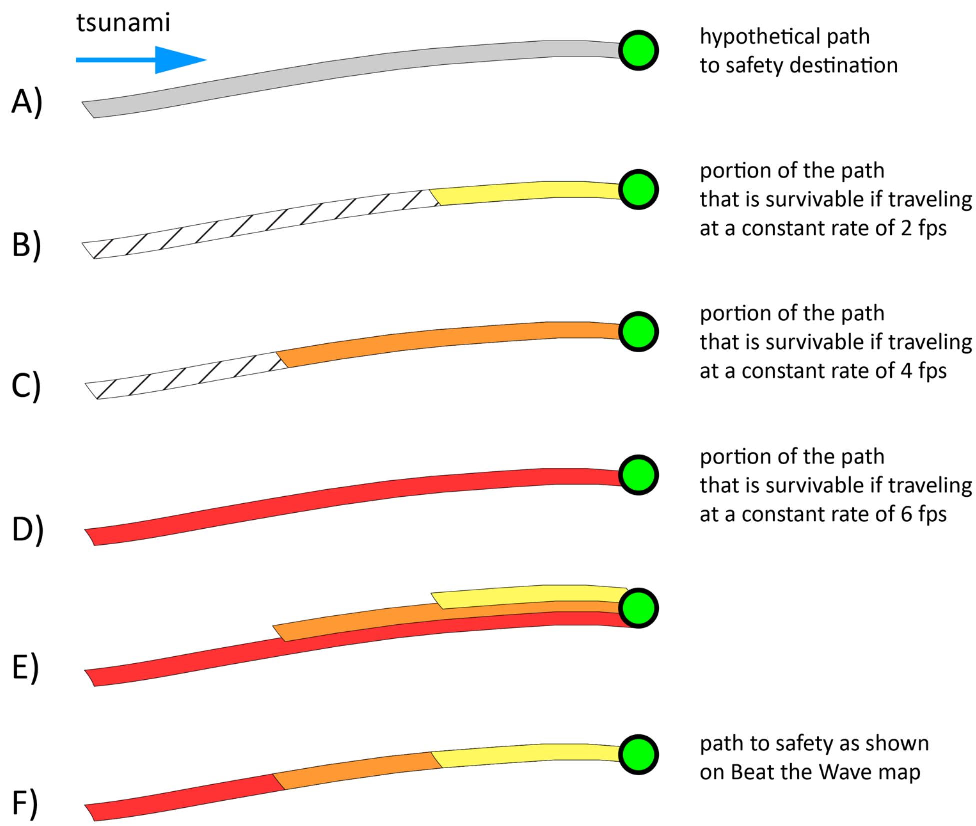
For areas with large campgrounds and few to no permanent residents, we reduced the delay from 10 minutes to 5 minutes to reflect the likelihood of people being outdoors (or inside an RV or tent) when the earthquake begins. We anticipate a shorter delay between earthquake shaking and evacuating for someone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

2.5.2 Evacuation time maps

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 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 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.

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 travel 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. We then gave speed categories in the map explanation qualitative names such as “slow walking” and “running,” so the public could relate speed bins to their experience. Of particular interest are groups that will be most vulnerable, such as impaired adults and the elderly with mean speeds of 3 fps and a range of ~2–4 fps (**Table 2-3**). In an earlier Seaside BTW study (Priest and others, 2015) we examined the range of BTW speeds and reviewed a number of references describing speed categories (Paul, 2013; Margaria, 1968) to settle on the following five speed bins:

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

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

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

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

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

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

2.5.3 Reading a BTW map

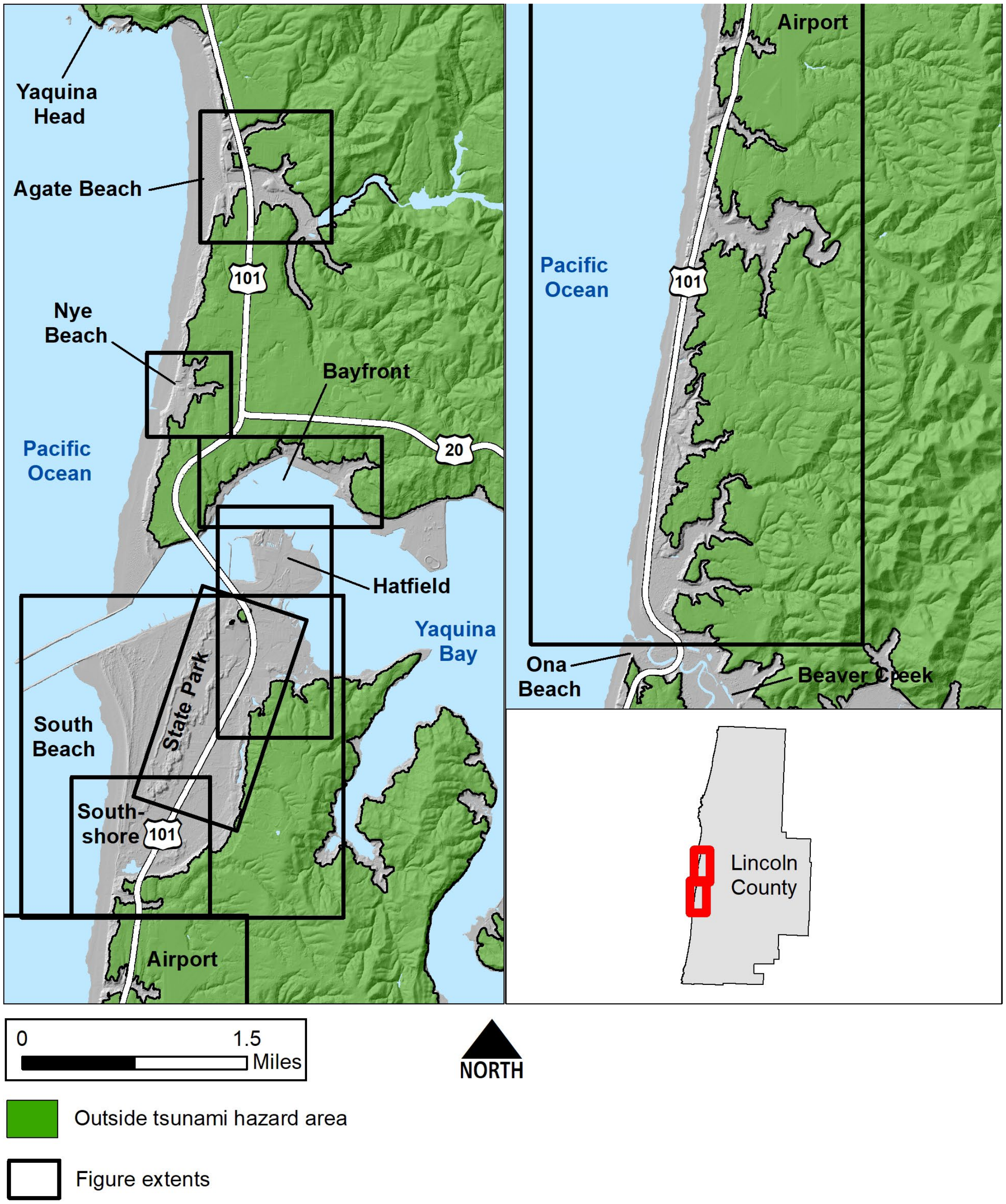
As previously stated, the modeling approach produces ***minimum*** evacuation speeds that must be maintained along the entire route to safety. Actual travel speeds on any evacuation route will require either variable expenditure of energy to maintain a constant speed in all conditions, or higher speeds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

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

3.0 RESULTS AND DISCUSSION

Results from our Newport tsunami evacuation and BTW analyses are presented separately for each community. The Newport project area extends from Yaquina Head in the north to Ona Beach in the south and includes the areas of Agate Beach, Nye Beach, the Bayfront, Hatfield Marine Science Center and surrounding peninsula (“Hatfield peninsula”), South Beach State Park (SBSP), Southshore community, and Ona Beach (**Figure 3-1**). In general, we find that evacuees in north Newport (area between Yaquina Head and Yaquina Bay) can escape a maximum-considered Cascadia tsunami by walking at a minimum speed of 4 fps (***walk***). This is not the case south of the bay, specifically South Beach State Park, where evacuees must travel a significant distance to reach the nearest safety destination. Although the area has relatively few permanent residences, many hundreds of people work and recreate here throughout the year.

Figure 3-1. Newport, Oregon, project area map: (left) north Newport; (right) south Newport. Results within figure extents (black boxes) are shown in more detail in this report. Green is outside the XXL tsunami hazard area.



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, base run results will not allow passage across a bridge. When applicable, additional scenarios such as liquefaction, evacuation trails, and vertical evacuation structures are 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.

Tsunami wave arrivals for the entire project area are presented in section **3.1**. Subsequent sections present detailed wave arrivals for each community. In most communities, evacuation flow zones are shown on their own for the base scenario to identify which safety destination is ideal for each sub-evacuation area of a community. This information will be especially useful for emergency officials, planners and other decision-makers to assist with mitigation efforts including signage and evacuation drills. Base BTW results and tsunami arrival data can be found in the Newport_Tsunami_Evacuation_Modeling geodatabase.

Unless otherwise noted, all scenarios include a 10-minute delay before commencing evacuation to account for the expected disoriented state of people following severe earthquake shaking and for the time required to exit buildings. This delay was reduced to 5 minutes for SBSP because evacuees in this area 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 quickly as possible in order to ensure they reach safety with ample time to spare.***

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

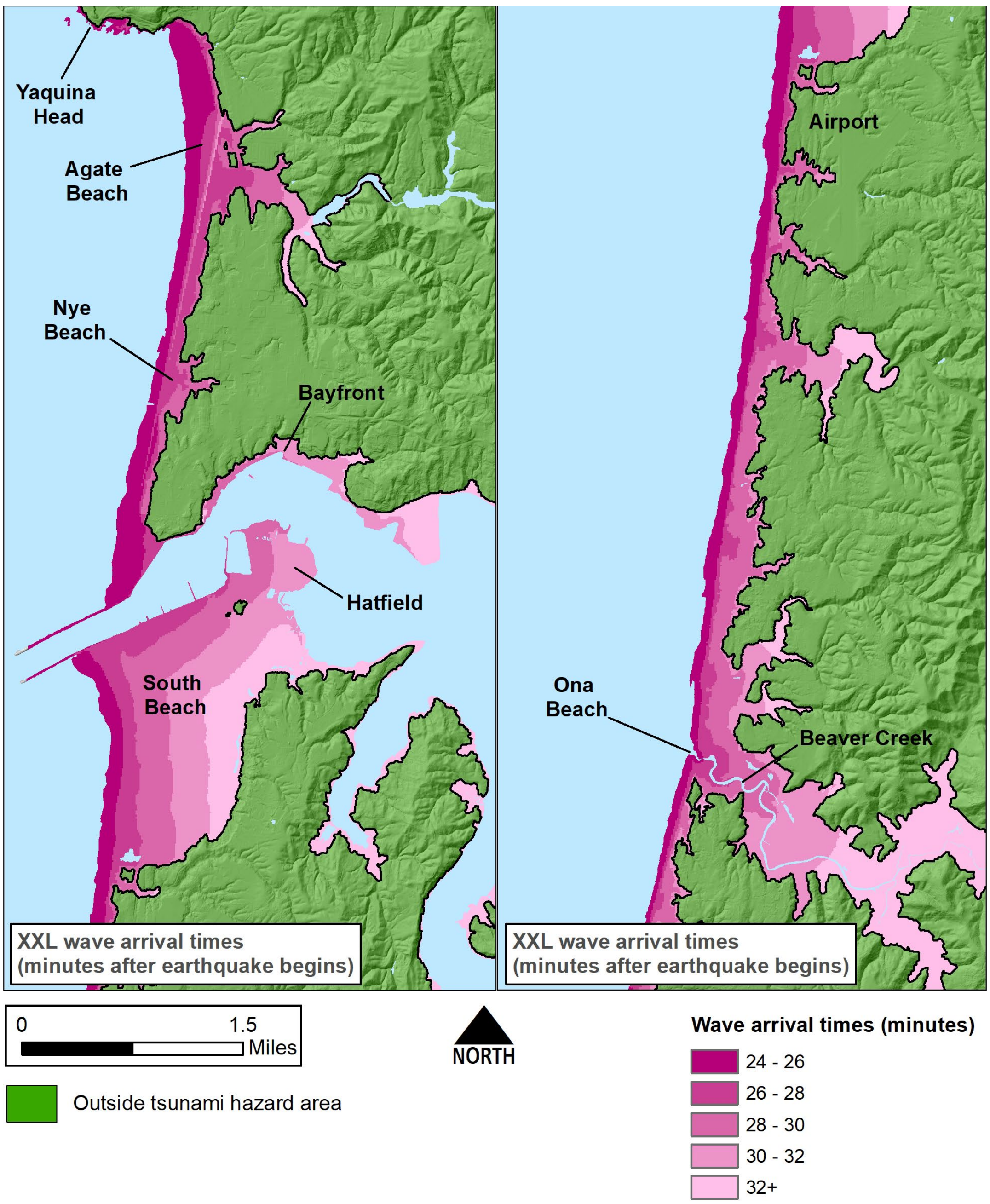
Description	Feet per Second (fps)	Miles per Hour (mph)	Minutes per Mile
Slow walk	>0–2	>0–1.4	>44
Walk	2–4	1.4–2.7	44–22
Fast walk	4–6	2.7–4.1	22–14.7
Jog	6–8	4.1–5.5	14.7–11
Run	8–10	5.5–6.8	11–8.8
Sprint	10–14.7	6.8–10	8.8–6.0
Unlikely to survive	>14.7	>10	<6.0

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 Tsunami wave arrivals

Figure 3-2 demonstrates the arrival times for an XXL tsunami in the Newport project area. The earliest wave arrivals are along the open coast; the tsunami reaches the beach ~24–26 minutes after the start of earthquake shaking. By 32 minutes, nearly the entire study area is expected to be inundated. The tsunami continues up the Yaquina River past Toledo, reaching its farthest upriver extent after ~2.3 hours, ~7 miles upstream from Toledo (not shown in figure). Additional waves will continue to strike the coast and enter the estuaries, causing water levels to fluctuate for up to 12 hours after the earthquake. Tsunami wave arrival time data are found in the Newport_Tsunami_Evacuation_Modeling geodatabase, TsunamiWaveArrival_XXL1 dataset.

Figure 3-2. Modeled tsunami wave arrival times for Newport project area after XXL Cascadia subduction zone earthquake: (left) north Newport; (right) south Newport.



3.2 North Newport

Nearly all of north Newport (Yaquina Head to Yaquina Bay) is outside of the tsunami zone with three exceptions: Agate Beach (including the Big Creek neighborhood), Nye Beach, and the Bayfront. These neighborhoods are characterized by high visitor and residential populations due to easy beach and bay access, restaurants and shops, and oceanfront housing. Although our modeling shows that these low-lying areas are inundated by a tsunami of any size, there is ample high ground nearby. Other than the U.S. Coast Guard station on the Bayfront, no critical facilities (i.e., schools or hospitals) are located within the inundated areas of north Newport.

Detailed wave arrivals and results will be described for the three geographic areas, each of which has its own set of challenges and mitigation options. Overall, results for north Newport are positive due to the proximity to high ground. Our modeling indicates the following:

1. Several evacuation routes are available. This means evacuation to high ground can be achieved in a timely manner; however, knowing which direction to travel is important.
2. Modeled BTW pedestrian evacuation speeds for much of the community were determined to be extremely low (***slow walk***), regardless of the potential for liquefaction or landslides. Because of this, no mitigation options were evaluated for north Newport (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.
3. Although landslides, liquefaction, and lateral spreading (and debris) are sure to pose a challenge to evacuation on the Bayfront, the prevalence of roads leading to high ground suggests that evacuation is possible despite these hazards.

3.2.1 Agate Beach

Figure 3-3 shows the least-cost (path) distance modeling for Agate Beach and Big Creek, assuming the existing road network remains intact (base run). Colors on top of the road network reflect minimum walking speeds required to reach safety ahead of the tsunami (**Figure 3-3, left**). Black dashed lines in **Figure 3-3, left** and colored polygons in **Figure 3-3, right** represent boundaries between evacuation flow zones that define the geographic extent of each safety destination. The purpose of this modeling is to identify detailed evacuation routes, which are used to define evacuation flow zones. Each evacuation flow zone 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.

The first tsunami wave arrives at the back of the beach in 27 minutes and takes another ~5 minutes to reach its maximum inundation at Big Creek reservoir (**Figure 3-4**). These relatively long wave arrival times combined with the fact that all locations are quite close to evacuation destinations (i.e., safety) results in the entire area being characterized with a **minimum** evacuation speed of ***slow walk*** (**Figure 3-3, left**).

The area is characterized by numerous evacuation community flow zones (corridors) due to the many roads that intersect high ground (**Figure 3-3, right**). For anyone on the beach itself (i.e., Agate Beach State Recreation Site, also known as Agate Beach Wayside) as well as for those at the Best Western hotel, high ground can be found in the Best Western parking lot (safety destination [green dot] for the yellow polygon in **Figure 3-3, right**). Although hotel guests are aware of the road up to the parking lot because they must drive it to park their vehicles, for the rest of their stay visitors use the pedestrian bridge between the parking lot and the sixth (top) floor of the hotel. Inside the hotel, most people take the elevator six floors down to ground level where beach access is available. Both the bridge and elevator will likely be unusable after the earthquake, so preparedness messaging by the hotel is essential.

Overall, there is ample high ground in many directions. However, how to reach high ground could be confusing, especially to the unacquainted/unprepared visitor. Education and signage are therefore imperative. No additional scenarios were considered for this area.

Figure 3-3. Beat the Wave modeling (XXL) in Agate Beach for the base run assuming the existing road network remains intact. (left) BTW minimum walking speeds and (right) evacuation flow zones only. These data can also be found in the Newport_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.

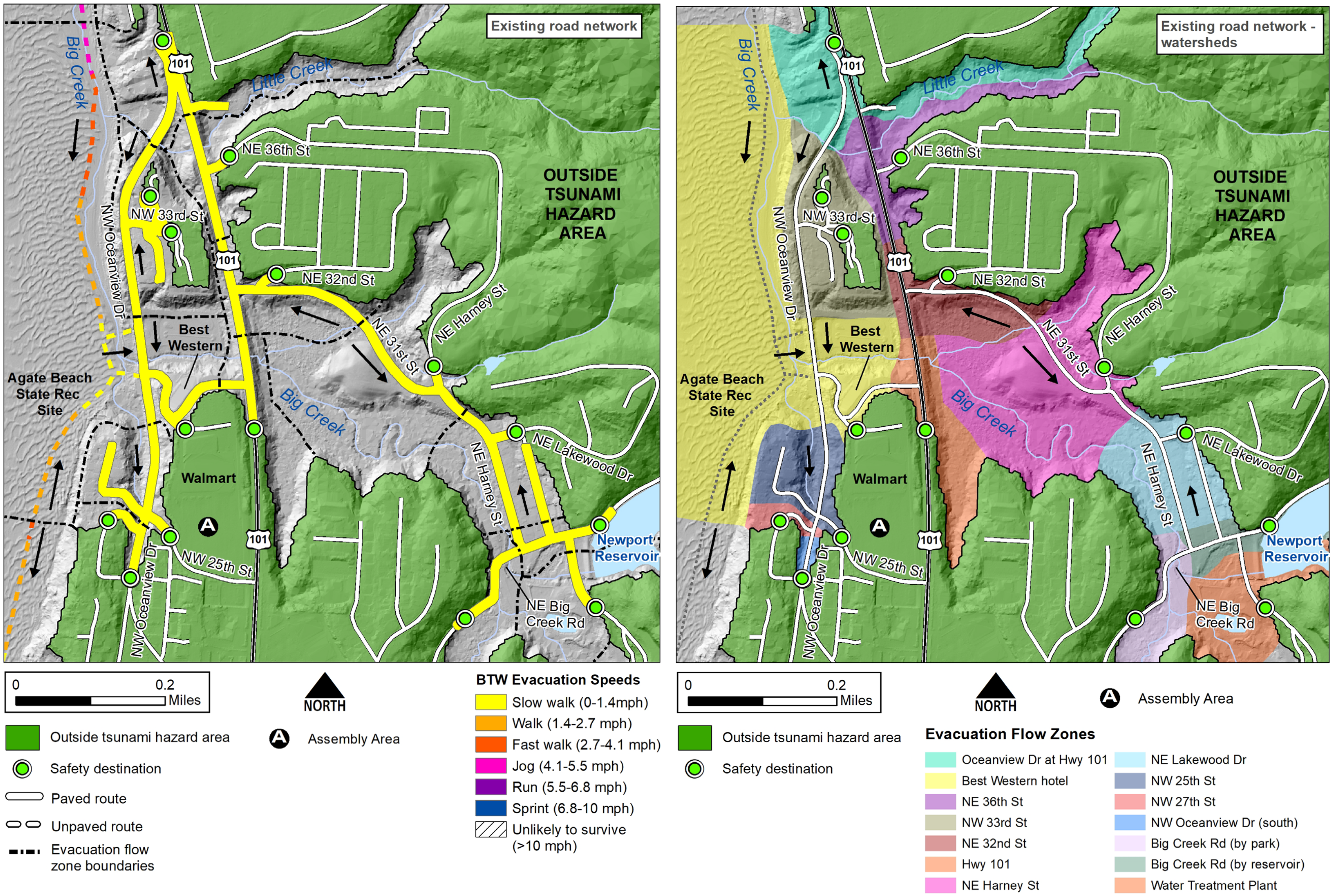
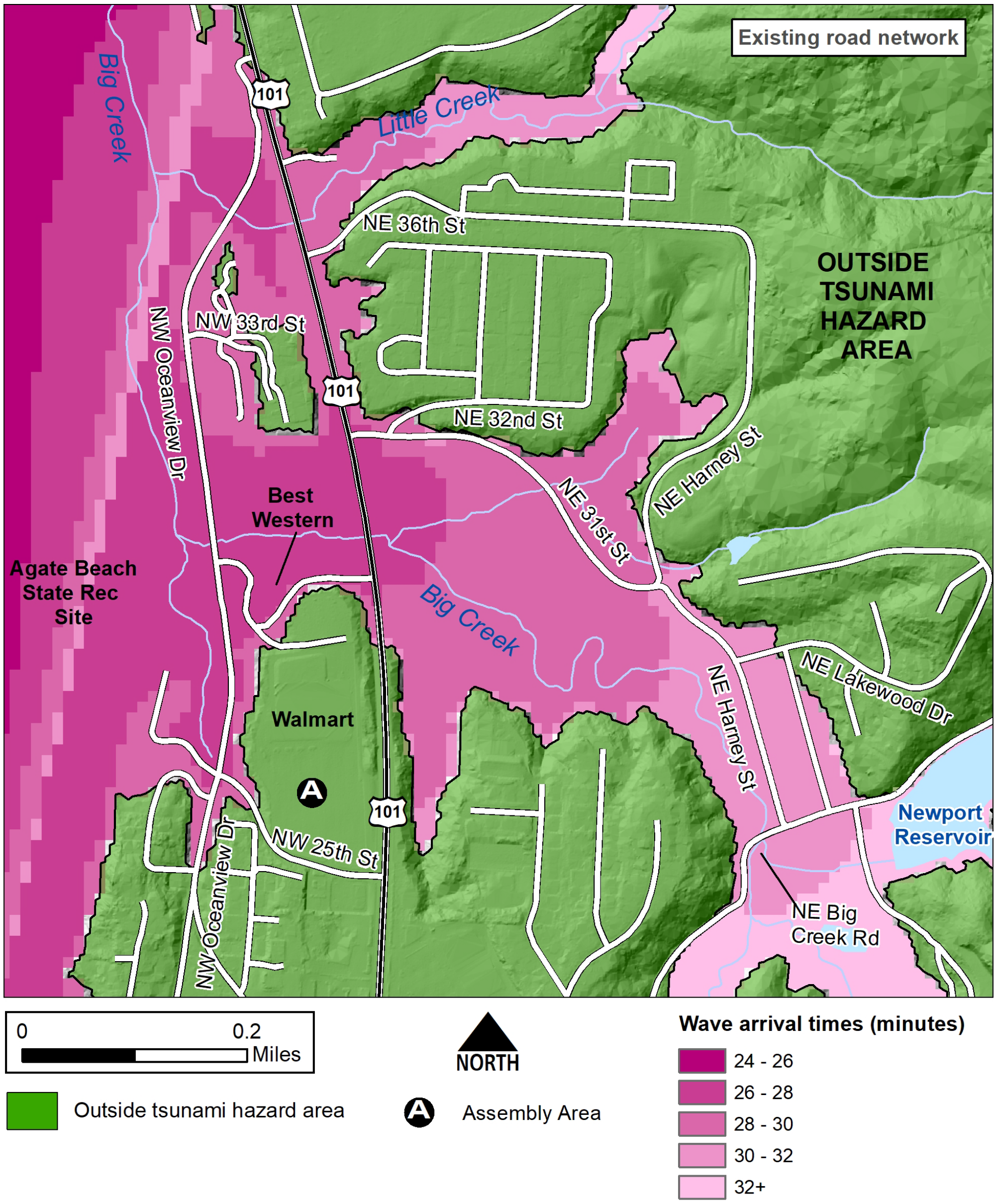


Figure 3-4. Modeled tsunami wave arrival times for Agate Beach and Big Creek after XXL Cascadia subduction zone earthquake.



3.2.2 Nye Beach

Figure 3-5 shows the least-cost (path) distance modeling for Nye Beach, assuming the existing road network remains intact (base run). As with Agate Beach, opportunities for evacuation in Nye Beach are good, with abundant high ground and **minimum** evacuation speeds of ***slow walk*** for the entire community (Figure 3-5, **left**). Tsunami wave arrival times are also comparable to Agate Beach, with an arrival time of 27 minutes at the Nye Beach turnaround (Figure 3-6). The area is characterized by numerous evacuation community flow zones to the north, east, and south due to the many roads that intersect high ground (Figure 3-5, **right**).

Figure 3-5. Beat the Wave (XXL) modeling in Nye Beach for base run assuming the existing road network remains intact. (left) BTW minimum walking speeds and (right) evacuation flow zones only. These data can also be found in the Newport_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.

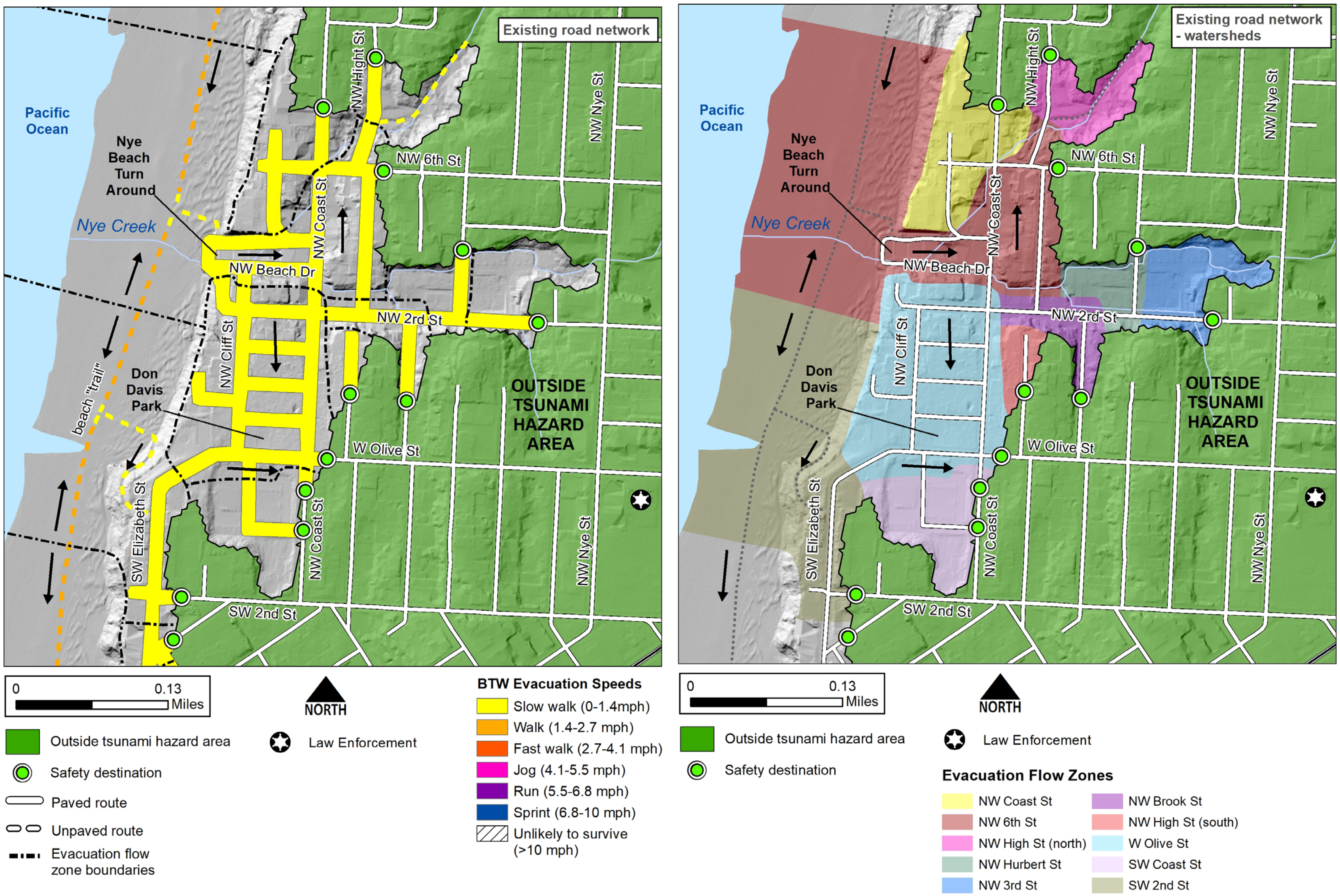
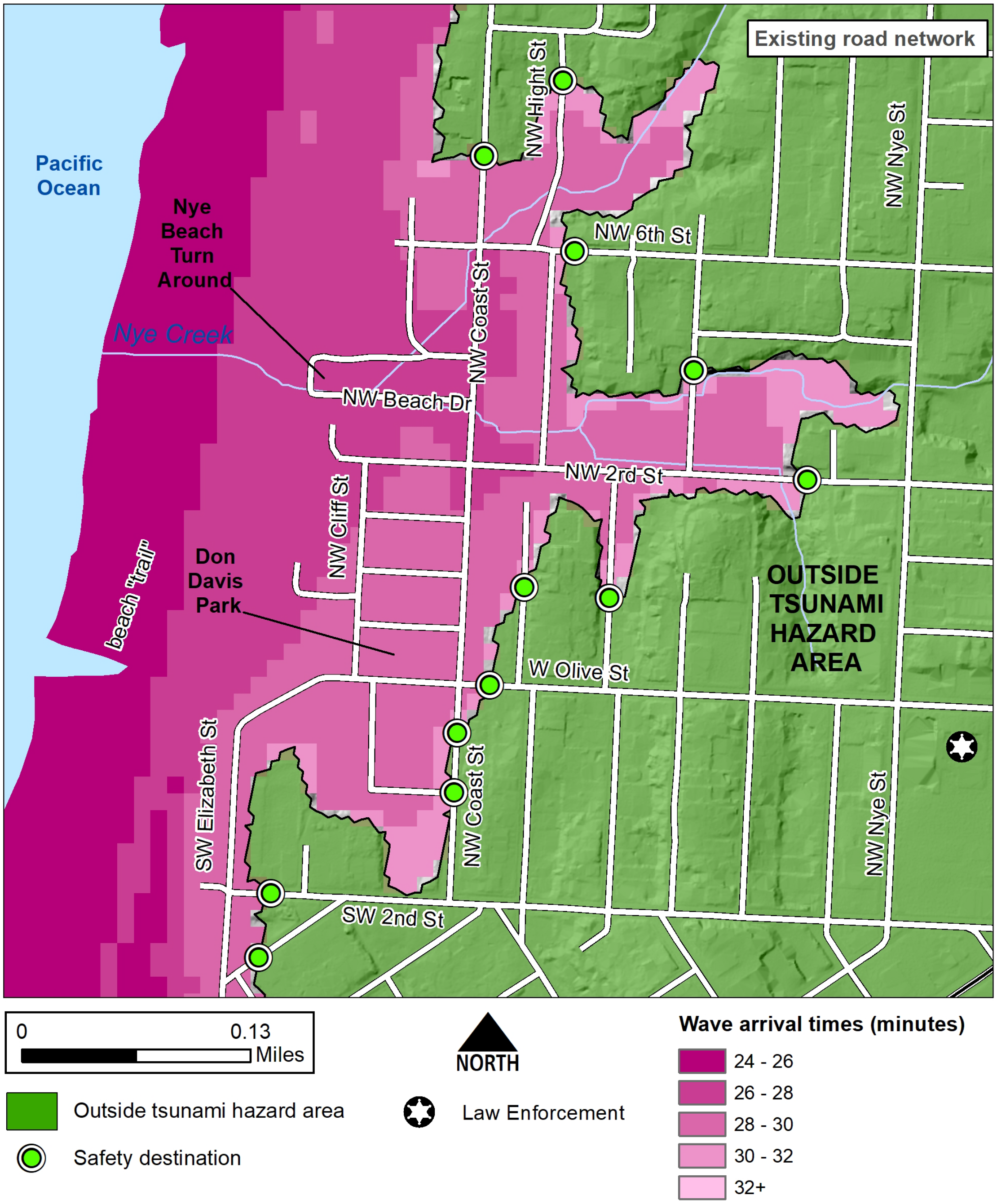


Figure 3-6. Modeled tsunami wave arrival times for Nye Creek after XXL Cascadia subduction zone earthquake.



3.2.3 Bayfront

The Bayfront is about a one mile stretch of road along Yaquina Bay containing restaurants, shops, lodging, and a commercial fishing fleet. It is visited by residents and visitors alike year-round with hundreds of people visiting the shops and restaurants on a summer weekend and hundreds more working in the canneries. The landward side of the road is characterized by steep hills and many roads reach safety after a very short distance. Although these hills provide nearby access to high ground for virtually everyone, landslides, liquefaction, and especially lateral spreading will be the major impediments to evacuation in this area. The tsunami enters the bay and reaches the west end of the Bayfront after 28 minutes; the tsunami reaches the east end of the commercial area about 4 minutes later (inundation shown in **Figure 3-16** as part of the South Beach area).

Figure 3-7, top shows the least-cost (path) distance modeling on the Bayfront for a base run that assumes the existing road network remains intact. As with Agate Beach and Nye Beach, opportunities for evacuation are good with prevalent high ground and **<u>minimum</u>** evacuation speeds of ***slow walk*** for the entire community. The area is characterized by numerous evacuation community flow zones due to the many roads that intersect high ground (**Figure 3-8** and dashed black lines in **Figure 3-7, top**).

Figure 3-7. Beat the Wave (XXL) modeling for the Bayfront: (top) Base run, (middle) Landslide hazard added, and (bottom) Liquefaction hazard added. Colors on top of the road network reflect BTW minimum walking speeds.

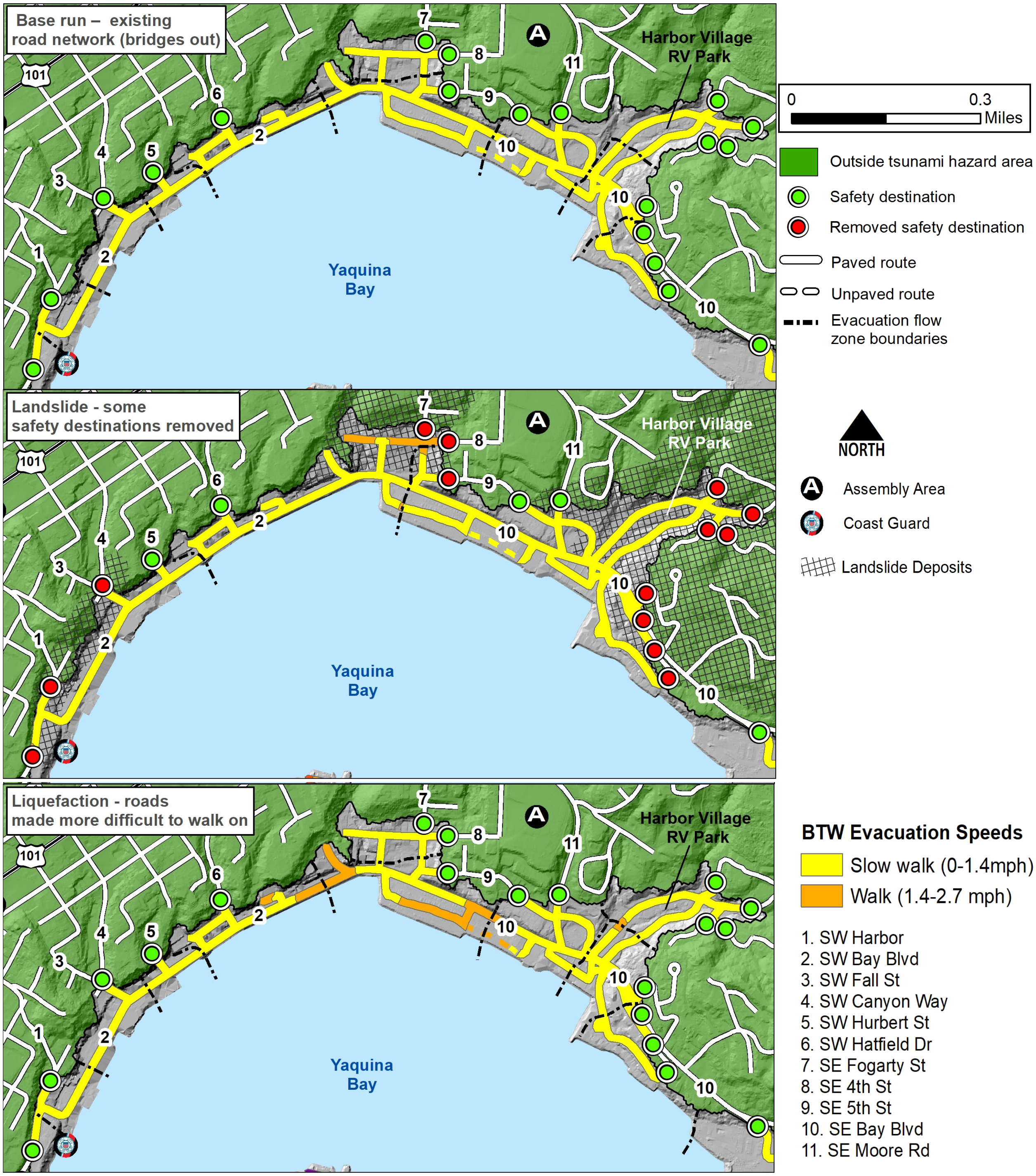
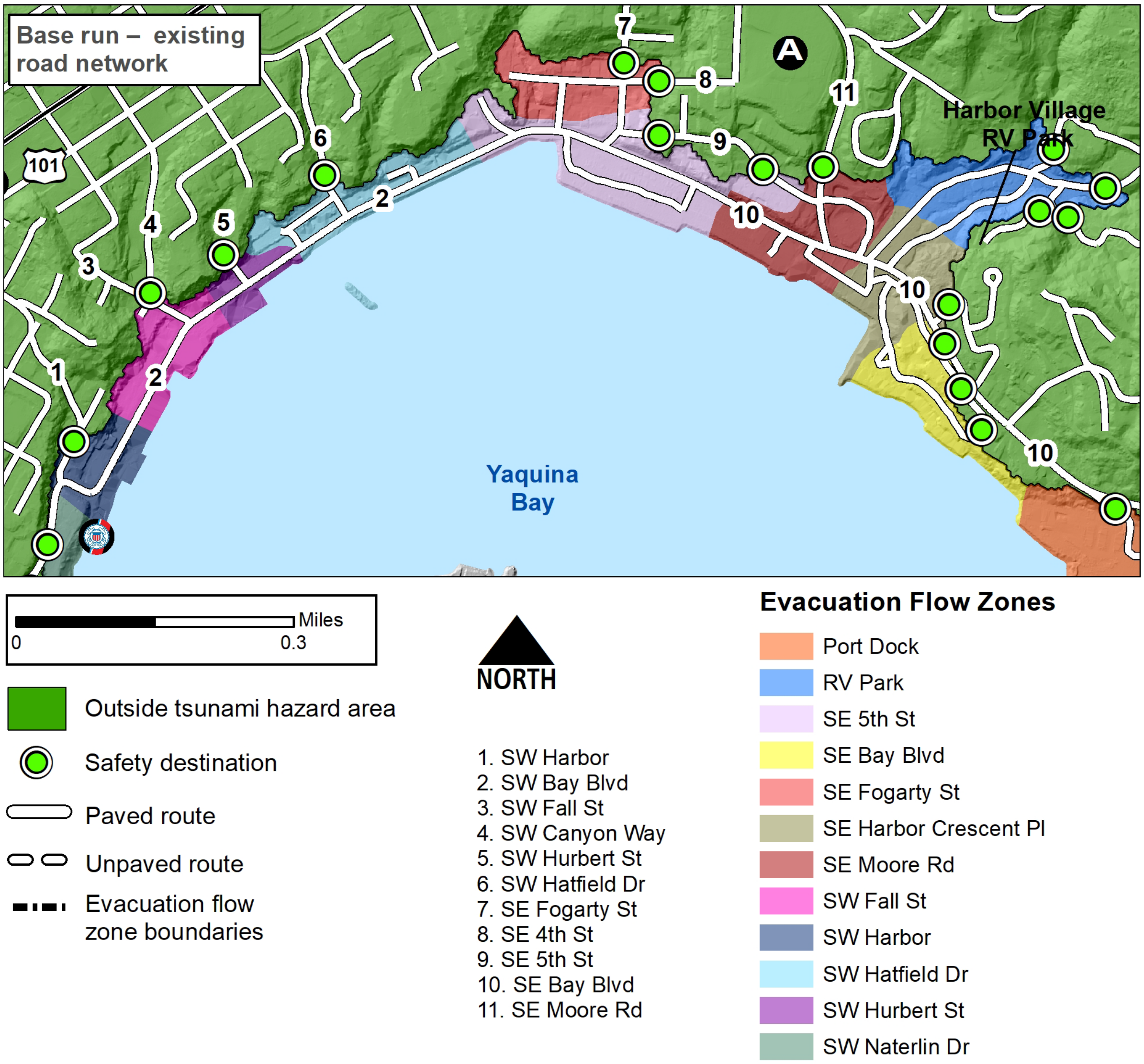


Figure 3-8. Tsunami evacuation flow zones for the base run on the Bayfront. These data can also be found in the Newport_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.



Because the Bayfront is bordered by steep slopes and has a history of intermittent slope failures, landslides are likely to influence evacuation to high ground. The hashed polygons in **Figure 3-7, middle** represent terrain identified as landslide prone (Statewide Landslide Information Database for Oregon, version 3.4, https://www.oregongeology.org/slido/index.htm). Because of this hazard, we considered a scenario where many of the Bayfront's safety destinations were blocked (red dots in **Figure 3-7, middle**). This approach requires that pedestrians travel longer distances to reach safety destinations farther away; however, results shows a negligible increase in modeled BTW speeds. This is due to the proximity of high ground.

The other primary hazards associated with earthquake shaking are liquefaction and lateral spreading. Both are difficult to incorporate into the BTW method due to their sporadic nature. Here, we considered a scenario where Bay Blvd was modeled with a loose sand land cover value. This approach simulates the difficulty evacuees could encounter when trying to walk across roads covered with sand and mud from sand boils and other liquefaction features and, as a result, reduces modeled evacuation speeds slightly (e.g., **Figure 2-1**). **Figure 3-7, bottom** shows a very small increase in modeled BTW speeds in a few select areas on the Bayfront. Overall results, including evacuation flow zones, are virtually unchanged from the base run, due to the area's proximity to high ground.

Bay Blvd itself is susceptible to lateral spreading because the seaward side of the road is essentially unsupported. Lateral spreading can result in major failures to road infrastructure as the road slumps toward the bay. However, we speculate that were we to model a blockade of Bay Blvd sections due to lateral spreading, the evacuation results would not significantly change. This is because the many roads leading to high ground along the entire length of the commercial district help minimize the potential for impediments caused by liquefaction or lateral spreading to evacuation. The modeling does not account for all possibilities that come with these hazards (e.g., the complete removal of a section of Bay Blvd). Mitigation options, including ways to reinforce Bay Blvd against lateral spreading to stabilize key routes, should be evaluated.

Understanding precisely where lateral spreading may or may not occur is well beyond the scope of this study, but we note that many buildings on the seaward side of the road are built on pilings driven into the mud underneath Yaquina Bay. The pilings upon which many buildings are built are old and will fail during the earthquake, collapsing the buildings into the estuary. People will then have to navigate to find exit points. Evacuating the buildings will be challenging, but modeling this hazard is beyond the scope of this work.

The above results present an initial assessment of how landslides, liquefaction, and lateral spreading could affect evacuation. The results suggest that evacuation is achievable on the Bayfront but is dependent on people being able to evacuate out of buildings in time.

3.3 South Newport

Unlike north Newport, where most of the developed land is outside of the inundation zone, most of south Newport is inside the inundation zone (**Figure 3-1**). The first two miles south of Yaquina Bay are virtually 100% inundated and this is also where many people work, recreate, and reside. Safehaven Hill is a small "island" of high ground at the south end of the Yaquina Bay Bridge and serves as the primary safety destination for South Beach State Park in the west and Hatfield peninsula to the east (**Figure 3-9**). A vertical evacuation structure is currently under construction on the HMSC campus and, when completed (estimated 2020), will provide an additional safety destination for the Hatfield peninsula. Several streets connect Highway 101 with high ground to the east, which also leads to the Oregon Coast Community College (OCCC), a designated tsunami assembly area. From the Newport Municipal Airport (south of 68th St), the inundation area is reduced to a small ~500 ft wide strip along the coast that continues to the south edge of the project area at Ona Beach. Results will be described for the distinct geographic regions, each of which has its own set of challenges and mitigation options.

Overall, BTW results for south Newport are wide-ranging and depend on location. Our modeling indicates the following:

1. Evacuation from South Beach State Park will be challenging but attainable if evacuation begins promptly and the route is clearly defined and understood ahead of time. We cannot stress enough the importance of education and outreach before the event as well as wayfinding signage to assist in an actual evacuation.
2. The vertical evacuation structure currently being built at HMSC will greatly improve evacuation potential for the peninsula. It introduces a second option for safety (the other being Safehaven Hill) that is much more centrally located and will also serve as a powerful education tool, bringing awareness with its presence and surrounding signage.
3. Liquefaction is highly likely to increase evacuation difficulty for SBSP and the Hatfield peninsula, making it doubly imperative to ensure that everyone knows to evacuate immediately and which route to take.
4. The Southshore community is limited to one egress route. However, safety can be reached by most at a ***walk*** if evacuation begins promptly and the route is known ahead of time.
5. The area between the airport and Ona Beach has high potential for successful evacuation; however, knowing which direction to travel, especially how to get off the beach, is important.

3.3.1 South Beach State Park

Results are presented for the South Beach State Park (SBSP) campground, Camp Gray (an Oregon Museum of Science and Industry facility), and the South Beach residential community. SBSP is home to as many as 2,000 people on a summer weekend (J. M. Bauer, written commun., 2019; SBSP staff, oral commun., 2019). The visitor population is especially vulnerable given their lack of knowledge about local geography. A similar situation applies at Camp Gray, where summer camp facilities house an average of 140 people during the week days (J. M. Bauer, written commun., 2019).

High ground for this area can be found at Safehaven Hill to the north and in the hills east of Highway 101 via SE 40th St, 42nd St, and 50th St (**Figure 3-9**). The most important factor for SBSP to consider is whether to direct people north to Safehaven Hill or south/east to SE 50th St via Highway 101. The following sections will discuss this topic in detail given existing road and trail conditions as well as with hypothetical challenges and mitigation options.

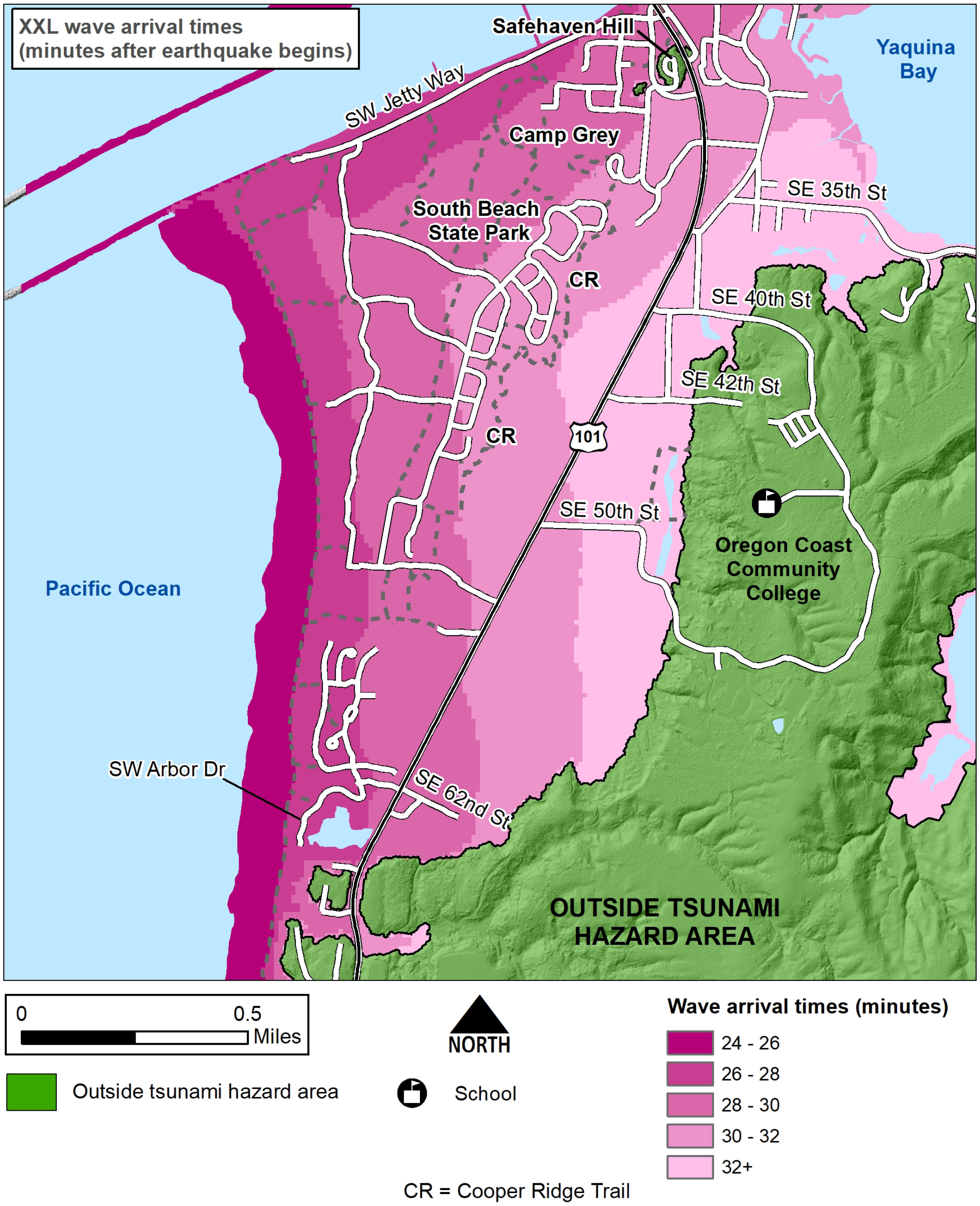
The first tsunami wave associated with an XXL tsunami arrives at the beach 25 minutes after the earthquake (**Figure 3-9**). The river mouth acts as a conduit for the tsunami, and water will overtop all of

SW Jetty Way about 2 minutes later. The tsunami will reach the base of Safehaven Hill after ~30 minutes. By ~33 minutes, all of South Beach is inundated.

Overall, the XXL results for South Beach are similar to what we have seen in other remote coastal areas, namely, that 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 by the campground means aside from construction of a vertical evacuation structure there are few options for mitigation. A vertical evacuation structure is considered in South Beach scenario 5, below. Although there is no safe ground within the campground for an XXL tsunami, there are a few adjacent dunes high enough to be considered safe in a Large (L1) tsunami scenario; accordingly, South Beach scenario 6, below, describes results for a L1 (Large) tsunami. These L1 results suggest that other evacuation options, such as directing the public to a high point on Cooper Ridge Trail that is considered safe for an L1 tsunami but inundated by an XXL1 tsunami, could be considered by local authorities.

We model in Scenario 3 a reduction from the 10-minute delay to a 5-minute delay because people in this area are more likely to be outdoors or in a tent, which means their evacuation can generally start quickly compared with people evacuating from buildings. Due to the lack of infrastructure, the only vulnerability considered for this area is the effect from liquefaction (Scenario 2).

Figure 3-9. Modeled tsunami wave arrival times for South Beach State Park after XXL Cascadia subduction zone earthquake.



3.3.1.1 Scenario 1 – Existing road network

Figure 3-10, left shows the least-cost (path) distance modeling for an XXL tsunami in South Beach State Park and surrounding roads. The road network includes a footpath connecting Camp Loop I and Camp Gray, which allows pedestrian passage from the campground to Safehaven Hill. This scenario reflects our base run; BTW model data can be found in the Newport_Tsunami_Evacuation_Modeling geodatabase. Evacuation for most of the park is characterized with **minimum** evacuation speeds associated with a ***fast walk*** with a smaller area at the north end of the park found to be ***walk*** (because it is closest to Safehaven Hill).

The park is characterized by two evacuation flow zones: all campground loops as well as the park trail system and SW Jetty Way evacuate to Safehaven Hill (grey-green polygon in **Figure 3-11**). Evacuees near the day use parking lot should head east out the park entrance and up SE 50th St on the east side of Highway 101 (dark blue polygon labeled Mike Miller in **Figure 3-11**). Once on SE 50th, the nearest safety destination is a few hundred yards up the Mike Miller trail or farther up SE 50th St.

Figure 3-10. Beat the Wave (XXL) modeling for South Beach: (left) Scenario 1 – Existing road network and (right) Scenario 2 – Liquefaction hazard added.

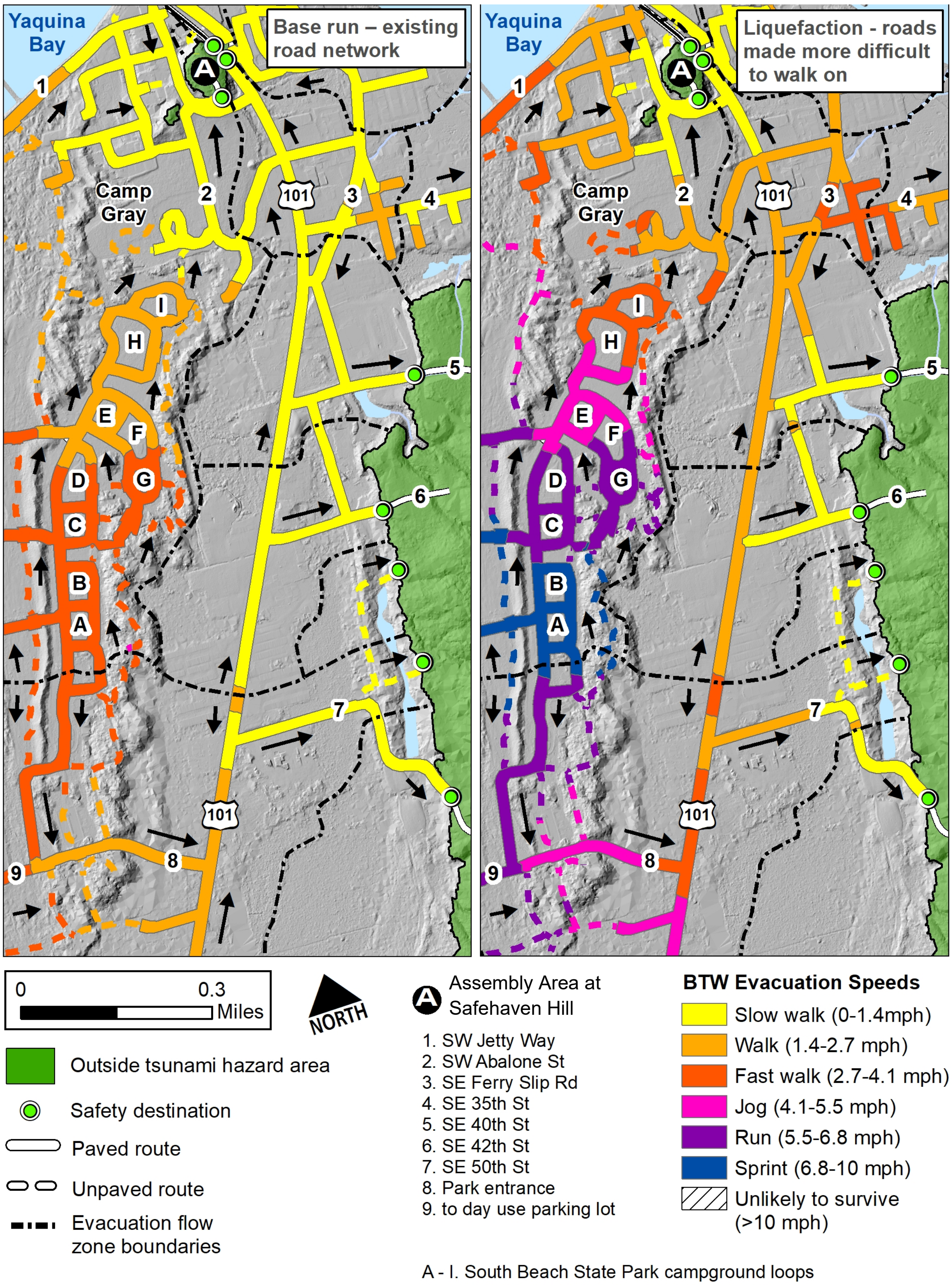
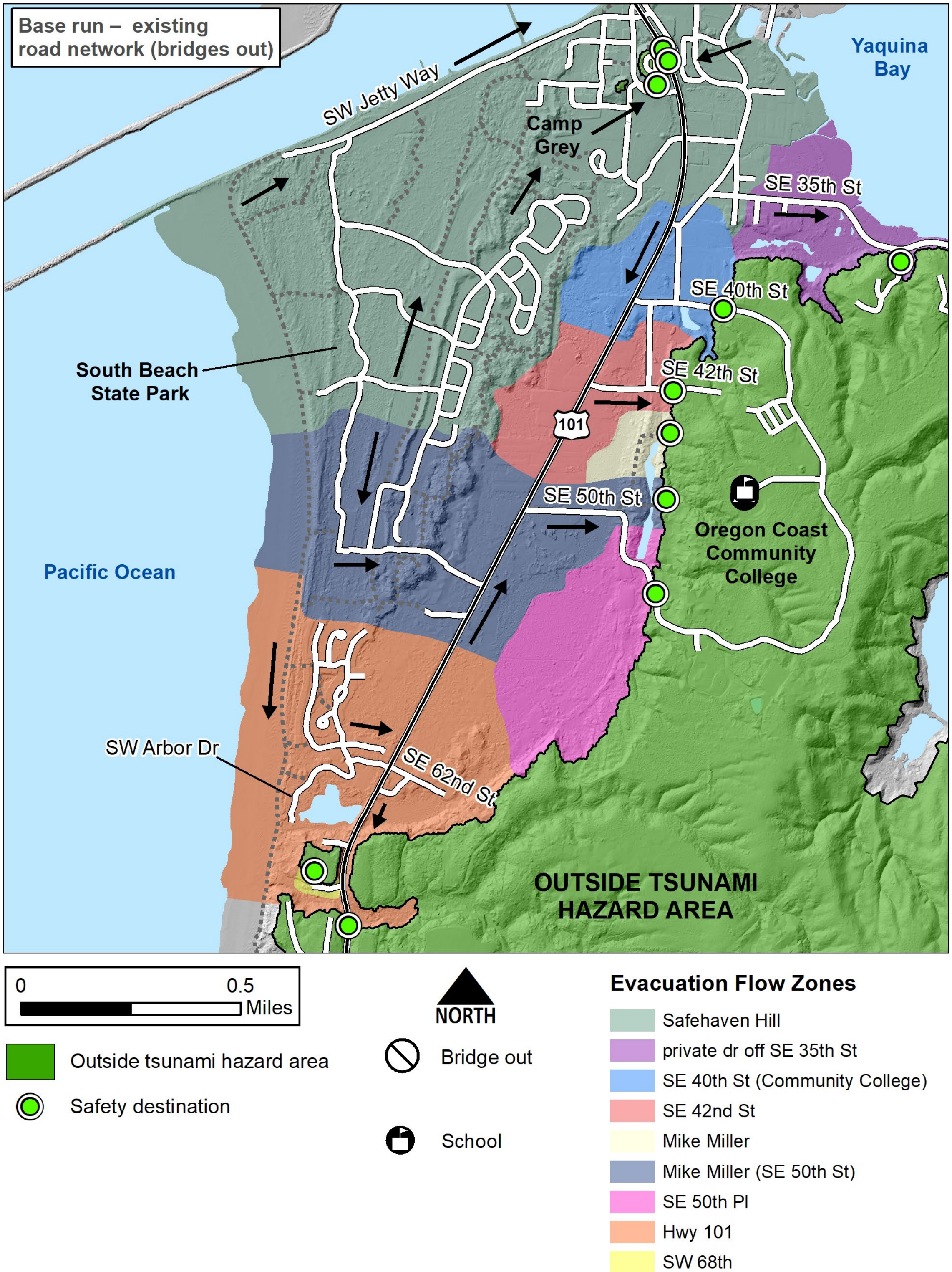


Figure 3-11. Tsunami evacuation flow zones for South Beach Scenario 1 – Existing road network. These data can also be found in the Newport_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.



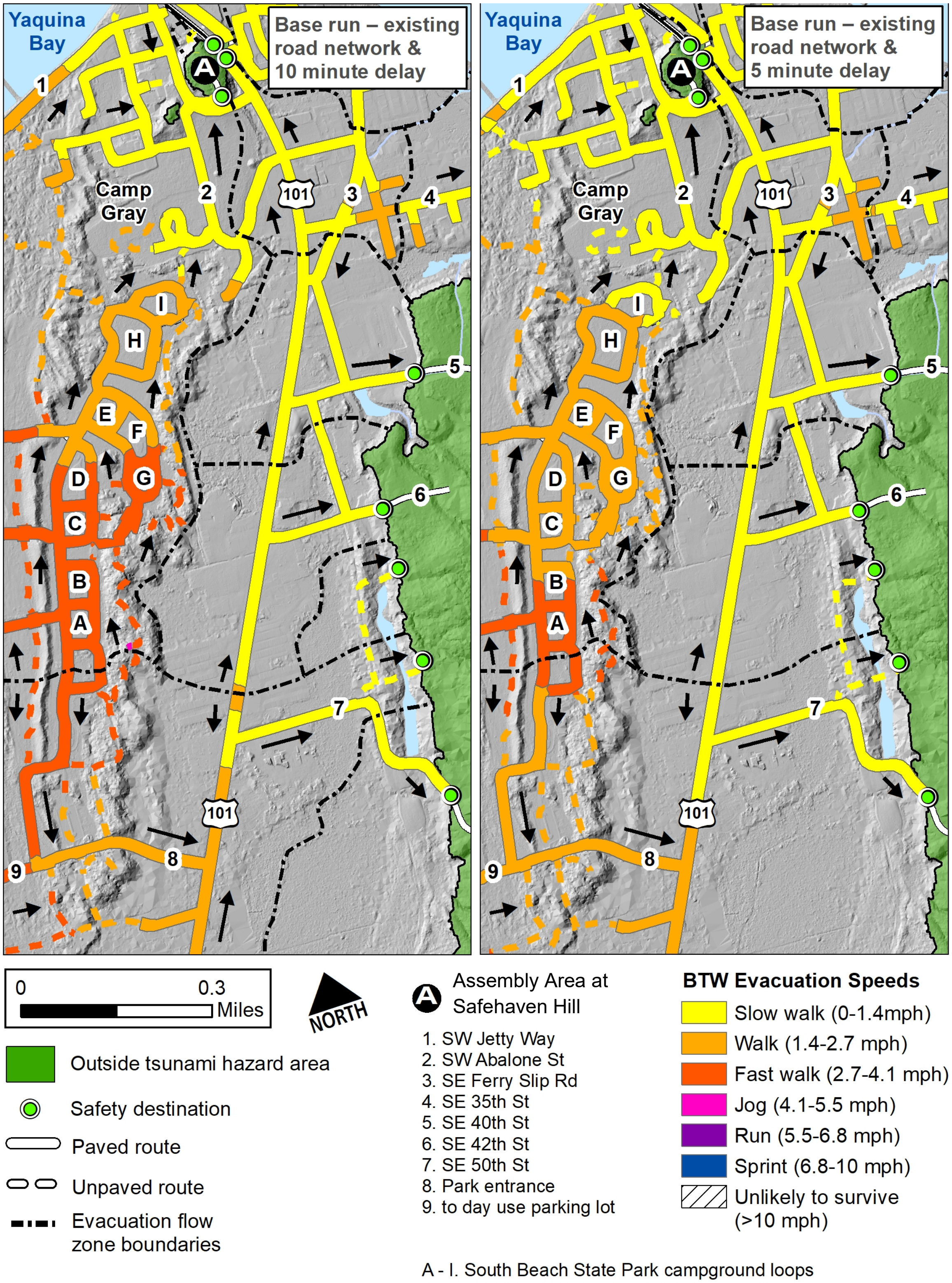
3.3.1.2 Scenario 2 – Liquefaction

Because South Beach sits on loose sediment adjacent to the Pacific Ocean and Yaquina Bay such that water tables are high, liquefaction may affect evacuation travel to high ground. To that end, we evaluated a scenario where all roads and trails were modeled with a loose sand land cover value; no routes were blocked. **Figure 3-10, right** shows an extreme increase in modeled BTW speeds throughout the park. The northernmost two campground loops (H and I) increase from ***walk*** to ***fast walk*** but the differences substantially increase in the south with campground loop A increasing from ***fast walk*** to ***sprint***. The day use parking lot increases from ***fast walk*** to ***jog***. Evacuation flow zones are virtually unchanged from Scenario 1. These results suggest that liquefaction could play a significant role on travel speeds and thus is likely to affect survivability. Additional mitigation measures should be considered such as constructing a vertical evacuation structure or hardening existing routes in order to minimize liquefaction effects.

3.3.1.3 Scenario 3 – 5-minute evacuation delay

To better understand the effects of evacuation delay, we reduced the 10-minute evacuation departure delay to 5 minutes to reflect those people already outside, in a tent, or in an RV. Such an approach allows for a faster transition from waiting out the earthquake shaking to evacuating and is especially pertinent for South Beach State Park and anyone recreating in the area. **Figure 3-12, right** demonstrates the resulting minimum walking speeds associated with a 5-minute evacuation delay. Scenario 1 results (**Figure 3-10, left**) are shown for a second time in **Figure 3-12, left** to provide a direct comparison. The day use parking lot decreases to ***walk***, and campground loops requiring a ***fast walk*** are reduced to loops A and B only. These results confirm the importance of evacuating as soon as possible after earthquake shaking begins.

Figure 3-12. Beat the Wave (XXL) modeling for South Beach: (left) Scenario 1 – 10-minute evacuation delay, and (right) Scenario 3 – 5-minute evacuation delay. Both use the existing road network.



3.3.1.4 Scenario 4 – Hypothetical new evacuation trails

One mitigation option is to connect the campground to high ground in the east by constructing new evacuation trails. For example, a trail connecting the campground to SE 40th St existed in the past but was eventually closed. BTW modeling was performed with this trail as well as two others (**Figure 3-14**) that connect the campground with SE 42nd St and with SE 50th St. **Figure 3-13, right** provides compelling evidence that a trail to 40th Street is unnecessary. Results are essentially identical to Scenario 1 (base model run) with no trails (**Figure 3-13, left**). With or without a trail to SE 40th St, camp loops A, B, C, D, and G must travel at a ***fast walk*** to reach Safehaven Hill. This is because the distance required to reach high ground on SE 40th Street (toward OCCC) is farther than the distance to Safehaven Hill.

Two other hypothetical trails we consider would provide some level of evacuation improvement. **Figure 3-14, left** presents BTW results for the park with a hypothetical trail connecting the campground with SE 42nd Street. The addition of this trail reduces all campground loop minimum walking speeds to a ***walk***. This contrasts with a hypothetical trail connecting the campground with SE 50th St (**Figure 3-14, right**). In this scenario, there is a nominal reduction in walking speeds, but the three camp loops remain at ***fast walk***. Hence, it is abundantly clear from **Figure 3-14** that a centrally located trail provides the most effective improvement to evacuation for the campground. Any trail in this area would have to be built to allow passage across a marsh that may contain significant amounts of water in the winter and be resistant to earthquake shaking. Black dashed lines delineating evacuation flow zones in **Figure 3-14, left** illustrate that camp loops A through G would use this new hypothetical trail.

Figure 3-13. Beat the Wave (XXL) modeling in South Beach for (left) Scenario 1 – Existing road network and (right) Scenario 4 – hypothetical trail to Highway 101 at 40th St.

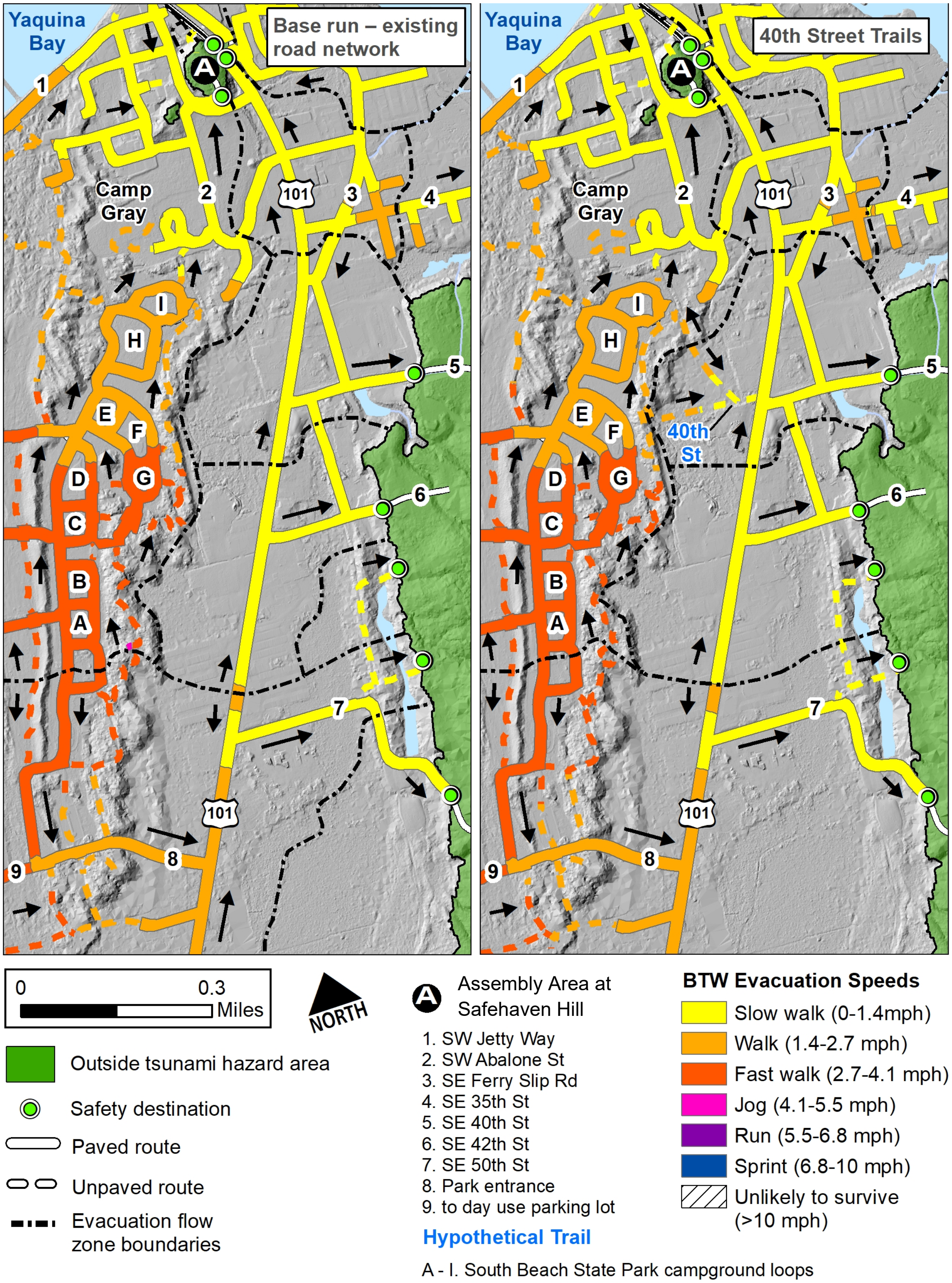
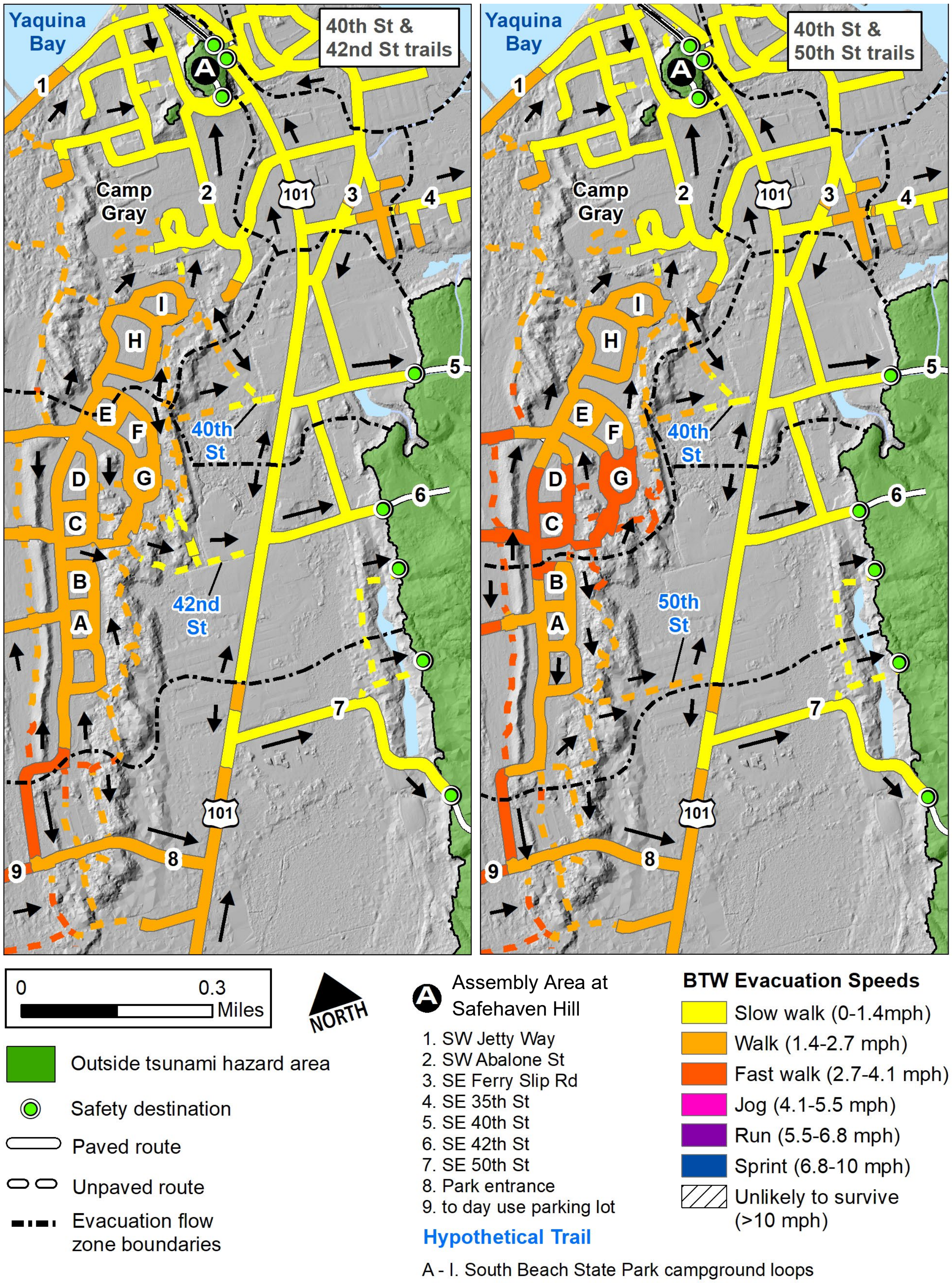


Figure 3-14. Beat the Wave (XXL) modeling in South Beach for Scenario 4 – Hypothetical new evacuation trails. (left) 42nd Street trail and (right) 50th Street trail. Both figures also include the hypothetical trail at 40th St; however, the objective in this figure is to compare the effectiveness of 42nd St and 50th St trails only.



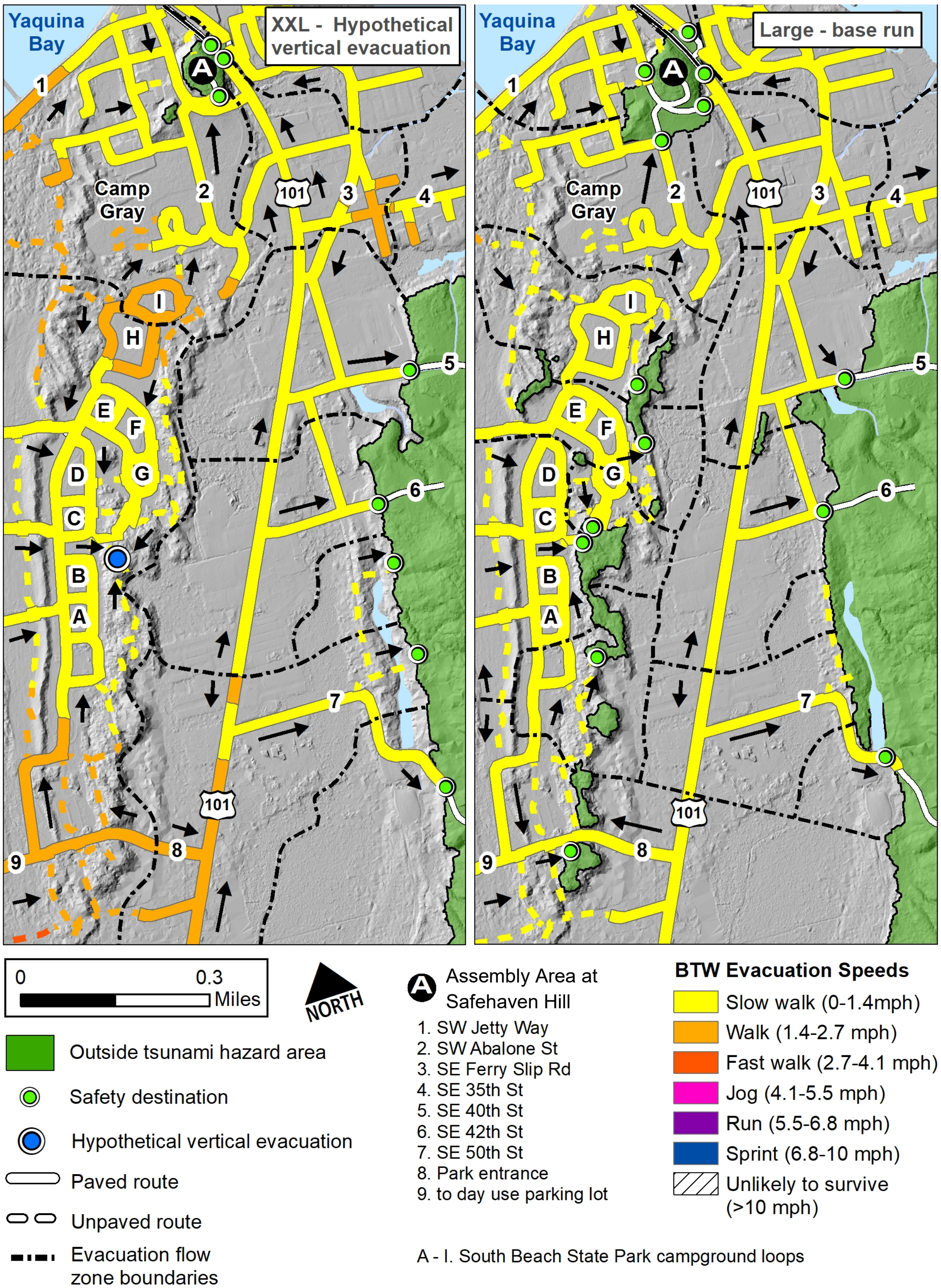
3.3.1.5 Scenario 5 – Vertical evacuation structure

A more significant mitigation option is to construct a vertical evacuation structure in the immediate vicinity of the campground. We chose a naturally high location along the Cooper Ridge dune east of the campground near loop B as the location for such a structure (Cooper Ridge is identified in **Figure 3-9**). As expected, BTW speeds are dramatically improved from Scenario 1, with the majority of the campground evacuation speed now reduced to a ***slow walk*** (**Figure 3-15, left**). Evacuation flow zones (black dashed lines) change to reflect the additional safety destination; evacuees in all but one camp loop now evacuate to the hypothetical structure. Only evacuees near Loop I, at the northern end of the campground, would continue to evacuate to Safehaven Hill.

3.3.1.6 Scenario 6 – Large tsunami scenario

The unfortunate reality is that surviving the XXL tsunami at South Beach is going to be difficult for some people. Another option is to consider the Large (L1) tsunami scenario instead of XXL. The Cooper Ridge dune is considered safe under this scenario. Recall, the L1 scenario covers 95% of the likely inundation (XXL covers 100%), meaning that there is a 5% chance that high ground outside L1 could be inundated by a larger tsunami. **Figure 3-15, right** demonstrates that minimum walking speeds are reduced dramatically when evacuating to high ground on Cooper Ridge immediately adjacent to the campground, rather than having to evacuate to Safehaven Hill. Results are similar to South Beach Scenario 4 (vertical evacuation structure, **Figure 3-15, left**) because the naturally high dune is in the same location as the hypothetical structure.

Figure 3-15. Beat the Wave (XXL) modeling in South Beach for (left) Scenario 5 – Hypothetical vertical evacuation structure and (right) Scenario 6 – Large (L) tsunami scenario (rather than XXL).



3.3.1.7 Discussion

South Beach State Park has significant evacuation challenges. There is one primary safety destination for the entire campground, Safehaven Hill, but it is not within park limits and cannot be seen until evacuation is well underway. This does not have to be a problem, but it does underscore the need for clear and prevalent wayfinding signage throughout the park to encourage prompt evacuation in the correct direction.

Mitigation options considered in this study include a vertical evacuation structure or the addition of new trails to alternate areas of high ground. Our modeling clearly demonstrates the improvement such efforts would have on improving evacuation. Of the options evaluated, we find that a vertical evacuation structure would be the most beneficial, allowing most campground visitors to reach high ground at a ***walk***. Hypothetical new trails are less effective when compared to a vertical evacuation structure, but still provide significant improvements at a far lower cost. Hardening an existing route to Safehaven Hill against liquefaction could also improve survivability.

These analyses presuppose that the vertical evacuation structure has 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.

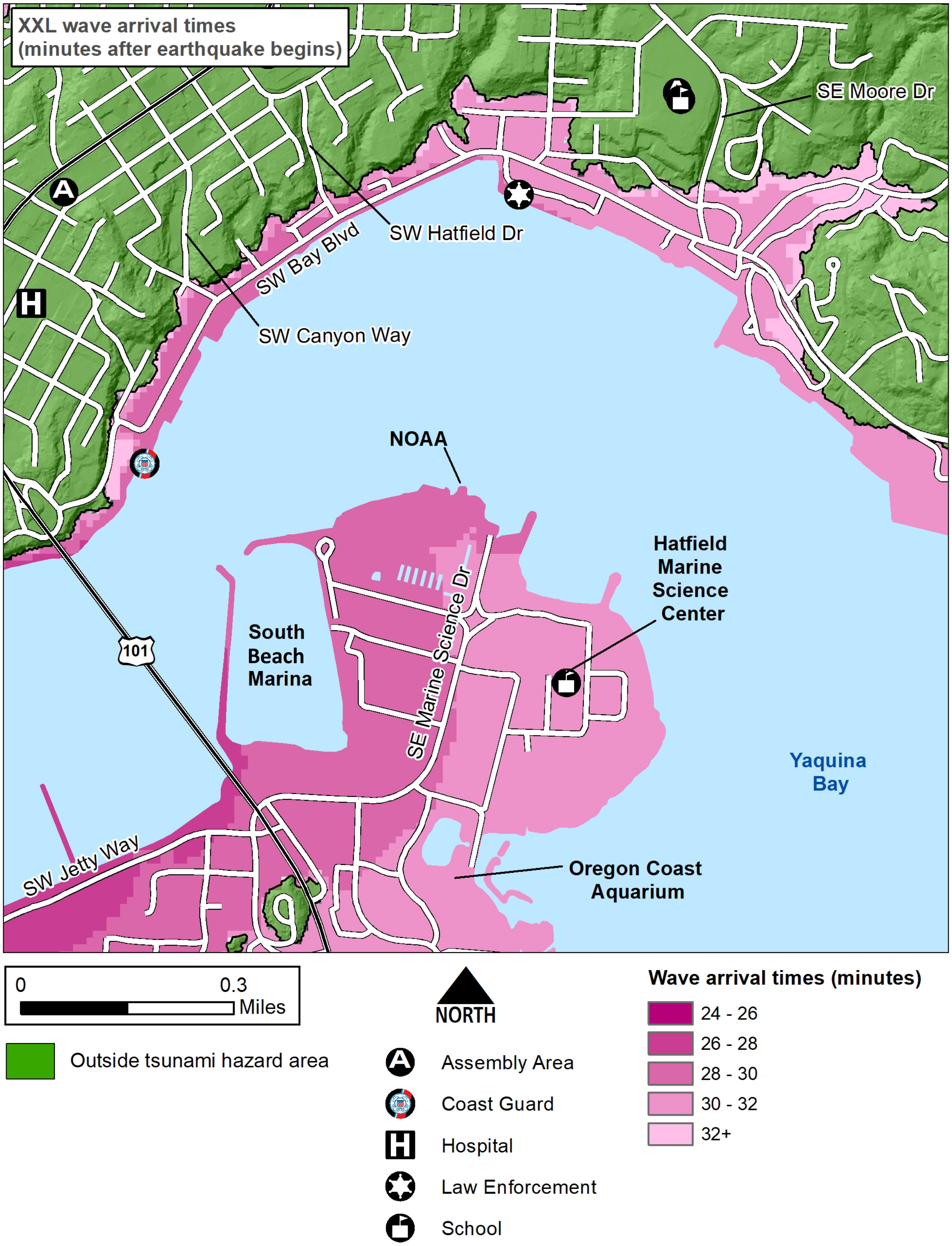
One alternative to constructing a vertical evacuation structure is to direct people to the vegetated Cooper Ridge dune, which is high enough to be outside the L1 tsunami zone (but not high enough to withstand XXL1).

3.3.2 Hatfield peninsula

Results are presented for the entire peninsula, locally known as the Hatfield peninsula, which includes the OSU Hatfield Marine Science Center (HMSC), National Oceanic and Atmospheric Administration (NOAA) Marine Operations Center, Port of Newport RV Park and Marina, and Oregon Coast Aquarium. As many as 400 people work here on a year-round basis and many more come to visit. There can be as many as 1,000 visitors to the Hatfield Visitor Center and up to 4 times that at the aquarium on a busy summer weekend (J. M. Bauer, written commun., 2019). As with SBSP, the primary safety destination is Safehaven Hill. The community college is another available destination, but it is much farther from HMSC than Safehaven Hill. HMSC is also the site of Oregon's first vertical evacuation structure, the Marine Studies Building, currently under construction. When completed (estimated 2020), it will become the primary safety destination for the peninsula.

Tsunami waves arrive at the site in about 29 minutes and total inundation is swift, taking only a few more minutes to cover the peninsula (**Figure 3-16**). Overall, BTW results are positive, especially with the inclusion of a vertical evacuation structure. We examine the impact of the vertical evacuation structure in detail as well as the difficulty presented by liquefaction (Scenarios 2 and 3, respectively, below). In Scenario 4 we investigate the viability of the community college as a safety destination for the peninsula.

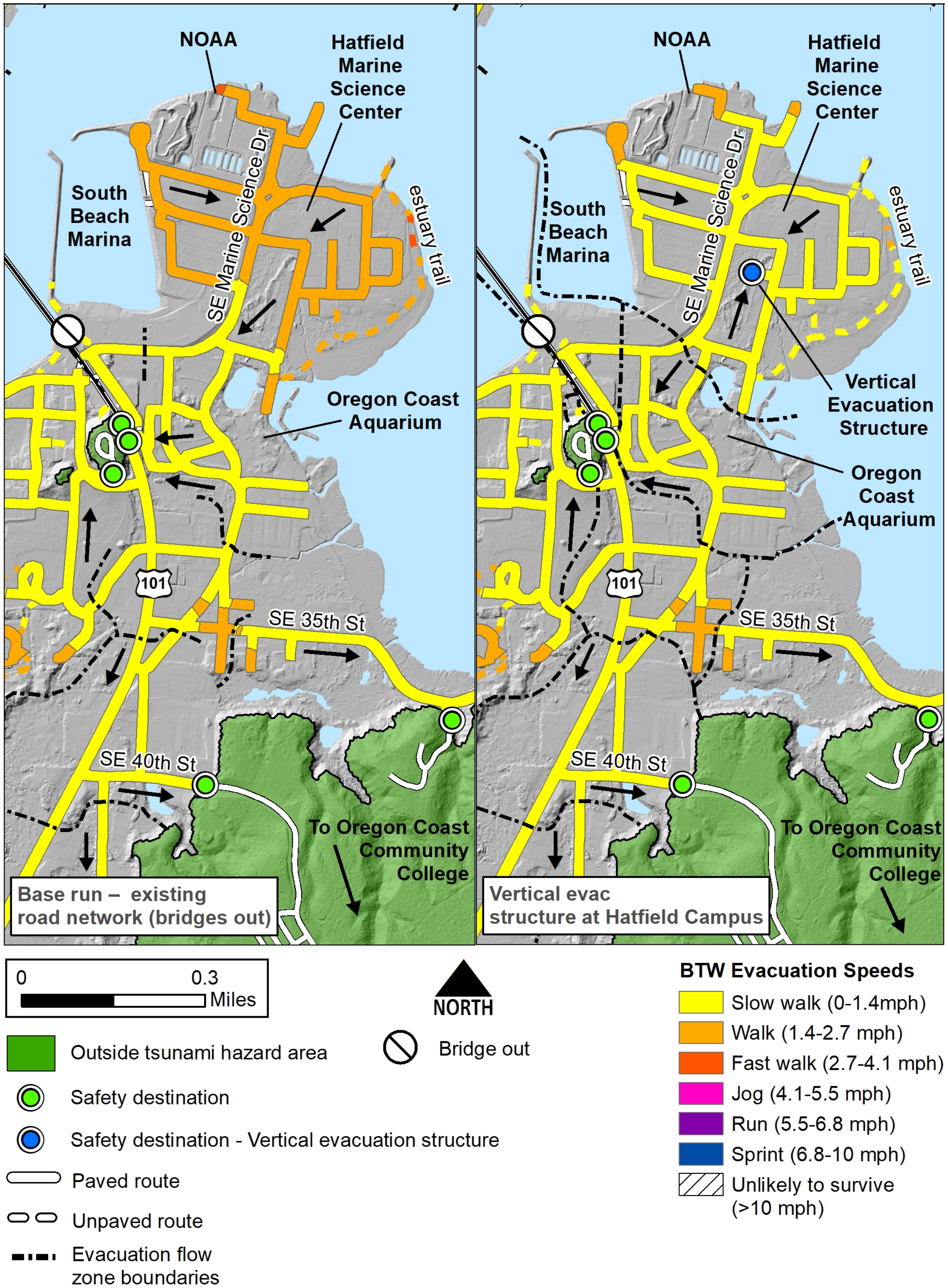
Figure 3-16. Modeled tsunami wave arrival times for South Beach and the Bayfront after XXL Cascadia subduction zone earthquake. NOAA is National Oceanic and Atmospheric Administration Marine Operations Center.



3.3.2.1 Scenario 1 – Existing road network (without vertical evacuation structure)

Figure 3-17, left shows the least-cost (path) distance modeling for the Hatfield peninsula, assuming the existing road network remains intact. This scenario *does not* include the vertical evacuation structure currently under construction at HMSC. Because the structure is not yet viable, current conditions require everyone to evacuate to Safehaven Hill. Evacuation for the peninsula is characterized with a minimum evacuation speed of ***walk***. These results are thus extremely promising. However, it can be difficult to know which way to travel, especially from within the Hatfield campus or the aquarium, and wayfinding will be extremely important in ensuring people do not extend their routes more than necessary by taking wrong turns.

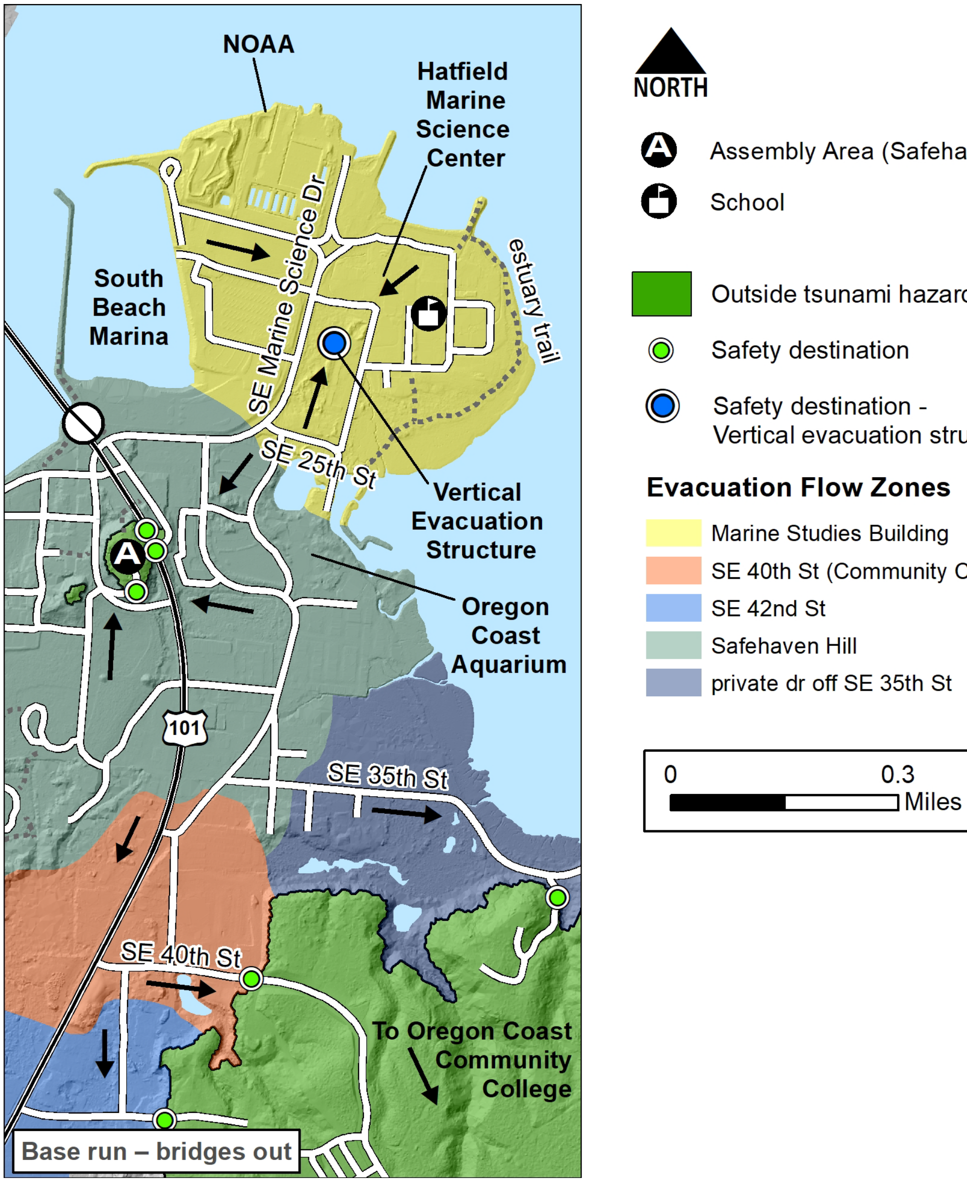
Figure 3-17. Beat the Wave (XXL) modeling for Hatfield peninsula (left) Scenario 1 – Existing road network and (right) Scenario 2 – Vertical evacuation structure.



3.3.2.2 Scenario 2 – Vertical evacuation structure

Within the next year, evacuees on the peninsula will have two options for evacuation: Safehaven Hill and the newly completed vertical evacuation structure on the Hatfield Marine Science Center campus (**Figure 3-17, right**). The inclusion of the new Marine Studies Building vertical evacuation structure reduces the BTW minimum evacuation speeds from ***walk*** to ***slow walk*** for most of the area. Evacuation flow zones in **Figure 3-18** show the divide between the two safety destinations: those at SE 25th St or north evacuate to the new structure (located in the yellow polygon), those south of SE 25th St travel to Safehaven Hill (in the dark teal polygon). The Rogue Brewery, Oregon Coast Aquarium, and Port of Newport RV park are in the Safehaven Hill flow zone. Rogue Distillery, Port of Newport Marina, NOAA Operations Center, and HMSC are in the vertical evacuation structure zone. This is considered the base run for the Hatfield peninsula and BTW data can be found in the Newport_Tsunami_Evacuation_Modeling geodatabase.

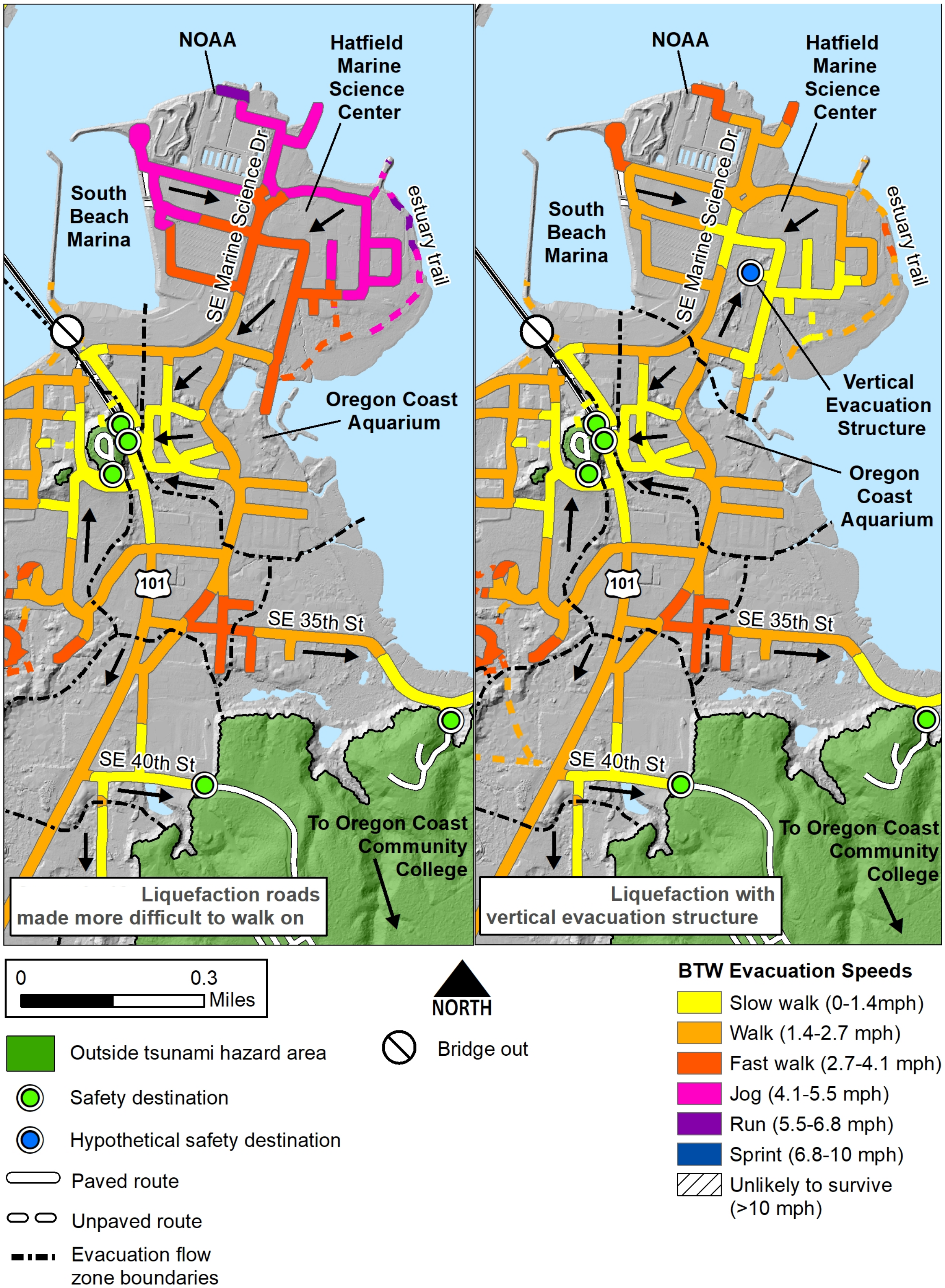
Figure 3-18. Tsunami evacuation flow zones for the Hatfield peninsula using Scenario 2 – Vertical evacuation structure. These data can also be found in the Newport_Tsunami_Evacuation_Modeling geodatabase, XXL1_BridgesOut feature dataset, EvacuationFlowZones feature class.



3.3.2.3 Scenario 3 – Liquefaction

Liquefaction is likely to influence evacuation travel to high ground, so we re-ran Hatfield Scenarios 1 and 2 (with and without the vertical evacuation structure) with the liquefaction hazard added. **Figure 3-19** shows how minimum BTW walking speeds for both scenarios increase significantly. Without a vertical evacuation structure, minimum walking speeds increase from ***walk*** to ***jog*** (**Figure 3-19, left**). With the vertical evacuation structure in place, walking speeds for most of the peninsula change from a ***slow walk*** to ***walk*** (**Figure 3-19, right**). Evacuation flow zones are virtually unchanged.

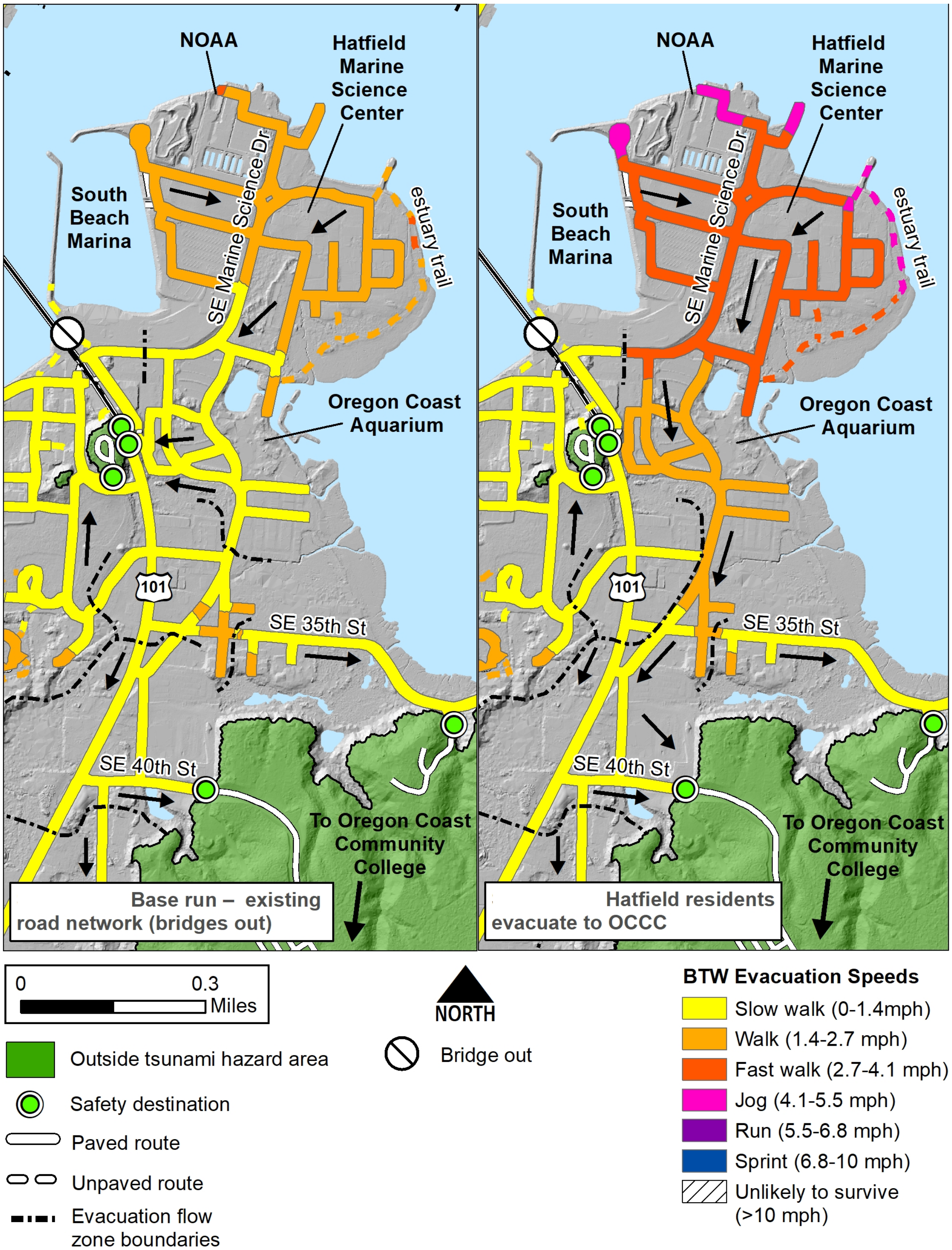
Figure 3-19. Beat the Wave (XXL) modeling for the Hatfield peninsula for Scenario 3 – Liquefaction hazard added. (left) Hatfield Scenario 1 (no vertical evacuation) with liquefaction hazard added, and (right) Hatfield Scenario 2 (with vertical evacuation) with liquefaction hazard added.



3.3.2.4 Scenario 4 – Oregon Coast Community College

The Oregon Coast Community College (OCCC) provides an additional safety destination for the peninsula, although the campus is considerably farther away than Safehaven Hill. OCCC's appeal as a destination lies in the fact that unlike Safehaven Hill, which is a small "island" of high ground that will be surrounded by tsunami flooding and provides no refuge from the elements, OCCC is on contiguous high ground, has multiple large structures capable of housing evacuees for a short period of time, and is in the process of stocking a cache of emergency supplies; Safehaven Hill is also developing a cache. **Figure 3-20, right** shows that minimum BTW walking speeds required to reach OCCC are one classification faster than needed to reach Safehaven Hill (**Figure 3-20, left**) — speeds increase from ***walk*** to ***fast walk*** and, at the farthest reaches of the peninsula, to ***jog***. These results do not include liquefaction, which will likely increase speeds by at least one more classification (i.e., to ***run***). We strongly urge anyone planning to reach OCCC from the peninsula to practice the route and plan for any potential obstacles (i.e., downed power lines). It is good practice to have multiple evacuation routes in mind so if a primary, planned route is blocked, other routes are known.

Figure 3-20. Beat the Wave (XXL) modeling for the Hatfield peninsula for (left) Scenario 1 – Existing road network (peninsula evacuates to Safehaven Hill) and (right) Scenario 4 – Oregon Coast Community College (peninsula evacuates to OCCC).

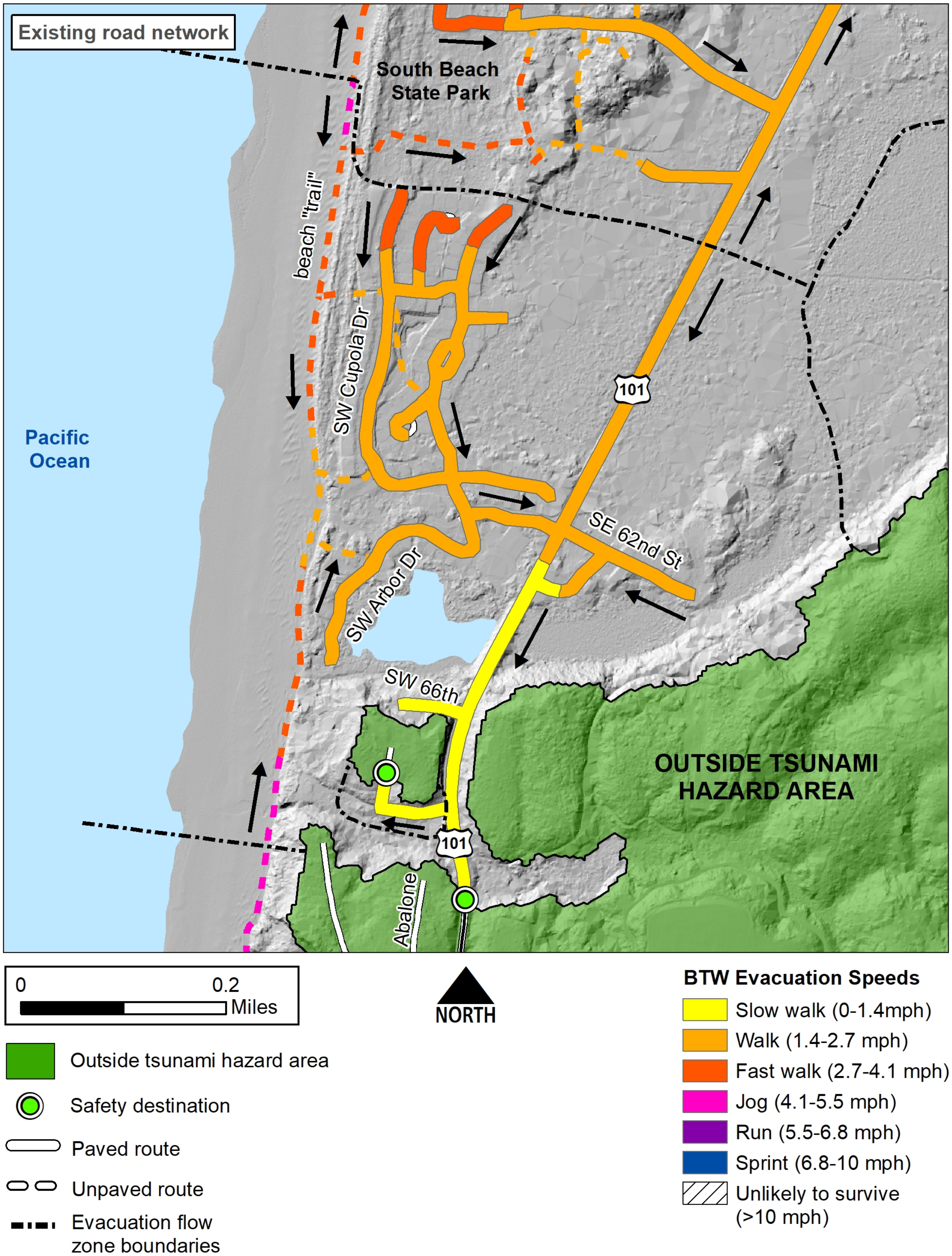


3.3.3 Southshore

The community of Southshore lies at the south end of the broad inundation plain of South Beach. The entire community resides within the tsunami inundation zone and has only one paved egress road (SW 62nd St). The nearest high ground is on Highway 101, ~0.4 miles to the south of SW 62nd St. **Figure 3-9** shows that the first tsunami wave arrives in 26 minutes and the community is completely inundated by 28 minutes.

Figure 3-21 shows the least-cost (path) distance modeling for the Southshore community, assuming the existing road network remains intact (base run). Nearly the entire community can reach high ground on Highway 101 at a ***walk*** (< 4 fps). A footpath connects the south end of SW Arbor Dr to SW 66th Dr (not shown in **Figure 3-21**) and provides a small shortcut to Highway 101; however, it does not change minimum BTW walking speeds (i.e., it is just as efficient to use SW 62nd St as it is to use this path). It may be beneficial to develop a trail connecting SW Arbor Dr to the island of high ground immediately south of SW 66th St. We did not model this scenario, but such a trail would reduce the evacuation route for some areas within the community by as much as half a mile based on distance alone (i.e. ignoring land cover or slope effects).

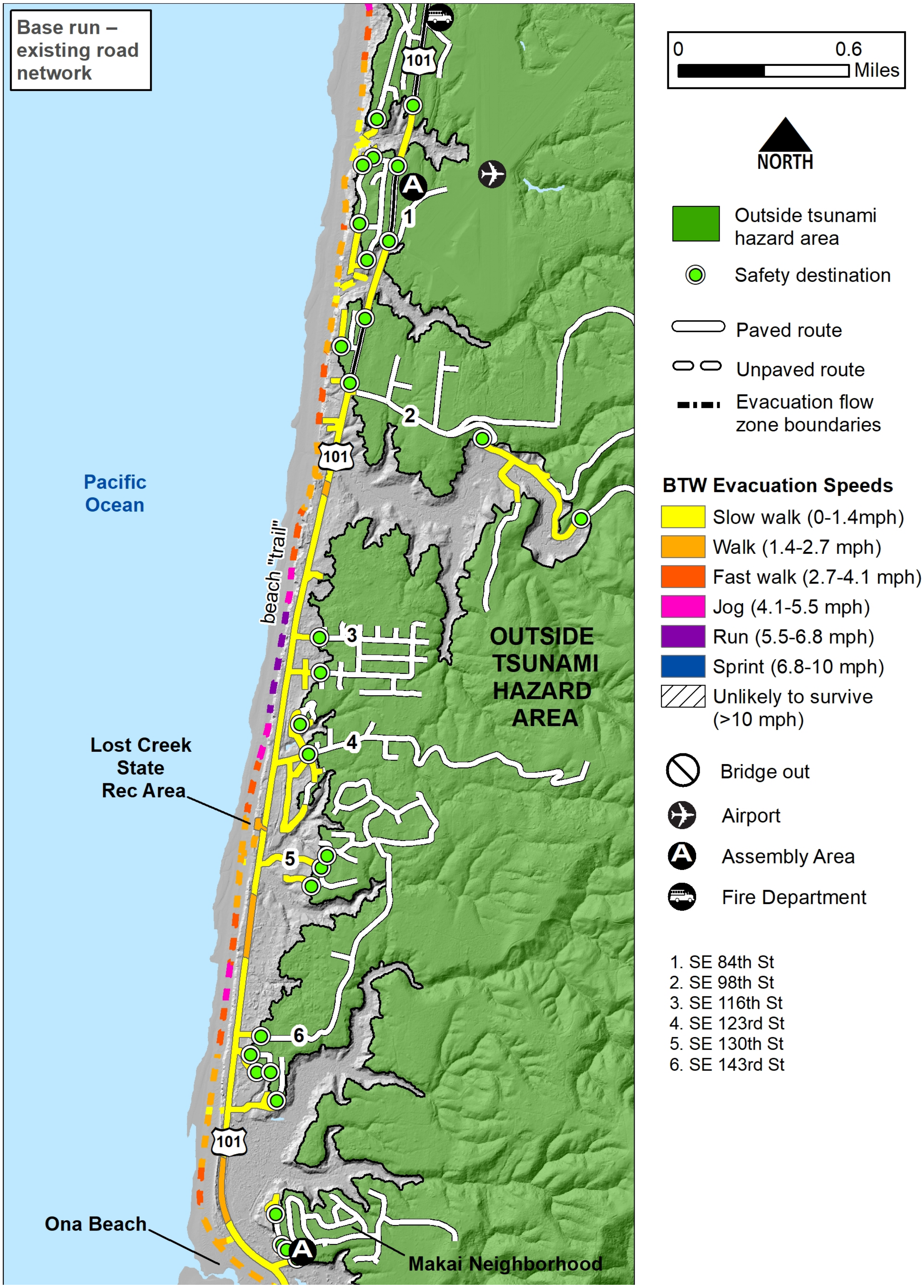
Figure 3-21. Beat the Wave (XXL) modeling at Southshore for the base run.



3.3.4 Airport to Ona Beach

The stretch of south Newport between the Newport Municipal Airport and Ona Beach has very little inundation; a narrow strip of the coastline adjacent to Highway 101 is affected. Roads connect the inundated area with high ground on a regular interval, meaning no inundated location has very far to travel to reach safety ahead of the tsunami. **Figure 3-2** shows that the first tsunami wave arrives on the beach in ~26 minutes and the extent of inundation is reached by 28 minutes. **Figure 3-22** shows the least-cost (path) distance modeling for this area, assuming the existing road network remains intact. Evacuees on all but ~0.3 miles of Highway 101 can reach safety by traveling at a minimum walking speed of ***slow walk*** (< 2 fps).

Figure 3-22. Beat the Wave (XXL) modeling of a base run for the area from the Newport Municipal Airport to Ona Beach .



4.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation accomplished the primary objective: to provide a quantitative assessment of tsunami evacuation attributed to a maximum considered XXL tsunami affecting the City of Newport and surrounding coastal communities (Yaquina Head to Ona Beach). 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 terrain 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 these coastal communities in response to a maximum considered (XXL) Cascadia Subduction Zone tsunami is attainable with the notable exception of South Beach State Park, where moderately high evacuation speeds are needed to survive. In this location, a dense network of wayfinding signage, coupled with a robust education program, is needed to reduce evacuation delays and direct evacuation along the shortest possible routes. Vertical evacuation is another mitigation opportunity here because of the scarcity of natural high ground (outside the XXL zone) in the immediate vicinity of the park. Such a structure (e.g., a berm or building) would need to be built to a sufficient height and with design specifications to withstand the tsunami forces, and importantly be able to accommodate safely the large number of people that visit the park. A third migration opportunity is construction of new evacuation trails in the park. New trails would provide significant improvement to evacuation at a far lower cost than a vertical evacuation structure. We recommend further evaluation to assess the cost versus benefits of these options.

Another option is to consider the Large (L1) tsunami scenario instead of XXL. Natural high ground is available on Cooper Ridge Trail, and the Large scenario covers 95% of the likely inundation (XXL covers 100%). The decision to direct people to nearby L1 high ground versus Safehaven Hill or Mike Miller (nearest XXL safety destinations) must be done with care and deliberation because this scenario requires a completely different evacuation route and carries a different set of risks, primarily that the tsunami will overtop the dune.

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

5.0 ACKNOWLEDGMENTS

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