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TSUNAMI EVACUATION ANALYSIS OF CANNON BEACH, ARCH CAPE, AND FALCON COVE, CLATSOP COUNTY, OREGON

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WHAT'S IN THIS REPORT?

This report shows modeled pedestrian evacuation routes to escape a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) for the communities of Cannon Beach, Arch Cape, and Falcon Cove, Clatsop County.

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GEOGRAPHIC INFORMATION SYSTEMS (GIS) DATA

See the digital publication folder for files.

Geodatabase is Esri® version 10.7 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

Cannon_Beach_Tsunami_Evacuation_Modeling.gdb:

XXL1_BridgesOut feature dataset:

XXL1_BridgesOut_EvacuationFlowZones
XXL1_BridgesOut_EvacuationRoutes
XXL1_BridgesOut_WalkingSpeeds_Roads

Metadata in .xml file format:

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

ABSTRACT

Pedestrian evacuation routes were evaluated for a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) in the City of Cannon Beach and nearby unincorporated communities of Arch Cape and Falcon Cove in Clatsop County, Oregon. Our analyses focused on a maximum-considered CSZ tsunami event, termed XXL, that could be produced by a locally generated magnitude (Mw) 9.1 earthquake Evacuation paths were limited to established roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

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

- Tsunami wave arrival times for the maximum-considered XXL event,
- Detailed *Beat the Wave* results for the XXL tsunami event, including evacuation routes and minimum walking speeds, and
- *Beat the Wave* results for multiple hypothetical scenarios.

Beat the Wave maps depict the ***minimum evacuation speed*** required to stay ahead of the tsunami wave for each scenario. For planning purposes, we present a variety of scenarios that increase and decrease evacuation difficulty (due to additional complications and mitigation options, respectively). Assumptions applied to all models (unless otherwise noted) include:

- Restricting evacuation to pathways rather than permitting cross county travel (i.e. backyard or golf course)
- Applying a 10-minute delay from the start of an earthquake before beginning evacuation to account for:
  - the time in which earthquake shaking takes place (3-5 minutes)
  - disorientation, shock and collecting family members, go-bags, et cetera
  - the time required to evacuate building and reach nearest road (navigating fallen debris inside building, exiting building, crossing fenced yard, etc)

In addition to the assumptions listed above, the current conditions scenario also assumes the failure of non-retrofitted bridges. 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 and summarized above, results show that evacuation for much of the region examined is achievable at a ***slow walk*** (4 fps, or 2.7 mph) or faster. This is due to a very narrow tsunami inundation zone and close proximity to high ground resulting in short evacuation distances. Evacuation distances in downtown Cannon Beach are generally much longer and present a greater challenge. Evacuees must travel at a ***fast walk*** (6 fps, or 4.1 mph) to reach safety prior to the arrival of the tsunami. Liquefaction could present additional challenges to evacuation across the region and is examined only in a cursory manor.

In this report, tsunami mitigation refers to actions used to improve the survivability of a local community population. This project is about evaluating ways to help move people out of the tsunami zone in the shortest amount of time possible between the start of earthquake shaking and the arrival of the tsunami. Mitigation options may include adding new evacuation routes, constructing earthquake-hardened roads and trails (that is, built or remodeled to withstand shaking from a major earthquake and liquefaction), enhancing tsunami wayfinding signage along core routes, and/or installing a tsunami vertical evacuation structure.

1.0 INTRODUCTION

The objective of this study is to provide local government with a quantitative assessment of challenges affecting tsunami evacuation in the city of Cannon Beach (**Figure 1-1**) and nearby unincorporated communities of Arch Cape and Falcon Cove (**Figure 1-2**) for the XXL tsunami scenario. These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, and land use planning. We recommend using these results in conjunction with Allan and others (2020) which evaluates the potential effect of a CSZ earthquake and accompanying tsunami on coastal Clatsop County by providing estimates of potential building losses, generated debris, fatalities and injuries, as well as numbers of displaced people. The study also provides an assessment of vulnerable population groups, essential facilities, and critical infrastructure that are integral to response and recovery.

A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For the majority of the population, spontaneous evacuation on foot will be the only effective means of limiting loss of life, because vehicle evacuation would be quickly compromised by traffic congestion and road blockages. CSZ earthquakes affecting the Oregon coast will likely be on the order of magnitude (Mw) ~9.0 (Priest and others, 2009; Witter and others, 2011), severely damaging bridges and other infrastructure that may be critical to evacuation. The most recent tsunami generated by a large subduction zone earthquake on the Oregon coast occurred on January 26, 1700 (Atwater and others, 2005). Goldfinger and others (2017) estimated the conditional probability of a full margin (coastwide) earthquake on the Cascadia subduction zone (CSZ) at ~16–22% in the next 50 years.

To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic tsunami scenarios, five of which are mapped statewide. Each scenario has a potential likelihood of being the size of the next Cascadia event. For example, 26% of past tsunamis were no larger than the Small scenario. This suggests that there is a 26% chance that the next CSZ event will also be size Small or smaller. Conversely, 74% of tsunami events in the geologic record have been larger than Small. XXL describes a scenario slightly larger than the largest tsunami in the 10,000-year historical record and therefore 100 percent of past tsunamis were smaller than this scenario. This implies that the XXL scenario encompasses the maximum possible tsunami that will occur next (Priest and others, 2013b) The five statewide tsunami scenarios with their potential likelihood are:

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

The maximum-considered CSZ tsunami (XXL1, referred to as “XXL” for the remainder of this report) inundates the majority of Cannon Beach (**Figure 1-1**) as well as a narrow strip of Arch Cape and Falcon Cove (**Figure 1-2**). Allan and others (2020) reports that 78% of permanent residents reside within the XXL tsunami zone in Cannon Beach and 90% in Arch Cape (rate not provided for Falcon Cove). The tsunami reaches the beach ~10 minutes after the start of the earthquake and the first roads and homes in another ~5 minutes. By ~28 minutes the XXL tsunami zone has been fully inundated. The region will continue to experience tsunami waves for up to 12 hours after the start of earthquake shaking.

Figure 1-1. DOGAMI (2013) tsunami evacuation map for Cannon Beach. 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/.

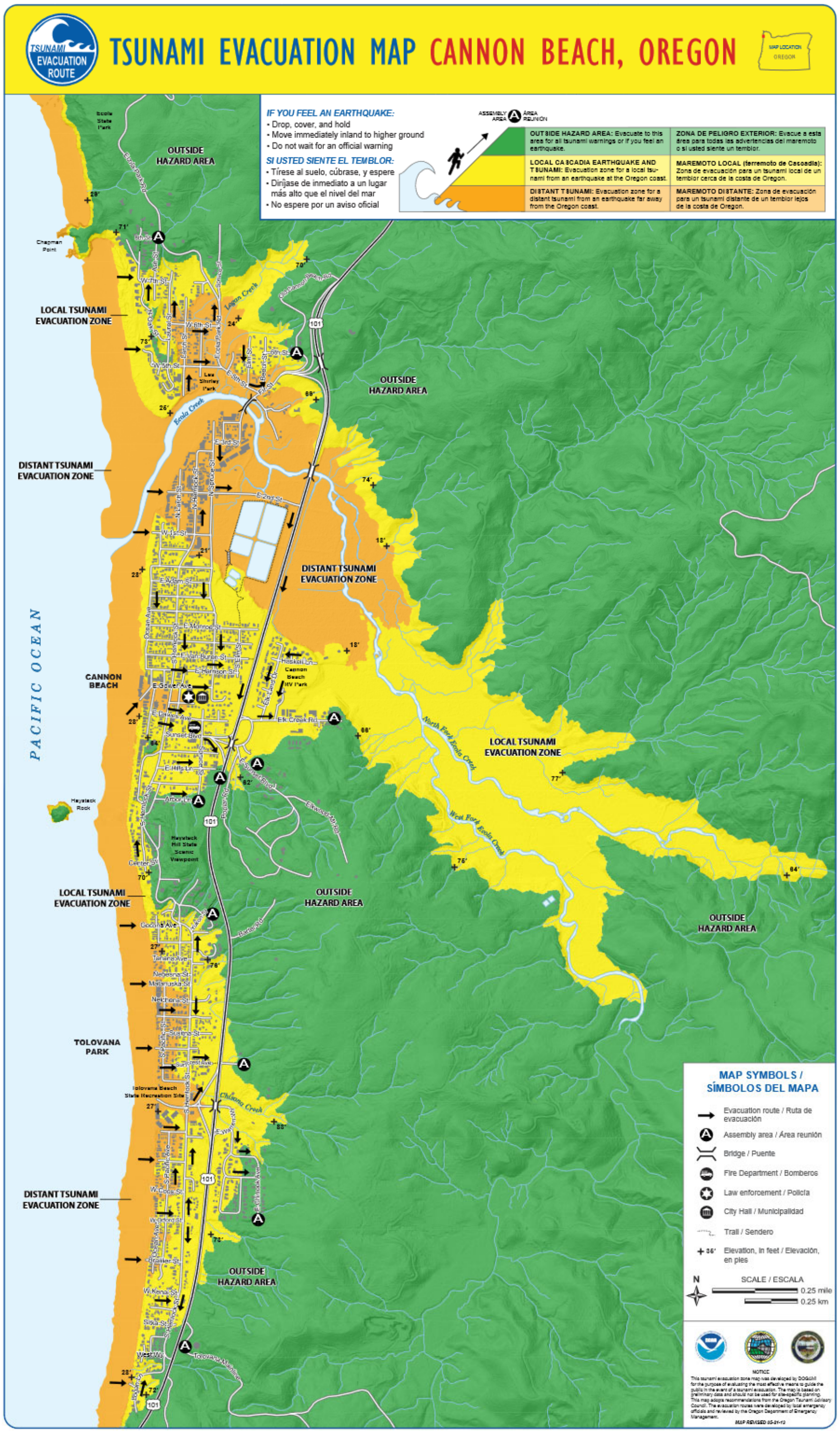
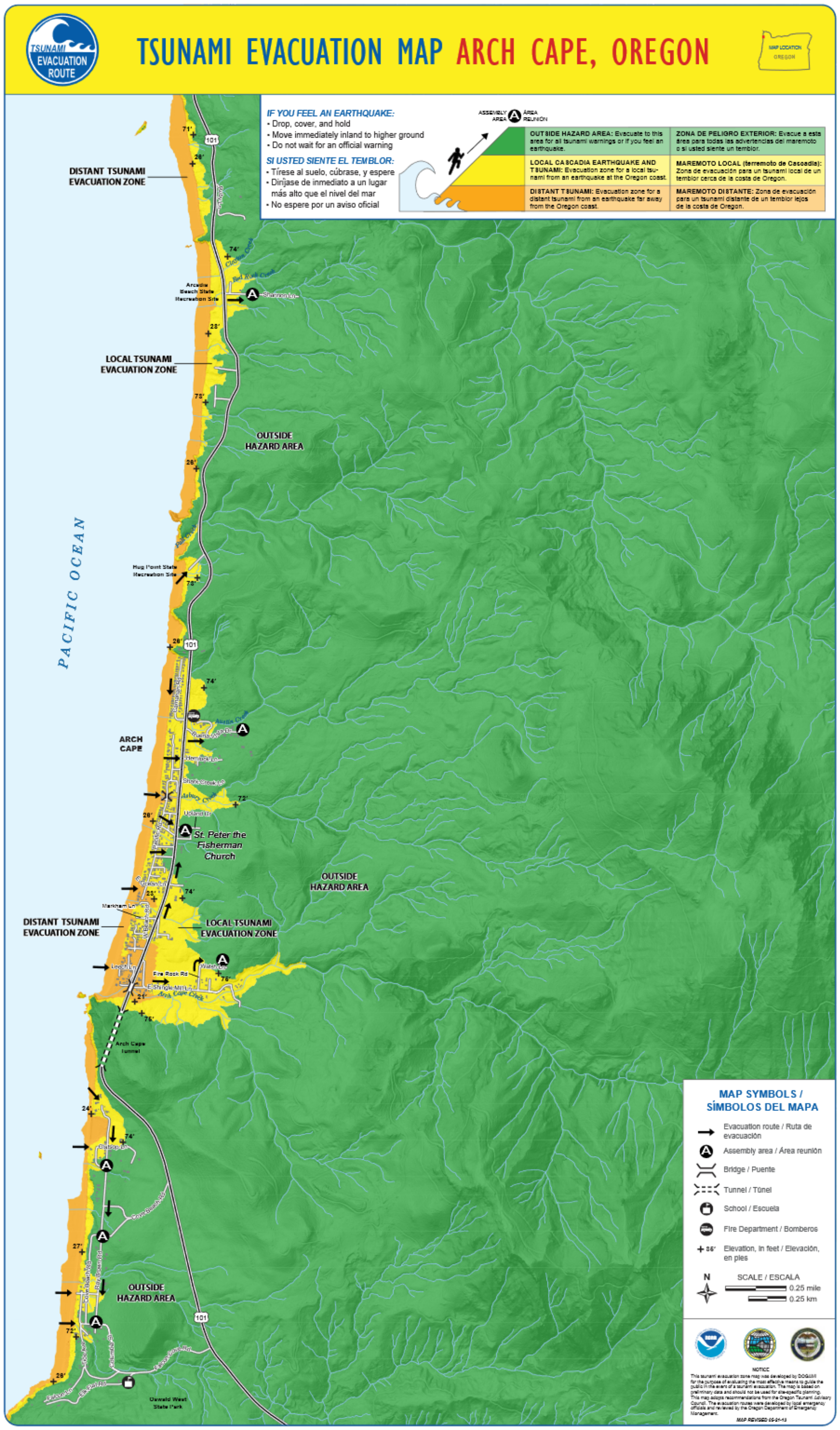


Figure 1-2. DOGAMI (2013) tsunami evacuation map for Arch Cape and Falcon Cove. Inundation for a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL) is shown in yellow, while the maximum-considered distant tsunami scenario is shown in orange; note the Cascadia scenario encompasses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



We evaluate tsunami evacuation difficulty using an approach termed *Beat the Wave*, developed by Priest and others (2015, 2016). It uses the least-cost distance (LCD) approach of Wood and Schmidtlein (2012), which provides estimates of evacuation travel times to safety assuming a constant travel speed. We can now account for variable speeds along a route due to differences in route characteristics including terrain (e.g., flat vs. steep, loose sand vs. pavement) and precise wave arrival times. Evacuation routes are restricted to roads and trails to enable more informative maps as well as to remove the complication of crossing private property. As a result, the *Beat the Wave* approach accomplishes in a single map what would require multiple maps in other approaches such as that of Wood and Schmidtlein (2012). In contrast, the single-evacuation-speed approach of Wood and Schmidtlein (2012) is more practical for regional analyses or where wave arrival times are not known.

This report provides the following maps and GIS data:

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

2.0 METHODS

Agent-based and least-cost distance (LCD) modeling are the two most common approaches for simulating pedestrian evacuation. Agent-based modeling focuses on the individual and how travel would most likely be impacted by localized effects in the landscape such as congestion points at bridges (Yeh and others, 2009). LCD modeling is similar but focuses more on evacuation difficulty across the landscape, which may be caused by both slope and land cover type (e.g., navigating a road versus traveling over a wetland or dune). LCD modeling essentially defines the most efficient path to the tsunami inundation limit for every point in the inundation zone, artificially increasing distances as terrain conditions change (e.g., slope increases, a person travels across a wetland versus on pavement) and ultimately defining the best evacuation routes. Time to traverse a route can then be estimated by dividing the least-cost path by a particular pedestrian travel speed (e.g., walk, jog, or run). We used the LCD model of Wood and Schmidtlein (2012) because we wanted to understand the spatial distributions of evacuation times throughout the region, without having to create a large number of scenarios for specific starting points required by agent-based models. *Beat the Wave* models integrate tsunami wave arrival data directly into the LCD analysis to produce maps of ***minimum*** speeds that must be maintained along the entire route in order to reach safety in time. Additional information on the methodology is provided by Priest and others (2015, 2016) and Gabel and Allan (2017).

2.1 Road and trail network

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

2.2 Hypothetical scenarios

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

Bridge failure was simulated by removing that section of the road network, forcing the model to recalculate routes that originally relied on bridge connectivity. Which bridges to remove for the simulations was based on discussion with local officials and on information about which bridges had been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. Our standard modeling process begins with a "base" scenario that includes all bridges, for comparison to scenarios without them. This highlights which bridges are important for evacuation and can be important when prioritizing which bridges to retrofit or to construct as part of a long-term resilience plan. For the Cannon Beach area, our modeling accounted for bridge failures over Ecola Creek that are expected to limit evacuation of downtown.

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

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

For landslide potential, we used the Statewide Landslide Information Database for Oregon (SLIDO) (Franczyk and others, 2019, https://www.oregongeology.org/slido/index.htm) to evaluate previously identified landslides in the area. We also considered possible landslide activity based on susceptibility mapping by Burns and others (2016). For areas where landslides have the potential to completely remove an evacuation route, we created hypothetical scenarios to reflect that. There are several landslides in the Cannon Beach area; however, none have the potential to significantly alter evacuation options. Therefore, we did not model any landslide scenarios. It is also likely that the area will be littered with smaller shallow slides (and, possibly, new deep-seated slides) after the earthquake, which will likely affect many roads; evaluating such landslides is beyond the scope of this study.

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

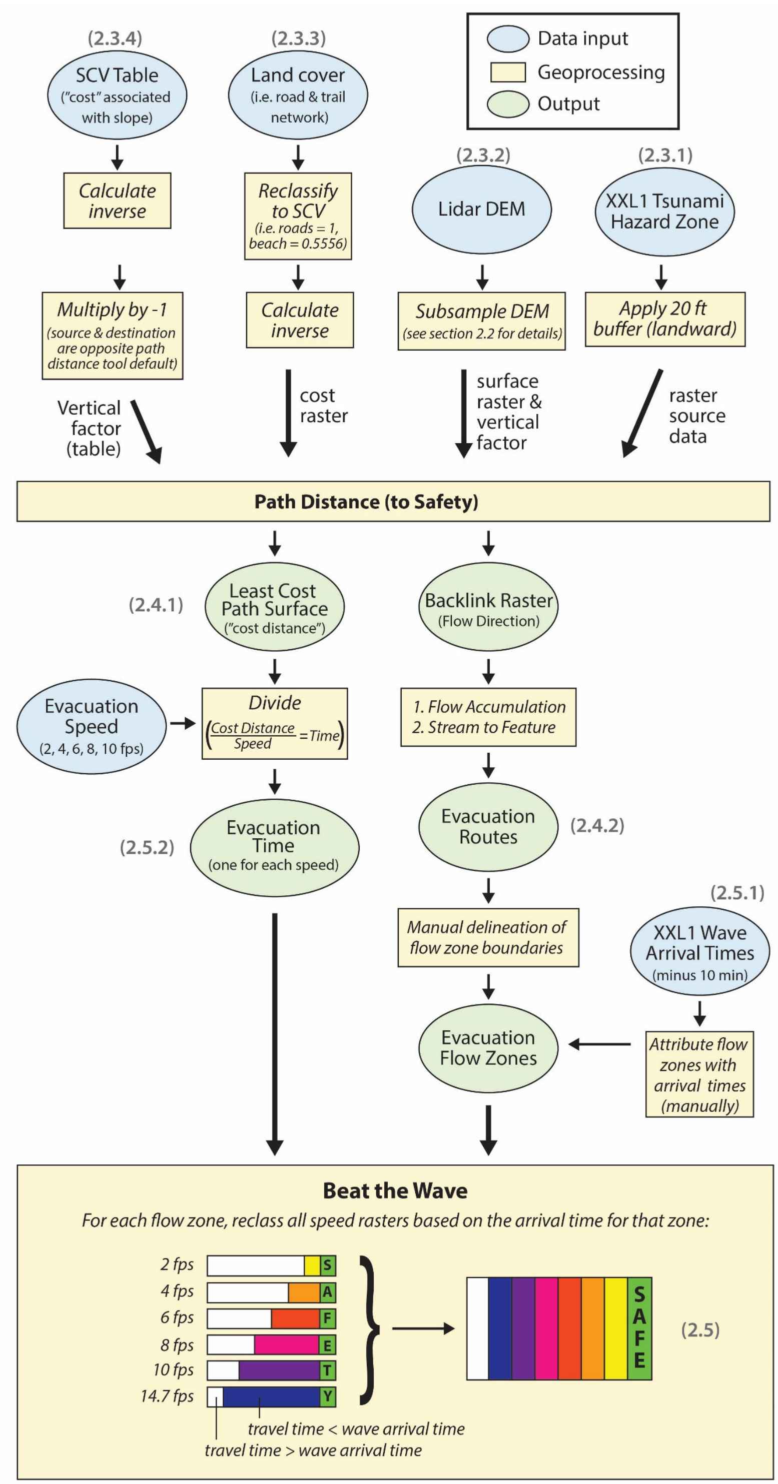
Regardless of infrastructure improvements considered for an area, wayfinding and outreach will always be an essential part of local tsunami evacuation planning.

2.3 LCD model inputs

Least-cost distance (LCD) modeling is based on four inputs: the XXL tsunami inundation limit, a digital elevation model (DEM), a land surface cost raster, and a table relating slope to cost. The road and trail network is provided via the land surface cost raster. The tsunami inundation limit 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 land cover . A detailed discussion of all four inputs is presented in the following sections.

We implemented LCD modeling by using Esri® ArcGIS® 10.7 and Esri ArcPro 2.8 software. The path distance tool uses geospatial algorithms to calculate the most efficient route from each point in the evacuation zone to “safety,” defined for the purposes of this study as ~20 lateral feet outside the maximum inundation limit, 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 *Beat the Wave* 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 XXL, derived from digital data of Priest and others (2013a,b) and updated recently by Allan and others (2021). This zone covers 100 percent of potential CSZ inundation (Witter and others, 2011), meaning it is the largest CSZ event likely to occur based on the 10,000 year record and reflects the zone used for evacuation as shown in DOGAMI evacuation brochures (https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm) and online (http://nvs.nanoos.org/TsunamiEvac) for the entire Oregon coast.

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

2.3.2 DEM

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

2.3.3 Land cover raster

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

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

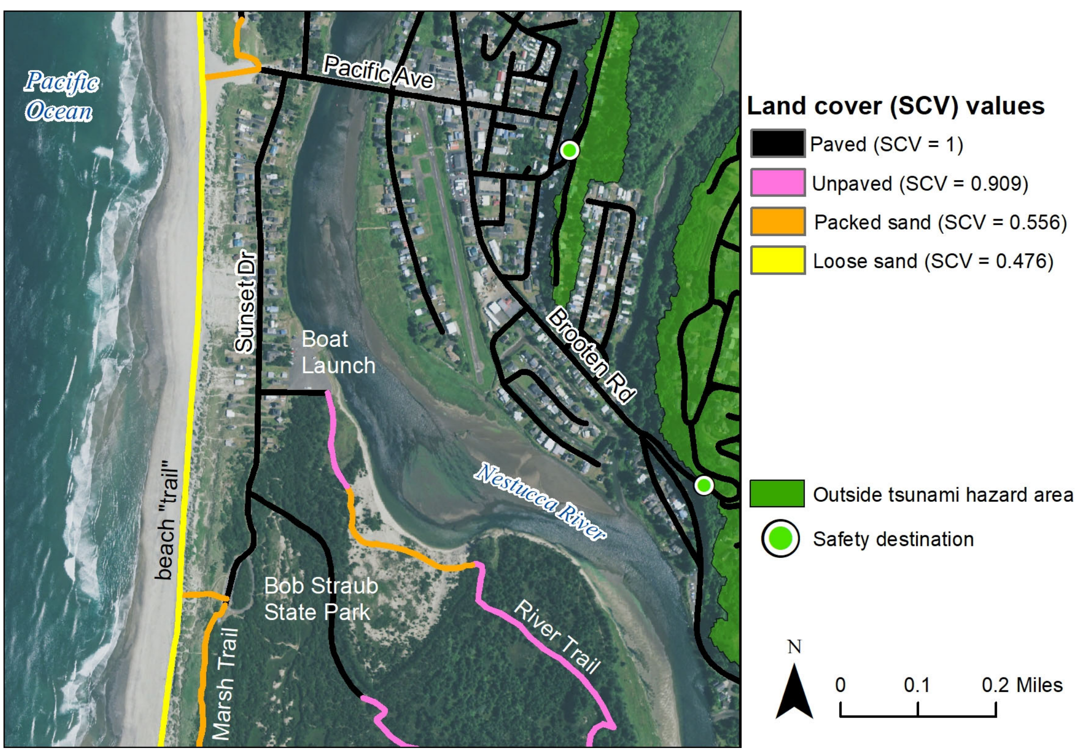
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

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

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

Polylines representing all roads and trails in the project area were converted to polygons (40 feet wide) and attributed with land cover values (i.e., 1 for paved surfaces, 0.556 for packed sand, etc.). The polygons were then converted into a raster (6-foot cell size) for input into the LCD model.

Figure 2-3. Example of a land cover raster in Pacific City, Tillamook County, Oregon, which serves the dual purpose of defining the road and trail network and classifying it with land cover values. Base map is 2016 National Agriculture Imagery Program (NAIP) imagery; the XXL inundation zone (area without green shading) 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.

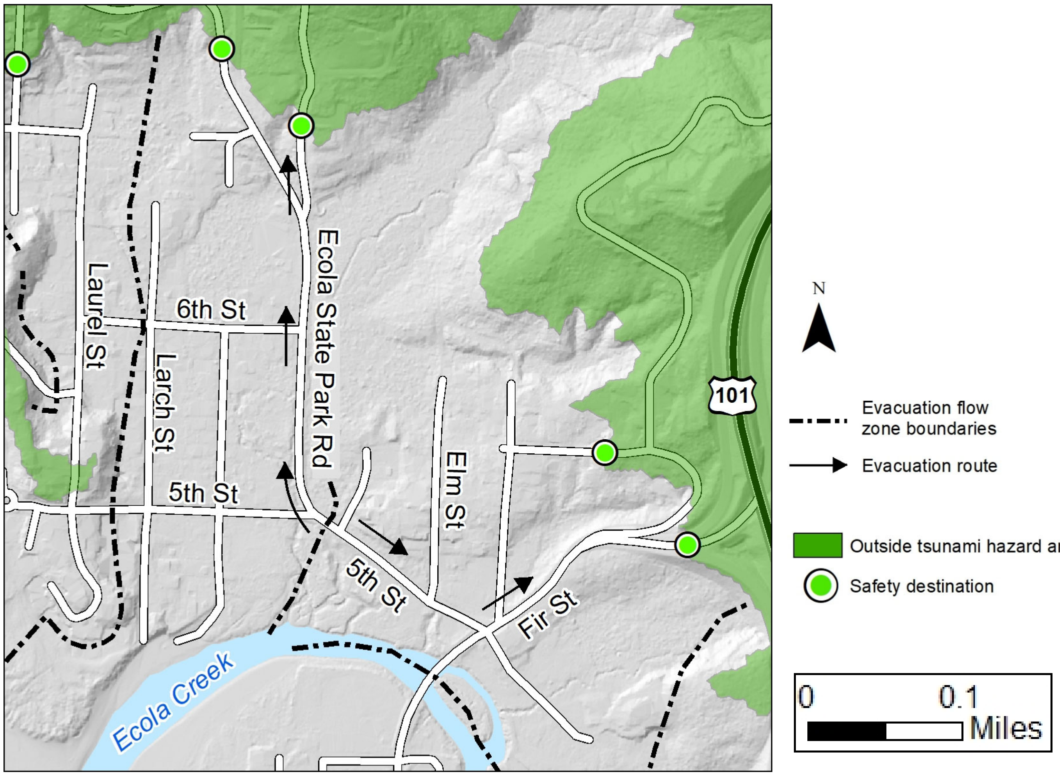
2.4 LCD model outputs

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 *Beat the Wave* 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 (designated as 20 feet beyond the XXL inundation limit). For example, from the intersection of Ecola State Park Rd and 5th St in Cannon Beach (**Figure 2-4**), the actual distance to safety up Ecola State Park Rd is 1,500 feet, while the least-cost path distance is 2,000 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 Ecola State Park Rd).

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 Cannon Beach, Clatsop County, Oregon. Base map on this and subsequent figures is shaded relief from 2009 lidar data (Oregon Lidar Consortium North Coast Project, https://www.oregongeology.org/lidar/index.htm).



2.4.2 Evacuation routes and flow zones

The LCD backlink raster shows, for each cell, the direction to the next cell on the least-cost path. This raster makes it possible to trace the path to safety from any pixel and is equivalent to a flow direction raster, which is the first step in hydrologic modeling of topographic surfaces. We use the hydrologic tools in ArcGIS 10.7 and the backlink raster to extract a "stream" network to visualize the paths depicting the most efficient pedestrian flow for evacuation on trails and roads. Evacuation flow zones with arrows depicting the most efficient routes are shown in **Figure 2-4**. These paths represent the shortest effective distances to the nearest safety destination and are referred to as evacuation routes. **Figure 2-4** shows what we call "generalized evacuation routes," meaning the arrows illustrate the overall direction of travel toward a safety destination and are not turn-by-turn directions. Detailed evacuation routes are found in the digital data.

The routes can be simplified by identifying the boundaries of evacuation flow toward the nearest safety location. At these boundaries, one could travel in alternate directions to reach safety on separate paths that require equal amounts of effort (distance with slope and land cover effects included). These evacuation flow zones are directly analogous to watershed boundaries or drainage divides in hydrologic modeling. As an example, **Figure 2-4** shows that the nearest safety destination for people on Elm St in Cannon Beach is the Highway 101 entrance to the east, while the nearest safety destination for people on Larch St is to the north on Ecola State Park Rd. The dashed black line delineates the evacuation flow zone boundary.

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

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

2.5 *Beat the Wave* modeling

Beat the Wave 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. *Beat the Wave* 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 *Beat the Wave* maps is to highlight areas that have more evacuation difficulty in order to direct future mitigation efforts and educate the public on where to go and how fast to travel.

2.5.1 Wave arrival times

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

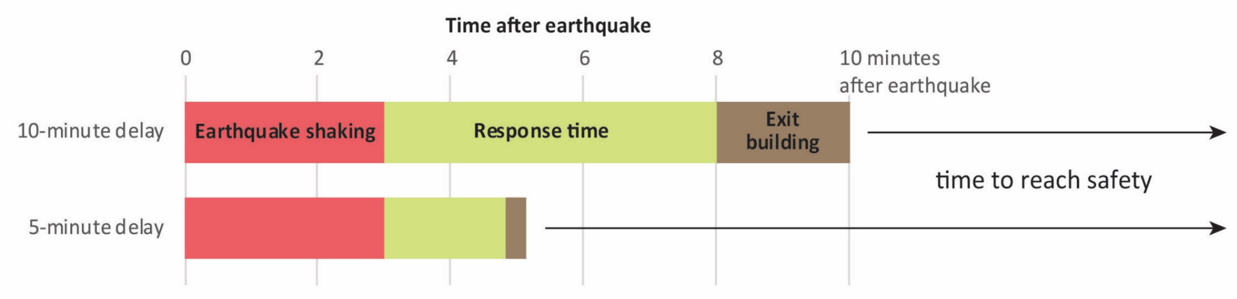
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted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

- the time in which earthquake shaking takes place,
- disorientation, shock and collecting family members, go-bags, et cetera, and
- the time required to evacuate buildings.

Using the March 11, 2011, Tohoku earthquake (U.S. Geological Survey, 2012) as an analogue to an XXL scenario, the minimum delay is probably ~3–5 minutes due to strong shaking for an ~Mw 9.0 event. There are few empirical data on how long it takes people to begin evacuation after shaking, but Mas and others (2013) determined a mean of 7 minutes in 2010 and 2011 surveys at La Punta, Peru, which has experienced several local earthquakes and tsunamis over the last ~400 years, the last being in 1974. **Figure 2-5** graphically describes how the three components of evacuation delay are related in this study. It is important to appreciate that the values adopted are not explicitly known because there are uncertainties associated with the length of the earthquake shaking, the human response dimension (i.e., how quickly people respond and how organized they are [e.g., packing a bag, time spent searching for family members and pets]) and lastly, how easy it may be to leave a building (e.g., digging out of rubble) and get underway.

For areas with large campgrounds and few to no permanent residents, or downtown commercial districts with large numbers of people in and out of shops, we reduced the delay from 10 minutes to 5 minutes to reflect the likelihood of people being outdoors (or inside an RV or tent) when the earthquake begins. We anticipate a shorter delay between earthquake shaking and evacuating for someone in a tent or RV compared with someone in a building. Results from the 5-minute evacuation delay also emphasize that the sooner one can begin evacuating, the more time one has to reach safety ahead of the tsunami.

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



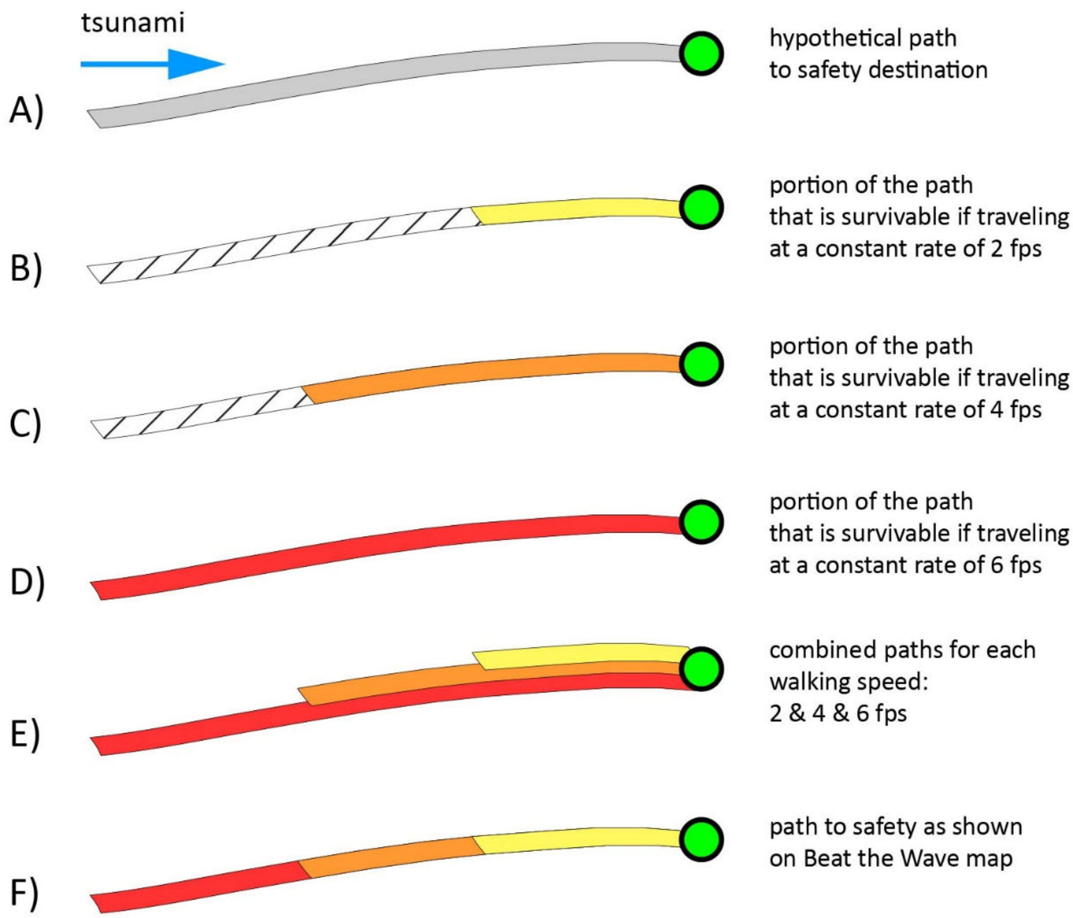
2.5.2 Evacuation time maps

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

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

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

Figure 2-6. Illustration of *Beat the Wave* 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 colored portion of a path represents the section that can reach safety at a given walking speed; the hashed area denotes the section that will be overtaken by the tsunami at that speed and is thus unsurvivable. The farther away from safety (green dot) evacuees begin the route, the faster they must travel to survive; 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 *Beat the Wave* map showing minimum constant speeds necessary to maintain to reach safety ahead of the tsunami.



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

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

A small experiment was conducted at Seaside, Oregon to evaluate the validity of the ***walk***, ***fast walk***, and ***slow jog*** *Beat the Wave* 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 *Beat the Wave* data, an evacuee will reach safety ahead of the tsunami. However, as speeds fall below the prescribed *Beat the Wave* speeds, the results of Gabel and Allan confirmed that the tsunami could overrun the individual. This limited test of *Beat the Wave* 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 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 *Beat the Wave* map

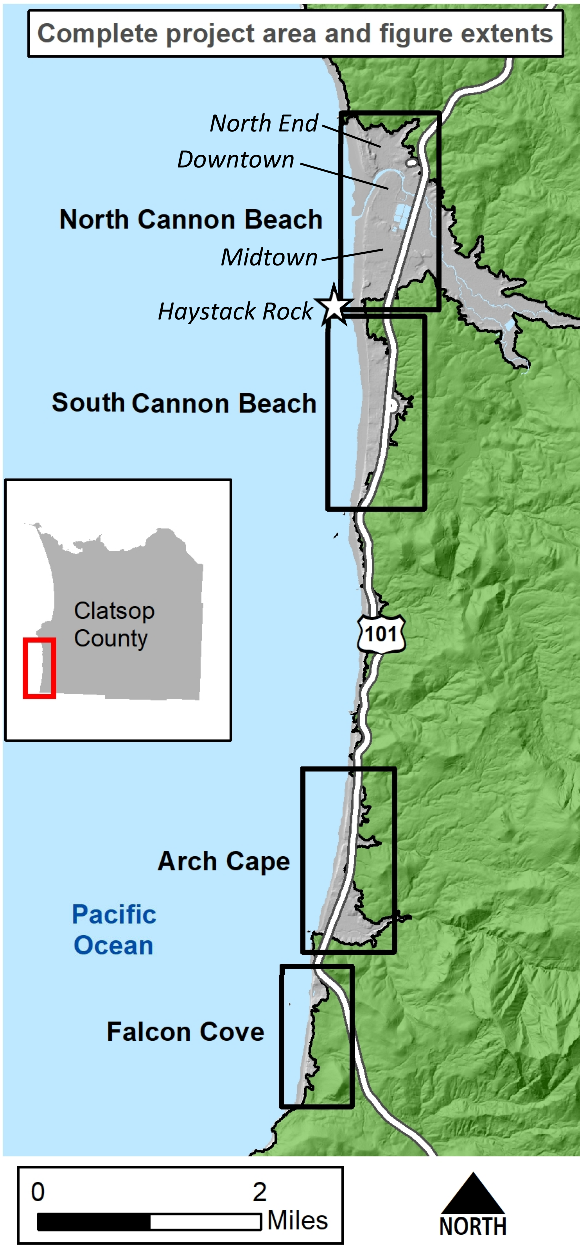
As previously stated, the modeling approach produces ***minimum*** evacuation speeds that must be maintained along the entire route to safety. Actual travel speeds on any evacuation route will require either variable expenditure of energy to maintain a constant speed in all conditions, or higher speeds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

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

3.0 RESULTS AND DISCUSSION

This report covers the City of Cannon Beach and the unincorporated communities of Arch Cape and Falcon Cove (**Figure 3-1**). Cannon Beach is divided into two panels, north and south, with Haystack Rock approximately at the dividing line. The North Cannon Beach panel includes the North End community on the north side of Ecola Creek, downtown Cannon Beach, and the midtown Cannon Beach neighborhood sandwiched between downtown and Haystack Rock. Results will be discussed separately for each panel.

Figure 3-1. Cannon Beach project area map.



We first present the baseline XXL scenario showing the minimum travel speeds required to reach safety using the existing road and trail network. This scenario assumes all bridges in the region fail during earthquake shaking and are not available for evacuation, including the Ecola Creek Bridge (Fir St) and Highway 101 over Ecola Creek in North Cannon Beach. These results represent the "current conditions" were evacuation to occur today. We also consider three hypothetical scenarios that improve evacuation for North Cannon Beach including a seismic retrofit of the two previously identified bridges, a vertical evacuation structure, and a reduced evacuation delay (5-minutes instead of the standard 10-minutes). Lastly, we consider the added difficulty of evacuation over liquefied terrain. Due to ease of safe evacuation under current-conditions and low liquefaction susceptibility, no additional scenarios were considered for Cannon Beach South, Arch Cape, or Falcon Cove.

Unless otherwise noted, all scenarios include a 10-minute delay before starting evacuation to account for the expected disoriented state of people following severe earthquake shaking and the time required to exit buildings. **Table 3-1** represents a summary of the range of speeds and their conversions that will be used throughout the remainder of this report.

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).

For South Cannon Beach, Arch Cape, and Falcon Cove, we find that the evacuation speed necessary to escape an XXL (maximum-considered) CSZ tsunami is a ***slow walk*** (2 fps, or 1.4 mph), with very small areas of ***walk*** (4 fps, or 2.7 mph). These data are very encouraging and are entirely due to the community's close proximity to high ground which results in narrow inundation zones and short evacuation routes. In North Cannon Beach, the North End neighborhood has a similarly positive outlook, however downtown and midtown have a much larger inundation zone and high ground is farther away, requiring evacuation speeds of ***walk*** and ***fast walk*** (6 fps, or 4.1 mph). Assuming the Ecola Creek Bridge fails, people in this area must travel south to high ground on Highway 101, Arbor Ln or other nearby residential streets near Haystack Rock. The option to evacuate north over the Ecola Creek Bridge would significantly improve survivability for downtown Cannon Beach as will be discussed below. People in the very northern extent of downtown must travel at a ***jog*** (8 fps, or 5.5 mph) when traveling south, however that speed is reduced to ***walk*** for a northerly route.

As with all coastal Oregon communities, logical and visible signage as well as community outreach are needed to ensure residents and visitors understand that they must evacuate immediately following the earthquake and move as quickly as possible because it will be the difference between life and death.

Finally, it is inevitable that following the earthquake other factors may also impede travel and increase evacuation time. This modeling does not account for these ancillary effects, which could include obstacles such as downed power lines or buildings. As a result, ***the public should evacuate immediately after the earthquake and move as rapidly as possible toward high ground to ensure they reach safety.***

3.1 Cannon Beach

Cannon Beach is comprised of four regions with unique inundation zones and evacuation situations: North End, downtown, midtown, and South Cannon Beach (**Figure 3-1**). Results for North End, downtown and midtown are presented together in a map referred to as "North Cannon Beach" for the remainder of this report. Results for current conditions in North and South Cannon Beach are presented first followed by four hypothetical scenarios for North Cannon Beach. No additional scenarios are considered for South Cannon Beach due to its positive evacuation outlook.

The North Cannon Beach panel covers the North End neighborhood, downtown and midtown. North End extends from the base of Tillamook Head (and Ecola State Park) in the north to Ecola Creek in the south. Safety from a maximum-considered tsunami (XXL) can be reached by heading north towards the state park or east towards Highway 101, with evacuation routes no more than ~0.5 miles in length. An "island" of high ground near Oak St is not included as a safety destination for this study due to its small size and the neighborhood's proximity to more significant areas of high ground previously described.

The area between Ecola Creek and Arbor Lane contains the downtown commercial district, various hotels as well as a residential neighborhood referred to as midtown. Downtown is where most visitors come to recreate and sleep, while midtown hosts the city's police and fire stations. People in downtown and midtown must travel south to reach the nearest XXL high ground near Arbor Lane, with evacuation distances up to ~1 mile. An "island" of high ground by the Hallmark Resort is not included as a safety destination for this study due to its small size and proximity to a more significant area of high ground to the south and east. For downtown, there is also closer high ground on the north side of Ecola Creek that will be discussed.

South Cannon Beach, also referred to as Tolovana, extends from Haystack Rock to the southern edge of the city. This area has a much narrower inundation zone, with high ground no more than ~0.4 miles away.

Detailed XXL tsunami wave arrivals for Cannon Beach are presented in **Figure 3-2**. The tsunami reaches the beach ~10 minutes after the start of earthquake shaking. Water reaches the first roads and homes in ~15 minutes and by ~28 minutes the XXL tsunami zone has been fully inundated. **Figure 3-3** and **Figure 3-4** present *Beat the Wave* results for the current-conditions scenario in North and South Cannon Beach, respectively. Evacuees from the North End neighborhood can travel at a minimum speed of ***slow walk*** and reach high ground ahead of the tsunami (**Figure 3-3**, *left*). Evacuation for downtown requires a minimum speed of ***fast walk*** with a small area of ***jog***, while the midtown neighborhood requires a ***walk*** to reach high ground to the south (**Figure 3-3**, *left*). Successful evacuation of South Cannon Beach can be achieved at a ***slow walk*** (**Figure 3-4**, *left*). Evacuation flow zones for the current-conditions scenario are presented in**, Figure 3-3** *right* and **Figure 3-4**, *right*. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location.

Figure 3-2. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) North and (right) South Cannon Beach.

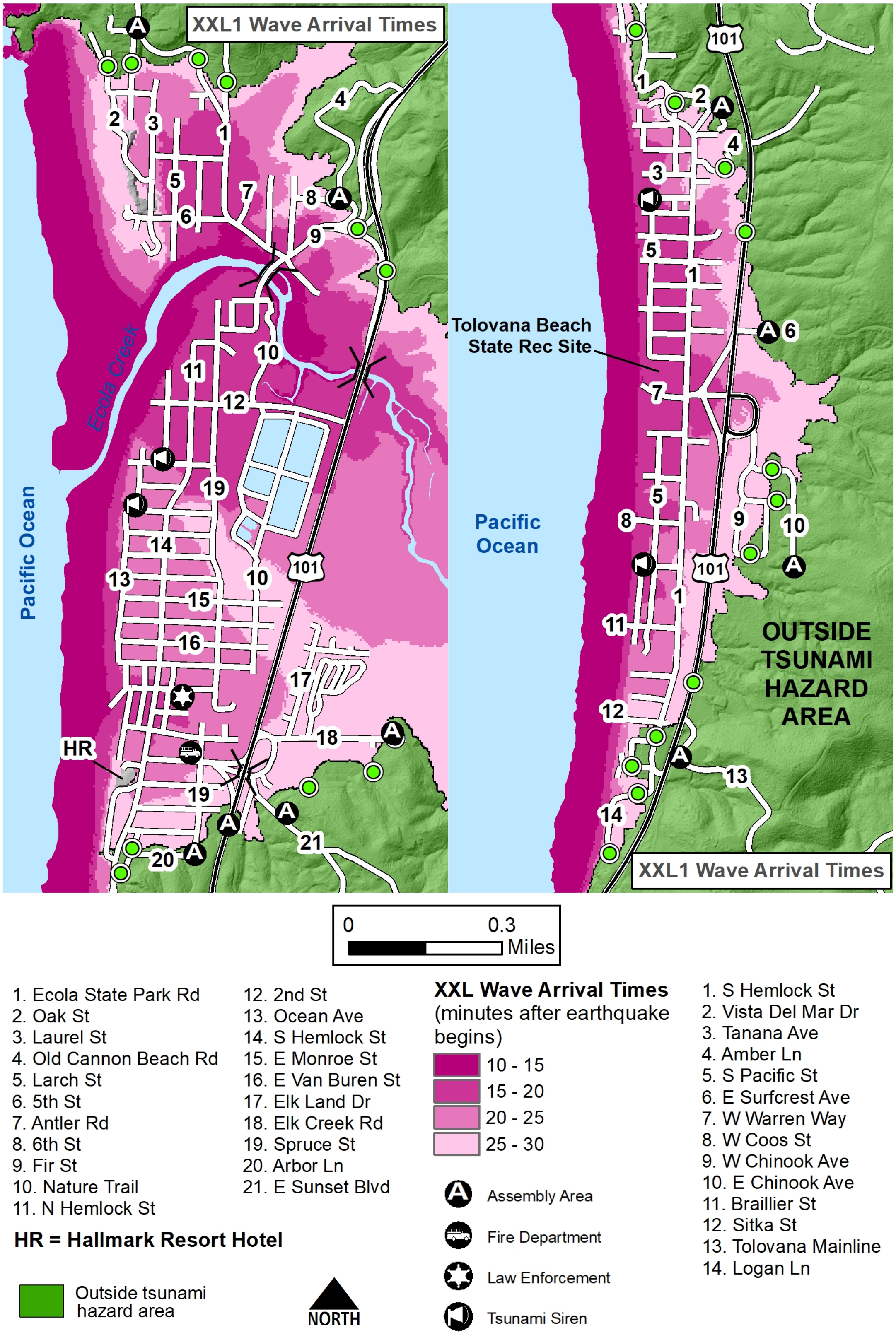


Figure 3-3. ***Beat the Wave*** **modeling in North Cannon Beach for the XXL current conditions scenario depicting the existing road and trail network and assuming the Ecola Creek & Highway 101 bridges fail during the earthquake. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (right) Evacuation flow zones displayed as colored polygons.**

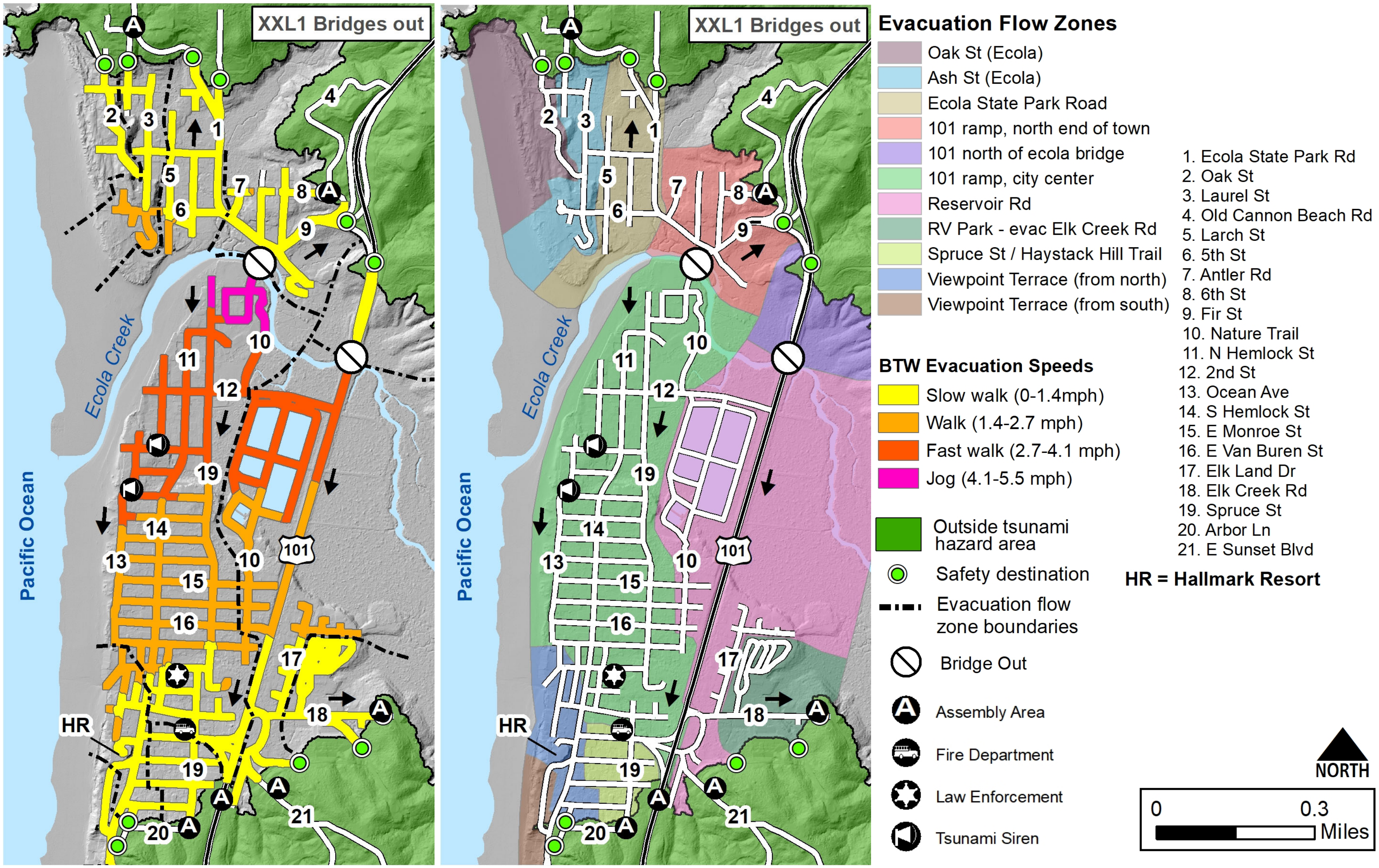


Figure 3-4. ***Beat the Wave*** **modeling in South Cannon Beach for the XXL current conditions scenario depicting the existing road and trail network and assuming the Ecola Creek & Highway 101 bridges fail during the earthquake. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (right) Evacuation flow zones displayed as colored polygons.**

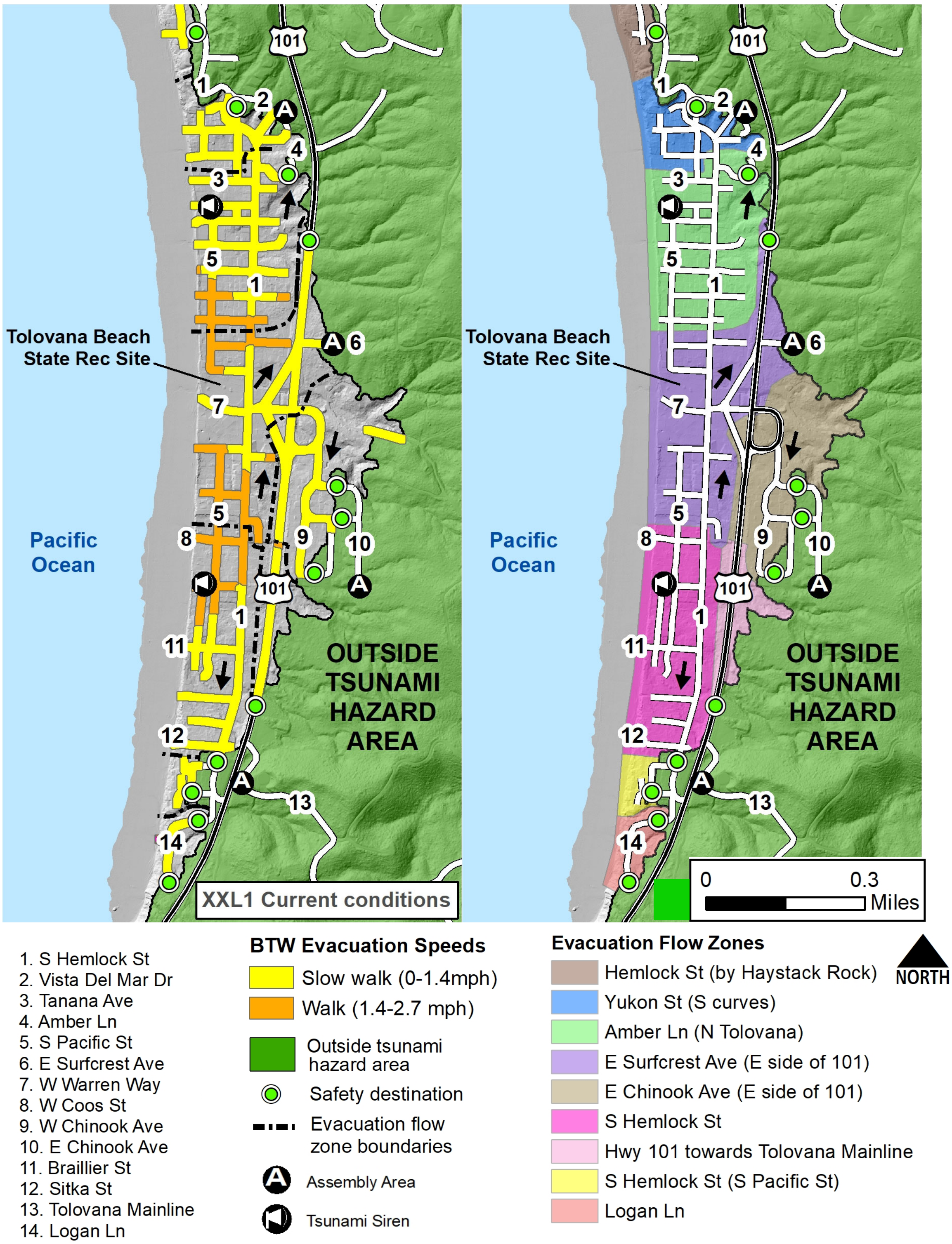
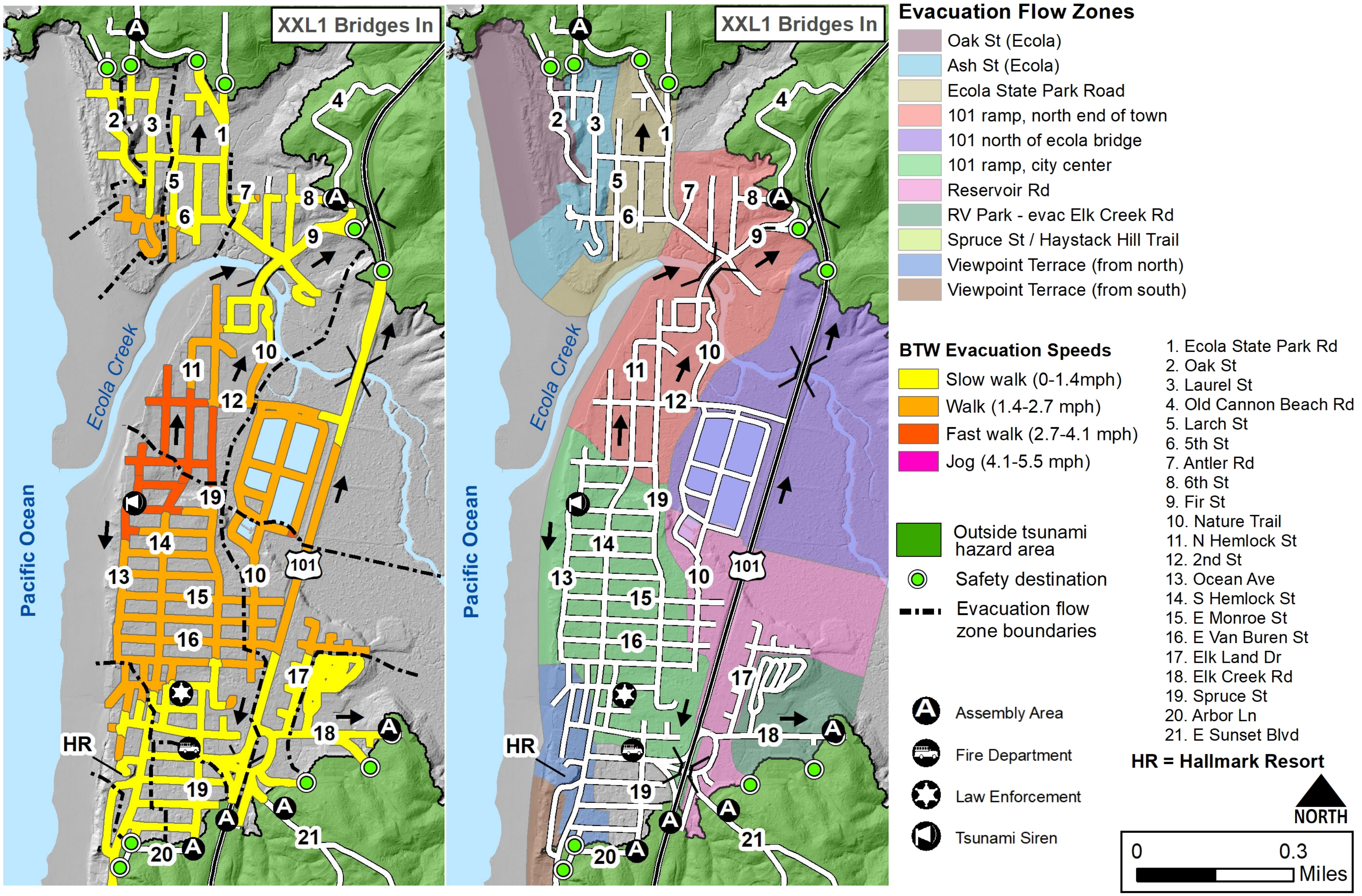


Figure 3-5 presents a scenario for North Cannon Beach assuming both Ecola Creek bridges are seismically retrofitted (or that a new pedestrian bridge is built adjacent to the current Ecola Creek/Fir St bridge). Black dashed lines in **Figure 3-5**, *left* and the red polygon in **Figure 3-5**, *right* demonstrate the extent of downtown that would use such a bridge to evacuate north. Minimum travel speeds in this area are reduced from ***fast walk/jog*** under current conditions to ***slow walk/walk***; the area around 2nd St remains ***fast walk*** under both scenarios.

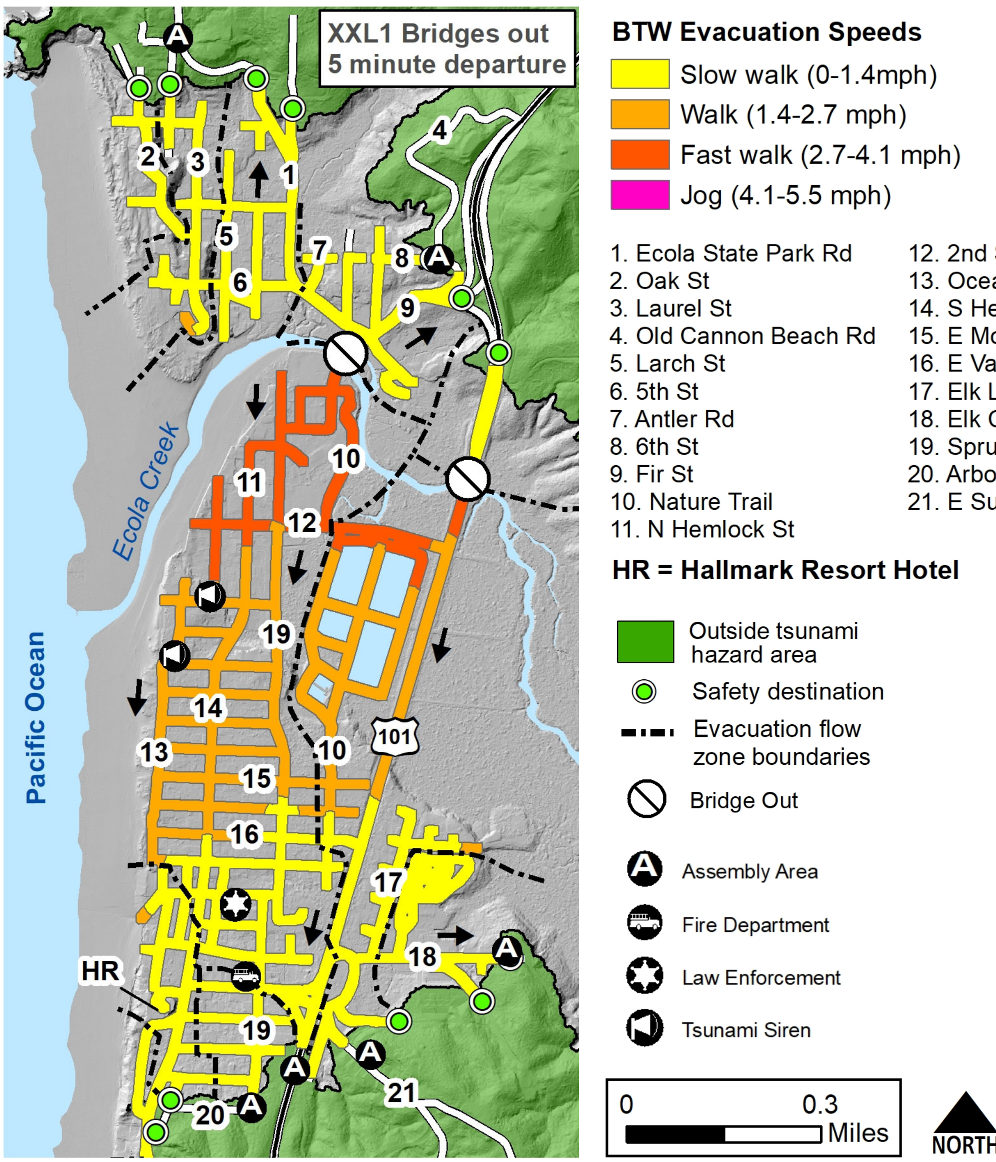
It is important to know that water levels will begin to rise in Ecola Creek well before the community itself is flooded and the bridge will only be passable for ~19 minutes (including earthquake shaking) despite it taking another ~11 minutes for the tsunami to reach its maximum extent by Highway 101. This is accounted for in travel speeds and evacuation flow zones presented in **Figure 3-5**.

Figure 3-5. ***Beat the Wave*** **modeling in North Cannon Beach assuming both Ecola Creek bridges remain passable after the earthquake. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (right) Evacuation flow zones displayed as colored polygons.**



When exploring ways to reduce the potential for tsunami fatalities, any effort directed at reducing people's evacuation delay will save lives. We define evacuation delay as the time a person lingers after the earthquake and before departing their location and beginning their evacuation. It is also sometimes referred to as "milling time". Here we re-evaluate the XXL current-conditions scenario with a 5-minute evacuation delay compared with the original 10-minute delay. The reduction in response time produces a moderate decrease in the required evacuation speed for North Cannon Beach. The ***jog*** in northern downtown is reduced to ***fast walk*** and more of midtown becomes ***slow walk*** instead of ***walk*** (Figure 3-6). Results are not presented for South Cannon Beach, Arch Cape or Falcon Cove because minimum travel speeds for the current-conditions scenario are already sufficiently low. The 5-minute-delay scenario demonstrates the importance of leaving as soon as possible as delay costs lives.

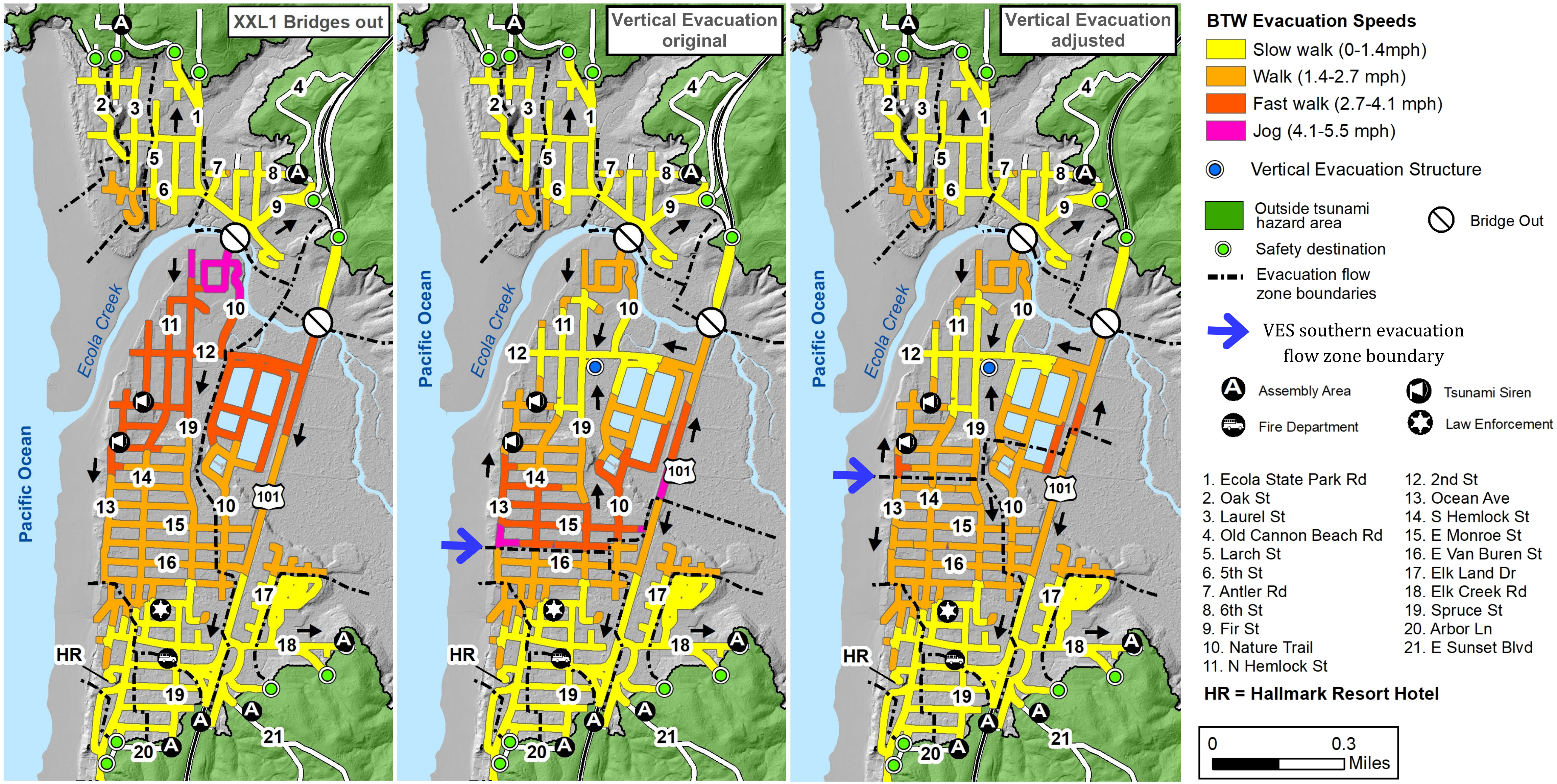
Figure 3-6. ***Beat the Wave*** **modeling in North Cannon Beach with a reduced evacuation delay (5 minutes instead of the standard 10 minutes).**



In some localities, safe and effective evacuation to high ground may not be feasible due to terrain challenges (i.e. high ground is too far away) or to potential failure of critical evacuation infrastructure such as bridges or roads. Given these circumstances, Cannon Beach may want to explore the construction of a vertical evacuation structure. A VES is a refuge designed to remain intact and accessible after the earthquake shaking while also resisting tsunami forces and scour. Such structures include soil berms or structures that can serve dual purposes such as parking garages, community facilities, commercial facilities (e.g., hotels), and schools (Applied Technology Council, 2012). We incorporate a VES into *Beat the Wave* modeling by editing the tsunami hazard zone to include a small polygon of safety at the location of a hypothetical structure. Such a structure would need to be carefully designed to accommodate the number of people in the relevant evacuation flow zone and built to a sufficient height. For the purposes of this study, we evaluated a VES established at the intersection of Spruce St and 2nd St, which corresponds to the location of the public restrooms. At this site, the modeled maximum flow depth is expected to reach ~50 ft for the XXL scenario. Importantly, a VES constructed at this site would improve evacuation by reducing the minimum speeds for all of downtown to ***slow walk*** and ***walk*** (**Figure 3-7**, *right*).

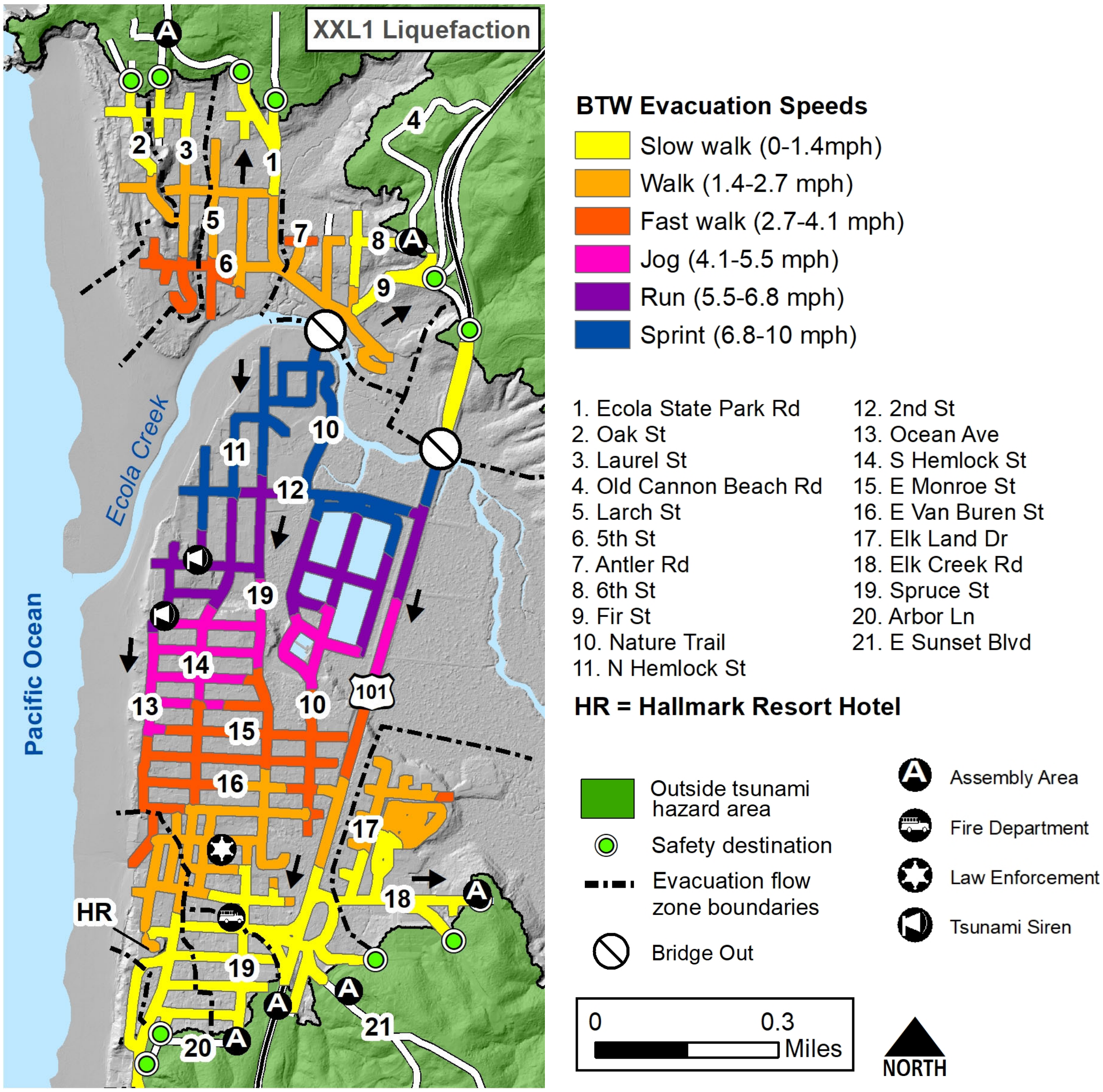
The area originally calculated to seek safety at this hypothetical VES (its evacuation flow zone) extends as far south as Jackson St (between Monroe St and Van Buren St). This means that on Jackson St, a person has an equal path distance should they choose to walk north to the VES or to natural high ground on Highway 101 to the south (marked with a blue arrow in **Figure 3-7,** *center*). The area from Jackson St to Jefferson St is defined as having a minimum travel speed of ***fast walk*** to reach the VES, however under the current-conditions scenario, this area can reach high ground at Highway 101 to the south at a ***walk*** (**Figure 3-7**, *left*). This disagreement is due to a discrepancy in wave arrival times at the two safety destinations. Evacuation flow zones are determined using path distance alone, while travel speeds also incorporate wave arrivals. The tsunami reaches the VES location ~19 minutes after the earthquake and at Highway 101 in line with Arbor Lane in ~29 minutes. The additional 10 minutes results in slower minimum travel speeds necessary to beat the wave to safety in the south (near Haystack Rock) versus the VES to the north. The final VES *Beat the Wave* scenario reflects a northward shift in the evacuation flow zone boundary to reflect this adjustment (marked with a blue arrow in **Figure 3-7**, *right*).

Figure 3-7. *Beat the Wave* modeling in North Cannon Beach with a hypothetical tsunami vertical evacuation structure at the intersection of 2nd St and Spruce St. (left) Current Conditions scenario for comparison, (center) original vertical evacuation scenario, (c) final vertical evacuation scenario after adjustment for disparate wave arrival times.



Liquefaction *Beat the Wave* results demonstrate the need for significantly faster evacuation speeds in order to safely reach high ground, and spans the entire North Cannon Beach area (Figure 3-8). Evacuation of downtown requires a ***run*** or ***sprint*** and much of midtown requires ***fast walk*** and ***jog***. Keep in mind liquefaction is not necessarily going to affect every road in the area and accordingly these results present a conservative outlook at how it might challenge evacuation.

Figure 3-8. ***Beat the Wave*** **modeling in North Cannon Beach with liquefaction.**



3.2 Arch Cape & Falcon Cove

The unincorporated communities of Arch Cape and Falcon Cove are perched above sea level and backed by steep hills, resulting in narrow inundation zones and short evacuation routes. There are no key pieces of infrastructure required to reach safety nor are there any critical facilities inside the inundation zone. Detailed XXL tsunami wave arrivals for Arch Cape and Falcon Cove are presented in **Figure 3-9**. The tsunami reaches the beach ~10 minutes after the start of earthquake shaking, however it does not reach the communities themselves for another 10–20 minutes. This is because most of these communities are perched on terrain located well above the beach. **Figure 3-10** and **Figure 3-11** present *Beat the Wave* results for the current-conditions scenario in Arch Cape and Falcon Cove, respectively. Evacuees in all locations except the very south end of Arch Cape can travel at a minimum speed of ***slow walk*** and reach high ground ahead of the tsunami. The area of Leech Ln in Arch Cape requires a ***walk***. Evacuation flow zones for the current-conditions scenario are presented in **Figure 3-10**, *right* and **Figure 3-11**, *right*. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. Due to ease of safe evacuation under current-conditions and low liquefaction susceptibility, no additional scenarios were considered for Arch Cape or Falcon Cove.

Figure 3-9. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for (left) Arch Cape and (right) Falcon Cove.

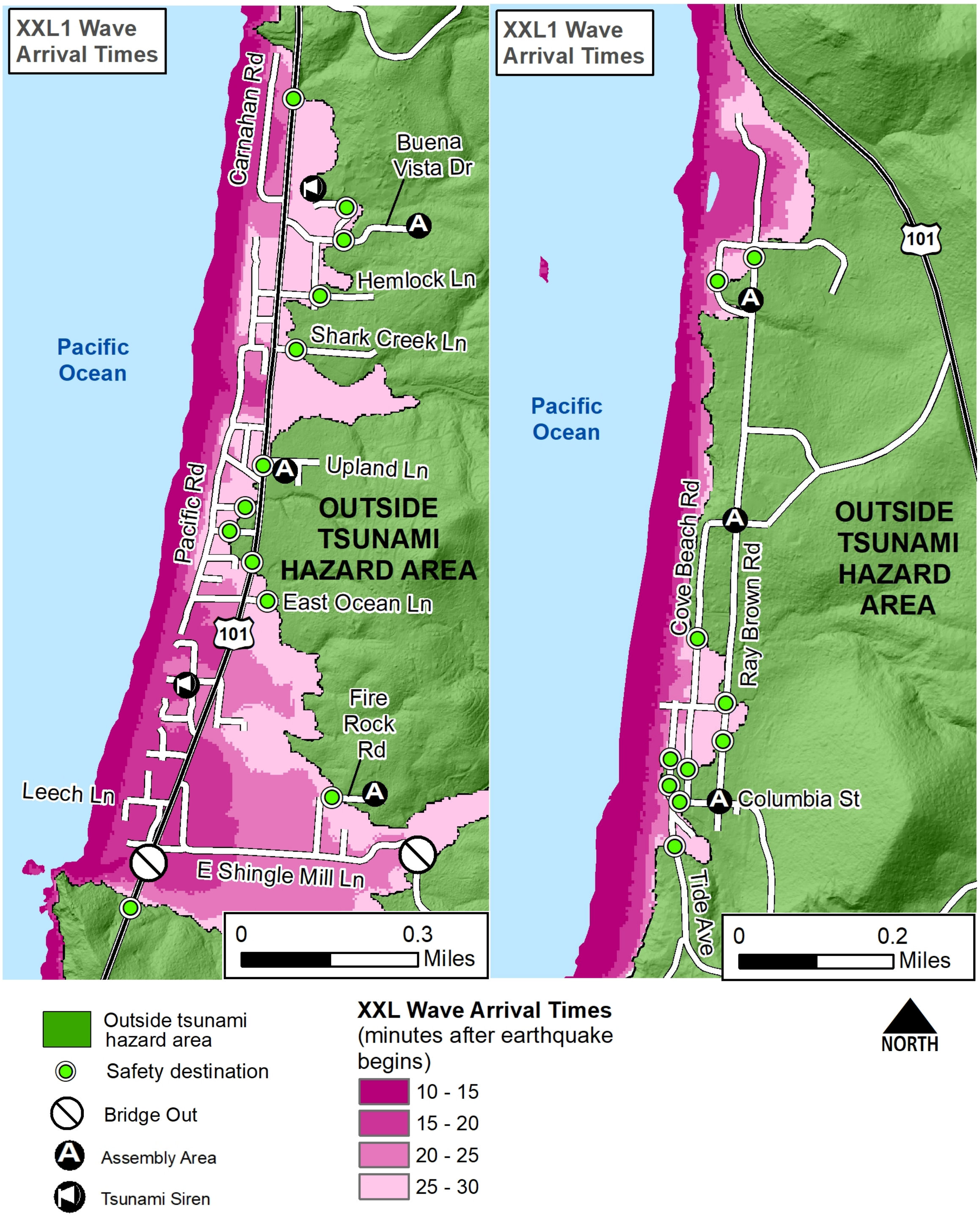


Figure 3-10. *Beat the Wave* modeling in Arch Cape for the XXL current conditions scenario depicting the existing road and trail network. (left) *Beat the Wave* evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (bottom) Evacuation flow zones displayed as colored polygons.

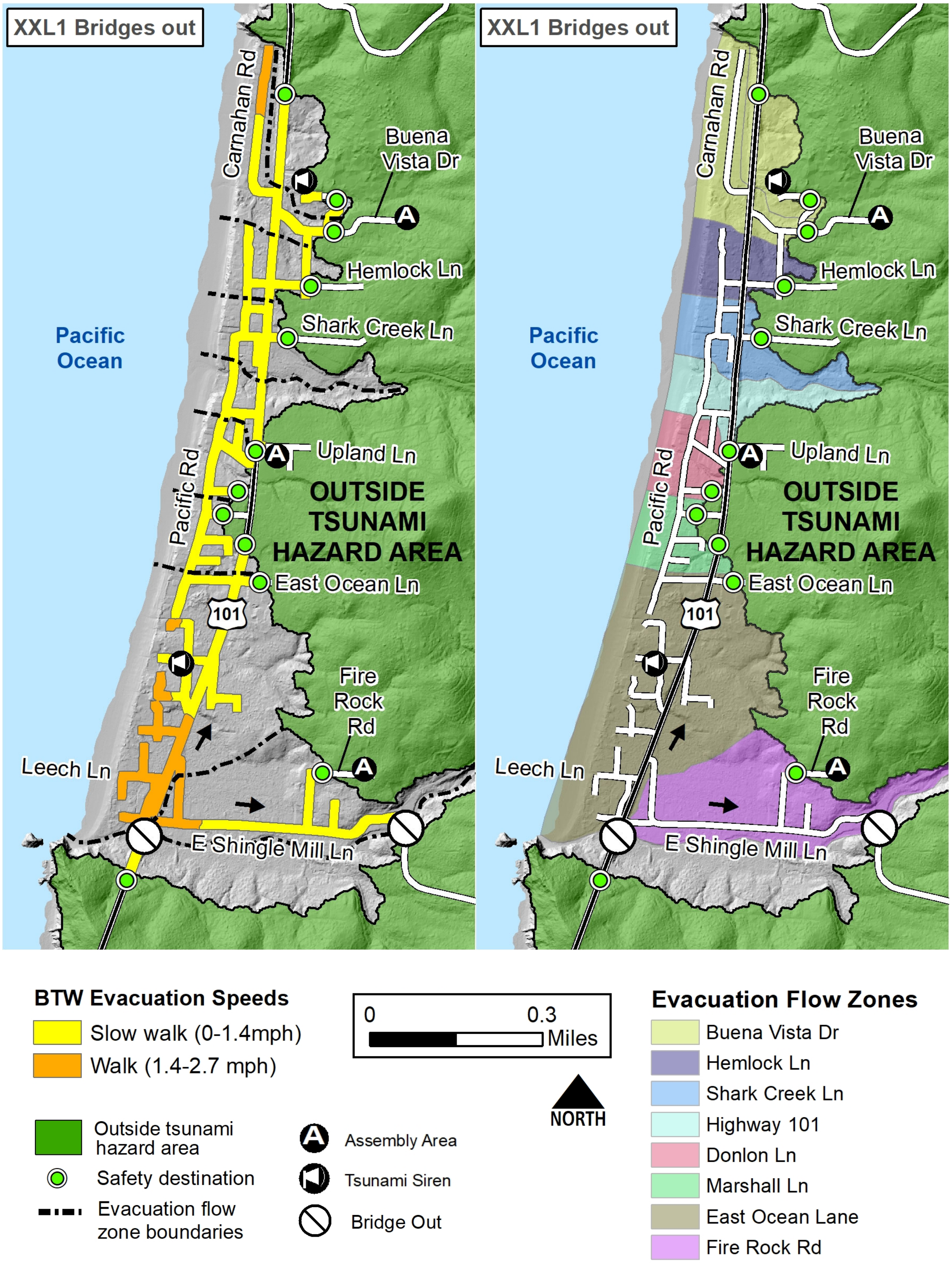
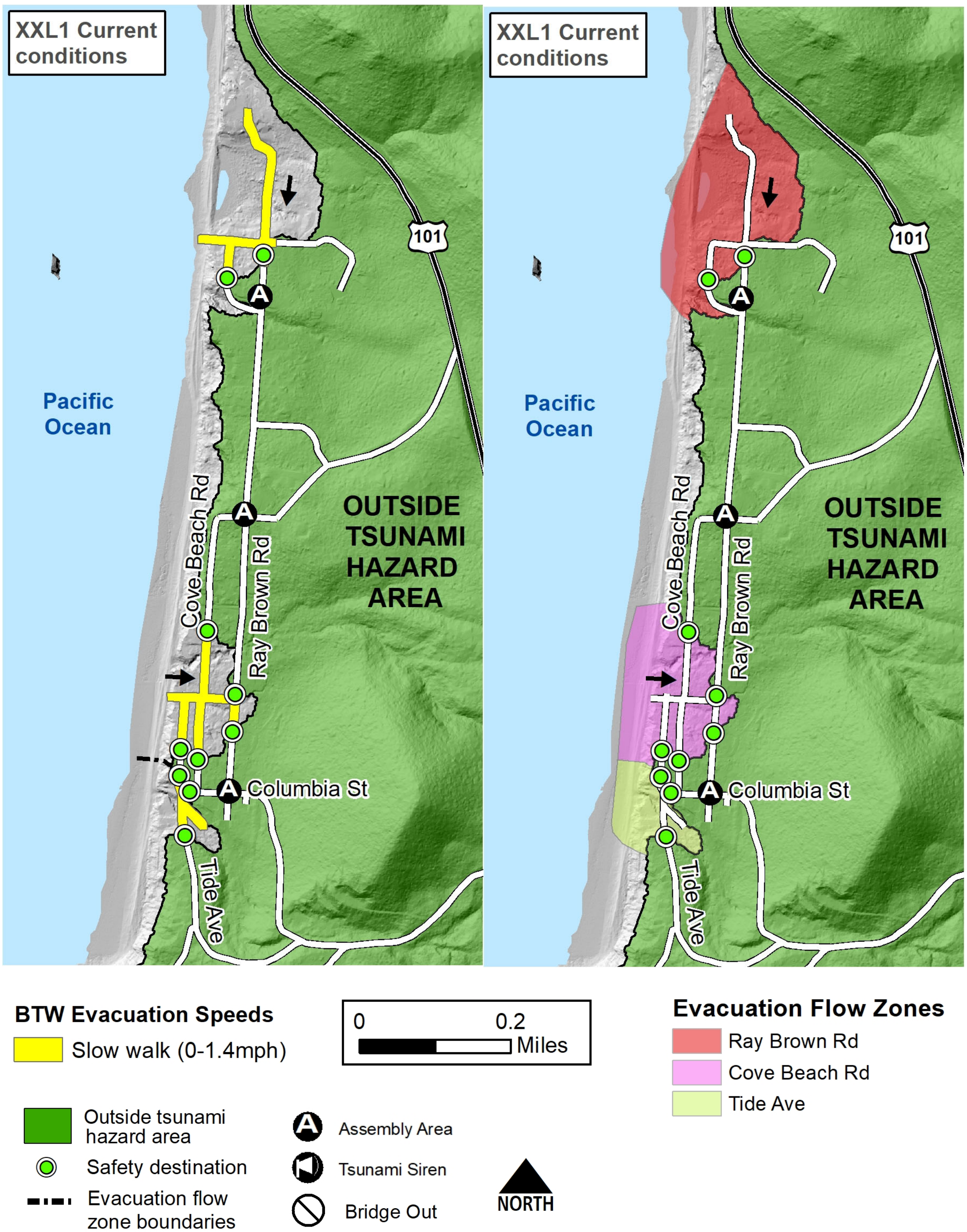


Figure 3-11. ***Beat the Wave*** **modeling in Falcon Cove for the XXL current conditions scenario depicting the existing road and trail network. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (bottom) Evacuation flow zones displayed as colored polygons.**



4.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study is to provide an assessment of tsunami evacuation difficulty in Cannon Beach, Arch Cape, and Falcon Cove. We accomplish this by implementing the *Beat the Wave* approach to evacuation analysis developed by Priest and others (2015, 2016). This quantitative approach to community-wide evacuation analyses provides new insight for the area's risk reduction efforts. We note several important findings based on the results of this study:

- **Evacuation of downtown Cannon Beach in response to a Cascadia Subduction Zone tsunami will be challenging.** This is primarily due to the long travel distances to safety in the south and the expected failure of the Ecola Creek bridge, which will likely preclude evacuation to closer high ground in the north. Evacuation is achievable only at relatively fast walking speeds (6 fps, or 4.1 mph) or greater. The very north end adjacent to Ecola Creek has an especially long travel distance to high ground (~1 mile), requiring a ***jog*** speed (8 fps, or 5.5 mph) for the duration of the route to survive. Evacuation for the seasonal visitor population will be especially challenging because visitors will likely have poor awareness of the hazard, a lack of familiarity with the terrain and where to evacuate to. Efforts directed at boosting community awareness, including outreach to hotels and vacation rentals along with appropriate signage that will help guide people out of harm's way are needed to help mitigate these challenges.
- **Evacuation of Arch Cape, Falcon Cove, South Cannon Beach and the North End neighborhood is attainable.** This is primarily due to narrow inundation zones and short evacuation routes. Evacuation in these areas is achievable at a ***slow walk*** (2 fps, or 1.4 mph) or greater.
- **Mitigation efforts will reduce loss of life from the tsunami.** *Beat the Wave* modeling clearly demonstrates the importance of construction of an earthquake-hardened bridge over Ecola Creek, which will enable the public in downtown Cannon Beach to more easily reach closer high ground on the north side of Ecola Creek, thereby reducing fatalities.
- **Education and outreach will reduce loss of life from the tsunami.** Awareness is crucial to lowering loss of life from the tsunami by ensuring that residents and visitors alike know they must evacuate immediately after the earthquake ends. Results from our evacuation delay scenario in downtown and midtown Cannon Beach illustrates the reduction in travel speeds required to survive if people depart immediately following the earthquake versus waiting an additional 5 minutes. While we recognize there may be unavoidable reasons to delay evacuation following the earthquake, the reality that there is very little time to reach safety cannot be ignored and leaving as soon as possible is key to survival.
- **Liquefaction, landslides and other earthquake-induced will further challenge evacuation.** Landslides, lateral spreading, and liquefaction are very site-specific hazards associated with earthquake shaking. Because we do not have the ability to predict precisely where these phenomena will occur, we are only able to perform a cursory examination of how they are likely to further challenge evacuation. Liquefaction *Beat the Wave* results demonstrate how faster evacuation speeds are required to reach high ground in the susceptible downtown region when compared to current conditions, further reinforcing the need to examine mitigation options. Landslides will undoubtedly occur during the earthquake, some that have potential to block evacuation routes. The narrow tsunami zone in much of the study area results in extremely short evacuation distances. This allows evacuees time to head to a secondary safety destination if their first choice is blocked by a landslide. We recommend site-specific evaluations along all key

evacuation routes to ensure they remain accessible after the earthquake. In addition to landslides and liquefaction, lateral spreading as well as downed power lines and trees may impede swift travel towards safety.

There are several limitations to keep in mind when interpreting the results of this tsunami evacuation assessment:

- Evacuation is restricted to pathways rather than permitting cross county travel (i.e. backyard or golf course). During an actual tsunami evacuation, people should take the fastest and safest route available to them.
- A 10-minute delay between the start of earthquake shaking and evacuation is incorporated into the model to account for the following actions:
  - the time in which earthquake shaking takes place (drop, cover and hold for 3-5 minutes)
  - disorientation, shock and collecting family members, go-bags, et cetera
  - the time required to evacuate the building and reach the nearest road (navigating fallen debris inside building, exiting building, crossing fenced yard, etc)

Regardless of walking speeds, physical limitations, and mitigation considerations, effective wayfinding through adequately spaced signage, battery-operated lighting, and other means is essential to survival. Even in areas where safety is nearby and all populations appear likely to survive, confusion about where to go will mean the difference between life and death. Clear and visible signage placed in key locations is extremely important, especially for tourist destinations like Cannon Beach where large numbers of visitors can cause the total population to grow by as much as 600% (Allan and others, 2020). 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).

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