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TSUNAMI EVACUATION ANALYSIS OF PORT ORFORD, CURRY COUNTY, OREGON

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DISCLAIMER

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 community of Port Orford, Curry County.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.

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

Port_Orford_Evacuation_Modeling.gdb:

XXL1_BridgesOut feature dataset:

XXL1_BridgesOut_EvacuationFlowZones
XXL1_BridgesOut_EvacuationRoutes
XXL1_BridgesOut_WalkingSpeeds_Roads
XXL1_BridgesOut_WalkingSpeeds_Trails

L1_BridgesOut feature dataset:

L1_BridgesOut_EvacuationFlowZones
L1_BridgesOut_EvacuationRoutes
L1_BridgesOut_WalkingSpeeds_Roads
L1_BridgesOut_WalkingSpeeds_Trails

Rasters

MaxTsunamiFlowDepth_XXL1
TsunamiWaveArrival_XXL1

Metadata in .xml file format:

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

ABSTRACT

Pedestrian evacuation routes were evaluated for a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) for the community of Port Orford, Curry County, Oregon. Our analyses focused on a maximum-considered CSZ tsunami event covering 100% of potential variability, termed XXL and generated by a magnitude 9.1 earthquake. Evacuation paths were limited to established roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes.

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

- Tsunami wave advance for an XXL event,
- Detailed “Beat the Wave” (BTW) results for the XXL scenario, including evacuation routes, minimum walking speeds, and evacuation flow zones,
- Detailed BTW results for the Large (L1) scenario, 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 base scenario uses the existing road network and includes a 10-minute delay from start of earthquake before beginning evacuation. Additional challenges, including failure of non-retrofitted bridges and effects from landslides and liquefaction to evacuation, are discussed. In all cases, ***the identified minimum speeds must be maintained for the entire time it takes to evacuate from the inundation zone*.**

Given the model limitations defined in the Methods section, results show that evacuation for much of the Port Orford region will be challenging because the tsunami arrives quickly (~10 minutes at the beach). Thus, required evacuation speeds are higher (i.e., ***jog***) when compared with other communities (i.e., ***walk*** and ***fast walk***).

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

1.0 INTRODUCTION

The objective of this study is to provide local government with a quantitative assessment of challenges affecting tsunami evacuation in the coastal communities of the Coos Bay estuary for the XXL scenario. These results are important for evaluating mitigation options such as evacuation route improvements, better wayfinding, land use planning, and potential vertical evacuation options.

A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For the majority of the population, spontaneous evacuation on foot will be the only effective means of limiting loss of life, because vehicle evacuation would be quickly compromised by traffic congestion and road blockages. CSZ earthquakes affecting the Oregon coast will likely be on the order of magnitude ~Mw 9.0 (Priest and others, 2009; Witter and others, 2011), severely damaging bridges and other infrastructure that may be critical to evacuation. To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic scenarios, five of which are mapped statewide, each covering the following percentages of potential variability of Cascadia tsunami inundation (Priest and others, 2013b):

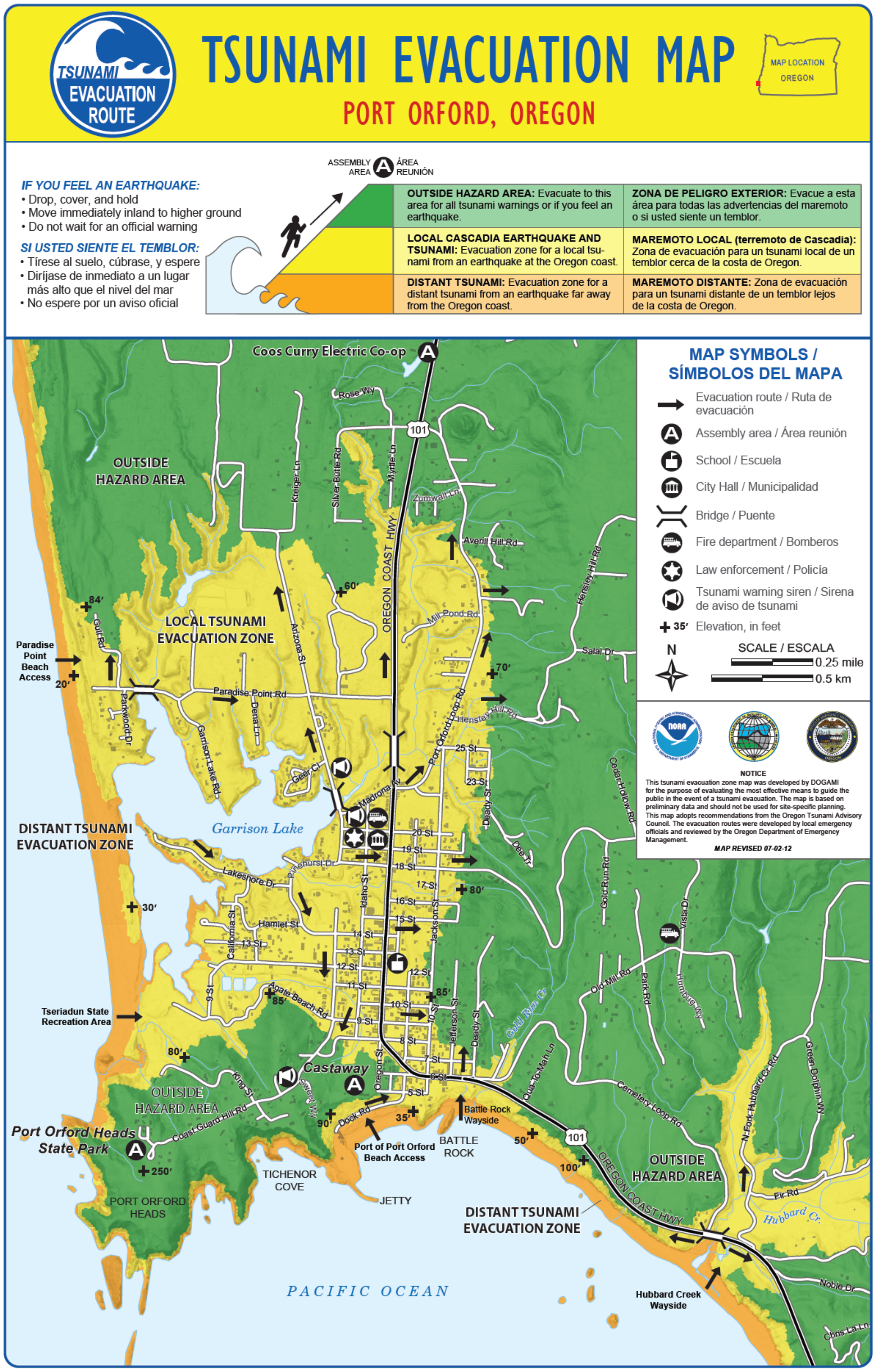
- Extra-extra-large (XXL1) (100%)
- Extra-large (XL1) (98%)
- Large (L1) (95%)
- Medium (M1) (79%)
- Small (SM1) (26%)

The maximum-considered CSZ tsunami (XXL1, referred to as "XXL" for much of the remainder of this report) inundates the entire Port Orford community (**Figure 1-1**). Furthermore, the entire community is essentially flooded within 17 minutes of the start of earthquake shaking.

A Note about Bridges and Tsunami Evacuation in Port Orford

Bridges can further complicate tsunami evacuation if they prove to be essential to a route and are not built to withstand the shaking from the earthquake. Because of this, DOGAMI tsunami evacuation analyses include both "Bridges In" and "Bridges Out" Beat the Wave (BTW) scenario modeling. For the Port Orford community, evacuation modeling indicates area bridges are not essential for tsunami evacuation (i.e., safety can be reached without needing to cross bridges). Because "Bridges In" and "Bridges Out" Beat the Wave results are similar—and in most cases identical—only "Bridges Out" results are included in this report.

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



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

This report provides the following maps and GIS data:

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

2.0 METHODS

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

2.1 Road and trail network

We used a model that considered only roads, paths, and the dry sand backshore of beaches as evacuation pathways, which effectively removes the complication of crossing private property; all other land cover classes were excluded, enabling 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-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" are intended to provide an approximation of the time and speeds required to evacuate those areas. We chose to ignore travel time from buildings or other parts of urban areas to the roads, because there is large uncertainty in conditions contributing to the time it will take an evacuee to reach the nearest road. For example, reaching the nearest road may require crossing a fenced yard. In addition, after the earthquake there will undoubtedly be fallen debris and other impediments. Because of these assumptions and factors, the modeling approach represents ***minimum*** evacuation speeds needed to safely evacuate from the inundation zone.

2.2 Hypothetical scenarios

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

Bridge failure was simulated by removing that section of the road network, forcing the model to recalculate routes that originally relied on bridge connectivity. Which bridges to remove for the simulations was based on conversation with local officials and on information about which bridges had been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. Our standard modeling process begins with a "base" run that includes all bridges, for comparison without them. This highlights which bridges are important for evacuation and can be important when prioritizing which bridges to retrofit or construct as part of a long-term resilience plan. For this area, modeling indicates local bridges are not essential for tsunami evacuation.

In coastal towns, landslide-prone slopes and saturated sandy soils are common; therefore slides, liquefaction (**Figure 2-1**, *left*), and lateral spreading (**Figure 2-1**, *right*) are likely to occur during an earthquake (Madin and Wang, 1999; 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. Although liquefaction is always a concern for coastal communities during a subduction zone earthquake, results from Madin and Burns (2013) suggest that the risk is not sufficiently high in Port Orford to merit a BTW analysis.

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

For landslide potential, we used the Statewide Landslide Information Database for Oregon (SLIDO, version 3.4, https://www.oregongeology.org/slido/index.htm) to evaluate previously identified landslides in the area. We also considered possible landslide activity based on susceptibility mapping by Burns and others (2016). For areas where landslides have the potential to remove completely an evacuation route, we created hypothetical scenarios to reflect that. There may be areas where landslide activity may make evacuation difficult but not impossible, and in those cases, we did not always model a landslide scenario. It is also likely that the area will be littered with smaller shallow slides (and possibly new deep-seated slides) after the earthquake, which will likely affect many roads; evaluating such landslides is beyond the scope of this study.

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

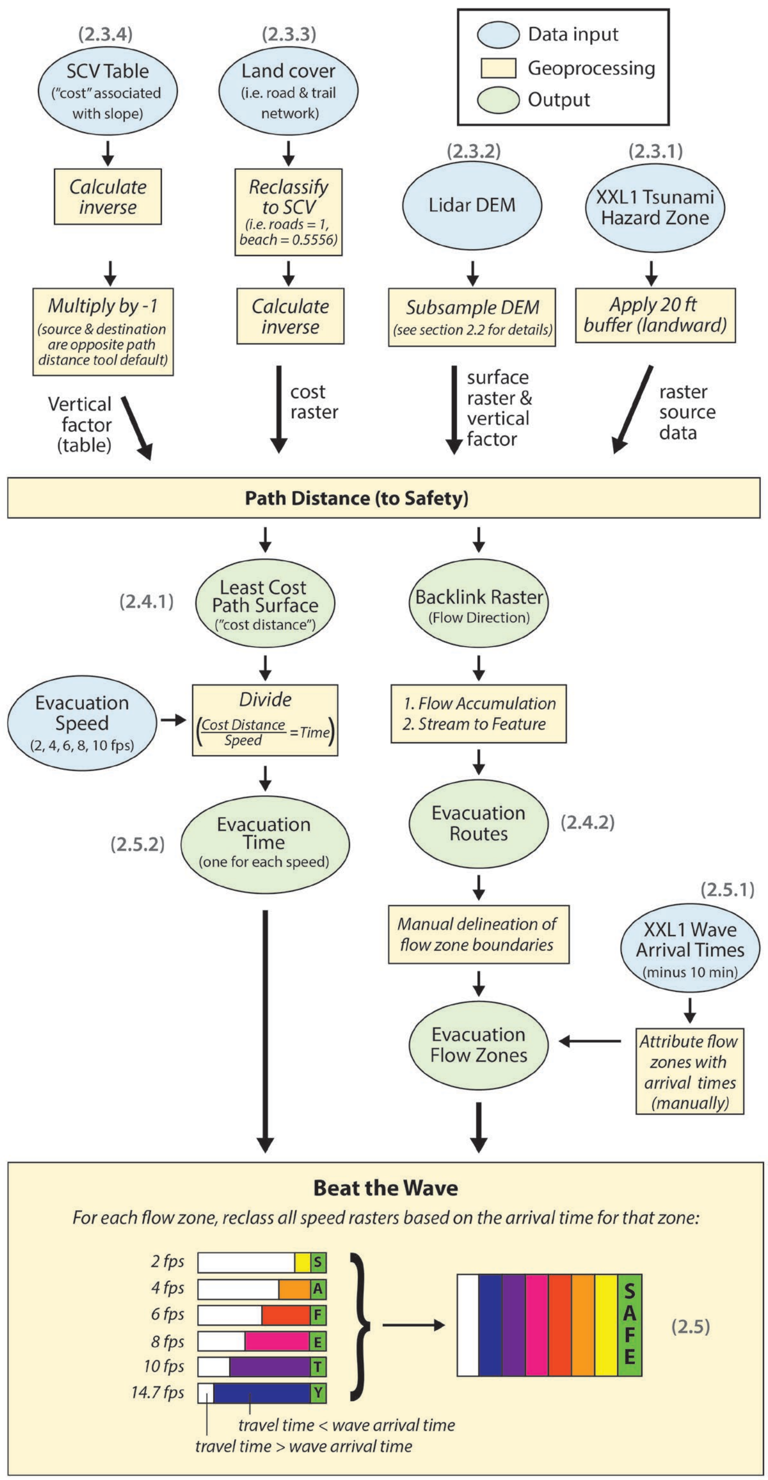
Regardless of infrastructure improvements considered for an area, wayfinding and outreach will always be an essential part of local tsunami evacuation planning.

2.3 LCD model inputs

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

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

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



2.3.1 Tsunami hazard zone

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

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

2.3.2 DEM

Initially, we created a high-resolution digital elevation model (DEM) by interpolating lidar ground points into a 6-ft-resolution raster; in areas characterized by bridges, we used lidar highest-hit data to define the bridge walking surface. We smoothed the DEM grid, because generated slope profiles are too noisy, introducing slope artifacts of significant amplitude (e.g., a 3-inch elevation difference between cells 1 foot apart yields a 14° slope) that add significantly more time to the total calculated time (Priest and others, 2015, 2016). To smooth the data, we created points at 50-foot intervals along all evacuation paths including major roads and at intersections, and we attributed those points with elevation values from the 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 ft cell size) that closely emulated the actual elevation values of the lidar while dramatically reducing slope noise.

2.3.3 Land cover raster

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

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

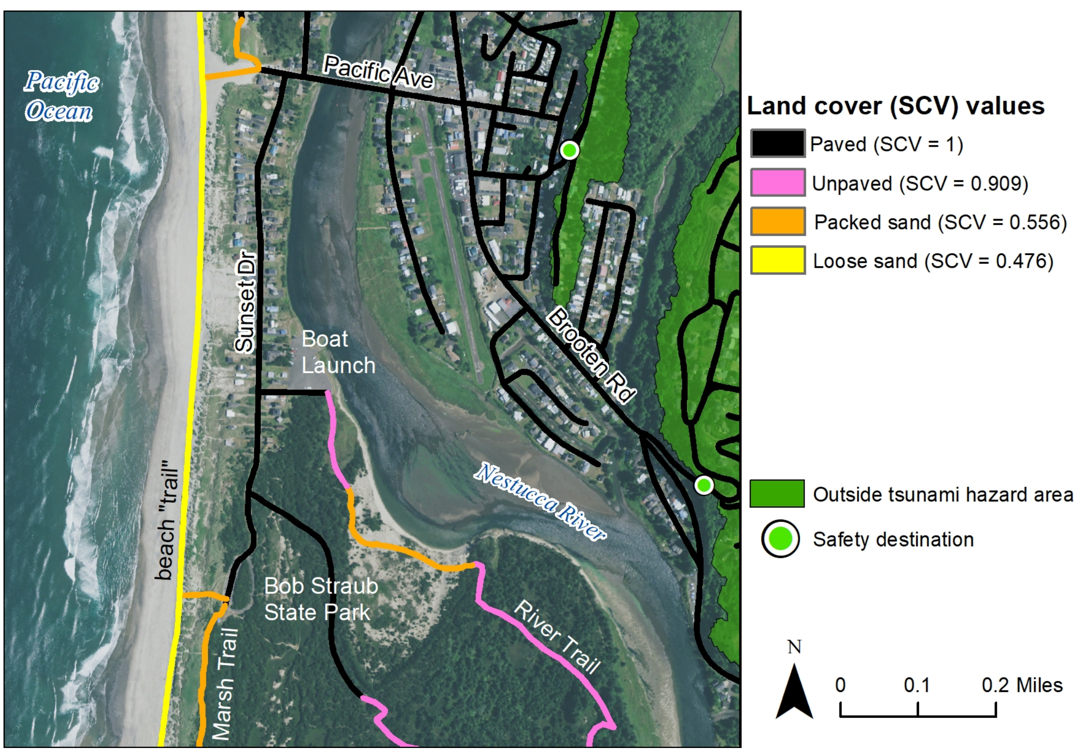
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

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

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

GIS polylines representing all roads and trails in the project area were converted to polygons (40 ft 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 ft cell size) for input into the LCD model.

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



2.3.4 Speed conservation value (SCV) slope table

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

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

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

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

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

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

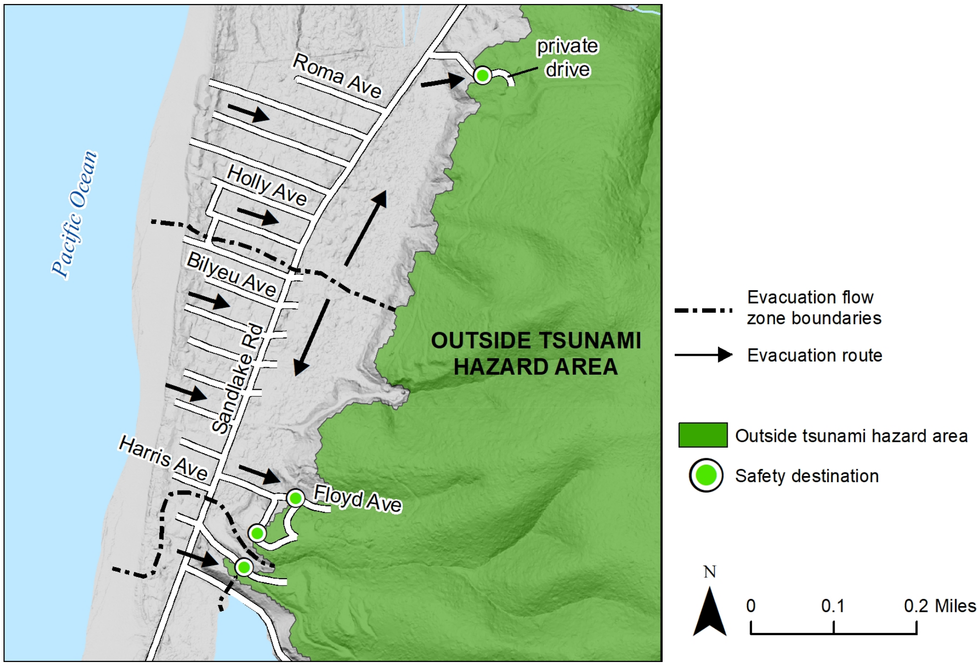
2.4 LCD model outputs

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

2.4.1 Path distance surface

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

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



2.4.2 Evacuation routes and flow zones

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

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

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

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

2.5 Beat the Wave (BTW) modeling

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

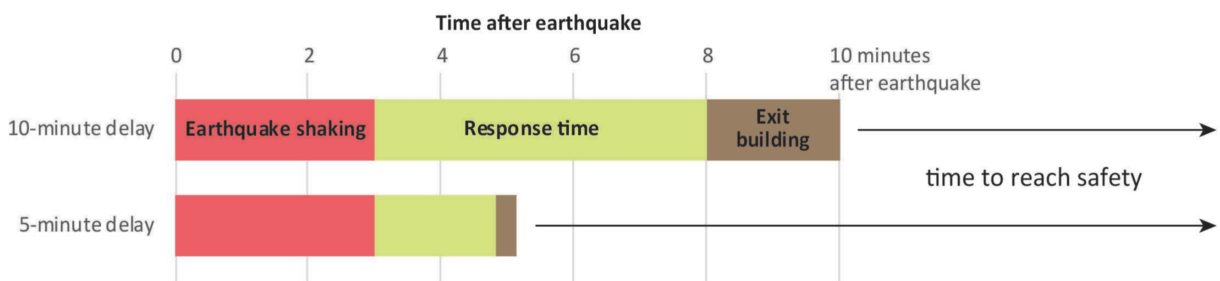
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted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

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

Using the March 11, 2011, Tohoku earthquake (U.S. Geological Survey, 2012) as an analogue to an XXL or L1 scenario, the minimum delay is probably ~3–5 minutes due to strong shaking for an ~Mw 9.0 event. There are few empirical data on how long it takes people to begin evacuation after shaking, but Mas and others (2013) determined a mean of 7 minutes in 2010 and 2011 surveys at La Punta, Peru, which has experienced several local earthquakes and tsunamis over the last ~400 years, the last being in 1974. **Figure 2-5** graphically describes how the three components of evacuation delay are related in this study. It is important to appreciate that the values adopted are not explicitly known since there are uncertainties associated with the length of the earthquake shaking, the human response dimension (i.e., how quickly people respond and how organized they are [e.g., packing a bag, time spent searching for family members and pets]) and lastly, how easy it may be to leave a building (e.g., digging out of rubble) and get underway.

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

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



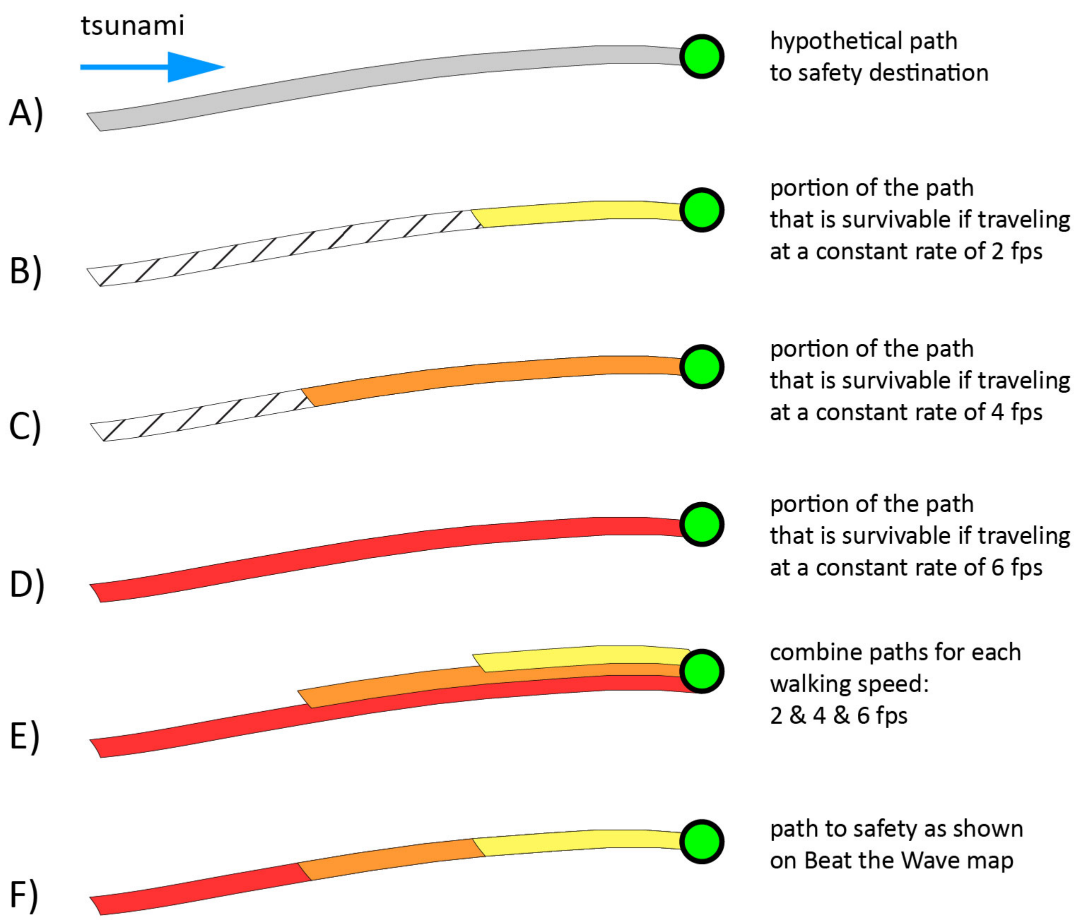
2.5.2 Evacuation time maps

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

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

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

Figure 2-6. Illustration of Beat the Wave (BTW) tsunami evacuation map construction. (A) shows a hypothetical evacuation route. (B), (C), and (D) show the path with constant walking speeds of 2 fps, 4 fps, and 6 fps, respectively. The farther away from safety (green dot) an evacuees begin the route, the faster they must walk route is survivable (hashed areas denote unsurvivable sections of the path at given walking speed); however, at faster walking speeds, evacuees can cover more distance and reach safety if they maintain the initial walking speed. (E) displays how the different constant walking speeds are combined to create the (F) final BTW map. The BTW map shows minimum constant speeds necessary to reach safety ahead of the tsunami.



Evacuation speeds were initially grouped into five categories, which allow enough contrast in color choice that areas can be easily perceived on the map. A literature review of typical pedestrian speeds by Fraser and others (2014) found five travel speed groups: adult impaired, adult unimpaired, child, elderly, and running (**Table 2-3**). The ranges of speeds for these groups at one standard deviation (the last two rows of **Table 2-3**) provide some guidance for establishing bins that would be useful on the BTW map. Speed categories in the map explanation were then given qualitative names such as “slow walking” and “running,” so the public could relate speed bins to their experience. Of particular interest are groups that will be most vulnerable, such as impaired adults and the elderly with mean speeds of 3 fps and a range of ~2–4 fps (**Table 2-3**). After examining the range of BTW speeds for Seaside (Priest and others, 2015) and reviewing a number of references describing speed categories (Paul, 2013; Margaria, 1968), we settled on the following five speed bins:

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

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

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

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

- Scenario 1: A maximum considered XXL1 scenario that assumes all evacuation routes are viable, including bridges, and people evacuate within 10 minutes from the start of earthquake shaking;
- Scenario 2: An XXL1 scenario that assumes "non-retrofitted bridges fail" due to earthquake ground motion. For Port Orford, two bridges that fall into this category: Mill Creek bridge and the Highway 101 bridge over Mill Creek. We also assume that a levee/culvert at the western end of Paradise Point Rd is impacted either through failure or as a result of subsidence making that route impassable. All subsequent scenarios assume these non-retrofitted bridges fail unless otherwise stated;
- Scenario 3: An XXL1 scenario that assumes people evacuate within 5 minutes (i.e., 3 minutes of shaking; 2 minutes of response time instead of 7) from the start of earthquake shaking;
- Scenario 4: An XXL1 scenario that assumes two "hypothetical trails" are constructed near Agate Beach Rd. The two trails would enable evacuation for visitiors at Tseriadun State Recreation Site and for the area adjacent to the Port Orford water treatment facility. Both trails would connect with high ground at the Port Orford Heads;
- Scenario 5: An XXL1 scenario that includes a "hypothetical vertical evacuation" structure at Buffington Memorial Park;
- Scenario 6: An XXL1 scenario that combines the hypothetical trails of scenario 4 and the hypothetical vertical evacuation center of scenario 5; and,
- Scenario 7: An L1 scenario that assumes "non-retrofitted bridges fail" due to the earthquake ground motion (Paradise Point Road culvert also removed for this scenario). The L1 scenario covers 95% of the potential historical tsunami variability.

In general, we find a wide variety of evacuation speeds that the public must take in order to escape an XXL1 (maximum-considered) Cascadia tsunami that cover the spectrum from a ***walk*** to ***sprint***. In areas adjacent to Garrison Lake, evacuation travel speeds approaching a sprint will be needed to ensure survival. For the Large tsunami event, the results improve significantly although evacuation remains challenging for a few discrete areas. Our analyses reveal that the issue is how quickly the tsunami arrives as opposed to access to high ground. Accordingly, how quickly people respond and evacuate to high ground will be the difference between life and death. To that end, tsunami wave arrival times will be presented first for the community. BTW evacuation modeling results will then be presented separately. Where applicable, hypothetical scenarios such as bridge failures, liquefaction, or the use of vertical evacuation structure will be evaluated in order to address potential future mitigation options.

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. **Table 3-1** represents a summary of the range of speeds and their conversions that will be used throughout the remainder of this report. Finally, after the earthquake other factors may also contribute to impede travel times. This modeling does not account for these ancillary effects, which could include obstacles such as downed power lines or buildings. As a result, ***people should maintain the overarching goal of immediately evacuating after the earthquake and moving as rapidly as possible in order to ensure they reach safety with ample time to spare.***

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

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

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

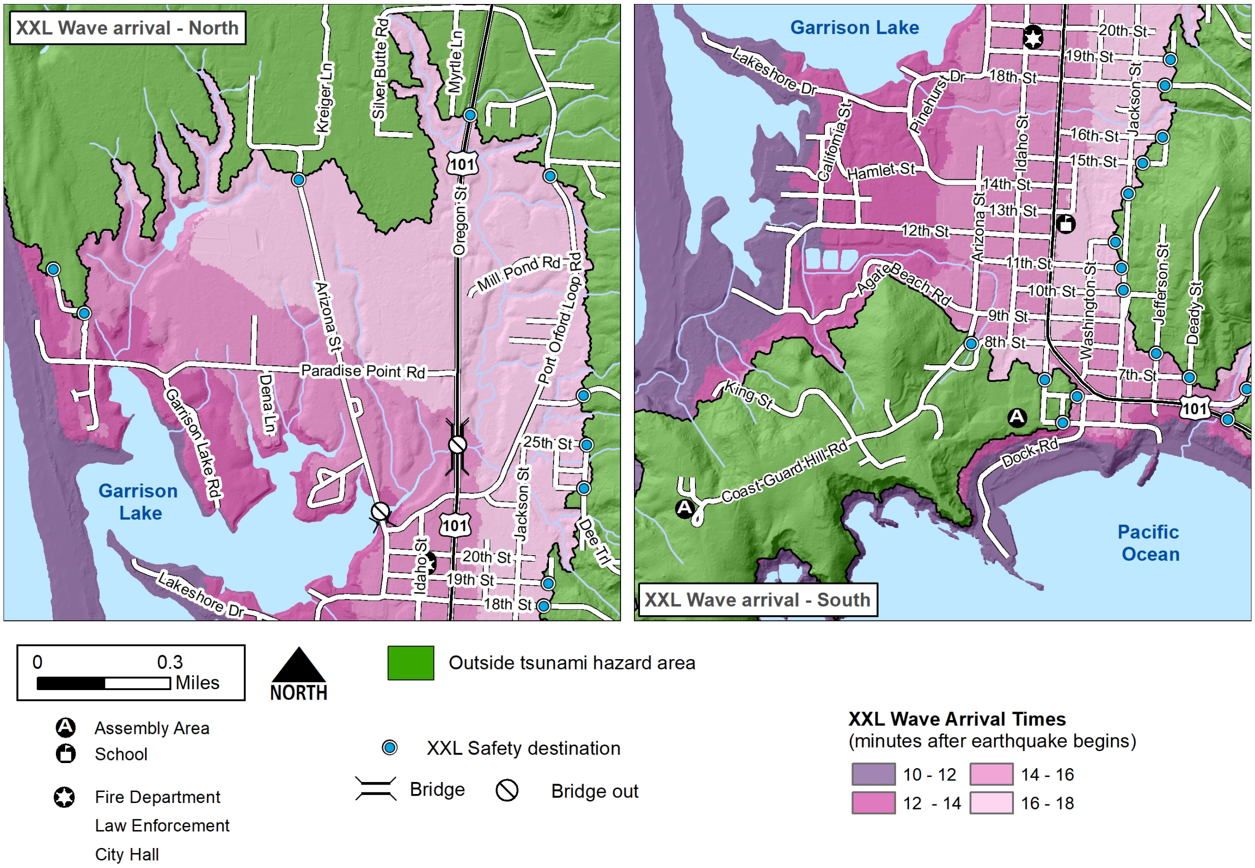
3.1 Tsunami wave arrivals

Figure 3-1 shows the arrival times for an XXL tsunami in the Port Orford project area. The earliest wave arrivals are along the open coast, where the tsunami reaches the beach in as little as 10 minutes after the start of the earthquake shaking. By 14 minutes, the tsunami has crossed Garrison Lake, and five minutes later has fully inundated the entire community. Although the first wave is the largest to impact the community, additional tsunami waves will continue to strike the coastline and impact the area for up to 5 hours after the earthquake. However, by about 12 hours effects from the tsunami are essentially negligible.

Proximity of Curry County to Cascadia subduction zone

The tsunami arrives more quickly at Port Orford and along the southern Oregon coastline because the Cascadia subduction zone is near the coast here (~30 miles).

Figure 3-1. Illustration of tsunami wave arrival times after a Cascadia subduction zone XXL earthquake for Port Orford (left) north and (right) south.



3.2 Tsunami Evacuation Modeling Results

3.2.1 Scenario 1 – Existing Road Network

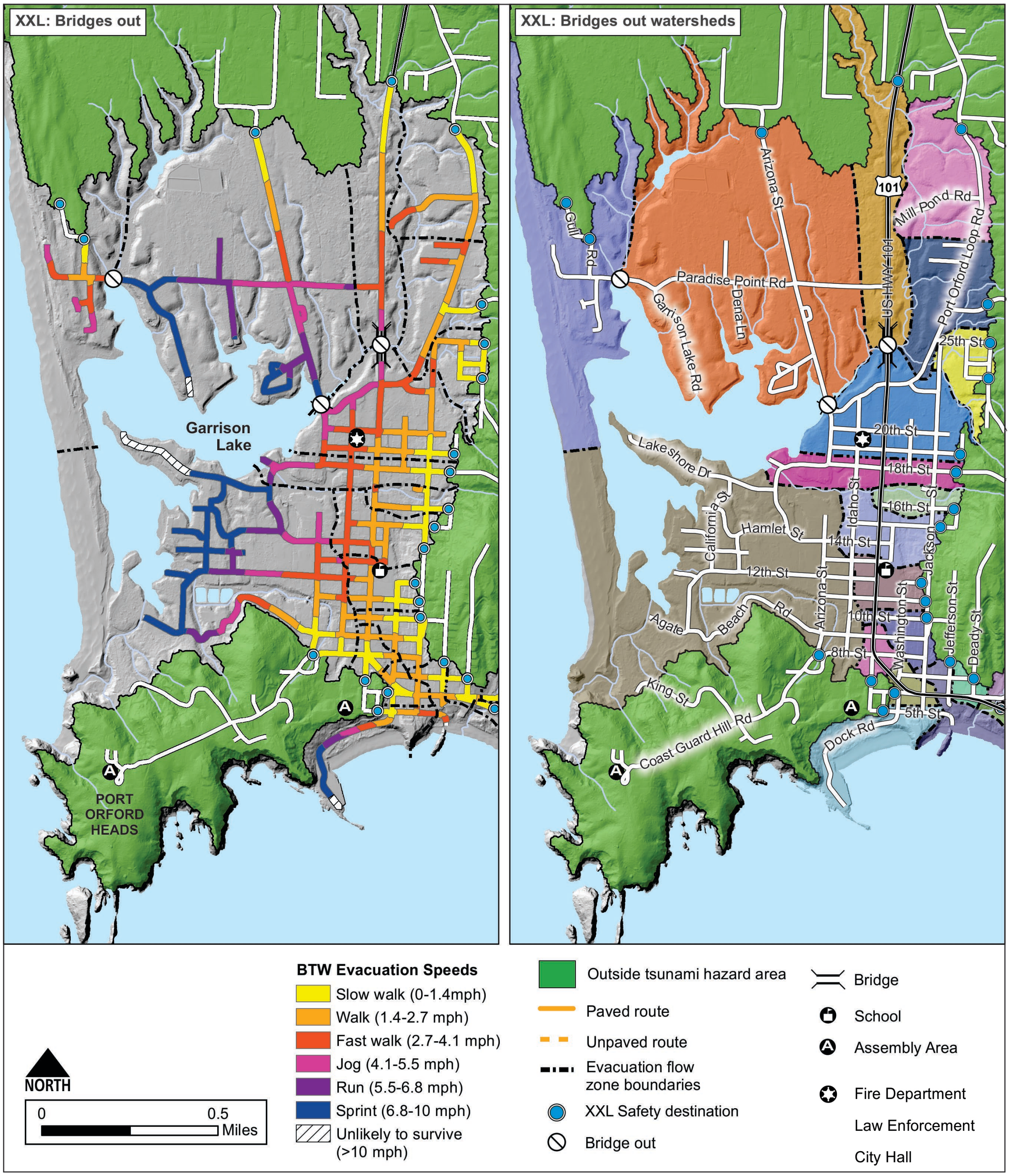
For scenario 1, we evaluated evacuation potential from a maximum considered XXL (local) earthquake and accompanying tsunami and assume that the existing road and trail network are all viable and are available for use, including evacuation over the Highway 101 and Mill Creek bridges. From the evacuation modeling, we established that neither the Highway 101 or the Mill Creek bridges are essential for evacuation purposes. This is because the distance to safety is equidistant on both sides of the bridges and, importantly, closer high ground can be reached using different routes. This is reinforced in a separate casualty study undertaken by Bauer and others (2020), who determined that there is no difference in the number of estimated tsunami fatalities when one includes or excludes evacuation over the bridges. Nevertheless, Bauer and others acknowledged that the Highway 101 bridge would be critically important for post-tsunami recovery. This is largely because Highway 101 south of Port Orford will likely be closed for some time due to the expectation of significant landsliding.

Because bridges do not prove to be essential for evacuation, results for this scenario are identical to scenario 2 (non-retrofitted bridges fail, **Figure 3-2**).

3.2.2 Scenario 2 – Non-retrofitted bridges fail

Our initial evacuation modeling of the immediate Port Orford area identified 18 discrete evacuation flow zones (**Figure 3-2**, *right*), the majority of which serve small neighborhoods located east of Highway 101 that are closest to high ground. Accordingly, people in these zones would evacuate toward their nearest designated safety destination in the eastern foothills. Other notable evacuation zones include those for residents located out near Paradise Point, the Arizona St community north of Garrison Lake, and the larger community nearest to southern Garrison Lake that includes residents on 12th St and Lakeshore Dr (**Figure 3-2**, *right*), all of whom would evacuate south toward Coast Guard Hill Rd. This scenario assumes the Highway 101 and Mill Creek bridges fail and that coseismic subsidence of the coastline makes a levee/culvert on Paradise Point Rd impassable (Albert Nako, Oregon Department of Transportation, personal communication, 2020).

Figure 3-2. Beat the wave tsunami evacuation modeling for Port Orford based on a bridge failure scenario (scenario 2). (left) Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries and (right) evacuation flow zones only.

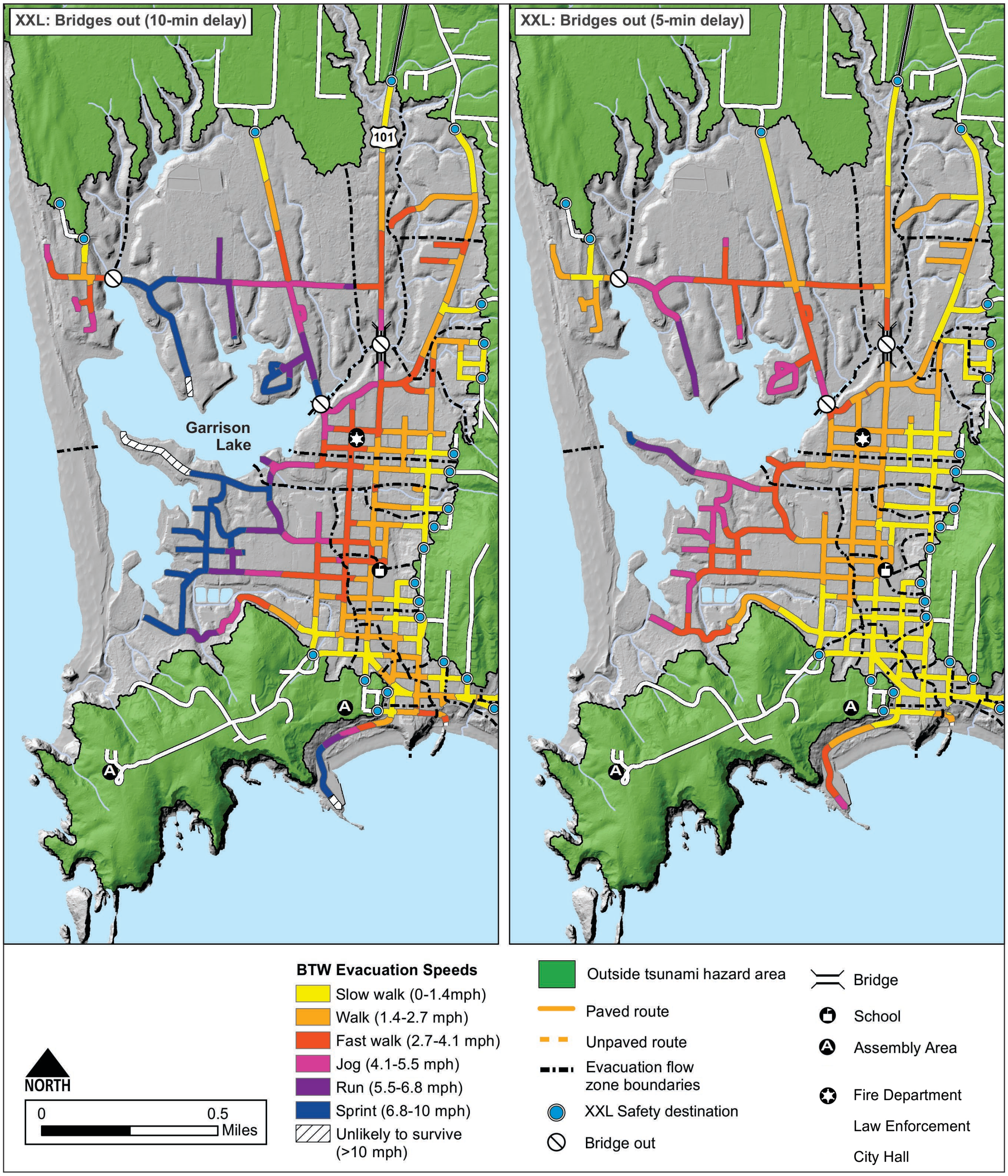


Broadly speaking, our evacuation modeling results for Port Orford can be divided east/west along the Highway 101 corridor. Residents east of Highway 101 should be able to reach high ground without much difficulty. This is because these evacuation flow zones are all located close to high ground and as such are classified with a minimum evacuation speed of ***slow walk*** and ***walk*** categories. However, these results are predicated on the assumption that people will leave the inundation zone within the allotted 10-minute delay that includes 3-5 minutes of earthquake shaking, and, further, that they are familiar with their evacuation routes. Hence, any delay beyond the assumed 10 minutes will increase the potential for an evacuee being killed due to how quickly the community is inundated. As can be seen in **Figure 3-2**, the modeled pedestrian evacuation speeds increase to a ***fast walk*** one block west of Highway 101 (i.e., Idaho St), and quickly escalate to ***jog*** and ***run*** for residents immediately adjacent to Garrison Lake (e.g., Lakeshore Dr and Greer Circle) required to ***sprint***. Again, we speculate that most people located in the ***fast walk*** area would probably survive the tsunami, assuming they evacuate quickly and do not delay. However, farther west and nearer Garrison Lake, it is apparent that maintaining the required minimum evacuation speeds over the full route becomes extremely challenging.

3.2.3 Scenario 3 – Reduced Evacuation Delay

When exploring ways to reduce the potential for tsunami fatalities, any effort directed at reducing evacuation delay will save lives. Here we evaluate a 5-minute evacuation delay, compared with the original 10-minute delay. For the 5-minute delay scenario, we assume the original ~3 minutes for the earthquake shaking, and factor in a 2-minute response time before getting underway. **Figure 3-3** shows a side-by-side comparison of the results (scenarios 2 and 3). Overall, the results demonstrate that by reducing the response time (i.e., reducing the amount of time between earthquake shaking and evacuation start; see **Figure 2-5**) is directly reflected in the necessary evacuation speeds—which are generally reduced by about one speed category (evacuation flow zones remain unchanged). For example, residents located adjacent to Garrison Lake must travel at a "sprint" pace if they wait 7 minutes (10-minute delay, **Figure 3-3**, *left*); however, a reduced response time results in speeds of "fast walk" and "jog" (**Figure 3-3**, *right*). Given the fact that these residences are ~0.5 to 0.75 miles from high ground and speeds must be maintained for the duration of the route, it would be extremely difficult for anyone to maintain the speeds required in scenario 2. By reducing response time (**Figure 3-3**, *right*), evacuation speeds are effectively reduced to a jog, enabling potentially many more people to reach safety in time. These results are reinforced by the fatality analyses undertaken by Bauer and others (2020), who demonstrate that significantly fewer lives will be lost if individuals evacuate as soon as possible and that they travel as fast as possible in order to reach high ground.

Figure 3-3. Beat the wave tsunami evacuation modeling for Port Orford based on different departure delays. (left) 10-minute evacuation delay (scenario 2) and (right) 5-minte evacuation delay (scenario 3). Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.

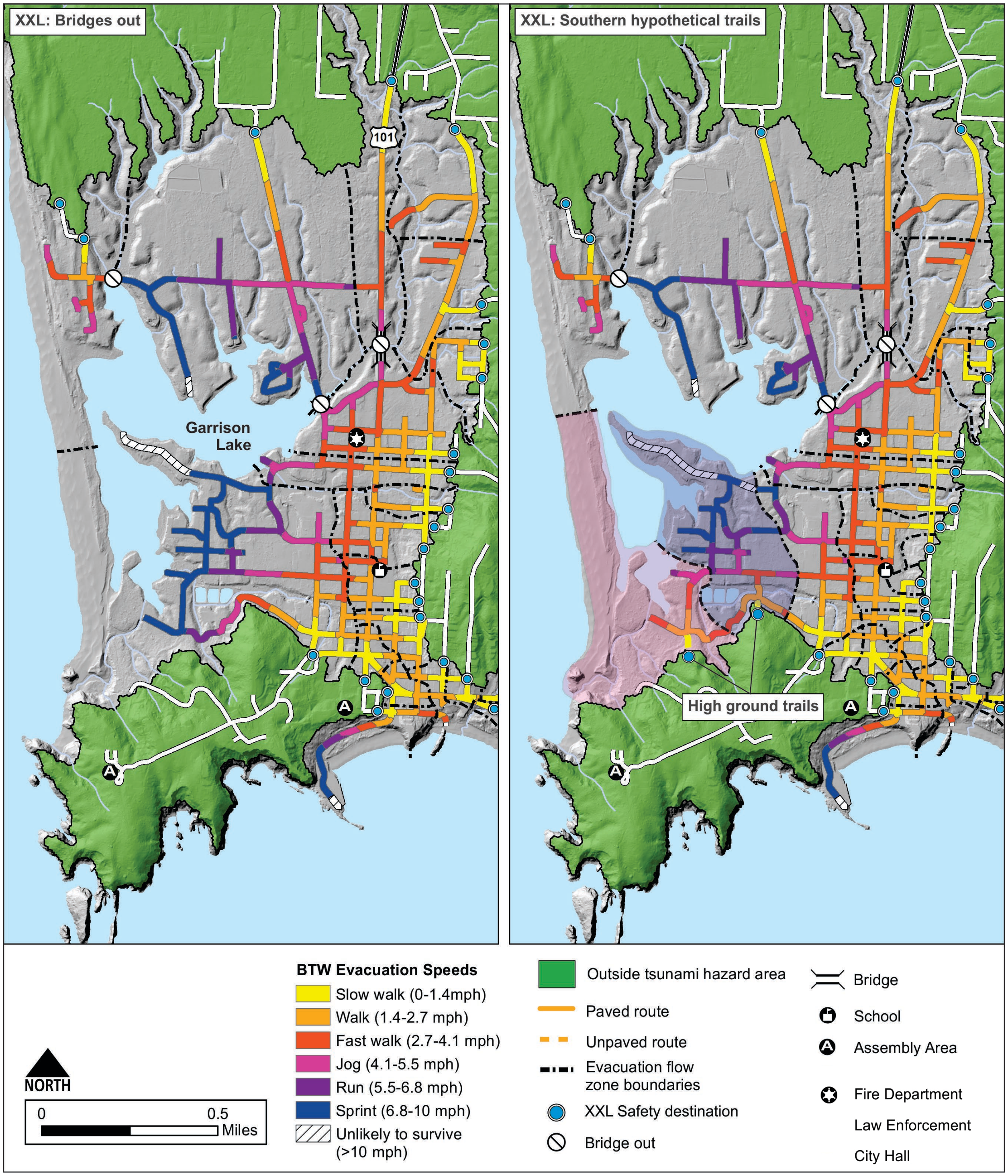


3.2.4 Scenario 4 – Hypothetical Evacuation Trails

Aside from reducing response time and other evacuation delays, several other approaches can be implemented to improve evacuation. One approach is to construct additional evacuation routes in areas where none previously existed. In this scenario we explore the construction of two hypothetical trails in south Port Orford. The first trail near the entrance to Tseriadun State Recreation Park provides a much shorter evacuation route from the park, while a second trail on the east side of the Port Orford water treatment plant would better serve residents in the vicinity of the plant, along California St and the western half of 12th St. Results from scenario 4 evacuation modeling are presented in **Figure 3-4,** *right*.

Overall, the modeling demonstrates some improvements in evacuation potential. Of note, the single evacuation flow zone identified in **Figure 3-4**, *left*, is now further subdivided into three zones: a western zone that serves the state park and Garrison Lake beach (highlighted in pink in **Figure 3-4**, *right*); a central zone that addresses residents on California St, western 12 St, Hamlet St and Lakeshore Dr (highlighted in blue); and a third zone that covers the remaining area (southern Arizona St). Although there are notable improvements in overall evacuation potential, within the central sub-community the modeling results still indicate evacuation speeds in the sprint category (e.g., along Lakeshore Dr and California St). Hence, for people living in these areas there would remain significant evacuation challenges with this scenario.

Figure 3-4. Beat the wave tsunami evacuation modeling for Port Orford based on hypothetical trails near the Port Orford Heads. (left) Original bridges-out results (scenario 2), and (right) with the inclusion of two hypothetical trails in the south (scenario 4). Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. The pink and blue shaded regions define the new evacuation flow zones associated with the hypothetical trails.



3.2.5 Scenario 5 – Vertical Evacuation Structure

The biggest challenge affecting evacuation potential at Port Orford is the fact that a Cascadia tsunami arrives very quickly, limiting the time available to reach high ground. As discussed above in scenario 3, reducing a person's departure delay (i.e., response time) from 7 minutes to 2 minutes makes an enormous difference in that person's chance of surviving the tsunami (**Figure 3-3**), by providing more time to reach high ground. Time to reach safety may also be accomplished by bringing high ground closer to residents. This can be achieved through the construction of a tsunami vertical evacuation structure (TVES), which may be a building or berm. Such a structure, when built correctly and in targeted locations, could potentially save many lives. In this scenario we evaluated the construction of a TVES at Buffington Memorial Park, located two blocks west of Highway 101, on 13th St. We chose the park site because of its central location within the community, its location relative to those areas where evacuation challenges remain high (e.g., adjacent to Garrison Lake), and because park area would fall under city control. Although a TVES building would likely have a lower footprint, a tall berm may be a better solution for this area, allowing it to be used for recreational purposes.

Results of our evacuation modeling for a TVES at Buffington Memorial Park are presented in **Figure 3-5**. The pink shaded region defines the overall area that would be served by a TVES, which is reduced in size when compared with the bridges-out scenario (scenario 2, **Figure 3-2**). In addition to the TVES, we established four connecting trails to allow for more direct access to the TVES. As can be seen from the modeling results, the TVES resolves some of the evacuation challenges with noticeable improvements in evacuation speeds around the structure (compare **Figure 3-5,** *left* and *right*). These improvements are essentially concentrated in a quarter-mile radius around the structure. Unfortunately, for those areas immediately adjacent to Garrison Lake (e.g., Lakeshore Dr), a TVES does not improve their situation. Again, this is because of how quickly the tsunami arrives and inundates this area. Bauer and others (2020) quantified the number of fatalities for Port Orford using our baseline bridges-out scenario (scenario 2) and compared that with the benefits of adding a TVES. Their results suggest that a Buffington Park TVES would probably save ~100 lives; more lives would be saved if evacuation travel speeds were increased. These results also imply that even more lives would be saved if a second TVES were built near Hamlet St, providing closer access for those residents located along the western shore of Garrison Lake.

3.2.6 Scenario 6 – Vertical Evacuation Structure and Southern Trails

Figure 3-6 integrates the results of the hypothetical vertical evacuation structure (**Figure 3-5,** scenario 5) and the southern trails model results (**Figure 3-4,** scenario 4). The purpose here is demonstrate that a single solution may not necessarily be the best option for Port Orford. Instead, a combination of approaches may be more likely to produce an overall better outcome. As can be seen from **Figure 3-6**, retaining the southern trails provides an escape route for people recreating at the state park (pink shaded region in **Figure 3-6**). Similarly, having the trail by the water treatment facility provides improved access for those located along western 12th St, California St, and Hamlet St (blue shaded region). With the inclusion of the trails, the evacuation model results for the TVES become more centralized around the structure, with some localized modifications (yellow shaded region). Of note, the boundary between heading east (toward the hills) and going west to the TVES is shifted slightly westward of Highway 101 (compare **Figure 3-6** with **Figure 3-5**), in order to emphasize that residents and businesses located along the Highway 101 corridor should evacuate eastward regardless of the presence of a TVES. Hence, the revised results confirm that if a vertical evacuation structure is present, U.S. Highway 101 acts as a natural divide, with anyone west of the highway evacuating to the structure and anyone to the east evacuating to the eastern foothills. Nevertheless, despite the inclusion of both evacuation combinations, it is apparent that the results remain very challenging for residents located near the Garrison Lake.

Another solution to this challenge could be the construction of a second TVES further west; however, our analyses suggest that there are diminishing returns on such an investment. The rapid wave arrival in Port Orford means that every minute counts—a TVES west of Buffington Memorial Park would have an even earlier wave arrival, and only people who were already very close to the structure could reach it in time.

3.2.7 Scenario 7 – Evacuation Modeling Using the Large Scenario

Finally, we evaluate evacuation modeling results generated using the Large (L1) tsunami inundation scenario. Recall, the L1 scenario accounts for 95% of the expected inundation modeled by DOGAMI. **Figure 3-7** presents the evacuation modeling results for Large (right) compared to XXL (left, scenario 2). As can be seen in the figure, the extent of inundation associated with the Large tsunami scenario is much reduced. With the exception of a small area near 15th and 16th Streets, everything east of Highway 101 is now outside the tsunami zone, including several critical facilities such as the Driftwood elementary school and the police/fire/city hall building. Furthermore, areas characterized as a ***sprint*** for XXL are now limited to small area at the very western end of Lakeshore Dr. The remaining areas located around Garrison Lake are now reclassified downward to a ***fast walk*** or ***jog*** (compare left and right panels in **Figure 3-7**). Overall, these results indicate that the majority of the Port Orford community could reach high ground and beat the wave in a Large tsunami scenario, providing they leave quickly (within 10 minutes from the start of the earthquake) and travel as fast as possible. As a reminder, XXL is the largest earthquake and tsunami scenario DOGAMI modeled and is meant to understand the maximum inundation possible from a Cascadia tsunami. As stated previously, the Large scenario accounts for 95% of the expected inundation, meaning there is only a 5% chance the next tsunami will be larger than DOGAMI's Large tsunami scenario.

Figure 3-5. Beat the wave tsunami evacuation modeling for Port Orford based on a hypothetical tsunami vertical evacuation structure (TVES). (left) Original bridges-out results (scenario 2), and (right) with the inclusion of a hypothetical tsunami vertical evacuation structure at Buffington Memorial Park (scenario 5). Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. The pink shaded region defines the overall area that would be served by a TVES.

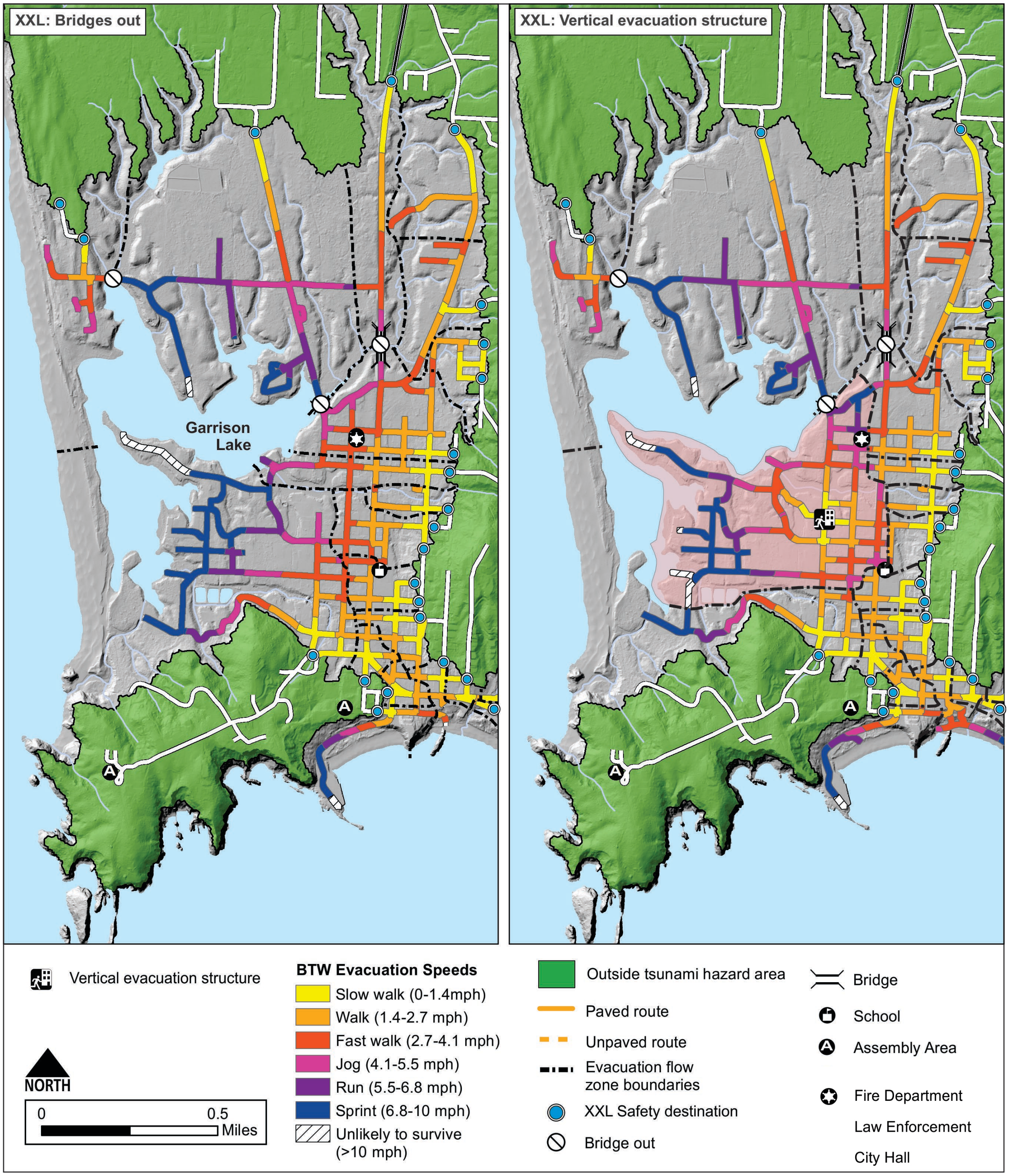


Figure 3-6. Beat the wave tsunami evacuation modeling for Port Orford based on the combined results from a hypothetical tsunami vertical evacuation structure (TVES) and hypothetical southern evacuation trails. Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries. The pink and blue shaded regions define the area that would be served by the proposed hypothetical trails; the yellow region defines the TVES evacuation flow zone. Highway 101 is highlighted in white to emphasize the divide between evacuating east to the foothills and west to the hypothetical TVES.

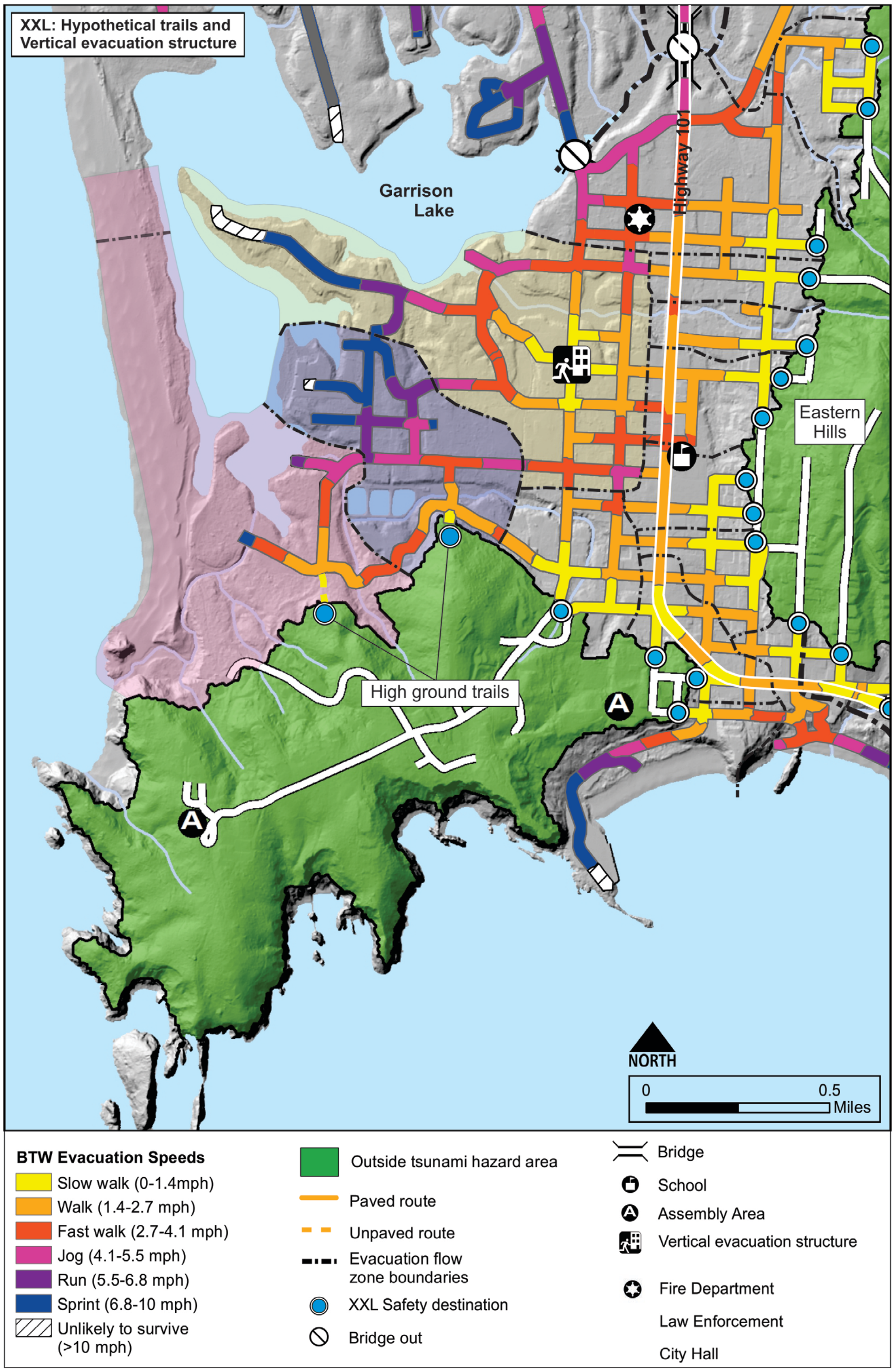
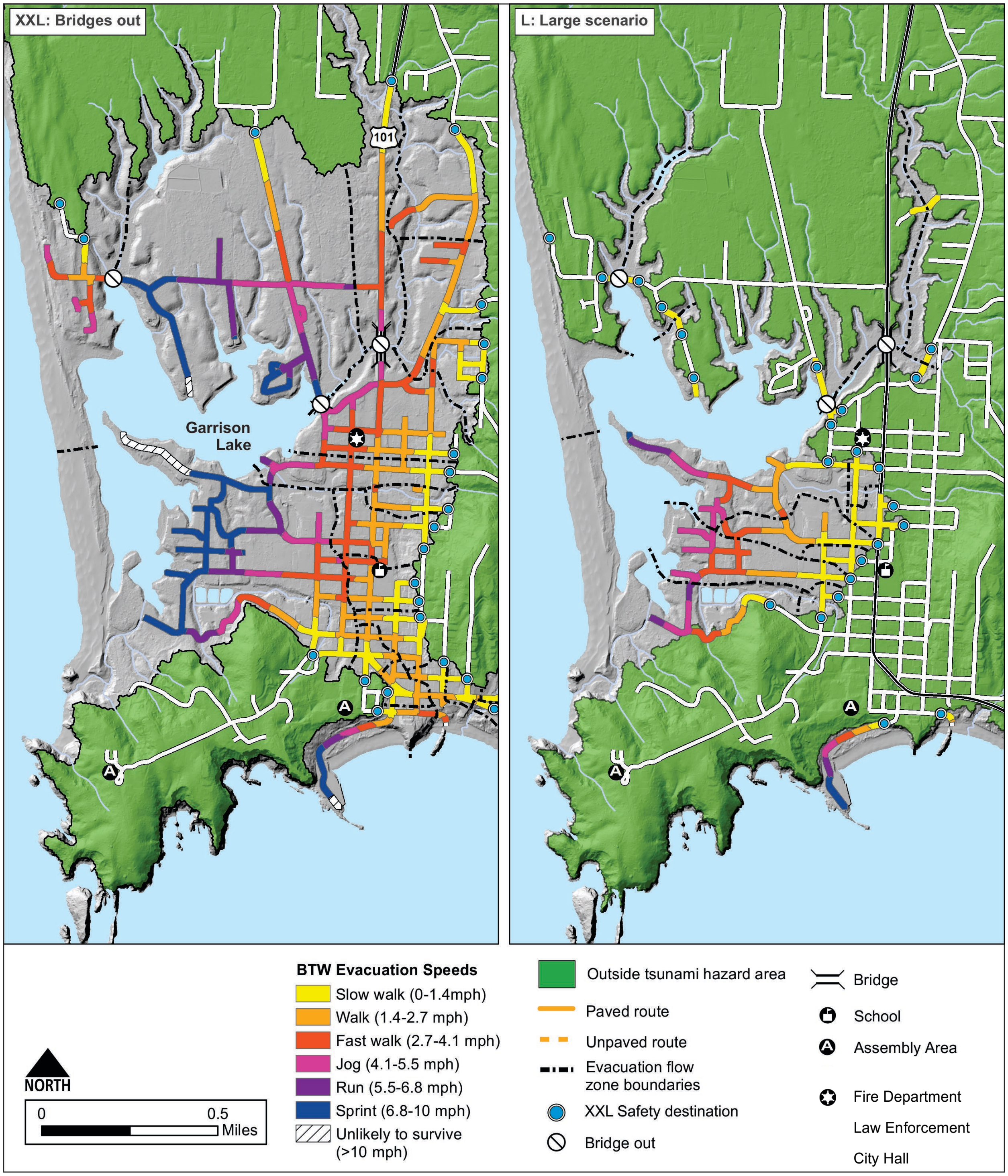


Figure 3-7. Beat the wave tsunami evacuation modeling for Port Orford based on the Large (L) tsunami inundation scenario. (left) Original XXL bridges-out results (scenario 2), and (right) L bridges-out results (scenario 7). Colors on top of the road network reflect BTW minimum travel speeds, while dashed lines define evacuation flow zone boundaries.



4.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation provides a quantitative assessment of evacuation difficulty in the Port Orford area. The investigation implemented the Beat the Wave (BTW) approach to evacuation analysis developed by Priest and others (2015, 2016). The results of this study demonstrate that evacuation of the Port Orford community in response to a maximum considered (XXL) Cascadia Subduction Zone tsunami is attainable for all areas east of Highway 101 (**Figure 3-2**). Similarly, successful evacuation is possible for residents located within 1-2 blocks to the west of Highway 101, including both Arizona and Idaho Streets. With continued westward progress, successful evacuation becomes more challenging, especially in the immediate vicinity of Garrison Lake. For residents living along Lakeshore Dr, successful evacuation will be difficult under existing conditions. However, if residents evacuate sooner (i.e., within 5 minutes from the start of the earthquake, **Figure 3-3**, *right*), then the chances of surviving a maximum considered XXL tsunami improve. Given the challenges facing people living around the shores of Garrison Lake, a vertical evacuation structure becomes the only viable mitigation option (**Figure 3-5**). Such a scenario, when coupled with hypothetical evacuation trails that would allow people to evacuate up to the Port Orford Heads (**Figure 3-6**), improves the chances of achieving successful evacuation. A large enough vertical evacuation structure (e.g., a berm or building) capable of holding the estimated number of people in the relevant evacuation flow zone would need to be built to a sufficient height. We recommend further evaluation to assess the cost/benefits of this option.

Our analyses also included an assessment of the Large (L1) tsunami inundation scenario, which may be used instead of XXL for planning purposes. In this scenario (**Figure 3-7**), there are significantly more areas of natural high ground available. The Large scenario covers 95% of the likely inundation, meaning there is a 5% chance the tsunami will exceed the Large inundation zone (XXL covers 100%). In this scenario, we find that essentially all areas east of U.S. Highway 101 are outside the tsunami zone; the exception is a small area near 15th and 16th Streets. Adjacent to Garrison Lake, we find that successful evacuation improves significantly. The decision to direct people to L1 high ground versus XXL must be done with care and deliberation. Evacuees east of Idaho Street do not need to adjust their evacuation regardless of which scenario they prepare for — in either scenario, they evacuate east, and every step brings them closer to high ground. This can be a powerful messaging tool, especially for those who feel they cannot reach XXL high ground in time. Evacuating as far as possible is advantageous because even if evacuees cannot reach XXL limit, the distance traveled may be sufficient to “Beat the Wave.”

Without suitable mitigation efforts directed at constructing a vertical evacuation structure or building trails southward onto the Port Orford Heads, evacuation from the western side of Port Orford will be challenging and the potential for significant loss of life remains high (Bauer and others, 2020). This is because the available time required to “beat the wave” to safety in this area is extremely short relative to how quickly the tsunami reaches the shore (10 minutes) and inundates the community (~another 8 minutes).

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

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES

Applied Technology Council, 2012, Guidelines for design of structures for vertical evacuation from tsunamis, 2nd ed. (FEMA P-646): Redwood City, Calif., Applied Technology Council, 174 p. https://www.fema.gov/media-library/assets/documents/14708

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

Burns, W. J., Mickelson, K. A., and Madin, I. P., 2016, Statewide landslides susceptibility overview map of Oregon: Oregon Department of Geology and Mineral Industries, Open-File Report O-16-02, 48 p., 1 pl., scale 1:750,000, GIS raster data. https://www.oregongeology.org/pubs/ofr/p-O-16-02.htm

Connor, D., 2005, The City of Seaside's Tsunami Awareness Program: outreach assessment—how to implement an effective tsunami preparedness outreach program: Oregon Department of Geology and Mineral Industries Open-File Report O-05-10, 86 p. https://www.oregongeology.org/pubs/ofr/O-05-10.pdf

Fraser, S. A., Wood, N. J., Johnston, D. M., Leonard, G. S., Greening, P. D., and Rossetto, T., 2014, Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling: Natural Hazards and Earth System Sciences, v. 14, no. 11, p. 2975–2991. https://doi.org/10.5194/nhess-14-2975-2014

Gabel, L. L. S., and Allan, J. C., 2016, Local tsunami evacuation analysis of Warrenton and Clatsop Spit, Clatsop County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-16-08, 56 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-16-08.htm

Gabel, L. L. S., and Allan, J. C., 2017, Local tsunami evacuation analysis of Rockaway Beach, Tillamook County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-17-06, 56 p., geodatabase. https://www.oregongeology.org/pubs/ofr/p-O-17-06.htm

Imhof, E., 1950, Gelände und Karte: Erlenbach-Zürich, Eugen Rentsch Verlag, 255 p.

Langlois, J. A., Keyl, P. M., Guralnik, J. M., Foley, D. J., Marottoli, R. A., and Wallace, R. B., 1997, Characteristics of older pedestrians who have difficulty crossing the street: American Journal of Public Health, v. 87, no. 3, p. 393–397. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1381010/pdf/amjph00502-0075.pdf

Madin, I. P., and Burns, B. W. J., 2013, Ground motion, ground deformation, tsunami inundation, coseismic subsidence, and damage potential maps for the 2012 Oregon Resilience Plan for Cascadia Subduction Zone Earthquakes: Oregon Department of Geology and Mineral Industries Open-File Report O-13-06, 36 p., 38 pl., geodatabase. https://www.oregongeology.org/pubs/ofr/p-O-13-06.htm

Madin, I.P., and Wang, Z., 1999, Relative earthquake hazard maps for selected coastal communities in Oregon: Astoria–Warrenton, Brookings, Coquille, Florence–Dunes City, Lincoln City, Newport, Reedsport–Winchester Bay, Seaside–Gearhart–Cannon Beach, Tillamook: Oregon Department of Geology and Mineral Industries, Interpretive Map 10, 25 p., 2 pl., scale 1:24,000. https://www.oregongeology.org/pubs/ims/p-ims-010.htm

Margaria, R., 1968, Positive and negative work performances and their efficiencies in human locomotion: Internationale Zeitschrift für angewandte Physiologie, einschliesslich Arbeitsphysiologie, v. 25, p. 339–351. https://doi.org/10.1007/BF00699624

Mas, E., Adriano, B., and Koshimura, S., 2013, An integrated simulation of tsunami hazard and human evacuation in La Punta, Peru: Journal of Disaster Research, v. 8, no. 2, 285–295. doi: 10.20965/jdr.2013.p0285

Oregon Department of Geology and Mineral Industries, 2013, Tsunami evacuation map for Port Orford: Oregon Department of Geology and Mineral Industries. https://www.oregongeology.org/pubs/tsubrochures/PortOrfordEvac7-2-12_onscreen.pdf

Paul, S., 2013, What are the right walking and running speeds?: Runner's World, online article, March 6, 2013. https://www.runnersworld.com/for-beginners-only/what-are-the-right-walking-and-running-speeds [accessed 4/17/2014]

Priest, G. R., Goldfinger, C., Wang, K., Witter, R. C., Zhang, Y., and Baptista, A. M., 2009, Tsunami hazard assessment of the northern Oregon coast: a multi-deterministic approach tested at Cannon Beach, Oregon: Oregon Department of Geology and Mineral Industries Special Paper 41, 87 p. plus 7 p. app. Includes report, GIS set, time histories, and animations. https://www.oregongeology.org/pubs/sp/SP-41.zip

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013a, Tsunami animations, time histories, and digital point data for flow depth, elevation, and velocity for the Central Coast Project Area, Coos, Douglas, Lane, and Lincoln Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-16, GIS data. https://www.oregongeology.org/pubs/ofr/p-O-13-16.htm

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013b, Tsunami inundation scenarios for Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-19, 14 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-13-19.htm

Priest, G. R., Stimely, L. L., Madin, I. P., and Watzig, R. J., 2015, Local tsunami evacuation analysis of Seaside and Gearhart, Clatsop County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-15-02, 36 p., GIS data. https://www.oregongeology.org/pubs/ofr/p-O-15-02.htm

Priest, G. R., Stimely, L. L., Wood, N. J., Madin, I. P., and Watzig, R. J., 2016, Beat the-wave evacuation mapping for tsunami hazards in Seaside, Oregon, USA: Natural Hazards, v. 80, no. 2, p. 1–26. https://dx.doi.org/10.1007/s11069-015-2011-4 [first online 10/19/2015]

Soule, R. G., and Goldman, R. F., 1972, Terrain coefficients for energy cost prediction: Journal of Applied Physiology, v. 32, no. 5, p. 706–708. https://doi.org/10.1152/jappl.1972.32.5.706

Tobler, W., 1993, Three presentations on geographical analysis and modeling: Non-isotropic geographic modeling; speculations on the geometry of geography; and global spatial analysis: University of Calif., Santa Barbara, National Center for Geographic Information and Analysis Technical Report 93-1, 24 p. https://escholarship.org/uc/item/05r820mz

U.S. Department of Transportation, 2012, Manual on uniform traffic control devices for streets and highways [2009 edition with revisions 1 and 2]: Federal Highway Administration. https://mutcd.fhwa.dot.gov/kno_2009r1r2.htm [accessed 11/25/2014]

U.S. Geological Survey (USGS), 2012, The March 11 Tohoku earthquake, one year later. What have we learned?: U.S. Geological Survey, Science Features blog post, March 9, 2012. https://www2.usgs.gov/blogs/features/usgs_top_story/the-march-11-tohoku-earthquake-one-year-later-what-have-we-learned/ [accessed 9/9/2014]

Witter, R. C., Y. Zhang, Wang, K., Priest, G. R., Goldfinger, C., Stimely, L. L., English, J. T., and Ferro, P. A., 2011, Simulating tsunami inundation at Bandon, Coos County, Oregon, using hypothetical Cascadia and Alaska earthquake scenarios: Oregon Department of Geology and Mineral Industries Special Paper 43, 57 p., 3 pl., GIS files, animations. https://www.oregongeology.org/pubs/sp/p-SP-43.htm

Wood, N., and Schmidtlein, M., 2012, Anisotropic path modeling to assess pedestrian-evacuation potential from Cascadia-related tsunamis in the US Pacific Northwest: Natural Hazards, v. 62, no. 2, p. 275–300. doi: 10.1007/s11069-011-9994-2. https://link.springer.com/article/10.1007/s11069-011-9994-2

Wood, N., Jones, J., Schmidtlein, M., Schelling, J., and Frazier, T., 2016, Pedestrian flow-path modeling to support tsunami evacuation and disaster relief planning in the U.S. Pacific Northwest: International Journal of Disaster Risk Reduction, v. 18, 41–55. doi: 10.1016/j.ijdrr.2016.05.010. https://www.sciencedirect.com/science/article/pii/S2212420916300140

Yeh, H., Fiez, T., and Karon, J., 2009, A comprehensive tsunami simulator for Long Beach Peninsula, phase 1: framework development: Tacoma, Wash., Washington Military Department, 27 p.