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TSUNAMI EVACUATION ANALYSIS OF ASTORIA AND NEARBY UNINCORPORATED COMMUNITIES, 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 Astoria and nearby unincorporated communities including Jeffers Garden, Clatsop County.

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

Astoria_Tsunami_Evacuation_Modeling.gdb:

XXL1_BridgesOut feature dataset:

XXL1_BridgesOut_EvacuationFlowZones
XXL1_BridgesOut_EvacuationRoutes
XXL1_BridgesOut_WalkingSpeeds_Roads
XXL1_BridgesOut_WalkingSpeeds_Trails

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 Astoria and nearby unincorporated communities of 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 XXL tsunami scenario,
- Detailed *Beat the Wave* results for the XXL tsunami scenario, including evacuation routes and minimum walking speeds, and
- *Beat the Wave* results for multiple hypothetical scenarios.

The *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). Model assumptions 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 nearly the entire region examined is achievable at a ***walk*** (4 fps, or 2.7 mph) or faster. This is due to steep terrain creating a very narrow XXL tsunami zone and short evacuation distances as well as long wave arrival times (~40 minutes). Evacuation distances in Jeffers Garden are much longer and present a greater challenge. Evacuees in western Jeffers Garden must travel at a ***fast walk*** (6 fps, or 4.1 mph) to reach safety prior to the arrival of the tsunami. Liquefaction, landslides, and lateral spreading could present additional challenges to evacuation across the region and are not examined in detail.

In this report, tsunami mitigation refers to actions used to improve the survivability of a local 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 refuge, otherwise known as a tsunami vertical evacuation structure.

1.0 INTRODUCTION

The objective of this study is to provide communities with a quantitative assessment of challenges affecting tsunami evacuation in the city of Astoria and nearby communities (**Figure 1-1**) 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 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):

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

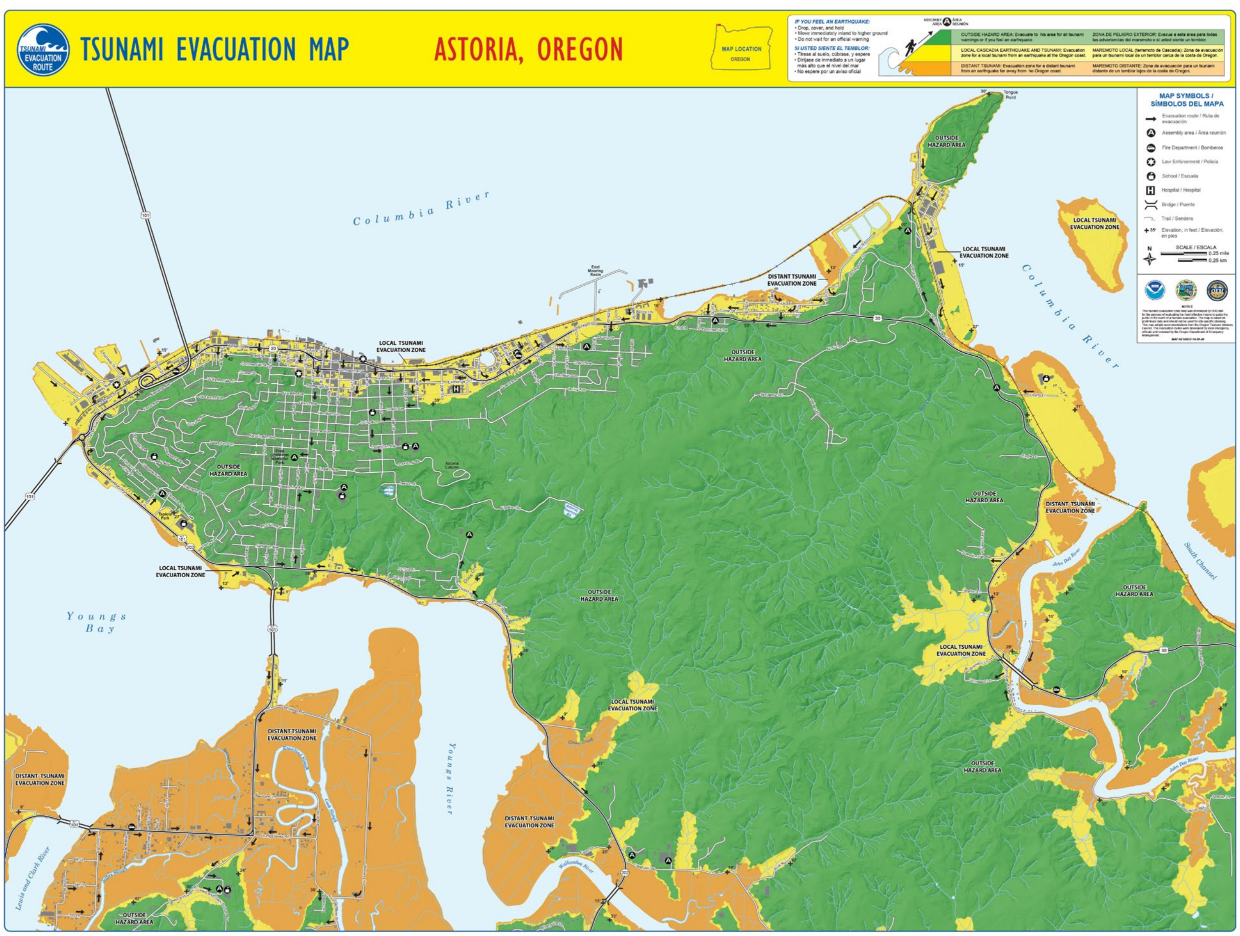
The maximum-considered CSZ tsunami (XXL1, referred to as “XXL” for the remainder of this report) inundates the low-lying sections of Astoria including the entire commercial district as well as nearly all of Jeffers Garden and many of the roads in the region (**Figure 1-1**). Allan and others (2020) report that 23% of permanent residents reside within the XXL tsunami zone in Astoria and 100% in Jeffers Garden. The tsunami enters the Columbia River ~7 minutes after the start of the earthquake and reaches the western edge of Astoria in ~17 minutes. Water levels in the river are only starting to rise at this time, and the streets of western Astoria are not flooded until ~38 minutes after the earthquake. Tongue Point is flooded 10 minutes later, ~48 minutes after the earthquake. Similarly, water levels at the south end of Youngs Bay begin to rise ~30 minutes after the earthquake, however Jeffers Garden is not affected until ~40 minutes.

The tsunami continues up the Columbia tributaries for another hour (Lewis and Clark River, Youngs River, and John Day River). The region will continue to experience tsunami waves for up to 12 hours after the start of earthquake shaking. Additional information on the timing of tsunami wave arrivals as well as inundation along the length of the Columbia River system is described in Allan and others (2018).

A Note about Bridges and Tsunami Evacuation in Astoria and nearby communities

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, Oregon Department of Geology and Mineral Industries (DOGAMI) tsunami evacuation analyses include both “Bridges In” and “Bridges Out” *Beat the Wave* scenario modeling. For the Astoria area, “Bridges In” and “Bridges Out” *Beat the Wave* results are similar so only “Bridges Out” results are included in this report. The Riverwalk is essentially one long bridge (a boardwalk built on pilings for much of its length) that will likely fail in numerous locations due to its age and construction. However, we do not block passage anywhere along its span because determining precisely where is beyond the scope of this study.

Figure 1-1. DOGAMI (2013) tsunami evacuation map for Astoria and Jeffers Garden (community in southwest corner of map). 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 these maps are 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 the different evacuation speeds required to reach safety, considering route characteristics (e.g. flat vs. steep terrain) 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 and the unknowns of traveling off-road (i.e. vegetation, fences, etc). 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: When the wave front of an XXL tsunami reaches each location in the area after the earthquake.
2. *Beat the Wave* results for existing road conditions: Determining how fast an evacuee must move to 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. The pedestrian travel speed needed to reach safety ahead of the wave (e.g., walk, jog, or run) can then be estimated by dividing the least-cost path by the time of wave arrival. 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 existing road data plus 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 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 hypothetical 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 discussion with public 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 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.

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, 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 completely remove an evacuation route, we created hypothetical scenarios to reflect that. 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. If these circumstances are relevant to a community, they 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.

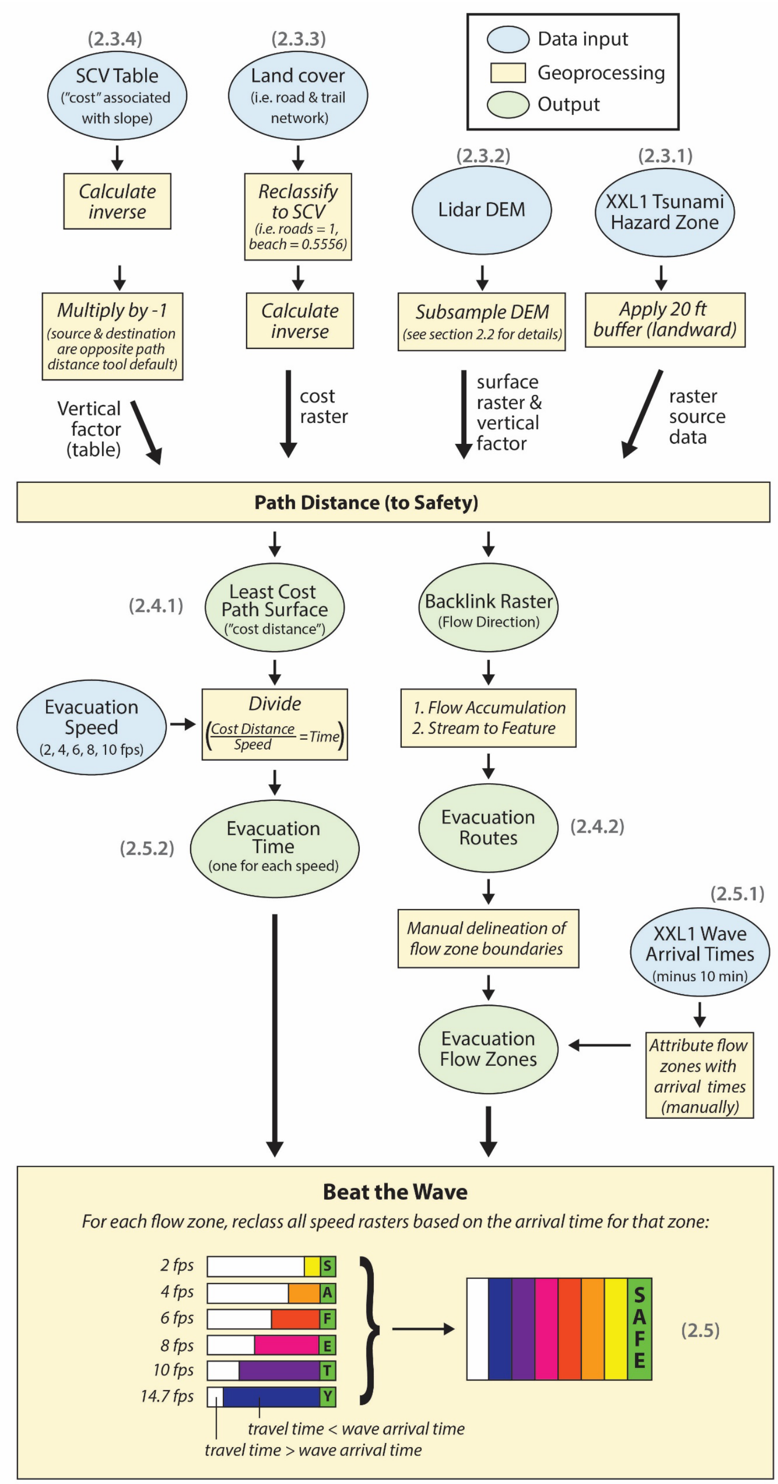
Regardless of infrastructure improvements considered for an area, wayfinding (e.g. signs) and outreach will always be an essential part of local tsunami evacuation planning.

2.3 LCD model inputs

Least-cost distance (LCD) modeling is based on four inputs: the XXL (and 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 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® 10.7 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 meters) 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 *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 (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.

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 meters) 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 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 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.

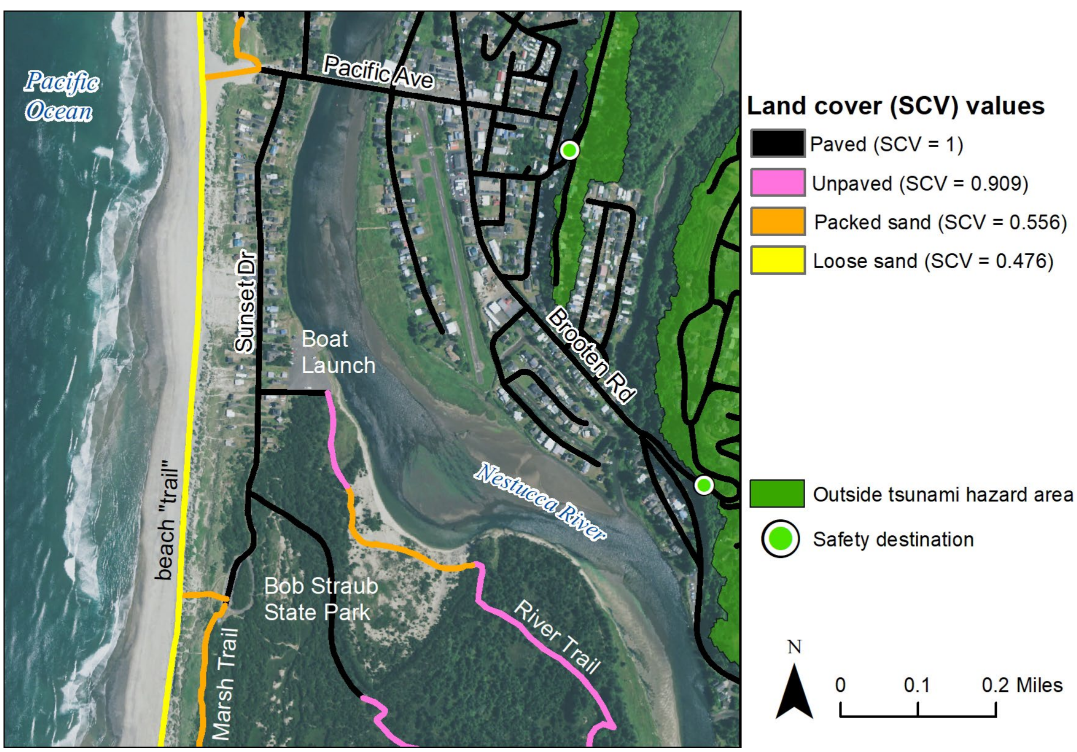
Feature Type	Speed Conservation Value*
Roads (paved surface)	1
Unpaved trails	0.9091
Dune trails (packed sand)	0.5556**
Muddy bog	0.5556
Beaches (loose sand)	0.476
Everywhere else	0

*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 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 (inside the tsunami hazard 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.

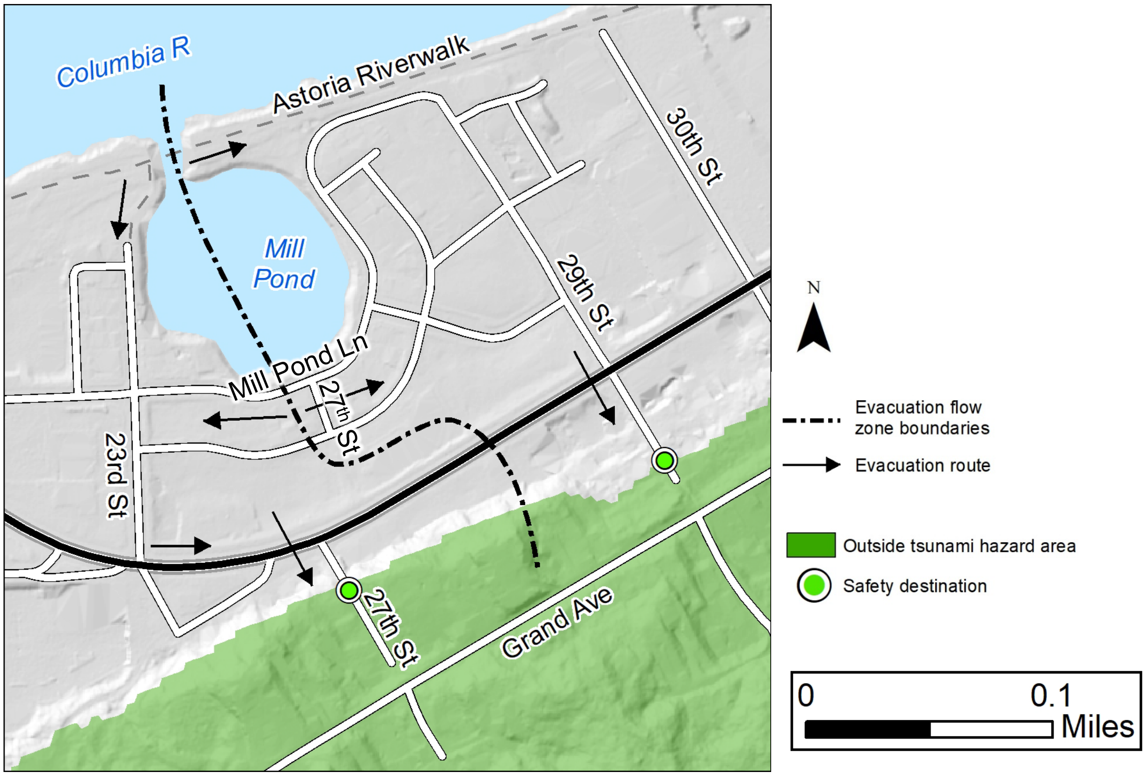
2.4 LCD model outputs

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 *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. For example, from the intersection of Mill Pond Ln and 27th St (**Figure 2-4**), the actual distance to safety up 29th St is 1,140 feet, while the least-cost path distance is 1,400 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 29th St).

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 Astoria. 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 the east end of Mill Pond Ln is 29th St, while the nearest safety destination for people on the west end of Mill Pond Ln is 27th St. 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 emergency managers and 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 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.

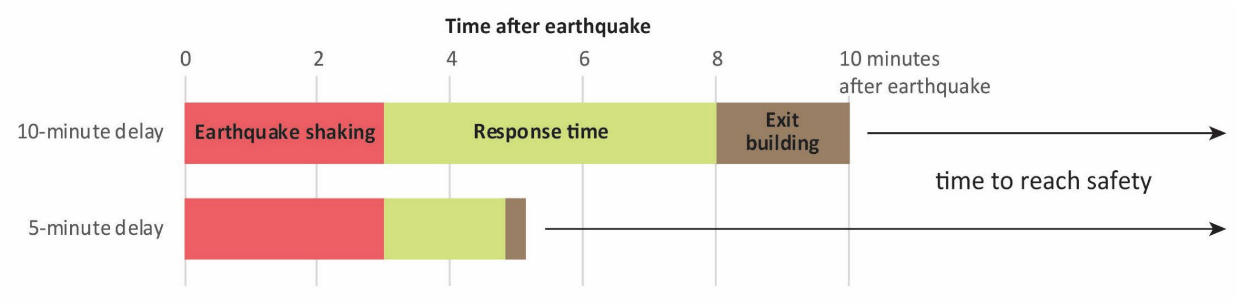
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted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

- the time in which earthquake shaking takes place,
- disorientation and shock, 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 L 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, 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.



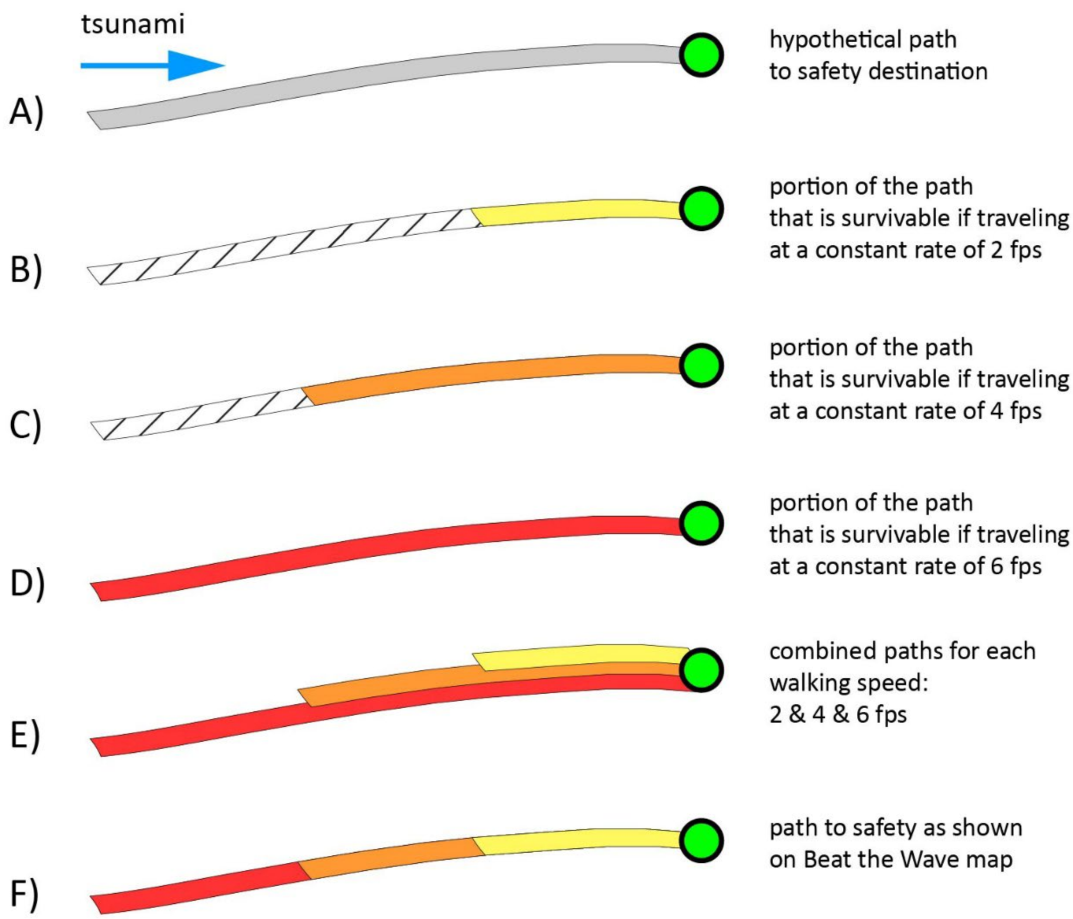
2.5.2 Evacuation time maps

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 used for calculating curb to curb crossing light times 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 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 farther away from safety (green dot) evacuees begin the route, the faster they must walk to survive (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 *Beat the Wave* map showing 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 *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 ≤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 ***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, when traveling at speeds below what is prescribed by *Beat the Wave*, safety may not reached in time and the tsunami could overrun the individual. This limited test of *Beat the Wave* data suggests that the data are reasonable guides to <u>minimum</u> evacuation speeds necessary to reach safety ahead of the tsunami.

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

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

2.5.3 Reading a *Beat the Wave* map

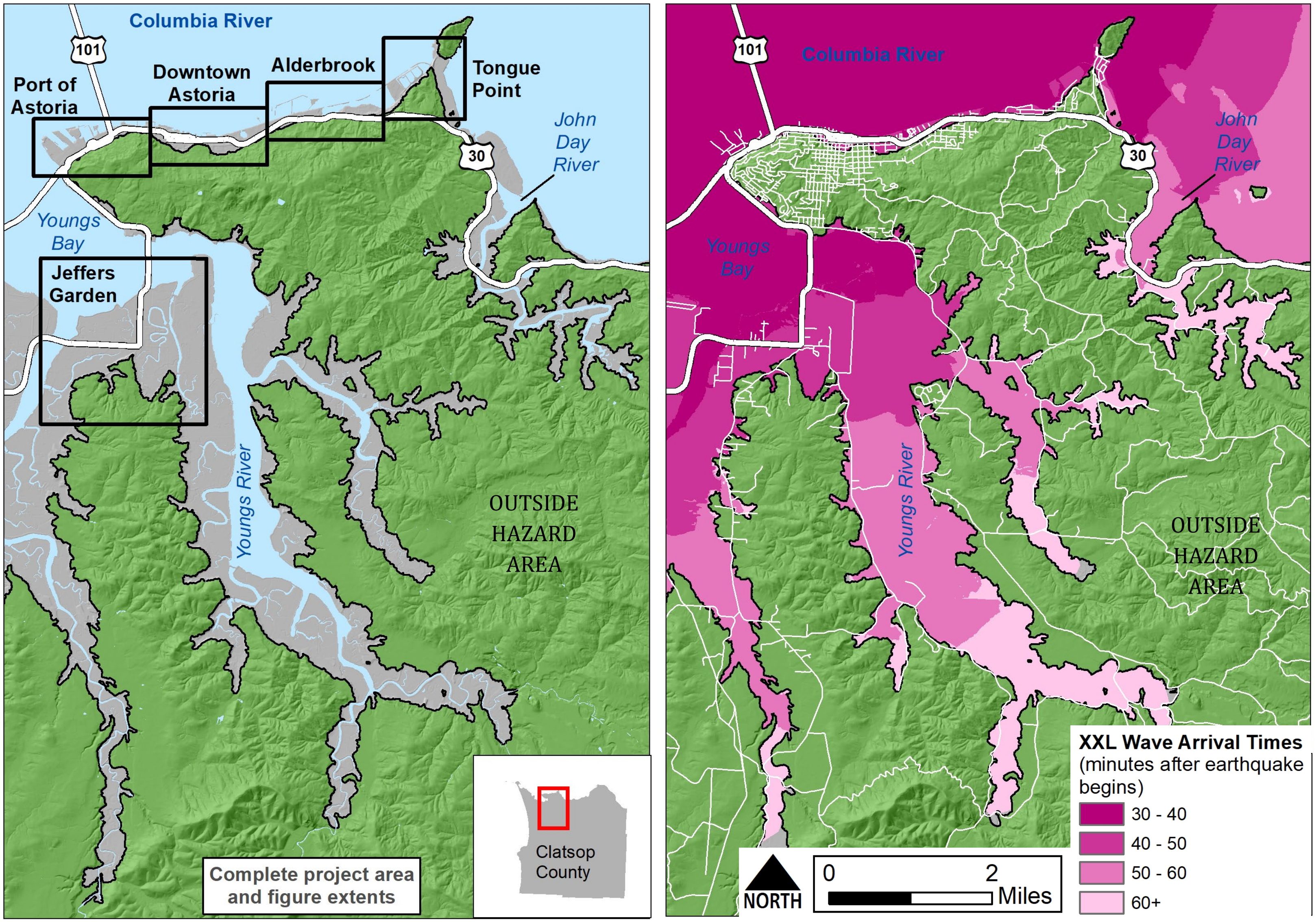
The *Beat the Wave* modeling approach produces ***minimum*** evacuation speeds that must be **maintained** from a particular starting location along the entire route to safety. If an evacuee slows down for some portion of the route, the evacuee must account for the time deficit by traveling faster than 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 Astoria and the unincorporated community of Jeffers Garden (**Figure 3-1**, **left**). Astoria is divided into 4 panels (Port of Astoria, Downtown, Alderbrook, and Tongue Point) and results will be discussed separately for each. Digital data are also provided for the surrounding lower Columbia River estuary roadways, which are concentrated along the Lewis and Clark, Youngs, and John Day Rivers. Due to their distance upriver and proximity to high ground, our evacuation modeling indicates that survivability is very high for these areas, such that no further discussion is included in this report.

Figure 3-1, **right** shows the arrival times for an XXL tsunami in the Astoria project area. Water levels begin to rise ~20-30 minutes after the start of earthquake shaking, however the streets of Astoria and Jeffers Garden are not flooded until ~38-48 minutes. The XXL tsunami is detectable upriver as far as the confluence of the Columbia and Willamette Rivers, where it arrives 4 hours and 40 minutes after the start of earthquake shaking (Allan and others, 2018). The tsunami travels up the Lewis and Clark, Youngs, and John Day Rivers approximately 2-3 miles, reaching its farthest upriver extents ~1.5-2 hours after the earthquake. Additional waves will continue to enter the Columbia River estuaries, causing water levels to fluctuate for up to 12 hours after the earthquake. Tsunami wave arrival time data are found in the Astoria_Tsunami_Evacuation_Modeling geodatabase.

Figure 3-1. (left) Astoria project area map. Results will be discussed separately for each panel. *Beat the Wave* was performed on the entire extent shown and is included in the digital data. (right) Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for the region.



We first present the "current-conditions" 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. These results represent the "current-conditions" were evacuation to occur today. Due to ease of safe evacuation under current-conditions, we only considered hypothetical scenarios representing various improvements for the Port of Astoria and Jeffers Garden neighborhoods. For the former, we examine the changes to evacuation speeds and routes if the Megler Bridge and on-ramp do not collapse during earthquake shaking. In Jeffers Garden, we explore a hypothetical evacuation trail across Jeffers Slough to shorten the distance to safety and consider the improvements that come from leaving sooner (by reducing the evacuation delay from the standard 10-minutes to 5-minutes).

A liquefaction scenario that assumes roads and trails are significantly more difficult to walk on is considered for all neighborhoods. As discussed in section 2.2, liquefaction is a very site-specific hazard associated with earthquake shaking. Because we do not have the ability to predict precisely where liquefaction will occur, we present a conservative view of its effects guided by knowledge of the liquefaction potential (a function of the underlying geology and water table) along those streets that have a moderate or high liquefaction susceptibility. This entails modeling paved roads as if they were made of loose sand. This approach simulates the difficulty evacuees could encounter when trying to evacuate across roads covered with sand and mud produced from sand boils and other liquefaction features. We recognize that liquefaction potential will be spatially variable throughout the region. We present these results merely to demonstrate that any impediments to immediate and swift evacuation will affect survivability.

While we do not know the precise probability or spatial distribution associated with landslides occurring during a CSZ earthquake, many will undoubtedly occur during earthquake shaking, potentially blocking evacuation routes. In general, we expect that landslide activity will make evacuation difficult in some areas but not impossible. A *Beat the Wave* landslide scenario involves removing a specific route and observing how evacuation speeds and/or routes are altered. We consider a landslide scenario that removes all safety destinations coinciding with historic landslide deposits using the Statewide Landslide Information Database for Oregon (SLIDO, version 4.2, Franczyk and others, 2019). This scenario impacts three of the Astoria neighborhoods where landslide deposits blanket the hills at the edge of the tsunami zone. Research to understand the relationship between landslides and subduction zone earthquakes is ongoing. For more information, see Burns and others (2017) and Schulz and others (2012).

Astoria is also susceptible to lateral spreading along its entire Columbia River shoreline where many sections of road and the Riverwalk are built on fill or pilings and are essentially unsupported on the side of the river. Lateral spreading can result in major failures to road infrastructure as the road slumps toward the river. We did not consider a scenario that blocked sections of road or the Riverwalk because we do not know precisely where this phenomenon might occur. We present simplified landslide and liquefaction scenarios and acknowledge lateral spreading to demonstrate that additional impediments to immediate and swift evacuation may occur that are not fully addressed in this study and mitigation options should be evaluated.

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 most of the region, 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). The western side of Jeffers Garden requires a ***fast walk*** (6 fps, or 4.1 mph). The ease of safe evacuation in the Astoria area is due to the extra time available for evacuation because the tsunami must travel more than 8 miles up the Columbia River as well as the steep terrain which results in narrow inundation zones and short evacuation routes.

While it is reassuring that there are almost no bridges or other key infrastructure that could compromise pedestrian evacuation, the significant landslide risk may compromise evacuation on any number of routes. Investigations into earthquake-induced landslides will be an invaluable tool in further improving evacuation potential in Astoria. Thankfully, narrow inundation zones and long tsunami arrival times mean people have longer to evaluate their route options, including going off-road. Despite the overall positive evacuation outlook in Astoria, clear 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 rapidly toward high ground to ensure they reach safety.***

3.1 Port of Astoria

The western edge of Astoria is bounded by Youngs Bay to the west, Columbia River to the north, and high hills within the interior. The inundation zone is restricted to the low-lying commercial areas and largely avoids residential neighborhoods. The inundated area includes a large Port facility containing numerous commercial enterprises including commercial fishing, timber, cruise ship docks, and a recreational marina. There are also numerous hotels and restaurants as well as the Astoria Riverwalk, a popular pedestrian-only path extending along the entire Columbia River shoreline. Astoria Fire Engine Station No. 2 and Oregon State Police are inside the tsunami zone as is the on-ramp and southern end of the Highway 101 bridge over the Columbia River (Megler Bridge). Because the inundation zone contains all of the commercial business and tourism areas and predominantly excludes residential areas, the visitor population is going to be especially hard hit. Their challenge will be compounded by a probable lack of knowledge about geological hazards and local geography.

Concerns in this area include the failure of the Megler Bridge and on-ramp during earthquake shaking, liquefaction, lateral spreading, and landslides. We investigate bridge failure, liquefaction and landslides through hypothetical *Beat The Wave* scenarios. Lateral spreading is beyond the scope of this study but will also present a significant challenge for the area.

Detailed XXL tsunami wave arrivals are presented in **Figure 3-2.** The tsunami reaches the Columbia River just west of Astoria ~30 minutes after the start of earthquake shaking. It takes another ~14 minutes for water levels to rise high enough to start affecting roads and trails and then another ~3 minutes for the XXL tsunami zone to be fully inundated. It takes the tsunami ~3 additional minutes to continue upriver past the Port to the east end of this section of Astoria (3rd St). It is notable that despite the long time for the wave to get to Astoria, town is inundated very quickly.

Figure 3-3, top presents minimum travel speeds required to reach safety assuming the existing road network remains intact. Virtually the entire area can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. The lone exception to this Marine Dr between the Megler Bridge and where the on-ramp crosses over it. This 1,500-foot stretch of road as well as 700 feet of the Riverwalk west of the bridge see their evacuation speed increase to ***walk*** (4 fps, or 2.7 mph). Evacuation flow zones for the current condition scenario are presented in **Figure 3-3, bottom**. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. Everyone west of the Megler Bridge evacuates to Hamburg Ave (red polygon), a residential street off Marine Dr on the western side of town. Because of the high density of safety destinations east of the Megler Bridge, we simplified evacuation zones by merging multiple safety destinations into single zones (yellow, teal, and brown polygons).

Current condition results demonstrate an additional challenge (albeit a small one) for those trapped by fallen bridge material. **Figure 3-4, top** demonstrates the potential reduction in evacuation speeds if the bridge and on-ramp are retrofitted to survive the earthquake shaking. In this scenario, the entire region can reach high ground at a ***slow walk***.

Liquefaction *Beat the Wave* results demonstrate slightly faster evacuation speeds required to reach high ground for the Port and the region compromised by fallen Megler Bridge material (**Figure 3-4, bottom**). The Port area increases to ***walk*** and the stretch of Marine Dr and Riverwalk increases to ***fast walk*** (6 fps, or 4.1 mph).

As shown in **Figure 3-5, top**, every safety destination in western Astoria overlays terrain likely to have experienced landslide activity at some point in the geologic past. Three of those roads (Flavel St, Hume Ave, and W Bond St) sit on terrain that has probably moved more recently (within the last 150 years). It is well documented that this area has in fact experienced numerous slides in the past 80 years including one this past winter on Alameda St. In other words, there is a distinct possibility that earthquake shaking will make it difficult to walk out of the inundation zone using the existing road network. **Figure 3-5**, **bottom** presents a *Beat The Wave* scenario where the three safety destinations previously identified are removed from the road network, forcing the area east of the Megler Bridge to travel slightly further west, to Columbia Ave. Evacuation speeds remain unchanged at a ***slow walk***, however, because the total distance to safety does not increase enough in relation to the long wave arrival time (42 minutes). While the positive outlook presented in this scenario suggests that landslides will not significantly challenge evacuation, landslide activity will undoubtedly make travel more difficult in some areas and people may need to travel off-road to get out of the tsunami zone.

Figure 3-2. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for the Port of Astoria neighborhood.

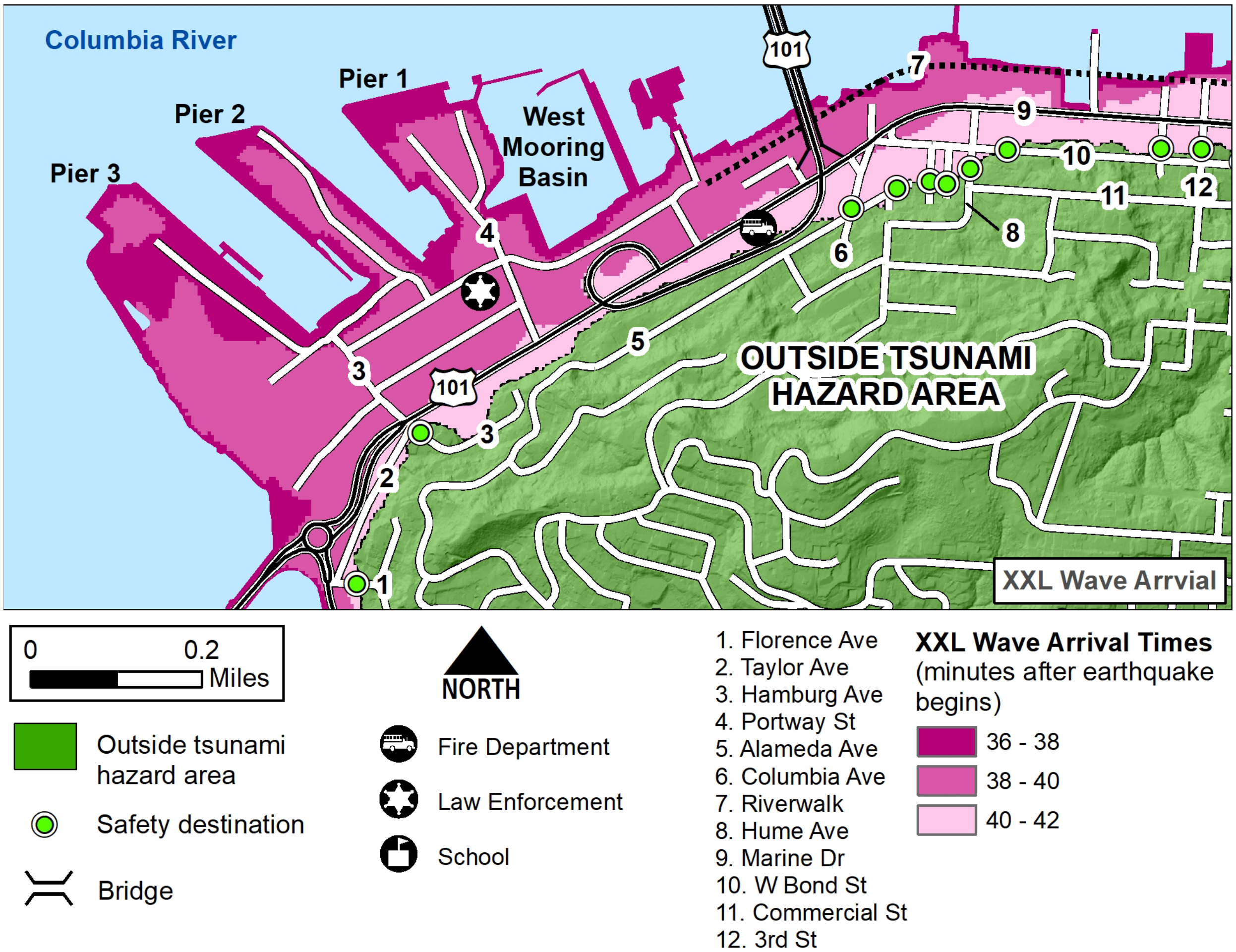


Figure 3-3. *Beat the Wave* modeling in the Port of Astoria neighborhood for the XXL current-conditions scenario depicting the existing road and trail network and assuming all bridges fail (except the Riverwalk). (top) *Beat the Wave* evacuation speeds and flow zones. Colors on top of roads reflect minimum 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.

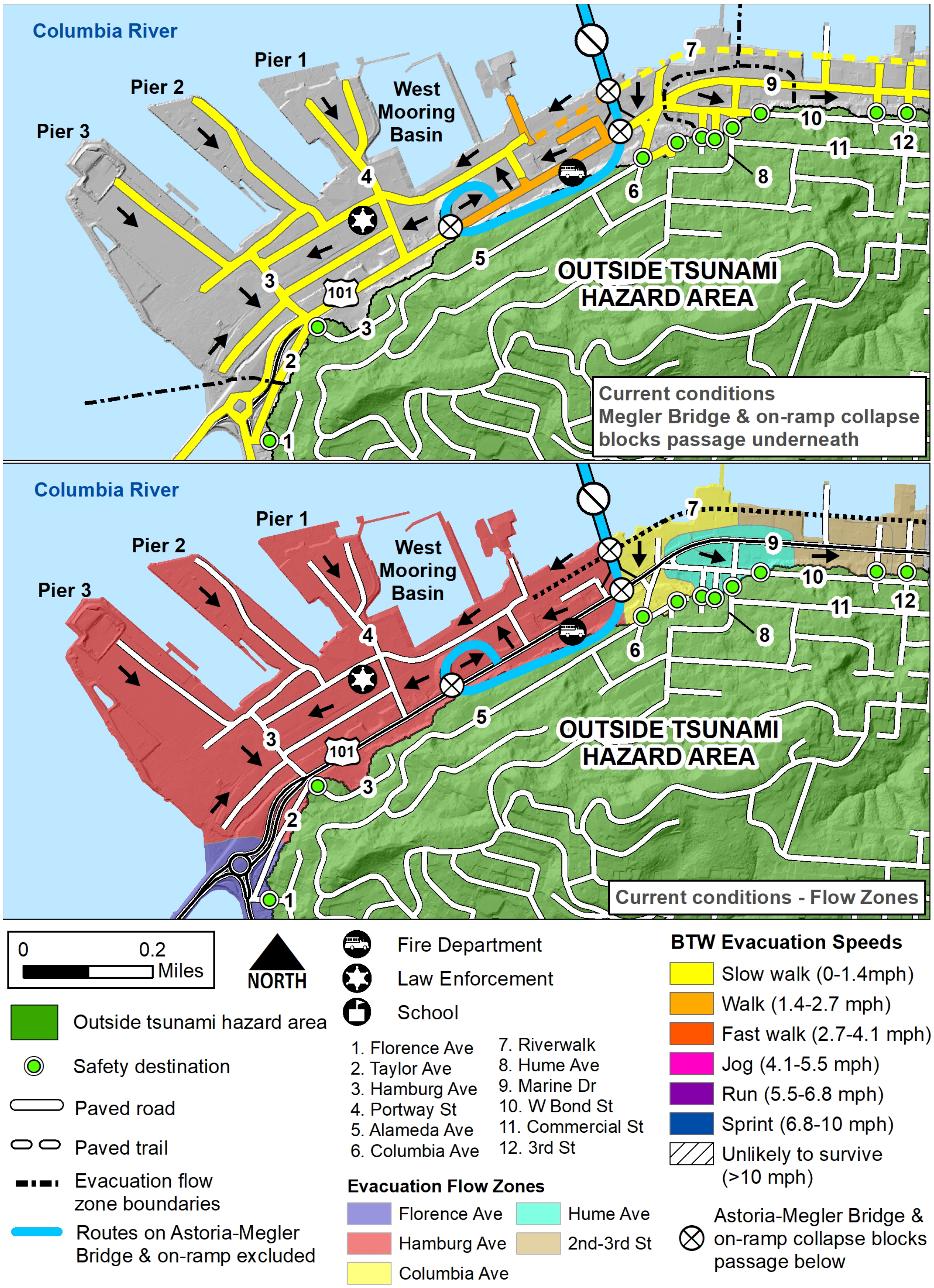


Figure 3-4. ***Beat the Wave*** **modeling in the Port of Astoria neighborhood (top) for a hypothetical seismic retrofit of the Megler Bridge and on-ramp that ensures evacuation routes underneath are accessible, and (bottom) for a liquefaction scenario where roads and trails are significantly more difficult to walk on (using current road conditions). All roads inside the XXL inundation zone are classified as having moderate to high liquefaction susceptibility (Madin and Burns, 2013).**

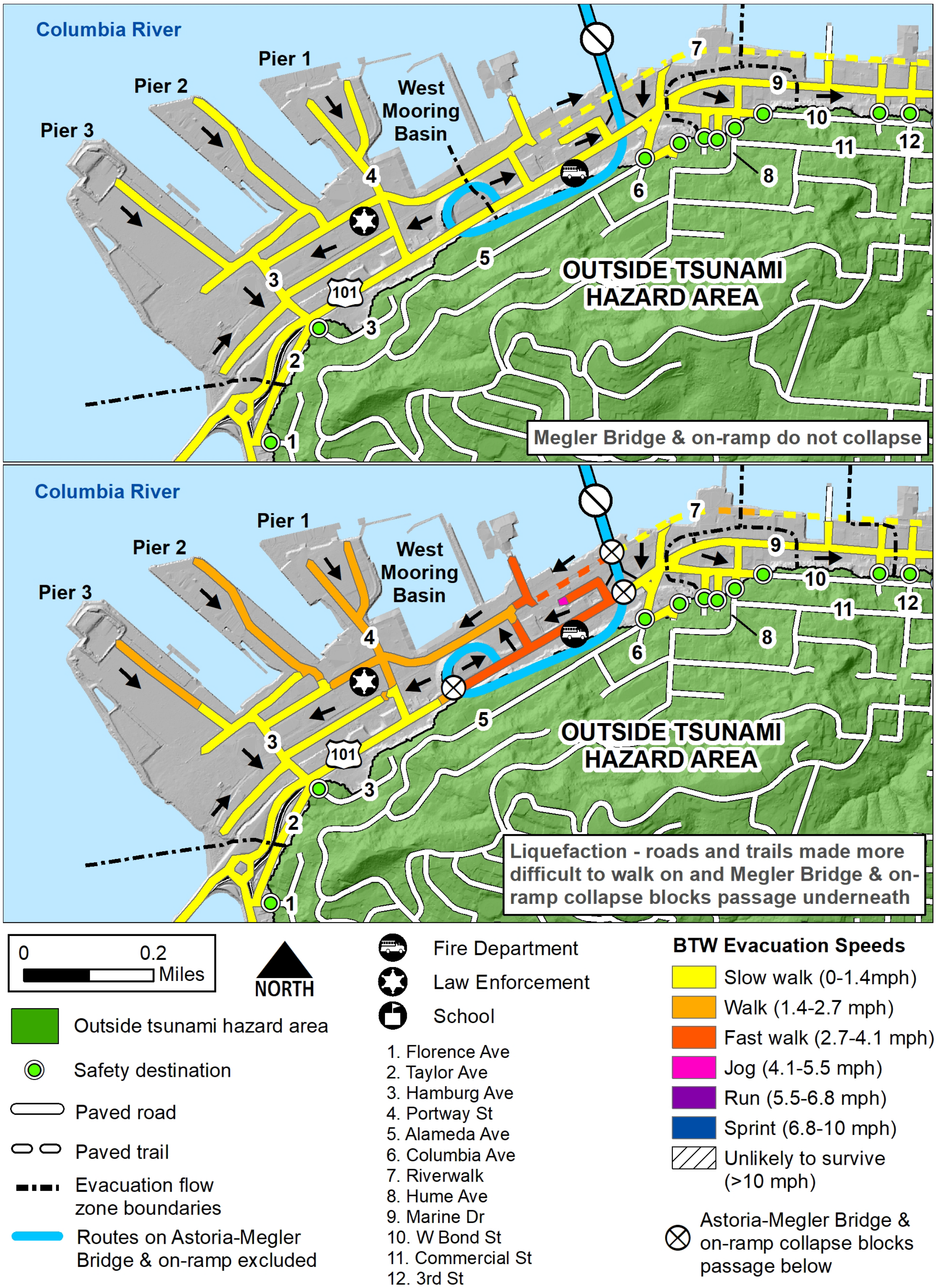
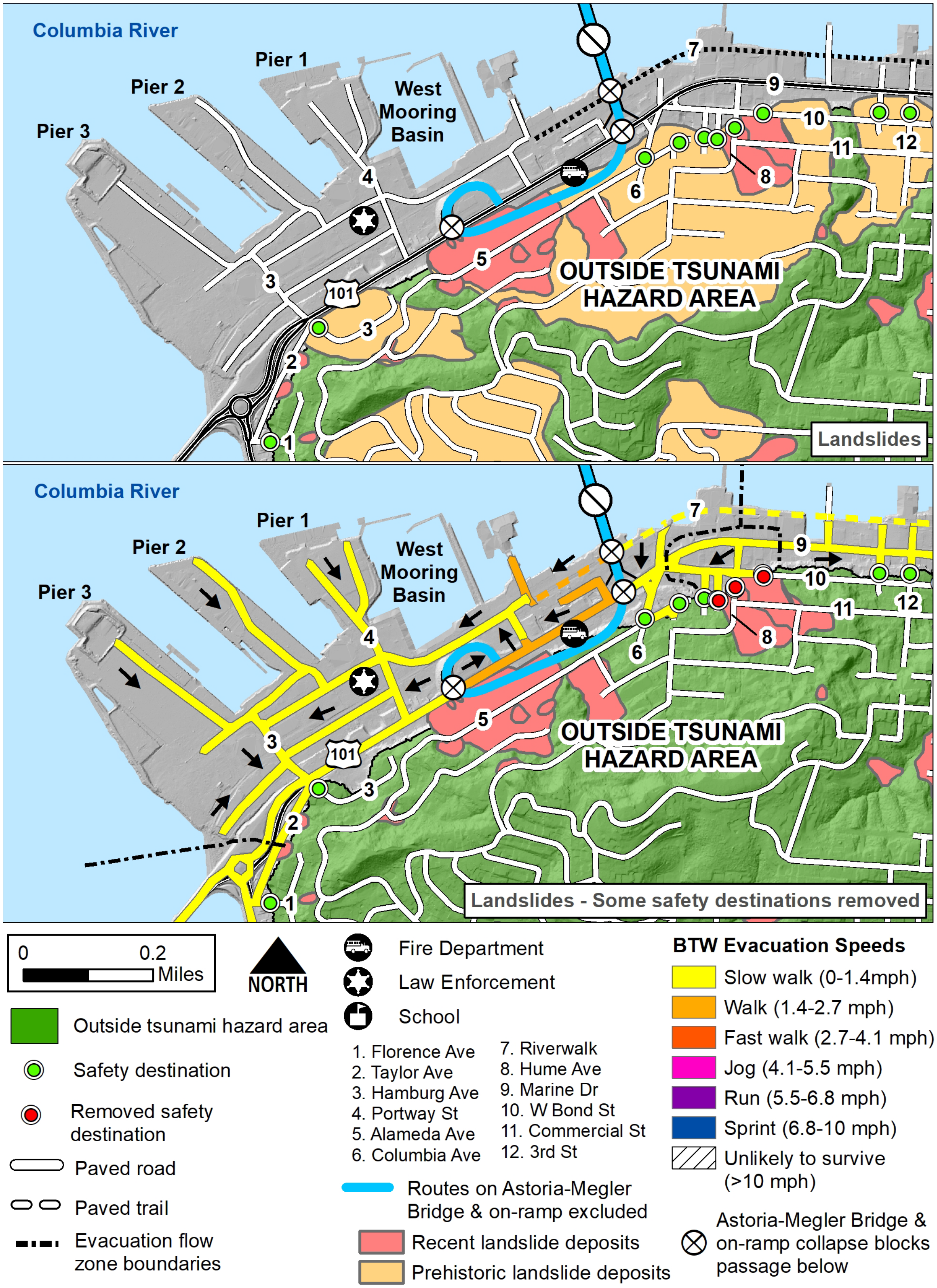


Figure 3-5. (top) Mapped landslides (SLIDO 4.2, Franczyk and others, 2019) in the Port of Astoria neighborhood. (bottom) *Beat the Wave* modeling in the Port of Astoria neighborhood for a hypothetical landslide scenario that removes safety destinations overlapping recent landslide deposits.



3.2 Downtown

The downtown Astoria neighborhood continues east, from 4th St to 31st St, with the Columbia River to the north and steep hills to the south. The inundation zone is relatively narrow (1,000 feet at its widest), however it encompasses virtually the entire commercial corridor including numerous restaurants, hotels, stores, and other tourist destinations such as the Columbia River Maritime Museum and the Riverwalk. Columbia Memorial Hospital, the Astoria Fire Department Headquarters, and the US Coast Guard are also inside the XXL tsunami zone. As with the Port of Astoria neighborhood, the inundation zone excludes most residential streets.

Evacuation concerns in this area were limited to liquefaction and landslides; there is no need to consider hypothetical improvements due to the positive evacuation outlook, nor are there any key pieces of infrastructure that could significantly compromise evacuation. Lateral spreading is beyond the scope of this study but will also present a significant challenge for the area.

Detailed XXL wave arrivals are presented in **Figure 3-6**. The tsunami continues up the Columbia River, with water levels rising to an elevation that will impact roads and people ~40 minutes after the start of earthquake shaking. **Figure 3-7, top** presents minimum travel speeds required to reach safety assuming the existing road network remains intact. Anyone in this entire area can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. This is due to short evacuation distances and long wave arrivals. Evacuation flow zones for the current condition scenario are presented in **Figure 3-7, bottom**. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. The western half of this region, from 4th St to 17th St, has a safety destination on every North-South street, meaning a person can walk south on any of the numbered streets in this area and reach their nearest high ground. To simplify the map, we merged evacuation zones in this area (pink polygon). The hospital sits right on a boundary between two evacuation flow zones, meaning it is equally suitable to head west on Exchange St to 17th St (brown polygon) or east on Exchange St to 27th St (blue polygon). Evacuation on north-south trending roads continues in the east, with safety destinations on 29th St (orange polygon) and 31st St (yellow polygon).

Liquefaction *Beat the Wave* results are virtually unchanged from the current-conditions scenario (**Figure 3-8**). This is due to the short distances to high ground and large amount of time available to get there.

As shown in **Figure 3-9, top**, all but a few safety destinations in downtown Astoria overlay terrain likely to have experienced landslide activity at some point in the geologic past. Six of those roads sit on terrain that has probably moved more recently (within the last 150 years); five of them (7th, 8th, 9th, 10th, and Exchange Sts) are on a well-documented active landslide. As with western Astoria, there is a distinct possibility that earthquake shaking will make it difficult to walk out of the inundation zone using the existing road network. **Figure 3-9**, **bottom** presents a *Beat The Wave* scenario where the five safety destinations previously identified (as well as 31st St in the east) are removed. Evacuation speeds remain unchanged at a ***slow walk***, however, because the total distance to safety does not increase enough in relation to the long wave arrival time (44 minutes). While the positive outlook presented in this scenario suggests that landslides will not significantly challenge evacuation, landslide activity will undoubtedly make travel more difficult in some areas and people may need to travel off-road to get out of the tsunami zone.

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

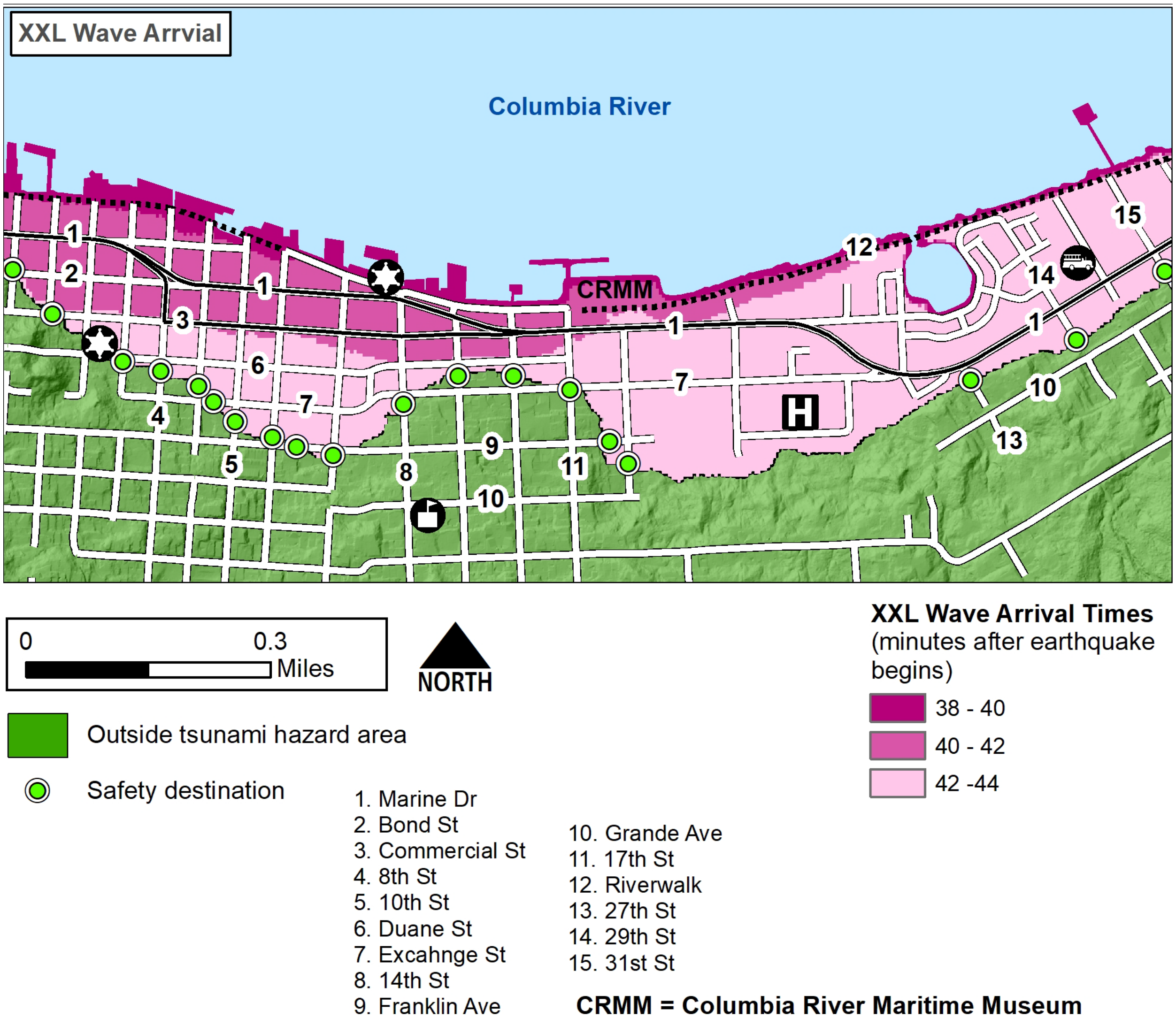


Figure 3-7. *Beat the Wave* modeling in Downtown Astoria for the XXL current-conditions scenario depicting the existing road and trail network. (top) *Beat the Wave* evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (bottom) Evacuation flow zones displayed as colored polygons.

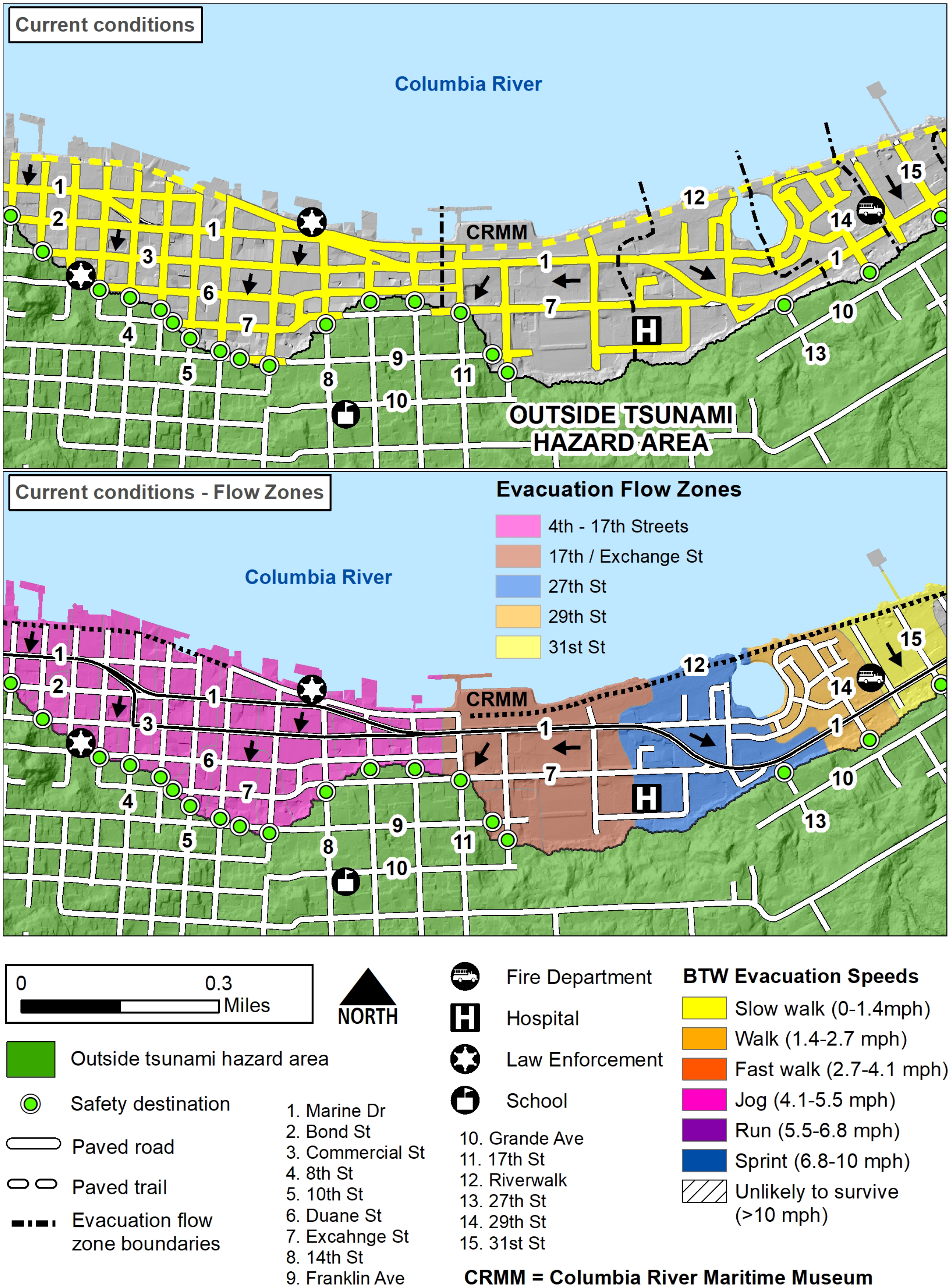


Figure 3-8. ***Beat the Wave*** **modeling in Downtown Astoria for a liquefaction scenario where roads and trails are significantly more difficult to walk on. All roads inside the XXL inundation zone are classified as having moderate to high liquefaction susceptibility (Madin and Burns, 2013).**

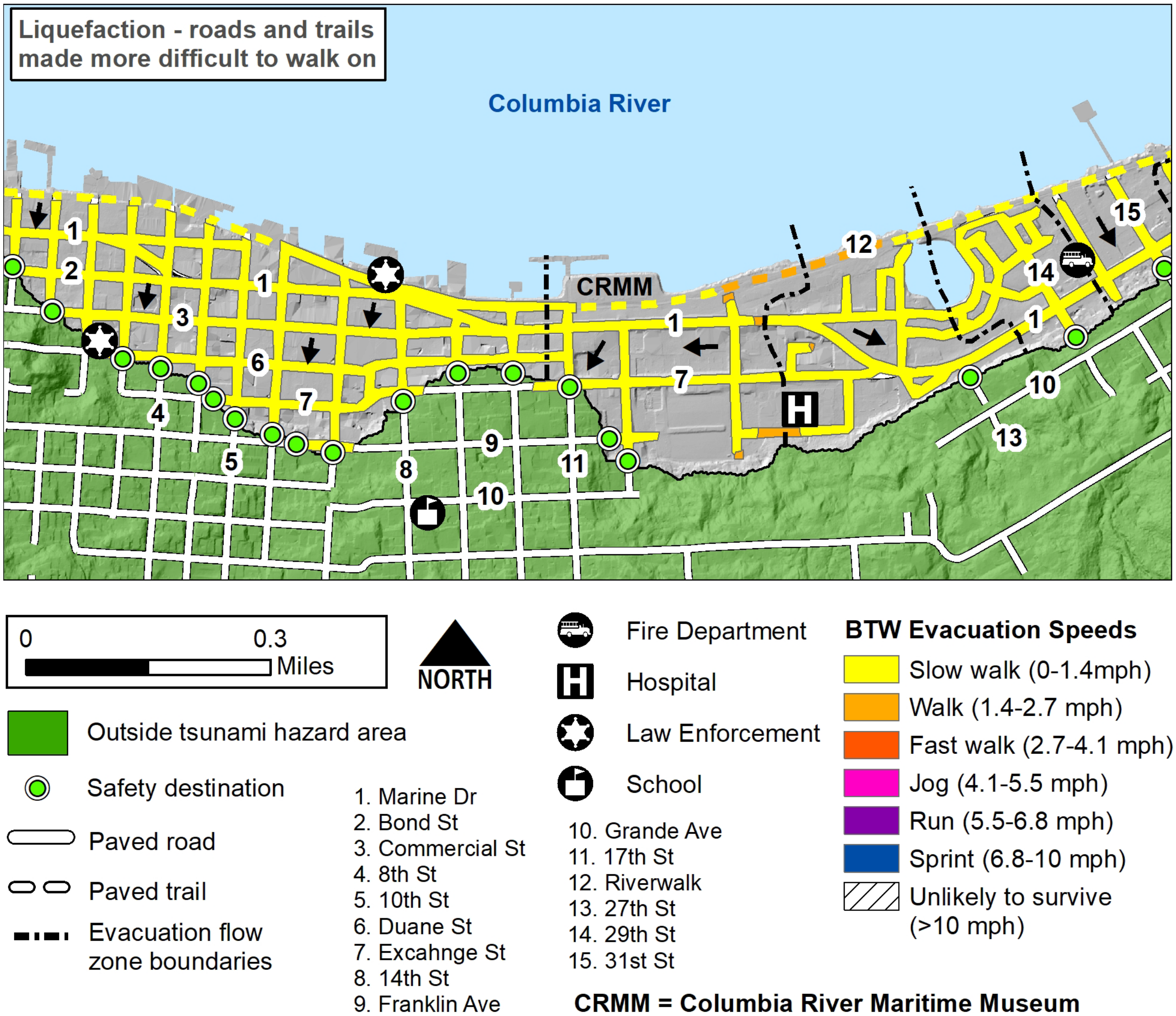
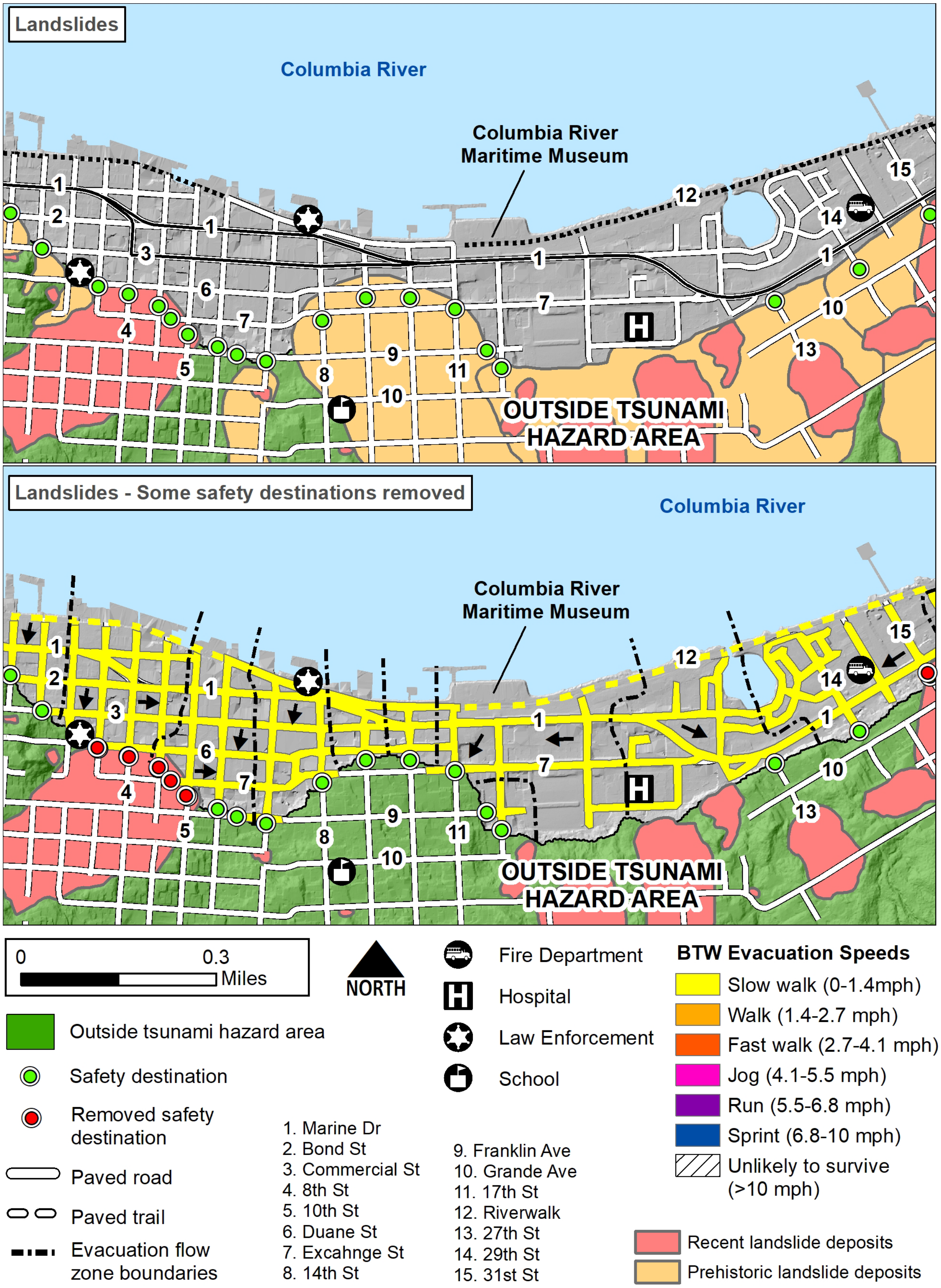


Figure 3-9. (top) Mapped landslides (SLIDO 4.2) in Downtown Astoria. (bottom) *Beat the Wave* modeling in Downtown Astoria for a hypothetical landslide scenario that removes safety destinations overlapping recent landslide deposits.



3.3 Alderbrook

East of downtown, the Alderbrook neighborhood sees the end of the commercial district as well as a narrowing of the inundation zone. The affected strip of land extends from Highway 30 to the Riverwalk and includes several hotels, Pier 39, the Riverwalk, and the Alderbrook residential neighborhood. The Riverwalk is supported by pilings all along the city shoreline, however here it truly crosses over water as opposed to sitting adjacent to solid ground. As with all other historic piling-supported docks in the area, we did not model *Beat The Wave* on these paths due to the uncertainty around whether they will remain standing after the earthquake.

Evacuation concerns in this area were limited to liquefaction and landslides; there is no need to consider hypothetical improvements due to the positive evacuation outlook, nor are there any key pieces of infrastructure that could significantly compromise evacuation. Lateral spreading is beyond the scope of this study but will also present a significant challenge for the area.

Detailed XXL wave arrivals are presented in **Figure 3-10**. The tsunami continues up the Columbia River, with water levels rising to an elevation that will impact roads and people ~43 minutes after the start of earthquake shaking. **Figure 3-11, top** presents minimum travel speeds required to reach safety assuming the existing road network remains intact. Virtually the entire area can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. Evacuation flow zones for the current-conditions scenario are presented in **Figure 3-11, bottom**. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. Much like the rest of Astoria, virtually every street heading south off Highway 30/Marine Dr reaches high ground. Unlike farther west, however, the density of streets drops. The western edge of this area evacuates to 33rd St and Franklin Ave (purple polygon), East Mooring Basin and Pier 39 evacuate to 37th St (teal polygon), the western half of the Alderbrook neighborhood evacuates to 45th St (yellow polygon) and the eastern half to 51st St (blue polygon).

Liquefaction *Beat the Wave* results are virtually unchanged from the current-conditions scenario (**Figure 3-12**). This is due to the short distances to high ground and large amount of time available to get there.

As shown in **Figure 3-13, top**, all but one safety destination in the Alderbrook area overlay terrain likely to have experienced landslide activity at some point in the geologic past. Two of those roads (33rd St and Franklin Ave) sit on terrain that has probably moved more recently (within the last 150 years). In other words, there is a distinct possibility that earthquake shaking will make it difficult to walk out of the inundation zone using the existing road network. Numerous landslides have plagued the region in recent years, further reinforcing the likelihood of road failures after a magnitude 9 earthquake. **Figure 3-13, bottom** presents a *Beat The Wave* scenario where the two safety destinations previously identified are removed from the road network. Evacuation speeds remain unchanged at a ***slow walk***, however, because the total distance to safety does not increase enough in relation to the long wave arrival time (46 minutes). While the positive outlook presented in this scenario suggests that landslides will not significantly challenge evacuation, landslide activity will undoubtedly make travel more difficult in some areas and people may need to travel off-road to get out of the tsunami zone.

Figure 3-10. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for the Alderbrook neighborhood.

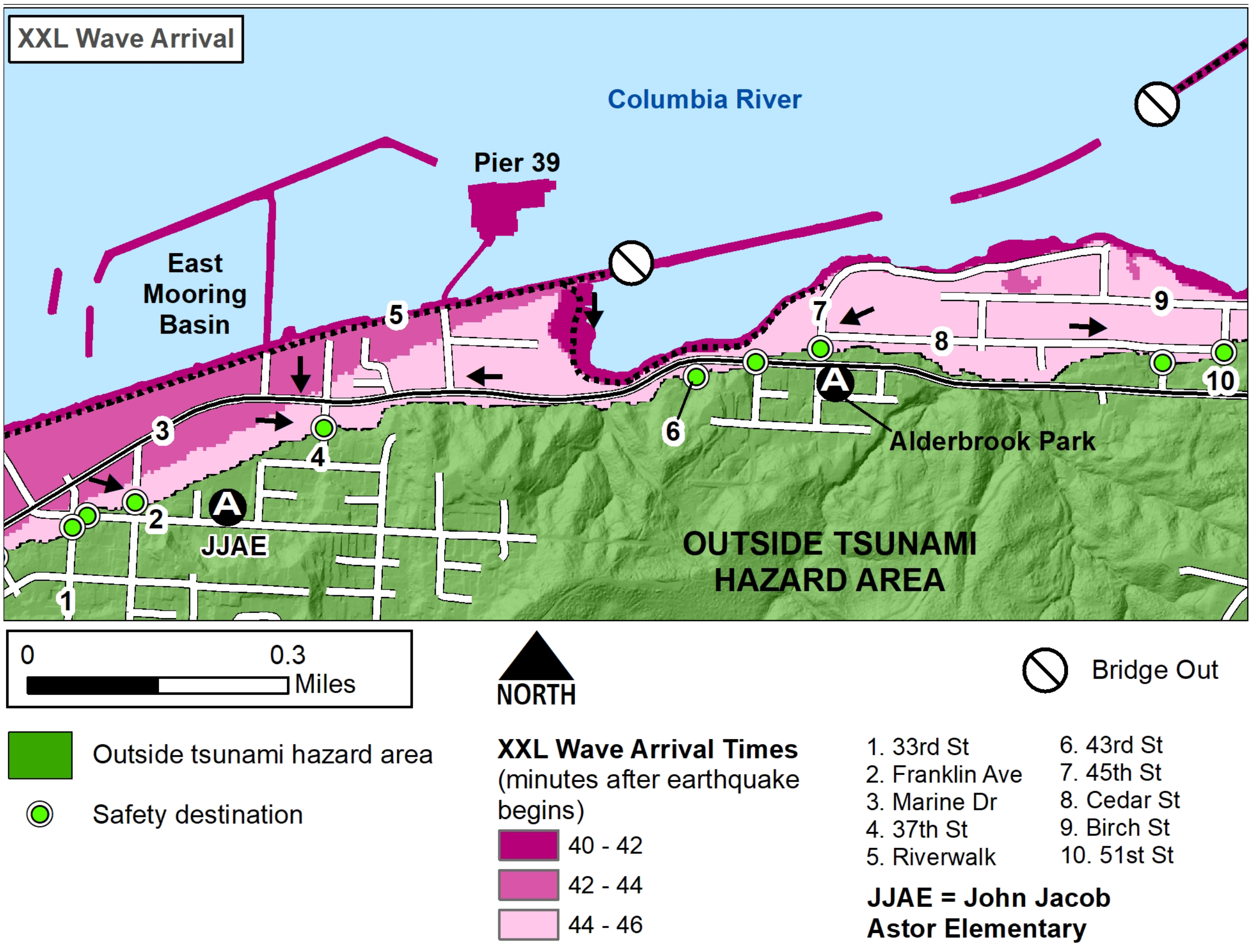


Figure 3-11. *Beat the Wave* modeling in the Alderbrook neighborhood for the XXL current-conditions scenario depicting the existing road and trail network. (top) *Beat the Wave* evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route.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

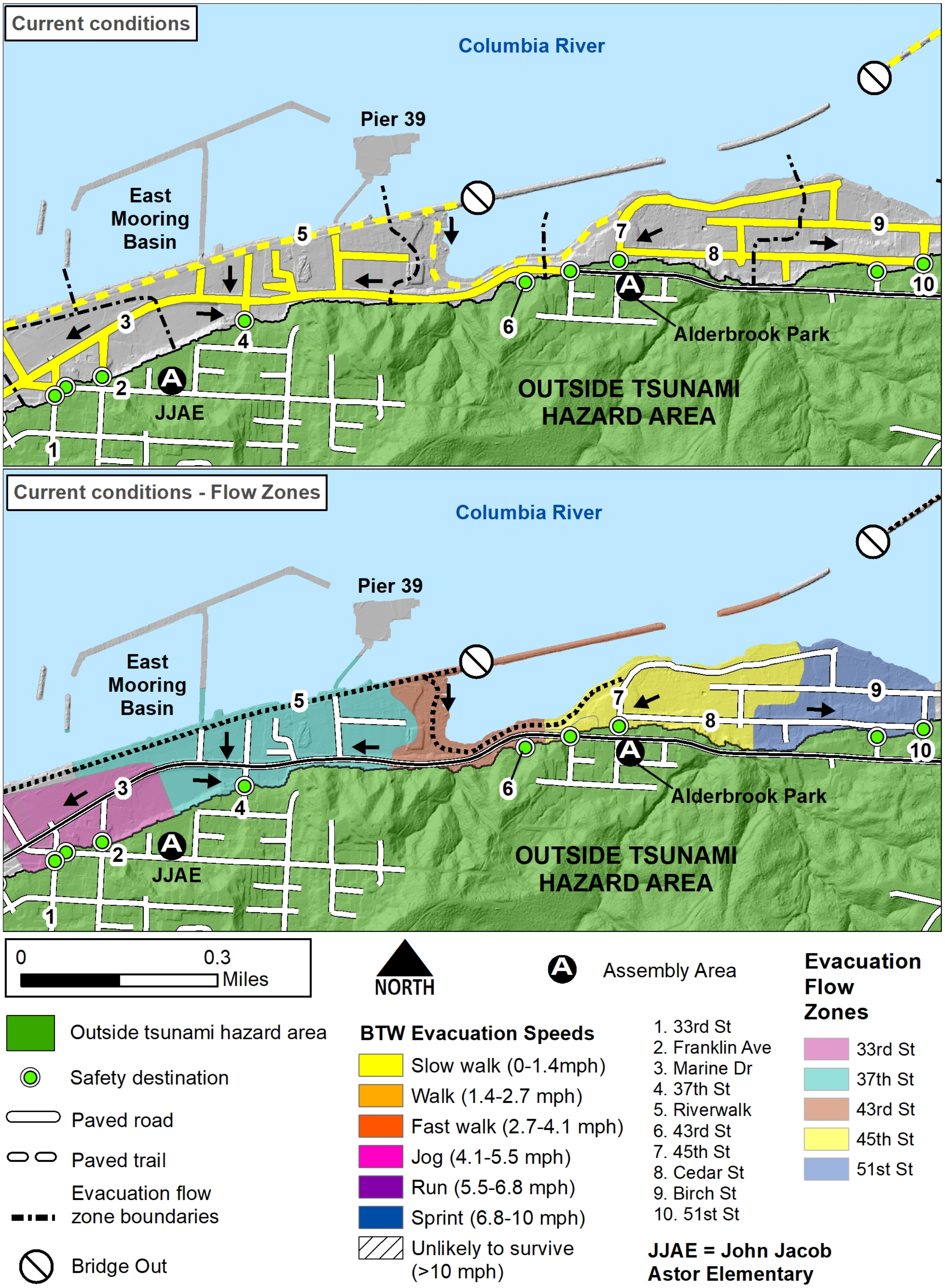


Figure 3-12. ***Beat the wave*** **modeling in the Alderbrook neighborhood for a liquefaction scenario where roads and trails are significantly more difficult to walk on. All roads inside the XXL inundation zone are classified as having moderate to high liquefaction susceptibility (Madin and Burns, 2013).**

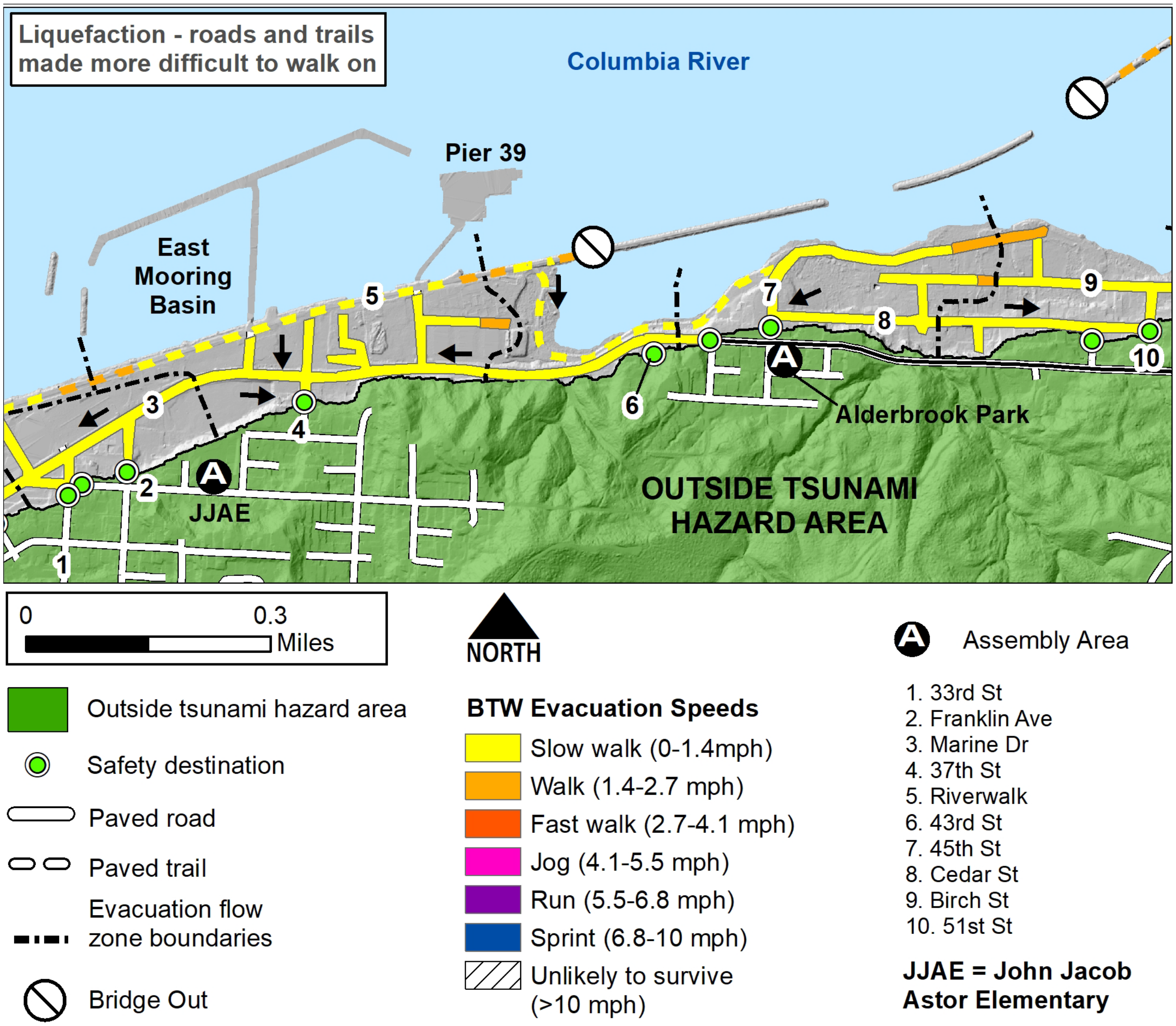
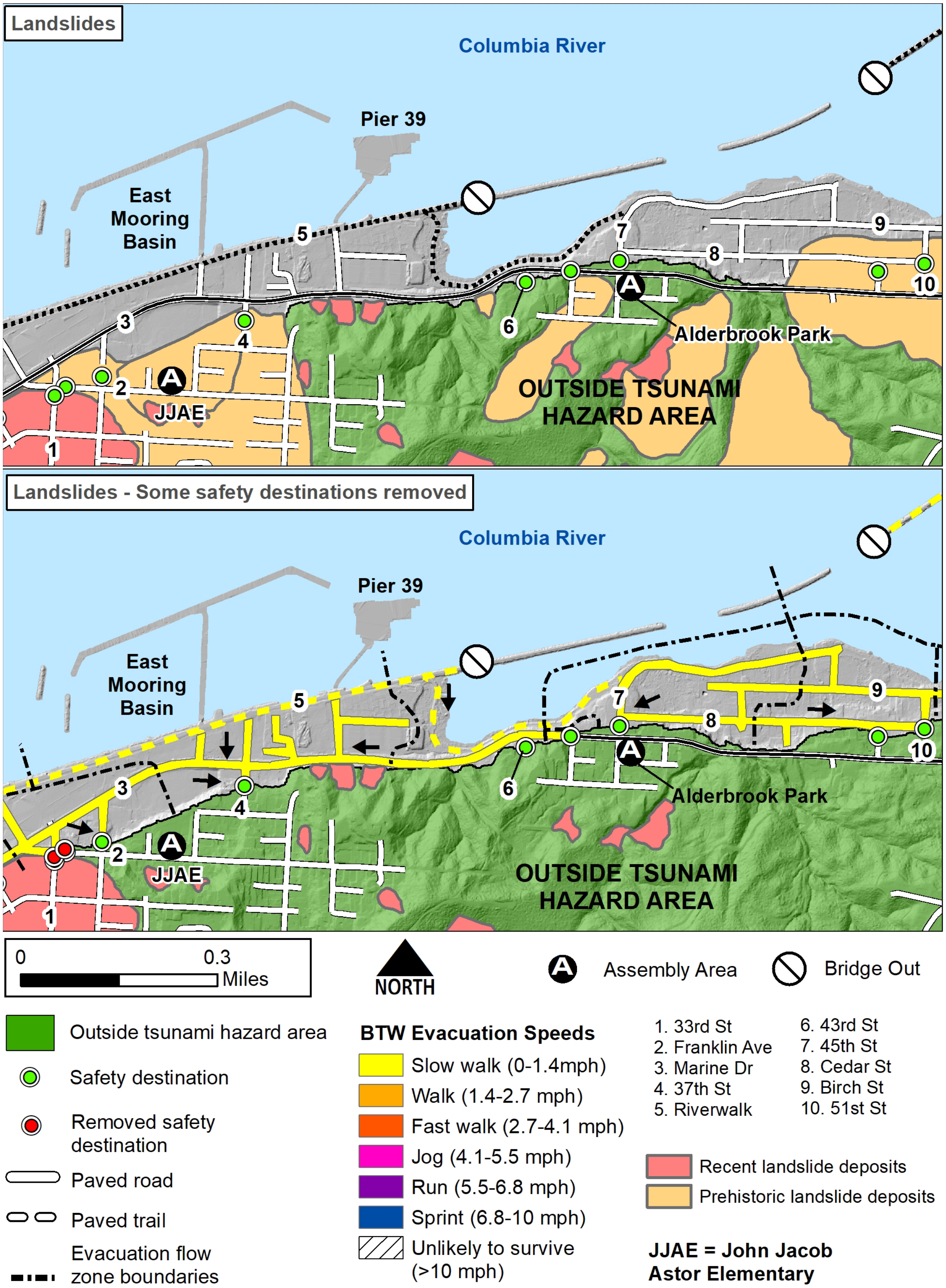


Figure 3-13. (top) Mapped landslides (SLIDO 4.2) in the Alderbrook neighborhood. (bottom) *Beat the Wave* modeling in the Alderbrook neighborhood for a hypothetical landslide scenario that removes safety destinations overlapping recent landslide deposits.



3.4 Tongue Point

Tongue Point marks the eastern edge of the City of Astoria. The inundated area is home to the city's water treatment plant, a US Coast Guard station, and several businesses in the low-lying saddle between Old Highway 30 and Tongue Point itself. A very small number of residential buildings are inside the tsunami zone in this area, at the very eastern edge of the Alderbrook neighborhood.

Evacuation concerns in this area were primarily limited to liquefaction; there is no need to consider hypothetical improvements due to the positive evacuation outlook. A bridge over railroad tracks on Tongue Point Rd may fail, which could compromise evacuation to the south. However, results without that safety destination were still extremely positive such that we did not run a seismic retrofit *Beat The Wave* scenario. Lateral spreading is beyond the scope of this study but will also present a significant challenge for the area.

Detailed XXL wave arrivals are presented in **Figure 3-14.** The tsunami continues up the Columbia River, passing by Tongue Point and inundating the low-lying saddle area, ~48 minutes after the start of earthquake shaking. **Figure 3-15, left** presents minimum travel speeds required to reach safety assuming the existing road network remains intact. The entire area can travel at a minimum speed of ***slow walk*** (2 fps, or 1.4 mph) and reach high ground ahead of the tsunami. This is due to short evacuation distances and long wave arrivals. Evacuation flow zones for the current-conditions scenario are presented in **Figure 3-15, right**. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. The north half of the saddle evacuates north to Tongue Point itself on Tongue Point Rd (purple polygon) while the southern half travels up Country Ln (blue polygon). The eastern side of the promontory evacuates south on Railroad Ave (orange polygon) and the west side including the water treatment plant and the end of the Riverwalk head south to Ash St (pink polygon).

Liquefaction *Beat the Wave* results are virtually unchanged from the current-conditions scenario (**Figure 3-16**). This is due to the short distances to high ground and large amount of time available to get there.

As shown in **Figure 3-17**, no safety destinations at Tongue Point directly overlay terrain likely to have experienced landslide activity at some point in the geologic past. Nonetheless, numerous landslides have plagued the region in recent years, blocking Old Highway 30, the railroad, and surrounding area. We do not present a landslide *Beat The Wave* scenario due to the lack of recent landslide deposits intersecting safety destinations, however recent landslide activity suggests that there is a distinct possibility that earthquake shaking will make it difficult to walk out of the inundation zone using the existing road network and traveling off-road may be necessary.

Figure 3-14. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Tongue Point.

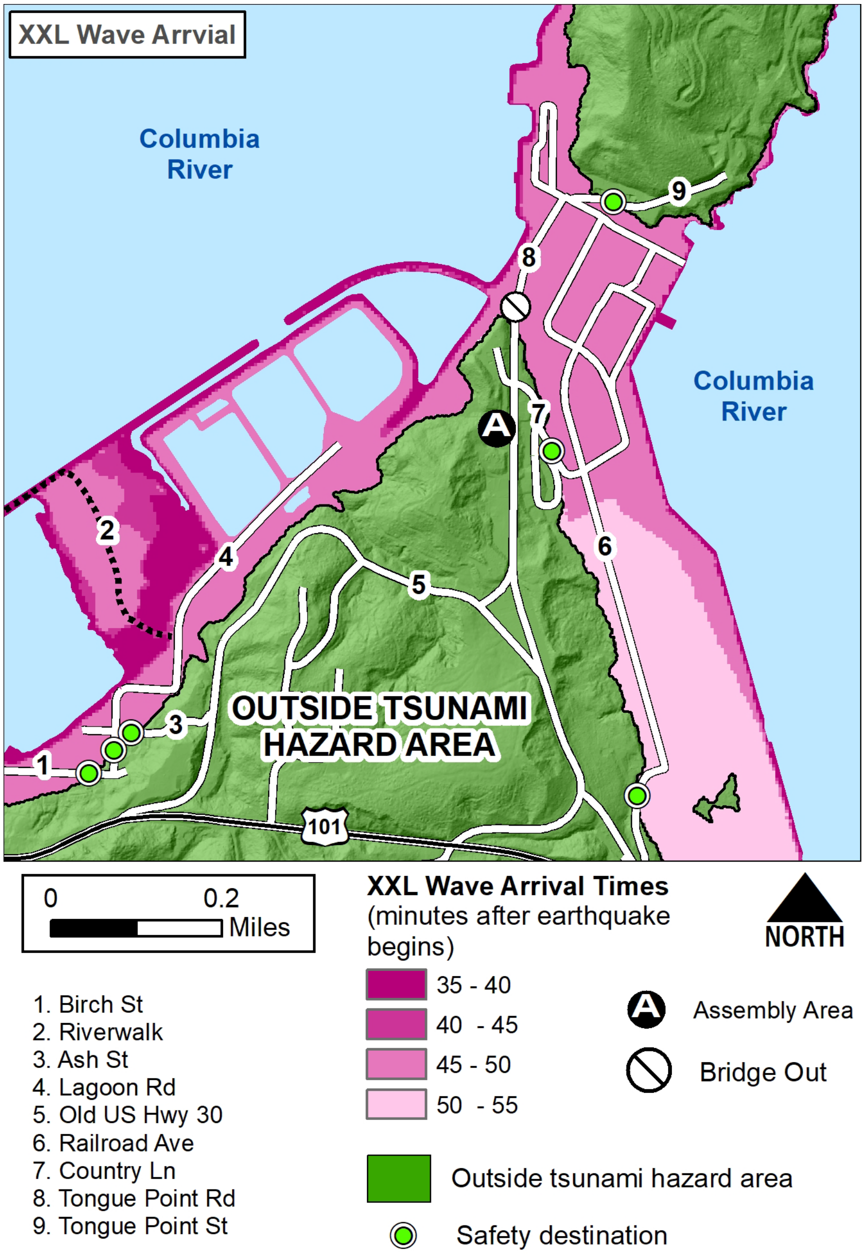


Figure 3-15. ***Beat the Wave*** **modeling in Tongue Point for the XXL current-conditions scenario depicting the existing road and trail network. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (right) Evacuation flow zones displayed as colored polygons.**

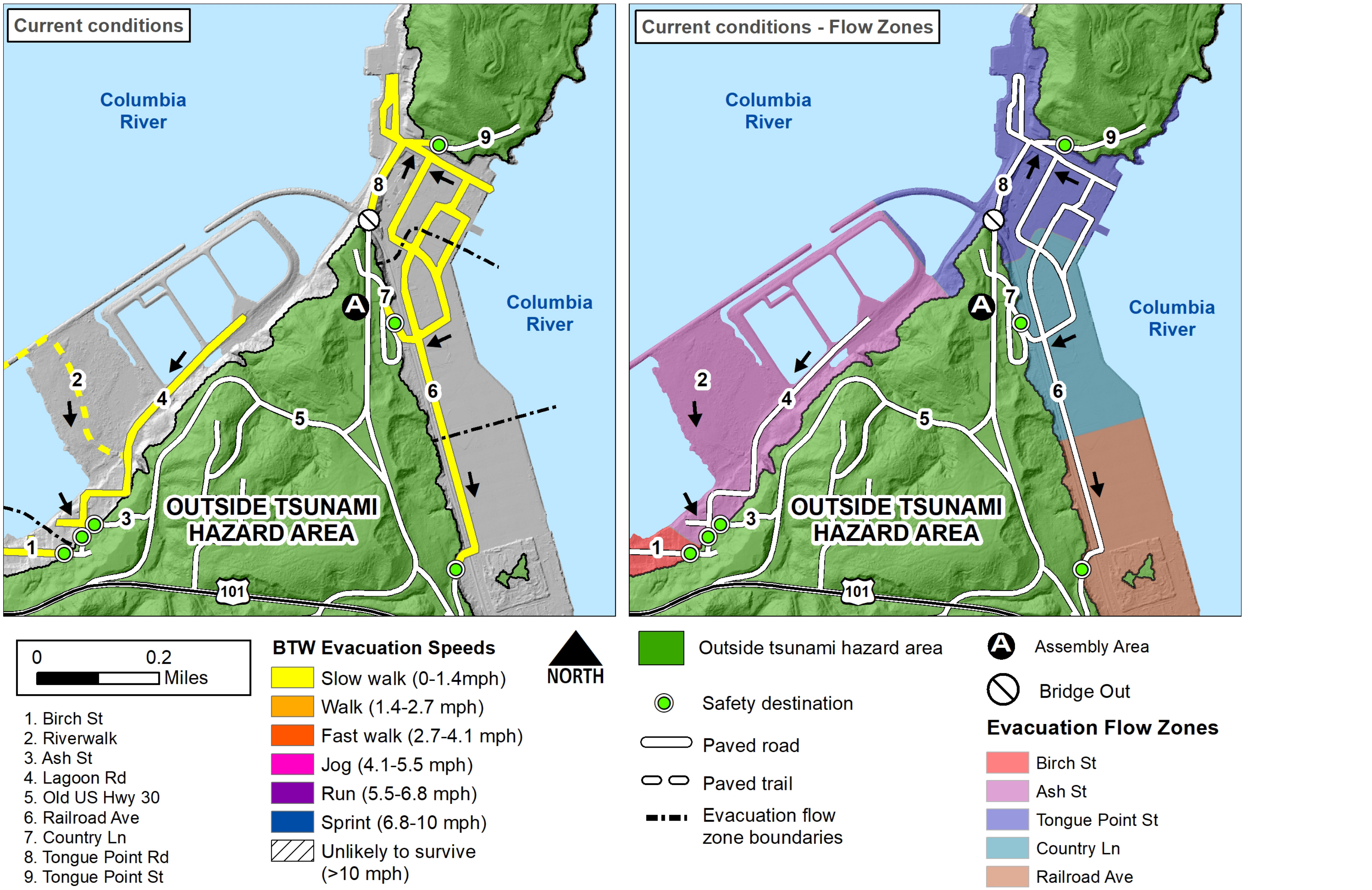


Figure 3-16. ***Beat the Wave*** **modeling in Tongue Point for a liquefaction scenario where roads and trails are significantly more difficult to walk on. All roads inside the XXL inundation zone are classified as having moderate to high liquefaction susceptibility (Madin and Burns, 2013).**

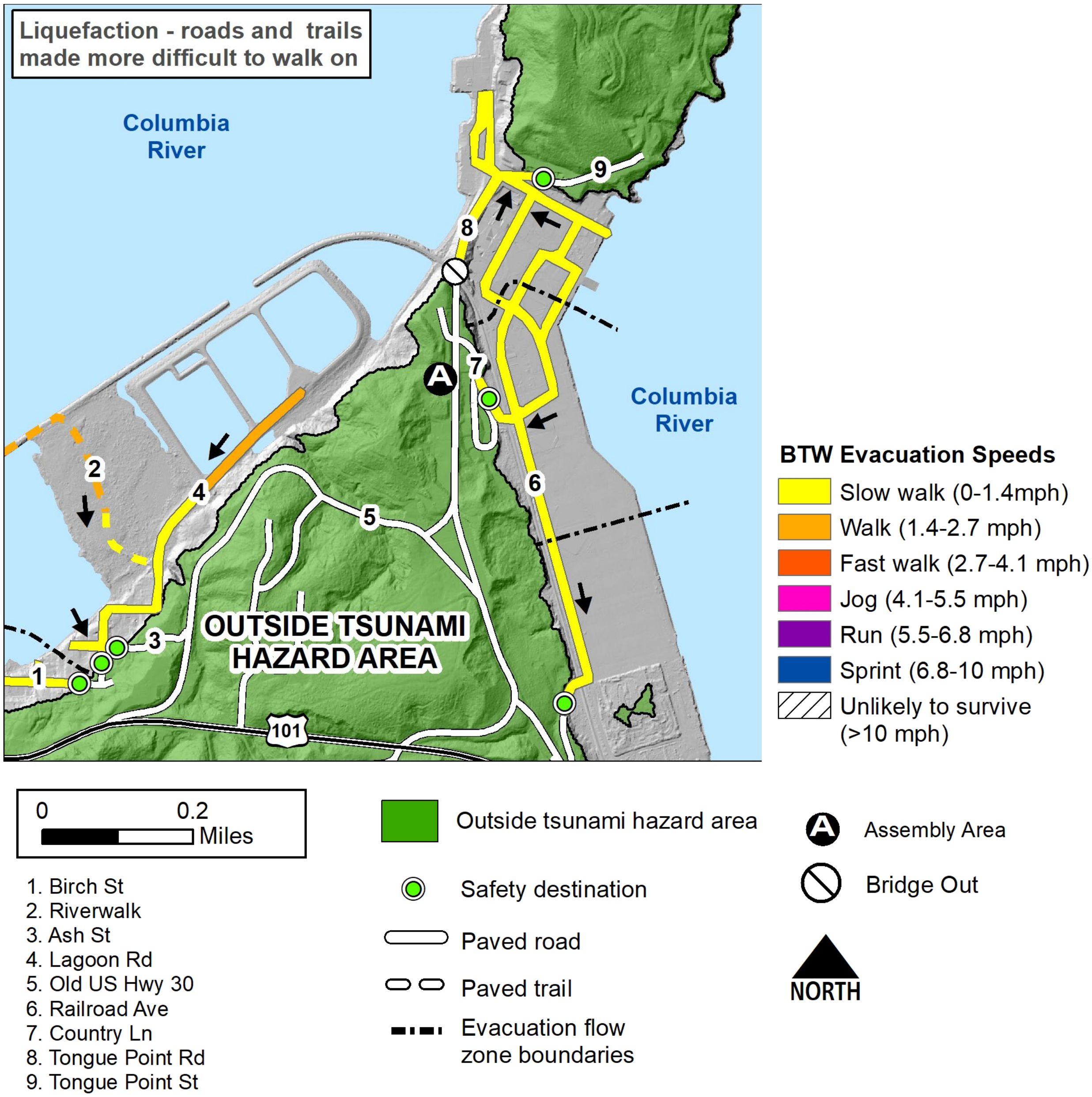
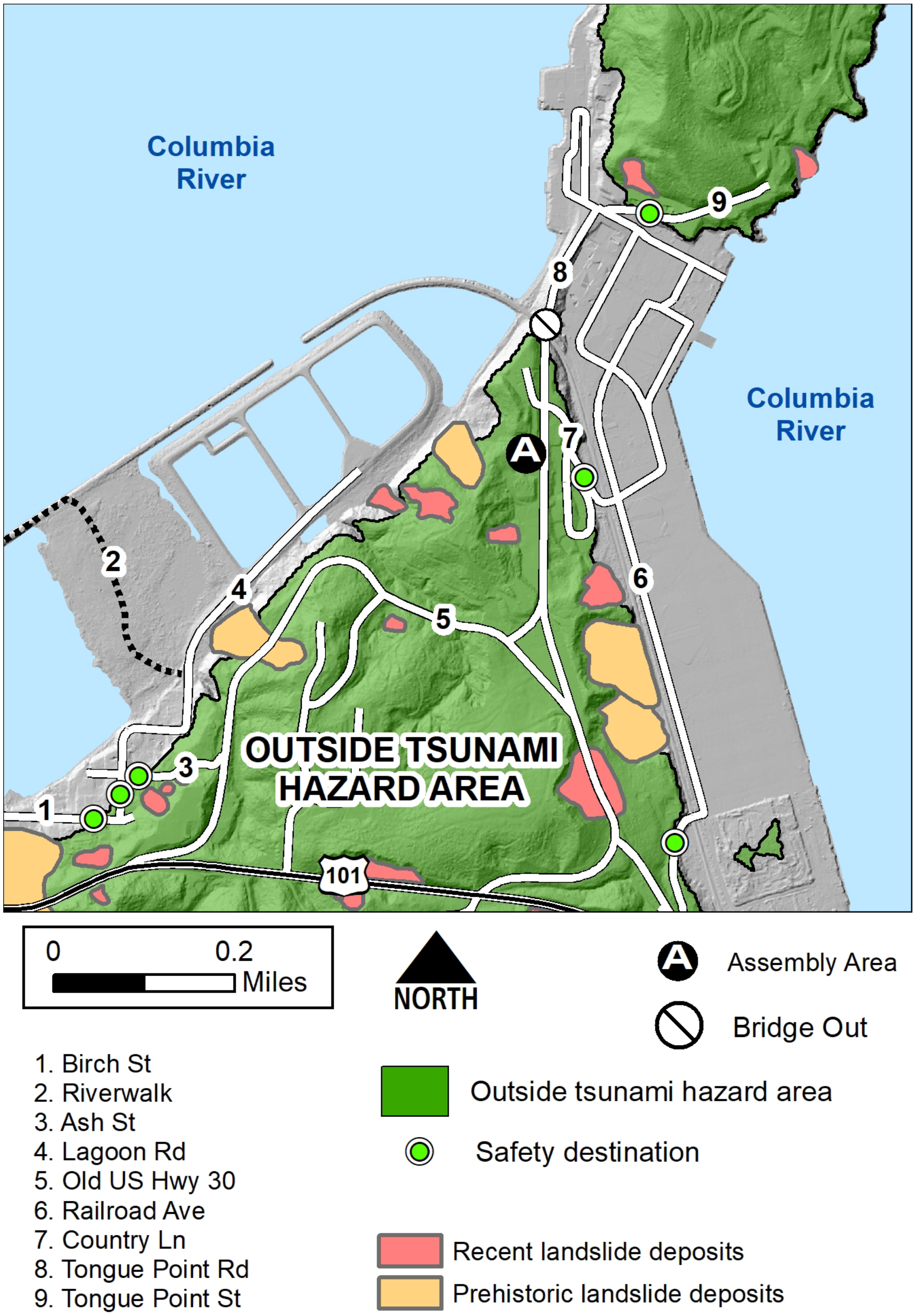


Figure 3-17. Mapped landslides (SLIDO 4.2) in Tongue Point.



3.5 Jeffers Garden

The community of Jeffers Garden lies on low-lying alluvial deposits across Youngs Bay from Astoria. The community is bounded on the west by the Lewis and Clark River and on the east by Cook Slough as well as Youngs Bay to the north. The tsunami zone encompasses a significant portion of the community, both residential and commercial. High ground can be found to the south up Lewis and Clark Rd and Youngs River Rd. Two bridges on the Warrenton-Astoria Highway connecting Jeffers Garden with Warrenton to the west and Astoria to the north are both susceptible to collapse from earthquake shaking and not included in the modeling. This does not affect evacuation for Jeffers Garden, however, because high ground on Lewis and Clark Rd to the south is much closer than what can be reached by crossing either bridge. Two roads crossing Cook Slough were kept in because they are levees as opposed to bridges (Wireless Rd and Youngs River Rd). While the earthquake may disrupt the road surface, it will still likely be available for evacuation.

Concerns in this area include long distances to safety, liquefaction, and lateral spreading. We considered two hypothetical improvements to the current-conditions, including the construction of an evacuation trail between Clover Rd and Lewis and Clark Rd and reducing the amount of time people delay the start of their evacuation (a parameter built into *Beat the Wave* modeling as described in section 2.5.1 and the start of this chapter). Lateral spreading is beyond the scope of this study but will present a significant challenge for the area, specifically locations immediately adjacent to waterways.

Detailed XXL tsunami wave arrivals are presented in **Figure 3-18.** The tsunami reaches the south end of Youngs Bay ~30 minutes after the start of earthquake shaking. It takes another ~14 minutes for water levels to rise high enough to start affecting roads and trails and then another ~3 minutes for the XXL tsunami zone to be fully inundated. It is notable that despite the long time for the wave to get to Jeffers Garden, town is inundated very quickly.

Figure 3-19, left presents minimum travel speeds required to reach safety assuming the existing road network remains intact. Most of the community can travel at a minimum speed of ***walk*** (4 fps, or 2.7 mph) and reach high ground ahead of the tsunami. The lone exception to this is Clover Rd where people must travel at a minimum speed of ***fast walk*** (6 fps, or 4.1 mph). Evacuation flow zones for the current condition scenario are presented in **Figure 3-19, right**. The evacuation flow zones make clear which safety destination evacuees should choose and which direction to travel based on their location. The majority of Jeffers Garden evacuates up Lewis and Clark Rd (orange polygon) and the very eastern edge along cook Slough heads south on Youngs River Rd towards Aspmo Rd (teal polygon).

Current-condition results demonstrate an additional challenge for the western edge of Jeffers Garden (Clover Rd) due to a long evacuation route required to circumnavigate Jeffers Slough and head up Lewis and Clark Rd. The addition of a trail connecting Clover Rd to Lewis and Clark Rd significantly shortens distances to safety, from ~1.8 miles to ~0.3 miles. Although trail construction over Jeffers Slough will be challenging, **Figure 3-20, left** demonstrates the tangible improvements such a trail provides. In this scenario, the area can reach high ground at a ***slow walk***.

When exploring ways to reduce the potential for tsunami fatalities, any effort directed at reducing the time people wait to start evacuating (evacuation delay) will save lives. Here we re-evaluate the XXL current-conditions scenario with a 5-minute evacuation delay compared with the original 10-minute delay (**Figure 3-20, right**). The reduction in response time produces a slight decrease in required evacuation speeds for the entire region. A larger decrease is not seen because evacuation speeds are driven predominantly by travel distances, not how much time people have to reach high ground. Increasing the time available by 5 minutes does not change the fact that people on Clover Rd must travel as much as 1.8 miles to reach high ground. While this scenario only yields slight decreases in evacuation speeds, it is always a good idea to leave as soon as possible as delay costs lives.

Liquefaction *Beat the Wave* results demonstrate significantly faster evacuation speeds required to reach high ground for all of Jeffers Garden, especially for the Clover Rd area (**Figure 3-21**). Necessary speeds for people in the central part of town increase from ***slow walk*** under current-conditions to ***walk***.

To the north and west, speeds increase to ***jog*** (8 fps, or 5.5 mph) and people along Clover Rd must maintain a ***run*** (10 fps, or 6.8 mph) or ***sprint*** (15 fps, or 10 mph) for their entire route. We recognize that liquefaction potential will be spatially variable throughout the region. We present these results merely to demonstrate that any impediments to immediate and swift evacuation will affect survivability.

As shown in **Figure 3-22**, no safety destinations in Jeffers Garden directly overlay terrain likely to have experienced landslide activity at some point in the geologic past. Unlike Astoria, landslides have not plagued the road network in recent years and for these reasons we do not present a landslide *Beat the Wave* scenario.

Figure 3-18. Illustration of tsunami wave arrivals after XXL Cascadia subduction zone earthquake for Jeffers Garden.

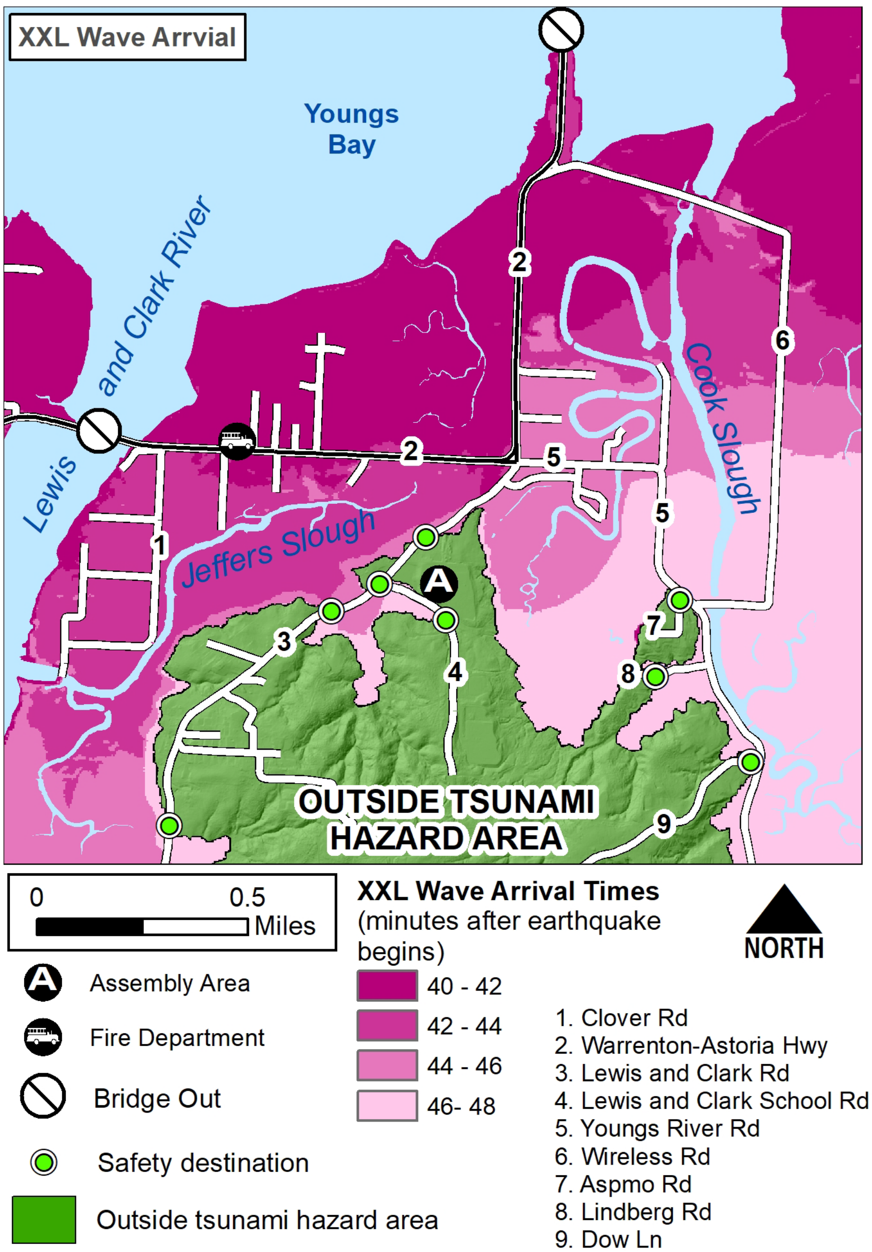


Figure 3-19. ***Beat the Wave*** **modeling in Jeffers Garden for the XXL current-conditions scenario depicting the existing road and trail network. (left)** ***Beat the Wave*** **evacuation speeds and flow zones. Colors on top of roads reflect minimum travel speeds that must be maintained along the route. Black dashed lines delineate evacuation flow zone boundaries. (right) Evacuation flow zones displayed as colored polygons.**

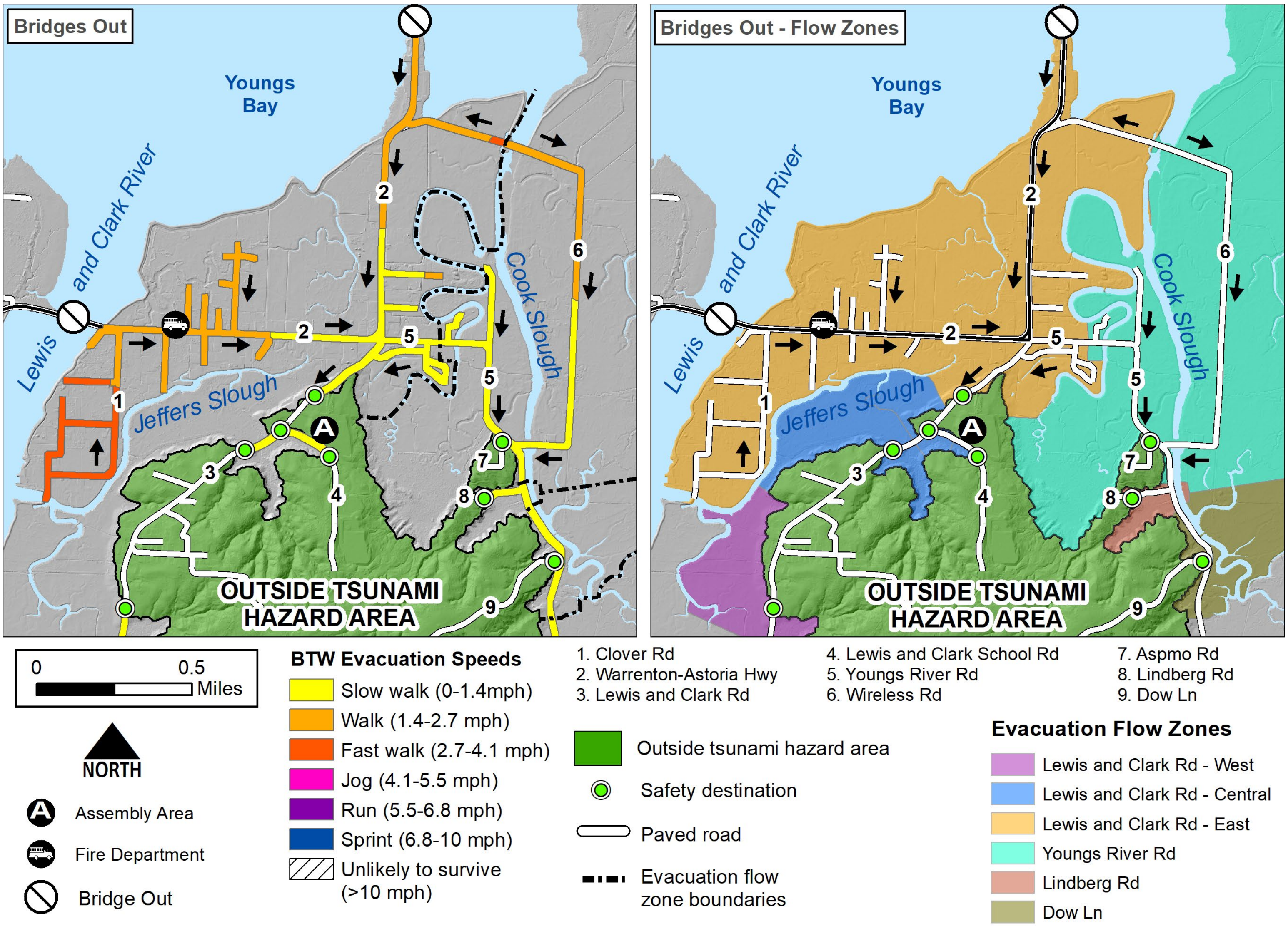


Figure 3-20. ***Beat the Wave*** **modeling in Jeffers Garden for (left) a hypothetical evacuation trail between Clover Ave and Lewis and Clark Rd, and (right) a reduced evacuation delay (5 minutes instead of the standard 10 minutes).**

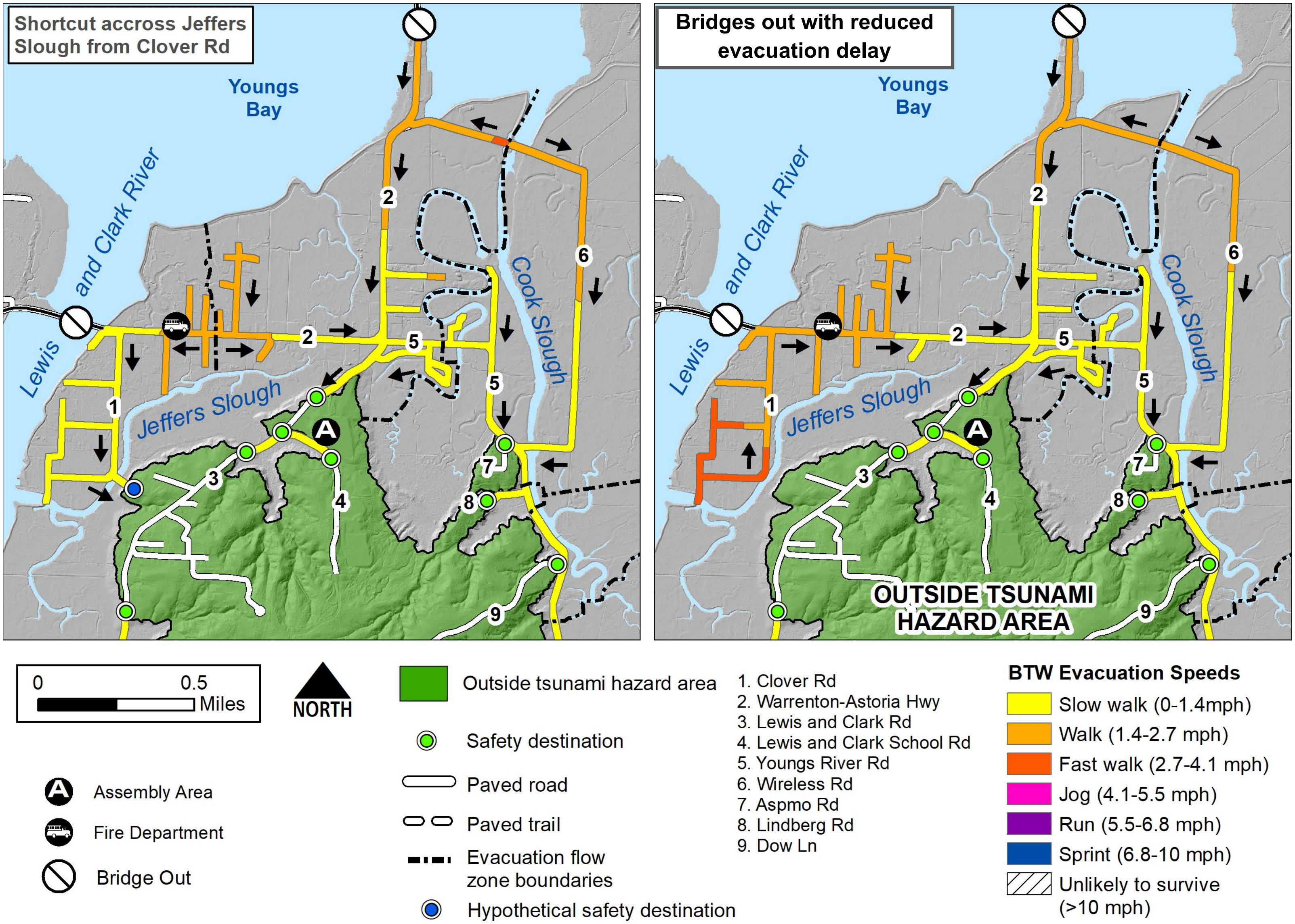


Figure 3-21. ***Beat the wave*** **modeling in Jeffers Garden for a liquefaction scenario where roads and trails are significantly more difficult to walk on. All roads inside the XXL inundation zone are classified as having moderate to high liquefaction susceptibility (Madin and Burns, 2013).**

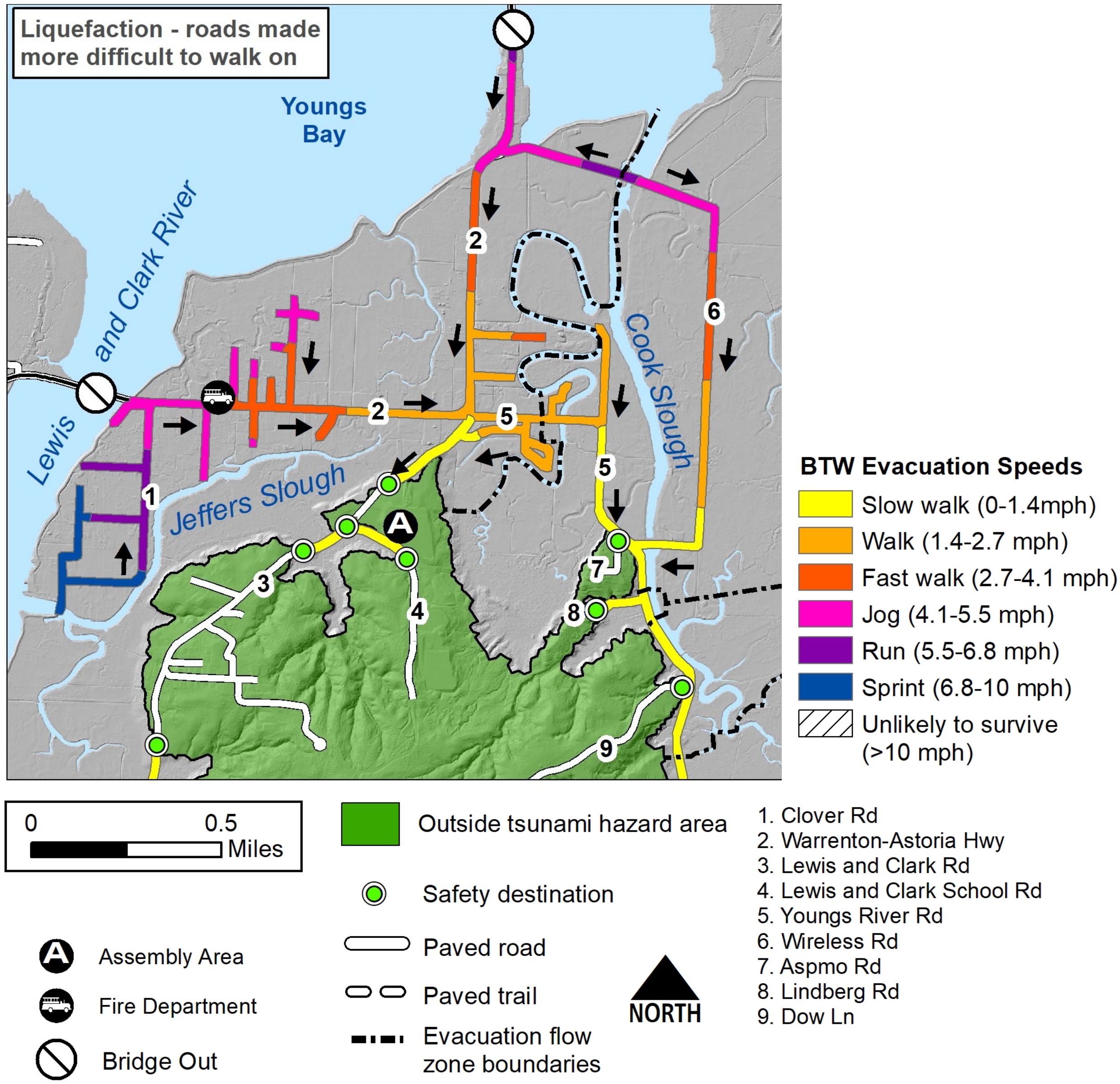
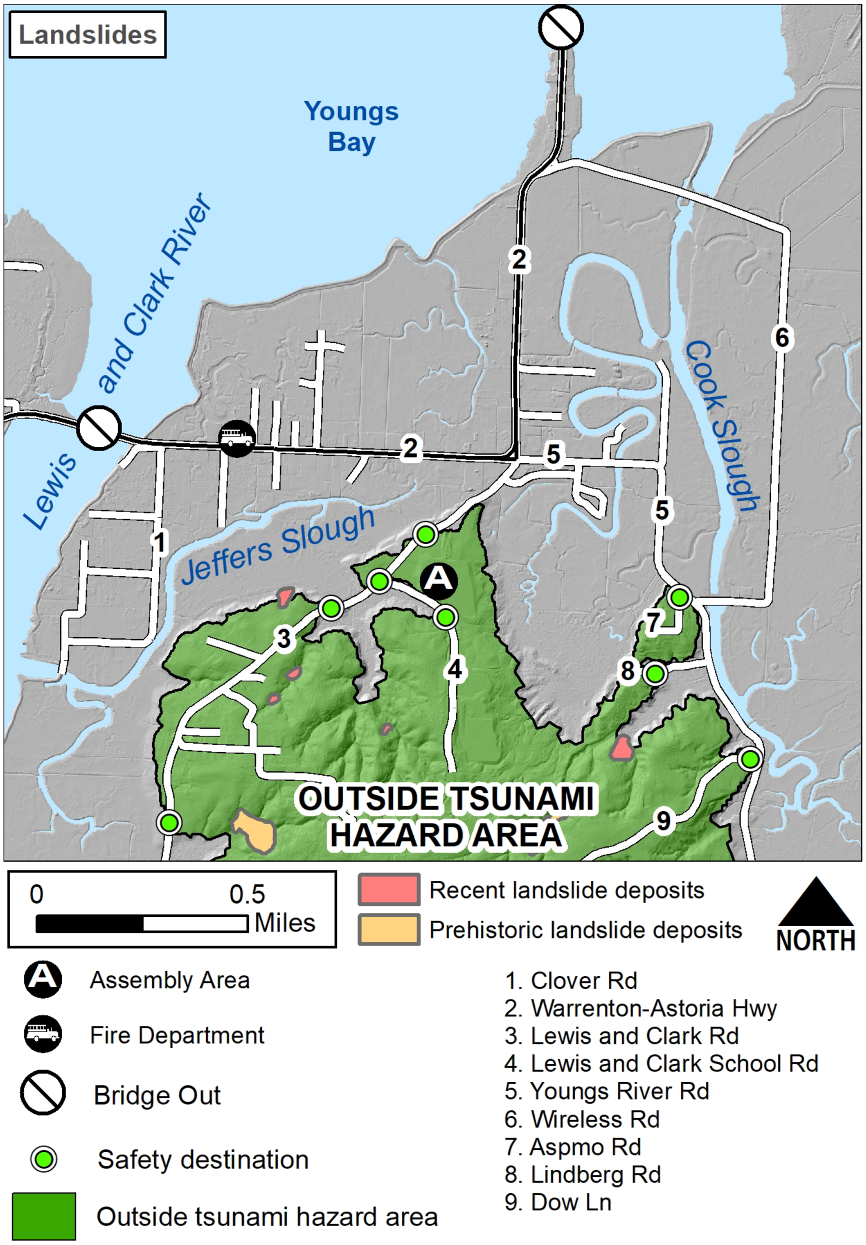


Figure 3-22. Mapped landslides (SLIDO 4.2) in Jeffers Garden.



4.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study is to provide an assessment of tsunami evacuation difficulty in the area around Astoria. 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 Astoria and surrounding area in response to a Cascadia Subduction Zone tsunami is attainable.** This is primarily due to late wave arrivals, with water levels in the

Columbia River and Youngs Bay starting to rise after ~20 minutes but only flooding Astoria and Jeffers Garden after ~38-48 minutes. Results show that evacuation in Astoria is achievable at a ***slow walk*** (2 fps, or 1.4 mph) or greater. Jeffers Garden has more lengthy distances to high ground and evacuees in the western residential area must maintain a ***fast walk*** (6 fps, or 4.1 mph) for the duration of the route to survive.

- **Mitigation efforts will reduce loss of life from the tsunami.** Results in Jeffers Garden show how mitigation efforts directed at reducing the distance to safety through a "shortcut" to high ground (i.e. evacuation trail) greatly improves the chances of achieving successful evacuation. Ensuring the Megler Bridge and its on-ramp do not collapse and block underlying roadways will also improve evacuation in western Astoria.
- **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 Jeffers Garden 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 throughout the region when compared to current conditions (i.e.intact paved roads). Areas with fast evacuation speeds under current conditions become even more challenging in this scenario (i.e. Jeffers Garden), further reinforcing the need to examine mitigation options. Landslides will undoubtedly occur during the earthquake, many that have significant potential to block evacuation routes. The narrow tsunami zone in Astoria results in extremely short evacuation distances, even in a landslide *Beat the Wave* scenario where several safety destinations have been removed. 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 make the difference between life and death. Clear and visible signage placed in key locations is extremely important, especially for tourist destinations like Astoria where large numbers of visitors can cause the total population to nearly double (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).

5.0 ACKNOWLEDGMENTS

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