State of Oregon
Oregon Department of Geology and Mineral Industries
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OPEN-FILE REPORT O-16-08

LOCAL TSUNAMI EVACUATION ANALYSIS OF WARRENTON AND CLATSOP SPIT, CLATSOP COUNTY, OREGON

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2016

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Oregon Department of Geology and Mineral Industries Open-File Report O-16-08
Published in conformance with ORS 516.030

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GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.
Geodatabase is Esri® version 10.2 format.
Metadata is embedded in the geodatabase and is also provided as separate .xml formatted files.

Warrenton_Tsunami_Evacuation_Modeling.gdb:

Feature dataset: Evacuation_modeling_data

feature classes:

- BTW_XXL1_AllBridgesIntact_10minDelay_Roads (polygon)
- BTW_XXL1_AllBridgesIntact_10minDelay_Trails (polyline)
- BTW_XXL1_AllBridgesIntact_Evacroutes (polyline)
- BTW_XXL1_AllBridgesIntact_EvacuationFlowZones (polygon)
- BTW_XXL1_RetrofittedBridgesOnly_10minDelay_Roads (polygon)
- BTW_XXL1_RetrofittedBridgesOnly_10minDelay_Trails (polyline)
- BTW_XXL1_RetrofittedBridgesOnly_Evacroutes (polyline)
- BTW_XXL1_RetrofittedBridgesOnly_EvacuationFlowZones (polygon)

Metadata in .xml file format:

- BTW_XXL1_AllBridgesIntact_10minDelay_Roads.xml
- BTW_XXL1_AllBridgesIntact_10minDelay_Trails.xml
- BTW_XXL1_AllBridgesIntact_Evacroutes.xml
- BTW_XXL1_AllBridgesIntact_EvacuationFlowZones.xml
- BTW_XXL1_RetrofittedBridgesOnly_10minDelay_Roads.xml
- BTW_XXL1_RetrofittedBridgesOnly_10minDelay_Trails.xml
- BTW_XXL1_RetrofittedBridgesOnly_Evacroutes.xml
- BTW_XXL1_RetrofittedBridgesOnly_EvacuationFlowZones.xml

ABSTRACT

We evaluated difficulty of pedestrian evacuation in the communities of Warrenton and Hammond and on Clatsop Spit, Clatsop County, Oregon, in the event of a local tsunami generated by an earthquake on the Cascadia subduction zone (CSZ). We examined a maximum-considered CSZ tsunami event covering ~ 100% of potential variability, termed XXL1 and generated by a magnitude 9.1 earthquake. We determined ***minimum*** walking times to safety (~ 20 ft beyond the inundation limit) for a moderate walking speed of 4 fps (feet per second, 22 minutes/mile) using least cost distance (LCD) routes determined by slight modification of the anisotropic path distance method of Wood and Schmidtlein (2012) and Wood and others (2016). Four feet per second is the standard speed for pedestrians to cross at signalized intersections. Evacuation was limited to roads and pedestrian pathways designated by local government reviewers as the most likely routes. In order to estimate whether pedestrians can stay ahead of a tsunami along entire routes, we produced tsunami wave advance maps for XXL1, LCD walking time maps (at 4 fps), and "beat the wave" (BTW) maps for the XXL1 scenario; detailed maps are also included for Clatsop Spit, Hammond and Alder Creek, Warrenton, Camp Rilea, and Fort Stevens campground. The BTW maps depict the ***minimum evacuation speed*** required to stay ahead of the wave for two levels of increasing evacuation difficulty: 1) all bridges intact, 10-minute delay from start of earthquake before starting evacuation, and 2) only retrofitted bridges intact, 10-minute delay. These minimum speeds must be maintained for the duration that it takes to safely evacuate from the inundation zone. The results show that evacuation from Clatsop Spit and Alder Creek areas is challenging for an XXL1 tsunami. In particular, evacuation from these areas will be extremely challenging for the XXL1 scenario for those with mobility limitations (i.e., those travelling at speeds less than 4 fps). LCD and BTW trials showed that any failure of bridges greatly expands areas that cannot be evacuated. Possible mitigation options include increasing the number of evacuation routes by construction of more earthquake-hardened bridges, the addition of new evacuation routes, and/or installation of tsunami refuges, otherwise known as vertical evacuation structures, in the Alder Creek area and at the tip of Clatsop Spit.

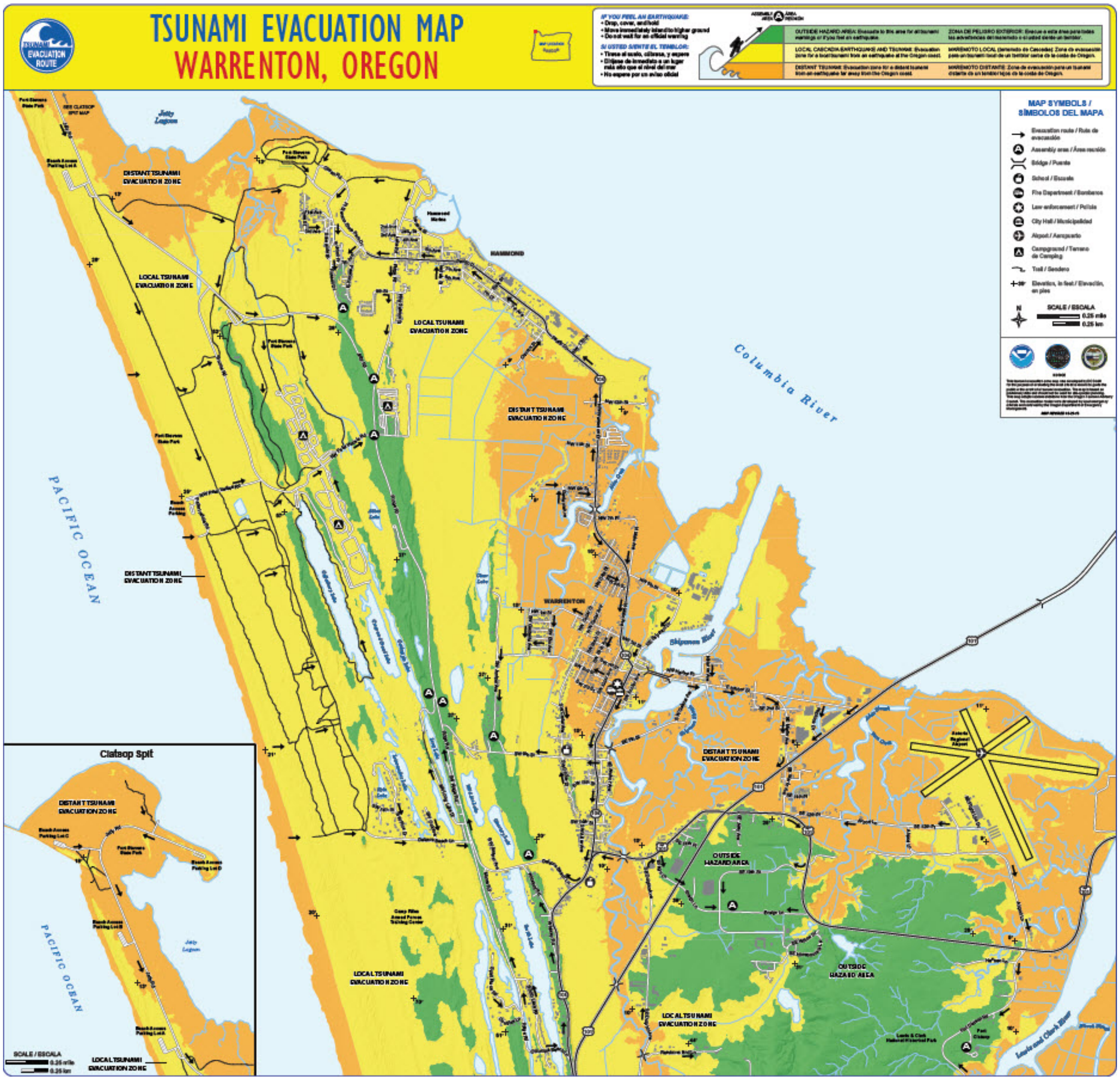
1.0 INTRODUCTION

A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011), making spontaneous evacuation on foot the only effective means of limiting loss of life, since vehicle evacuation would be quickly compromised by traffic congestion and road blockages. CSZ earthquakes affecting northern Oregon will likely be on the order of ~ Mw 9.0 (Priest and others, 2009; Witter and others, 2011), severely damaging bridges and other infrastructure critical to evacuation.

To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic scenarios, five of which are mapped statewide, each covering the following percentages of potential variability of Cascadia tsunami inundation: XXL1 (100% of potential CSZ inundation), XL1 (98%), L1 (95%), M1 (79%), and SM1 (26%) (Priest and others, 2013b). In these scenarios a maximum-considered CSZ tsunami (XXL1) inundates virtually the entire Clatsop Spit and Warrenton area, Oregon (**Figure 1-1**). Further complicating evacuation in the area is the need to evacuate via bridges crossing the Skipanon River and Alder Creek, over complex dune structures, and over distances on the spit tip (**Figure 1-1**).

The objective of this study is to provide local government with a quantitative assessment of the difficulty of evacuating Warrenton and Clatsop Spit for the XXL1 scenario in order to evaluate mitigation options such as evacuation route improvement, better wayfinding, land use planning actions, and implementation of vertical evacuation. We achieve the objective by 1) using the least cost distance (LCD) approach of Wood and Schmidtlein (2012) to provide estimates of walking times to safety, here defined as 20 feet beyond the inundation zone, for every place of origin in the community, 2) illustrating how quickly the wave front of an XXL1 tsunami advances across the area after the causative earthquake, and 3) determining whether an evacuee can stay ahead of the tsunami all the way to safety on the routes defined by the LCD analysis. The latter method is implemented by a new approach termed “beat-the-wave” (BTW), an analysis of evacuation difficulty that shows ***minimum*** speed that must be maintained to stay ahead of the tsunami all the way to safety (Priest and others, 2015a). We then summarize which parts of Warrenton and Clatsop Spit are most in need of tsunami hazard mitigation.

Figure 1-1. Portion of DOGAMI (2013) tsunami evacuation map for Warrenton and Clatsop Spit. Areas inundated by a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL1) are shown in yellow, while areas inundated by the maximum considered distant tsunami scenario (AKMax) are shown in orange. (Note: the Cascadia scenario encompasses BOTH the yellow and orange zones.) High ground outside the XXL1 hazard area is shown in green. See Witter and others (2011) for detailed explanations of the tsunami scenarios shown on this map.



2.0 METHODS

Agent-based and least cost distance (LCD) modeling are the two most common approaches for simulating pedestrian evacuation difficulty. Agent-based modeling focuses on the individual and how travel would most likely occur across various "cost" conditions, such as congestion points (Yeh and others, 2009). LCD modeling focuses on characteristics across the evacuation landscape, such as slope and land cover type. LCD modeling calculates a least-cost path to the tsunami inundation limit for every point in the inundation zone. Time to traverse a route can then be estimated from a given pedestrian walking speed under optimal conditions (e.g., a near flat paved street that has a slight downward decline), increasing or decreasing speed to account for changes in slope and other ground conditions. Generally speaking, a positive slope (upward) will produce slower speeds, as does a negative steep slope (downward), while a slight decline (< 4 degrees) in the slope reflects the optimal speed and no punishment. We used the LCD model of Wood and Schmidtlein (2012) because we wanted to understand the spatial distributions of evacuation times across Clatsop Spit without having to create a large number of scenarios for specific starting points required by agent-based models. We assumed a pedestrian walking speed of 4 feet per second (fps) [22 minute/mile; 1.22 meters/second], 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).

LCD modeling is based on a cost raster, where each pixel represents a level of difficulty of movement across the surface. 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 using terrain-energy coefficients 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 most natural/undeveloped areas for this case study). The base travel speed assumes constant energy expenditure. Geospatial data representing roads, pedestrian paths, and backshores were generated through manual classification of imagery, which was then field verified and reviewed by local officials.

At the urging of local government and technical reviewers, we used a model that considered only roads, paths, and the dry sand backshore of beaches as evacuation pathways; all other land cover classes were essentially excluded. The backshore is defined as areas landward of the beach-dune junction approximated by the 18-ft North American Vertical Datum of 1988 (NAVD88) 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. However, travel times for the back of the beach are probably a good indication of the time and speeds required to evacuate the beach. We chose to ignore travel time from buildings or other parts of urban areas to the roads, because there is large uncertainty in conditions both before (e.g., fenced yards) and after the earthquake (e.g., fallen debris). The modeling approach thus produces ***minimum*** evacuation times that must be maintained for the duration that it takes to safely evacuate from the inundation zone. To force the model to use only these routes, we used the SCV values presented in **Table 2-1**.

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
Beach access pathways (loose sand)	0.5556**
Everywhere else	0

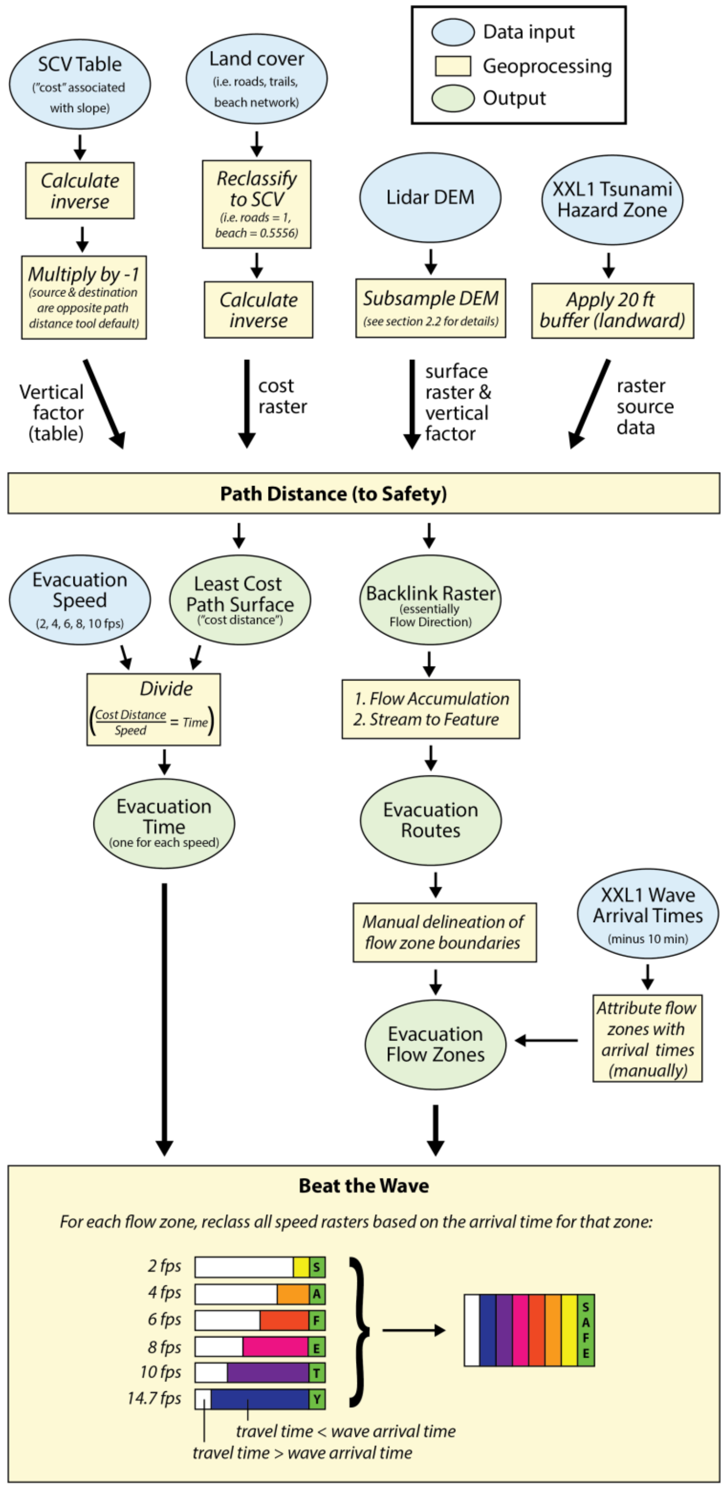
*Speed conservation values (SCV) are derived from Wood and Schmidtlein (2012).

**Beach access pathways have the same SCV as sand given by Wood and Schmidtlein (2012).

In coastal towns, landslide-prone slopes and saturated sandy soil are common, so slides, liquefaction, and lateral spreading are likely to occur during an earthquake. These hazards will damage roads and reduce walking speeds by significant but uncertain amounts. Although it is possible to model potential distribution of these hazards for Warrenton and Clatsop Spit, such modeling was beyond the original scope of this study. Even if mapped, assigning cost values to these hazard areas is highly uncertain, because actual slowing of pedestrian speed will likely be highly site specific.

We implemented LCD modeling by using Esri ArcGIS® 10.2 software. The path distance tool uses geospatial algorithms to calculate the most efficient route from each point in the evacuation zone to "safety," defined for the purposes of this study as ~ 20 feet (6 m) beyond the maximum inundation limit; this is where the tsunami flow depth and velocity are effectively zero. The product of this step is referred to as the "least cost path distance surface." The safety destination was 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. **Figure 2-1** summarizes the steps and inputs into the path distance tool as well as the subsequent BTW approach.

Figure 2-1. Model diagram of path distance approach from Wood and Schmidtlein (2012) and Wood and others (2016). SCV is speed conservation value, DEM is digital elevation model (Priest and others, 2015b).



2.1 Tsunami hazard zone layers

The tsunami inundation zone used in this study is XXL1 derived from digital data of Priest and others (2013a,b). This particular zone covers 100 percent of potential CSZ inundation (Witter and others, 2011). Several small areas of high ground outside the XXL1 inundation zone were removed from consideration due to potential confusion in location (i.e., a short unmarked stretch of trail or road) and/or because they were such small areas that they would not be able to support a large enough group of people. Great care was taken in determining whether or not to exclude an area, with the main priority being that alternative high ground exists nearby. These areas are indicated in all figures as green with a black hash overlay; while these areas were excluded from the BTW and LCD modeling, they still may be considered a safety destination for people who are unable or unwilling to travel further.

2.2 Lidar elevations layer

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. The grid was further smoothed as it became clear that the slope profiles were too noisy and introduced slope artifacts of significant amplitude (e.g., a 3-inch elevation difference between cells 1 foot apart yielded a 14-degree slope) that added significantly more time to the total calculated time (Priest and others, 2015a,b). To smooth the data, we created points at 50-foot intervals along all evacuation paths including major roads and at intersections, and we attributed those points with elevation values from the native 3-foot-cell lidar DEM. Priest and others (2015a,b) performed trials at 25, 50, and 100 feet and found that 50-foot intervals achieved the best compromise between accuracy and smoothness. Final sampling interval was ~ 50 feet on straight paths and somewhat less for curved paths in order to accurately depict curvatures. We then interpolated those points using an Esri Natural Neighbor function to produce a smoothed DEM that closely emulated the actual elevation values of the lidar while dramatically reducing slope noise.

2.3 Speed conservation value slope table

We created a table that associates slopes with a specific SCV value. This table used 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:

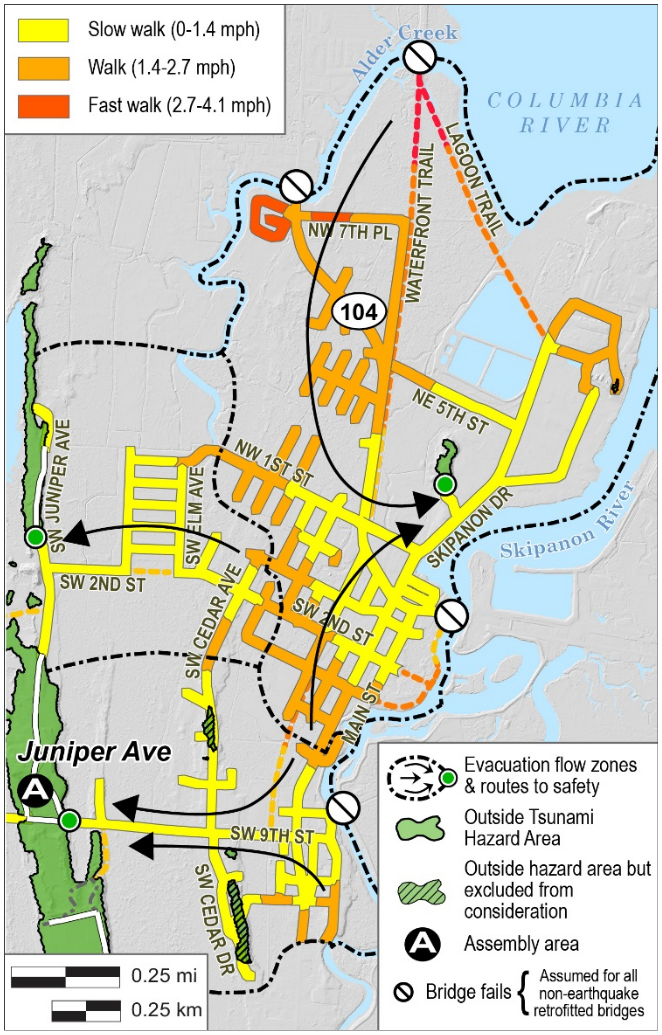
$$\text{walking speed (km/hr)} = 6e^{-3.5 \times \text{abs}(\text{slope} + 0.05)}$$

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 (−5%) downslopes.

2.4 Path distance modeling

The output of the LCD model is a path distance surface showing the effective distance to safety from each pixel. We also calculated an LCD backlink raster that shows, for each cell, the direction of the next cell on the least-cost path. This raster makes it possible to trace the path to safety from any pixel and is equivalent to a flow direction raster, which is the first step in hydrologic modeling of topographic surfaces. We use the hydrologic tools in Esri ArcGIS 10.2 and the backlink raster to extract a "stream" network to visualize the paths depicting the most efficient evacuation. These paths represent the shortest effective distances to safety. The pixel value for cost distance is the effective distance, along the least-cost path, from the pixel to the point where the path intersects safety. For example, from the west end of the Skipanon Bridge on the Warrenton-Astoria Highway (**Figure 2-2**), the actual distance to Marina Hill is 2,179 feet while the least-cost path distance is 2,780 feet. This difference is due to the model accounting for variations in slope and landcover along the route. The resulting direction of travel on each path is depicted in GIS as arrows along streets with opposing arrows at point where one could travel to safety on two equal alternative paths. The latter define boundaries of evacuation flow toward critical points, such as the nearest safety location or which bridge to cross, and are directly analogous to watershed boundaries or drainage divides in hydrologic modeling (**Figure 2-1**).

Figure 2-2. Example of the network of evacuation paths from the least-cost distance analysis limited to trails and streets. In this example, bridges across Alder Creek are excluded from the LCD and BTW analyses. Evacuation flow zones are illustrated for the three main safety destinations (green dots) in the Warrenton area west of the Skipanon River. Base map boundary on this and subsequent figures is shaded relief from 2009 lidar data; XXL1 inundation boundary on this and following figures is from Priest and others (2013b).



These boundaries are particularly important in Warrenton and on Clatsop Spit, where one must choose which bridge to evacuate across from each part of town, or which path to take in order to reach safety. At typical map scales, the large number of arrows output by the software can be hard to decipher, in some cases obscuring the evacuation flow zones, so depicting the zones on hazard maps as in **Figure 2-2** is recommended.

We also produced LCD maps for the XXL1 scenario showing the effect of different evacuation mitigation options as well as the effect of collapse of some bridges not retrofitted to withstand a Cascadia subduction zone earthquake. As of the date of this publication, none of the bridges have been designed to withstand significant seismic forces (Mark Buffington, ODOT District 1 Manager, personal communication, 2016). LCD maps depicting walking times were also modeled in order to compare tsunami arrival times to pedestrian arrival (at 4 fps) at various critical junctures.

As we constructed these maps, it became apparent we would require many more maps to fully explore the array of evacuation speeds appropriate for specific populations (e.g., children, the elderly, physically impaired adults). In the next section (2.5) we discuss the consequent development of tsunami wave front advance maps and integration of tsunami wave arrival data directly into the LCD analysis to produce "beat-the-wave" (BTW) maps that estimate the ***minimum speed*** needed to reach safety ahead of the wave.

2.5 "Beat-the-wave" (BTW) modeling

"Beat the wave" (BTW) models integrate tsunami wave arrival data directly into the LCD analysis to produce a map of minimum speeds that must be maintained to reach safety. In order to understand the complexities of tsunami wave advance across the landscape, we extracted the time after the CSZ earthquake at which the XXL1 tsunami flow depth reached more than 0.5 ft at each computational grid point, and we interpolated those arrival data to create a continuous map showing wave arrival times (**Figure 2-3**). The decision to define the first wave arrival in this manner came out of a need for an automated approach due to the large amount of grid points (1.8 million). Half a foot was found to be the smallest water level rise that successfully ignored small fluctuations which resulted in anomalously low arrival times. We examined profiles of the data on various LCD paths (**Figure 2-4**) to identify possible locations along routes where waves will arrive early enough to compromise evacuation (Priest and others, 2015a). Where applicable, we also determined when the XXL1 tsunami water elevation reached the bottoms of bridge spans, considering that circumstance the most likely time bridges might be compromised by the full hydraulic force of the tsunami.

Figure 2-3 illustrates that the XXL1 tsunami arrives along the open coast beach sites of the Clatsop Plains in < 10 minutes, inundating the plains ~ 30 minutes after the event. In contrast, the communities of Hammond and Warrenton experience generally later wave arrivals, ~ 34–40 minutes after the earthquake, because it takes a little longer for the tsunami to travel into the lower Columbia River estuary (**Figure 2-4**).

Figure 2-3. Illustration of XXL1 tsunami arrival times after a Cascadia subduction zone earthquake: *A)* on the Clatsop Plains; *B)* Warrenton inset *[next page]*; ***C)* Hammond inset** *[next page]*.

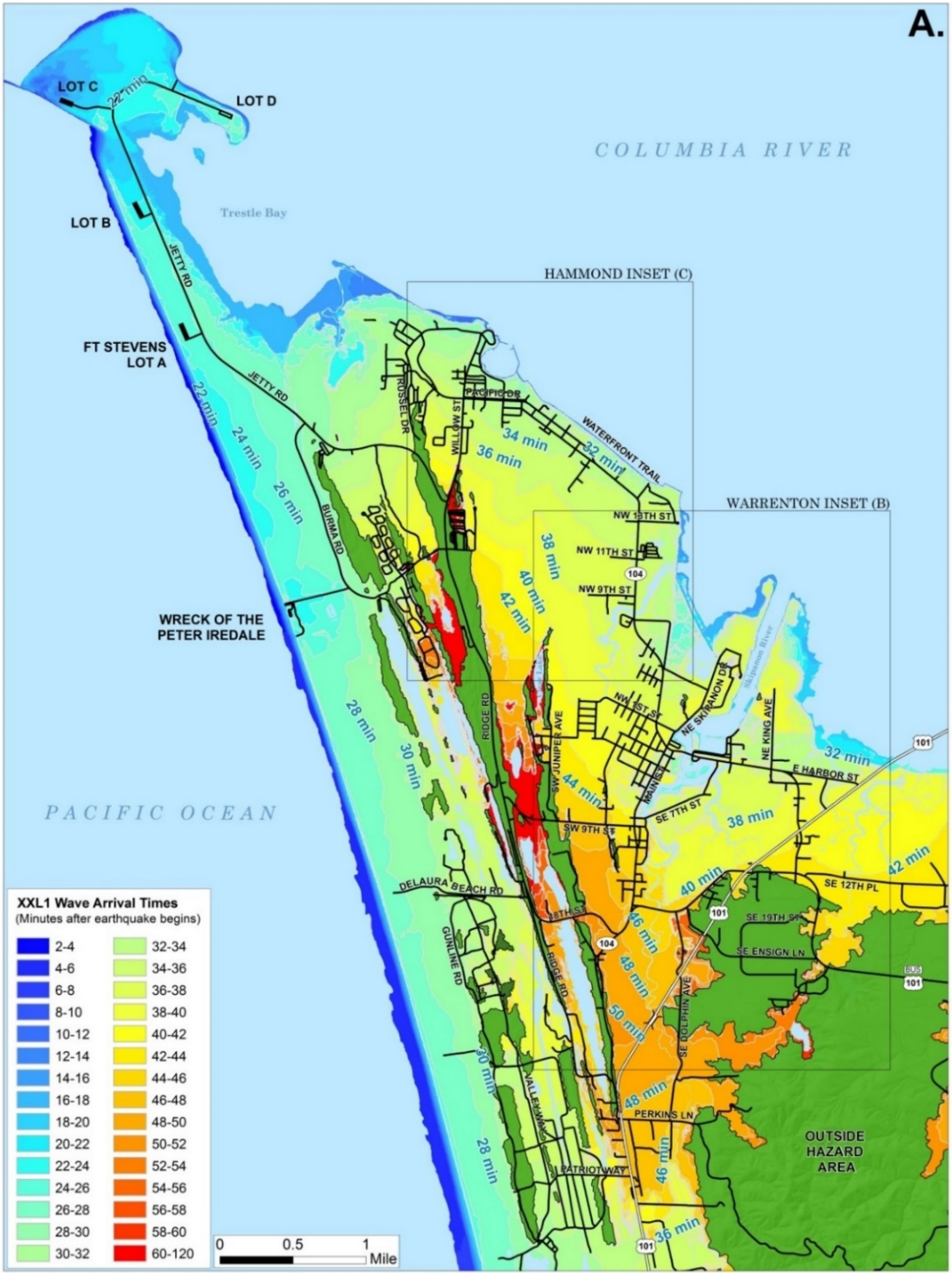


Figure 2-3, *continued*. **Illustration of XXL1 tsunami arrival times after a Cascadia subduction zone earthquake: A) on the Clatsop Plains; B) Warrenton inset; C) Hammond inset.**

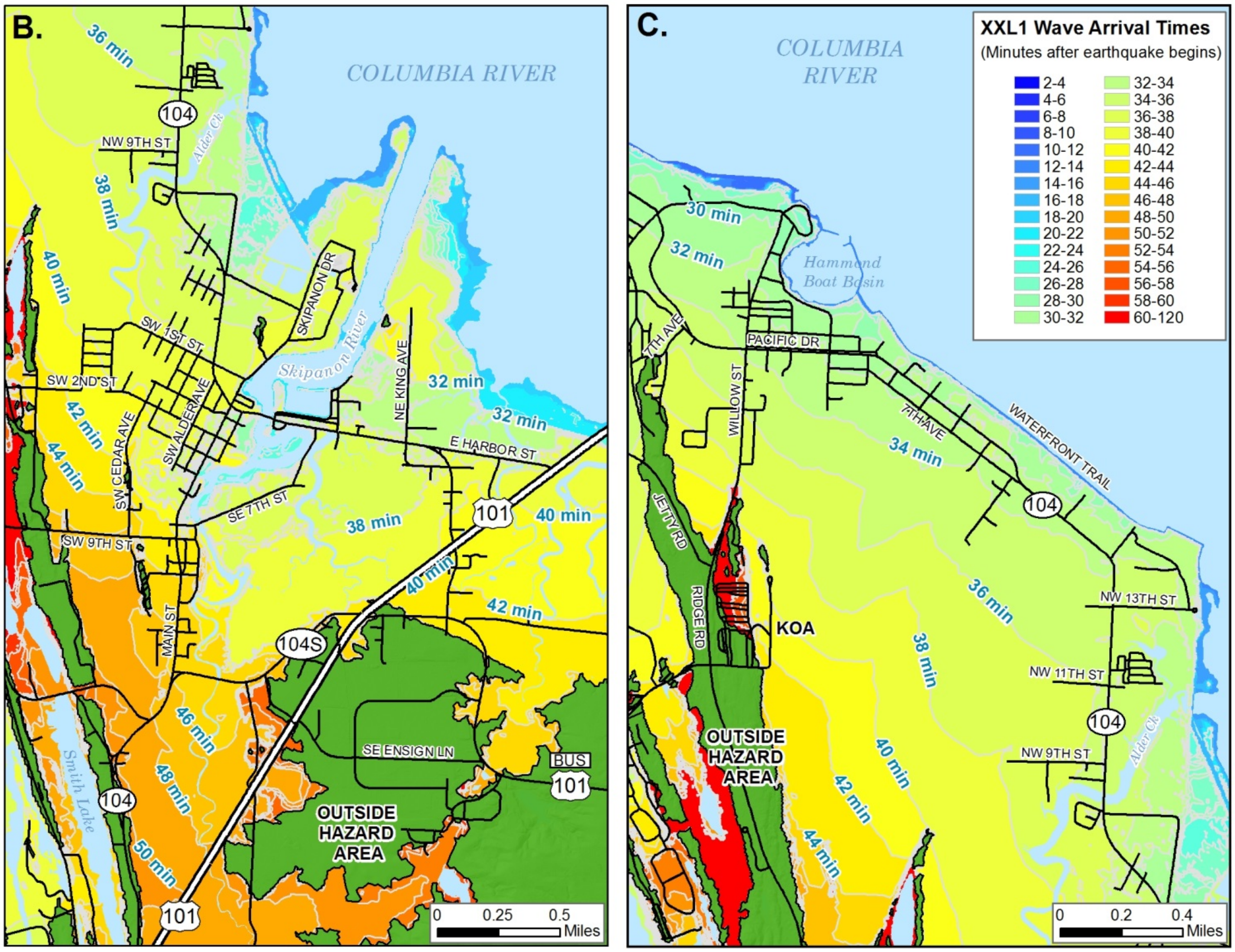
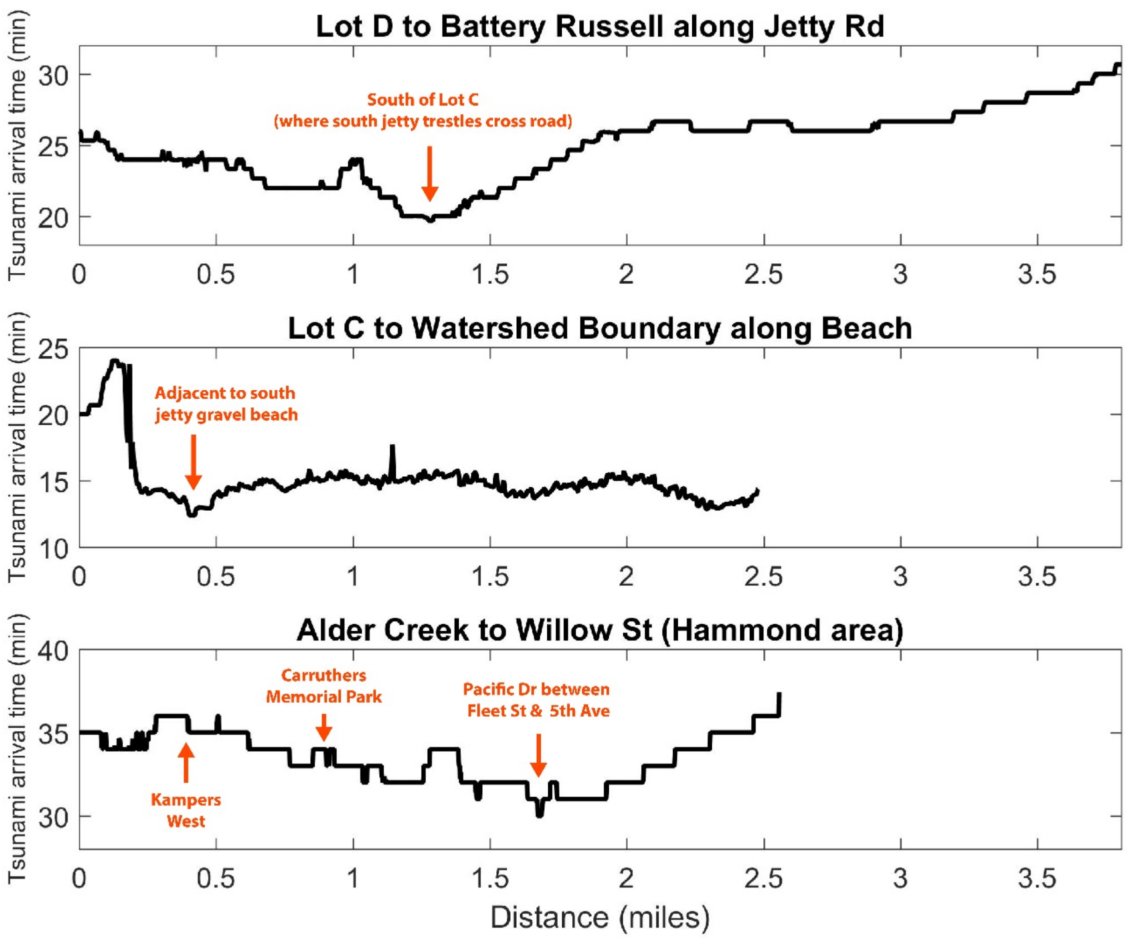


Figure 2-4 illustrates early wave arrivals along select routes near the Clatsop Spit tip and along the Columbia River between Alder Creek and Hammond. These latter data were used to assess the potential for early wave arrival, which could cut off parts of the evacuation route and thereby strand evacuees in those areas.

Figure 2-4. Time after an XXL1 earthquake when simulated tsunami flow depth exceeded 0.5 ft for selected evacuation routes on the northern Clatsop Plains. Early tsunami wave arrival *(top)* at parking lot D on Jetty Road, *(middle)* just south of the turn off to parking lot C on Jetty Road, and *(bottom)* in Hammond near the boat basin were examined to see if they were critical points setting the times for evacuation for the entire evacuation flow zone seaward of each point. In all three cases we found that the early wave arrivals were not critical, and the speeds required to reach safety were fast enough to place evacuees past these low points before the tsunami arrived. Keep in mind that while tsunami arrival times are reduced by 10 minutes for BTW mapping to account for a delay in evacuation from effects of earthquake shaking, the times shown here are not reduced.



The next step in the BTW analysis was to divide the landscape into evacuation flow zones and assign wave arrival times to each zone. Flow zone polygons were drawn manually by using evacuation routes, which are a derivative product from the path distance tool. Flow zone rasters may also be generated using the watershed tool in the Esri Hydrology toolset. However, we found this latter method to be useful as a guide only and not as functional data. Wave arrival times were assigned based on the time when the first wave reached the point of safety for each zone. Ten minutes were then subtracted from the simulated tsunami arrival times to account for the time in which earthquake shaking takes place, as well as disorientation, and the time required to evacuate buildings. Using the March 11, 2011, Tohoku earthquake (USGS, 2012) as an analogue to an XXL1 or L1 scenario, the minimum delay is probably ~ 3–5 minutes of strong shaking for the ~ Mw 9.0 event. There are little 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 had experienced several local earthquakes and tsunamis over the last ~ 400 years, the last in 1974. We therefore simulated a delay of 10 minutes mainly for earthquake shaking (the minimum of 3 minutes for shaking plus 7 minutes based on the La Punta survey).

After creating flow zones, we divided the path distance surface by pre-determined evacuation speeds to yield multiple evacuation time maps of the region (cost distance divided by speed equals time). We then clipped these time maps 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, we clipped the surface at the point where the time to reach safety was greater than the wave arrival time. We then mosaic'ed together the clipped grids, with the minimum speed for each cell maintained. These steps are described graphically in **Figure 2-1**.

We treated potential early wave arrival locations as unique flow zones (the low point is the effective destination) and we compared the resulting BTW speeds to that of the flow zone as a whole to determine if BTW speeds needed to be adjusted upward to "beat the wave" at all points along a route. In all three cases shown in **Figure 2-4**, the speeds required to reach safety were faster than the speeds required to get past the critical intermediate point, and therefore no adjustments were made to final BTW data. This is not always the case, as demonstrated in our Seaside analysis, where BTW speeds required to cross Neawanna Creek were higher than evacuation speeds necessary to reach safety (Priest and others, 2015a,b).

Finally, we also examined the effect of bridge collapse, running trials for two scenarios with increasing evacuation difficulty: 1) all bridges intact, 10-minute delay from start of earthquake before starting evacuation, and 2) only seismically retrofitted bridges intact, 10-minute delay.

Binning of evacuation speeds was initially limited to five categories, which is typically the maximum number of categories that people can easily interpret on a map. A literature review of typical pedestrian speeds by Fraser and others (2014) found five travel speed groups: elderly, child, adult impaired, adult unimpaired, and running (**Table 2-2**). The ranges of speeds for these groups at one standard deviation (**Table 2-2**) 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 2-2**). While modeled speeds assume constant velocity, actual travel speeds on any path will require either variable expenditure of energy to maintain the BTW speed in all conditions, or higher speeds in easier terrain (flat paved streets) to compensate for slowing in difficult terrain (steep slopes or sand).

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

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

After looking at the range of BTW speeds for Seaside (Priest and others, 2015b) and reviewing a number of references describing speed categories (Paul, 2013; Margaria, 1938), we used 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; and,
- Running at >8 fps.

However due to the extremely long path distances and short wave arrival times on the Clatsop Plains, we further divided the highest bin (>8 fps) into three additional bins to better understand the likelihood of survivability. These additional bins include:

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

The authors of this report conducted a small experiment in Seaside to evaluate the validity of the evacuation speed bins chosen and to assess the difficulty in actually maintaining a constant minimum speed over the course of an entire evacuation route. Five key routes were walked; the authors recorded their average speed along each route and when they reached critical locations (bridges, low areas, and safety). Overall, the results show that when traveling at the speed requested by the BTW data, an evacuee will reach safety ahead of the tsunami. However, as speeds fall below the prescribed BTW speeds our results confirmed that the tsunami would overrun the evacuee, making survival highly unlikely. This limited test of our BTW data suggests that they are reasonable guides to minimum evacuation speeds necessary to reach safety ahead of the tsunami. A complete description of the experiment and results are summarized in Appendix A.

3.0 RESULTS

Analyses of tsunami wave arrival times, pedestrian evacuation times using a standard 4 fps speed, variable BTW evacuation speeds, and evaluation of various scenarios such as bridge failures, construction of alternate routes, and vertical evacuation for an XXL1 Cascadia Earthquake are presented and discussed for the Clatsop Plains. Here we initially examine the broader regional findings, followed by an examination of evacuation modeling results for five specific areas: Warrenton, Hammond/Alder Creek, Clatsop Spit tip, Fort Stevens campground, and Camp Rilea.

Recall that **Figure 2-3** shows the wide range of tsunami arrival times for an XXL1 local tsunami that inundates the Clatsop Plains. As described previously, these arrival times range from as little as 10 minutes on the open coast beaches, ~ 34–40 minutes in Warrenton (Hammond), and as much as 60 minutes for the tsunami to reach its maximum runup limits.

Given these tsunami arrival times, **Figure 3-1** presents modeled pedestrian evacuation times based on intact and unimpeded routes using an average pedestrian evacuation speed of 4 fps (classified as a “walk”) and identified path distances. As can be seen in the figure, pedestrian evacuation times are generally about 10–15 minutes (yellow/orange colors) across much of the area, as many of the routes are relatively close to areas outside of the hazard zone; in this and all subsequent figures “safety” is designated as green and dashed lines indicate trails. Along the peripheral edges of the Clatsop Plains, the default ***“walk”*** evacuation times increase significantly. We identify three broad areas where evacuation to safety will be challenging. These include 1) the spit tip, where evacuation times reach ~ 60+ minutes, 2) Alder Creek located north of Warrenton, where evacuation times are also ~ 60+ minutes, and 3) on the Skipanon Peninsula, where evacuation times are ~ 40–45 minutes. This assumes that evacuees walk at the modeled speed of 4 fps. Nevertheless, these results highlight several challenges for evacuation at these locations.

Figure 3-1. Modeled pedestrian evacuations assuming a 4fps speed during an XXL1 local tsunami event: *A)* northwest Clatsop County, Oregon; *B)* Warrenton inset *[next page]*; *C)* Hammond inset *[next page]*.

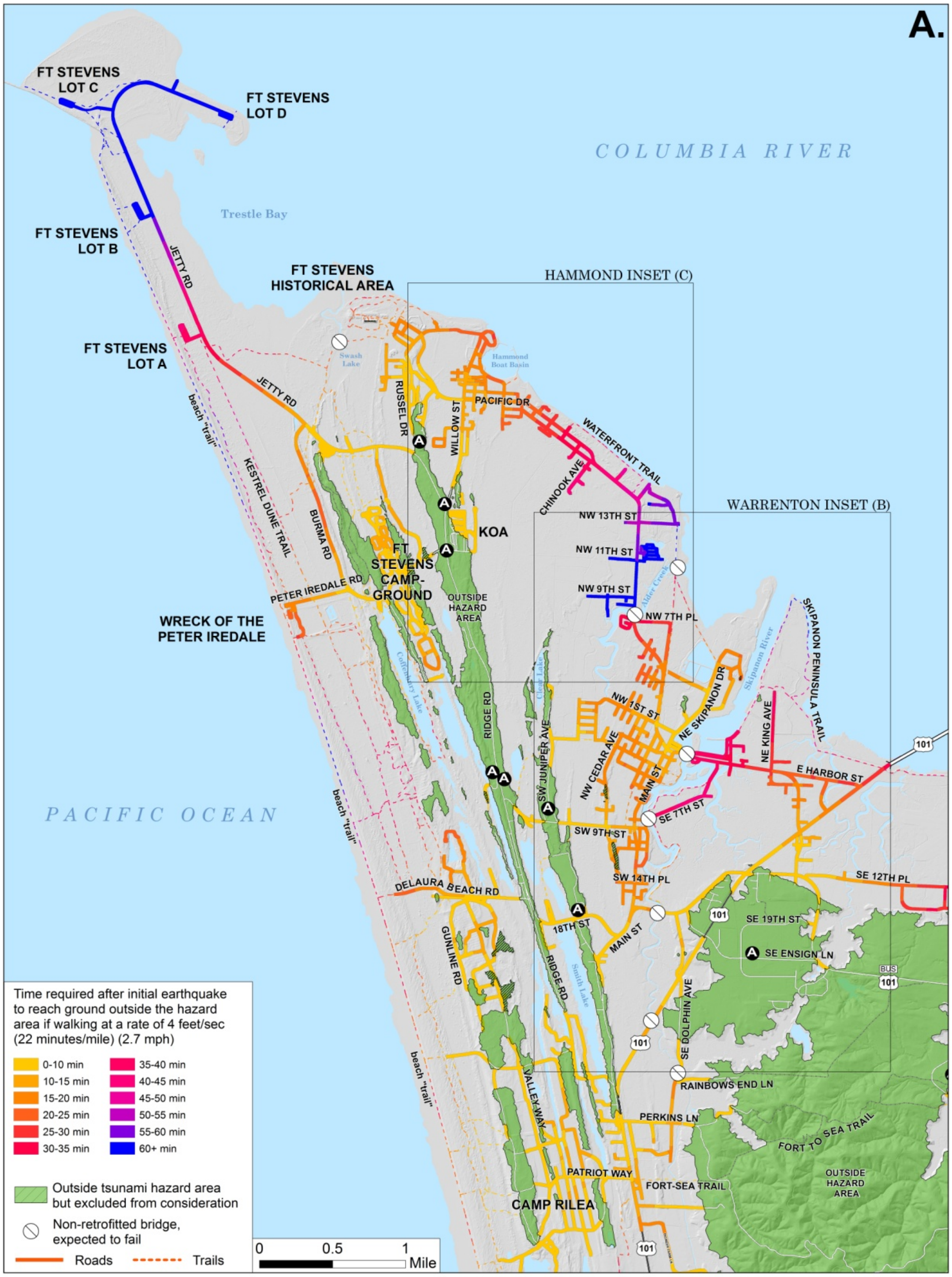
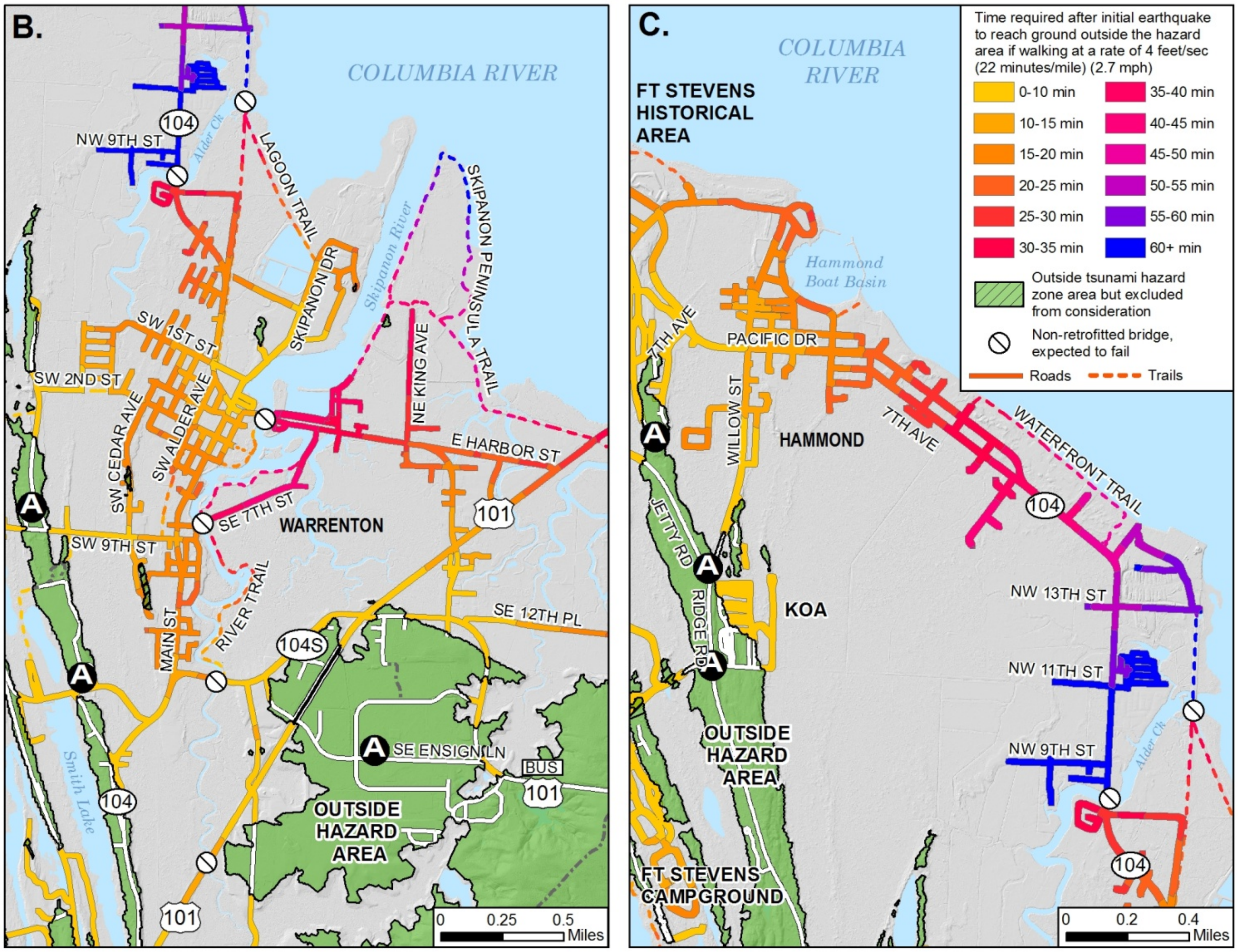


Figure 3 1, *continued*. **Modeled pedestrian evacuations assuming a 4 fps speed during an XXL1 local tsunami event: A) northwest Clatsop County, Oregon; B) Warrenton inset; C) Hammond inset.**



Modeled "beat the wave" (BTW) speeds are presented in **Figure 3-2** for the entire study area, while **Figure 3-2B** and **C** provide more detailed views of the BTW speeds required in the communities of Warrenton and Hammond/Alder Creek. Recall that these figures integrate the results of the tsunami wave arrival times and the least cost path distance analyses enabling the public to better understand the ***minimum speeds*** required to evacuate the inundation zone before being caught by the approaching tsunami. For the purposes of this map, we assume that bridges that have not been retrofitted to withstand a > Mw 9.0 earthquake will fail. In addition, we include a 10-minute delay before commencing the evacuation to account for the expected dazed and disorientated state of evacuees following the severe earthquake shaking, and the time required to exit buildings.

Figure 3-2. Modeled "beat the wave" (BTW) speeds for XXL1 local tsunami event: A) northwest Clatsop County, Oregon; *B)* Warrenton inset *[next page]*; *C)* Hammond inset *[next page]*.

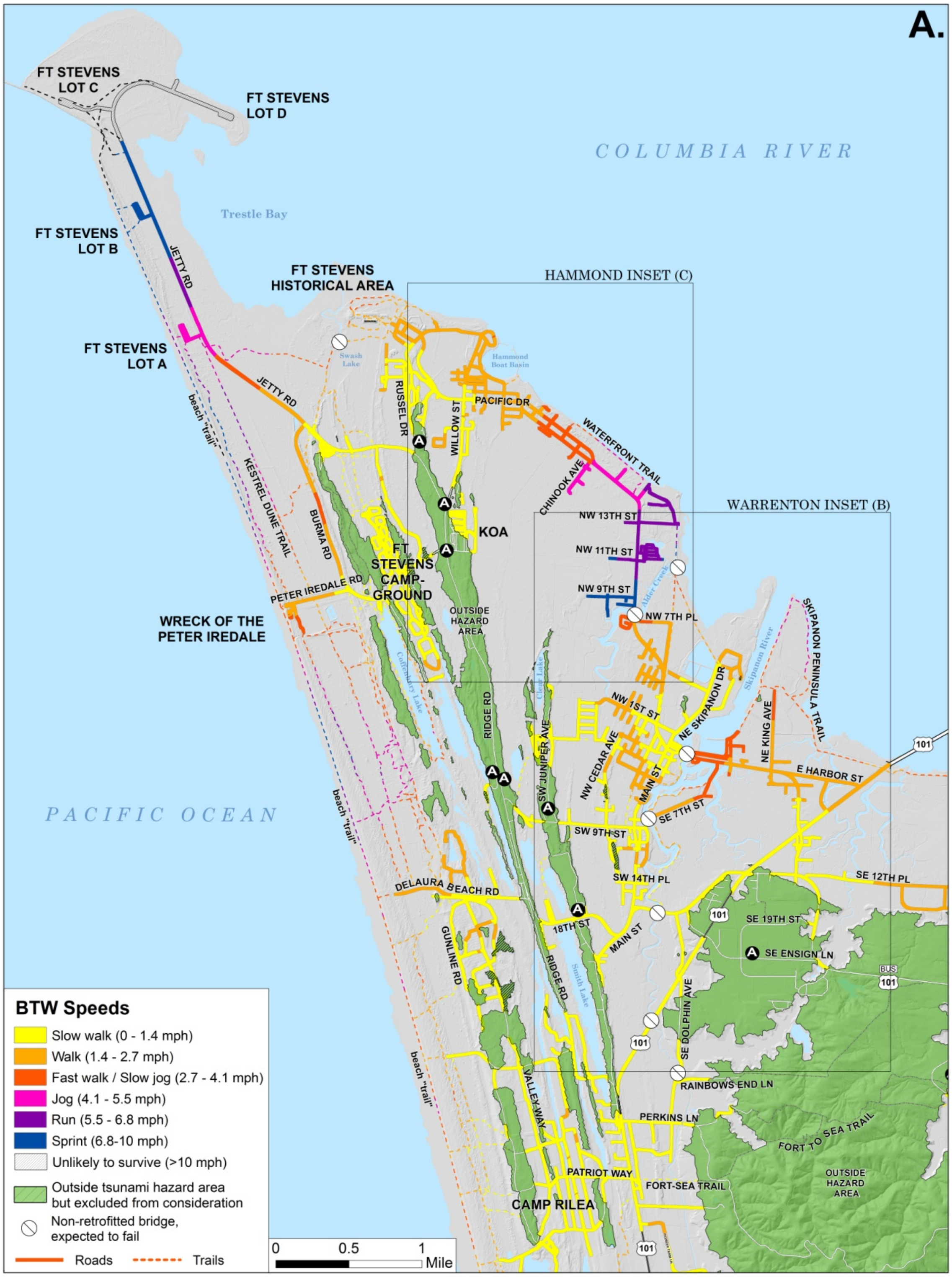


Figure 3.2, *continued*. **Modeled Beat the wave (BTW) speeds for XXL1 local tsunami event: A) northwest Clatsop County, Oregon; *B)* Warrenton inset; *C)* Hammond inset.**

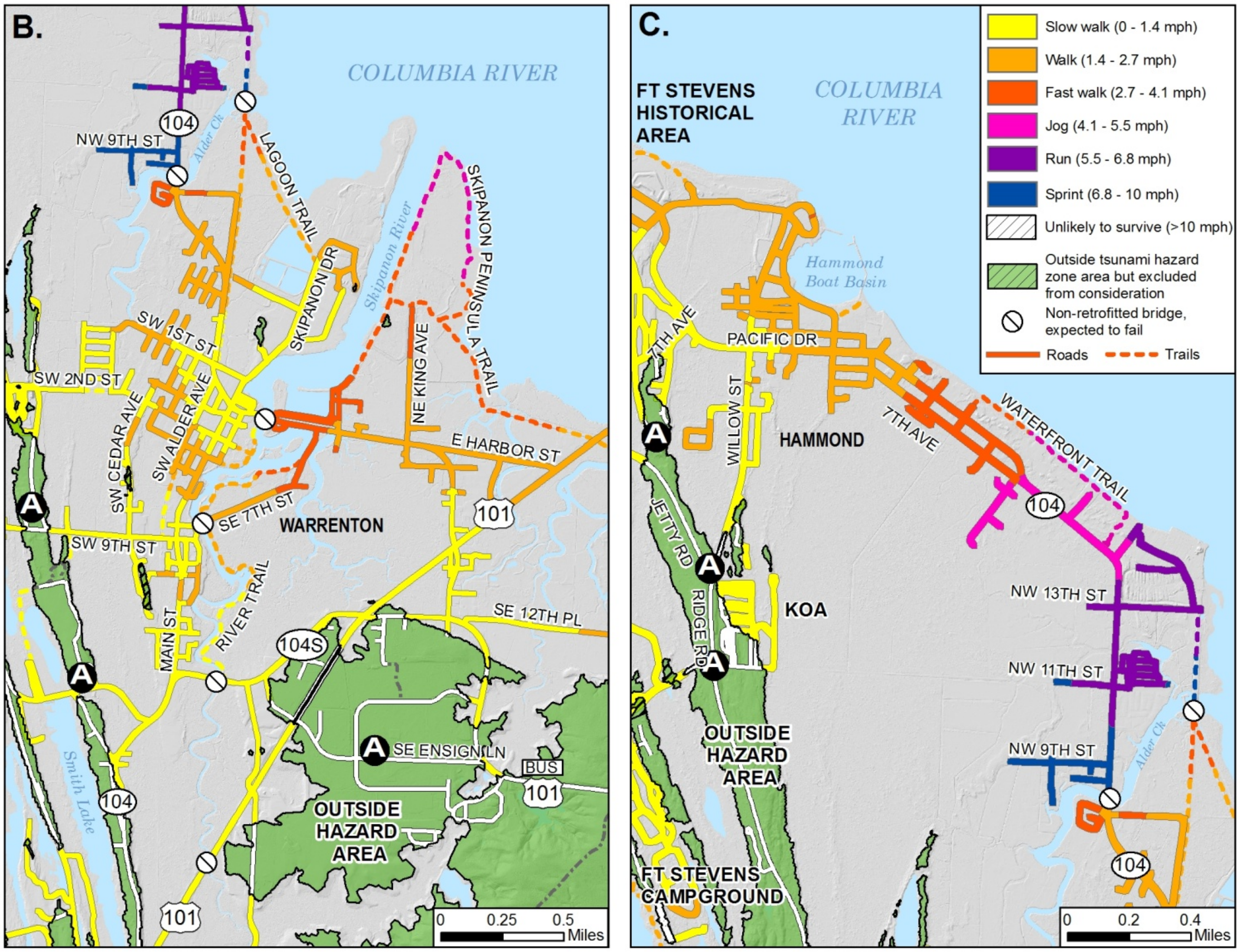


Table 3-1 presents a summary of the range of speeds and unit equivalents used in **Figure 3-2** that will be used throughout the remainder of this report.

Table 3-1. Evacuation speed categories and their equivalents.

	Speed		
Description	**Feet/ Second**	**Miles/ Hour**	**Minutes/ Mile**
Slow walk	0–2	0–1.4	44
Walk	2–4	1.4–2.7	44–22
Fast walk / slow jog	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 impaired adults (see Figure 6 of Fraser and others [2014]).

As can be seen in **Figure 3-2**, our modeled BTW results confirm that much of the Clatsop Plains is classified with ***minimum speed*** characterized as a ***"slow walk"*** (yellow roads). This suggests that evacuation to safety is achievable for much of the area. Nevertheless, following a disaster other factors will almost certainly contribute to impede travel times. Our current modeling does not account for these potential ancillary effects. As a result, ***evacuees should maintain the overarching goal of immediately evacuating following the earthquake, and moving as rapidly as possible to ensure they reach safety with ample time to spare.***

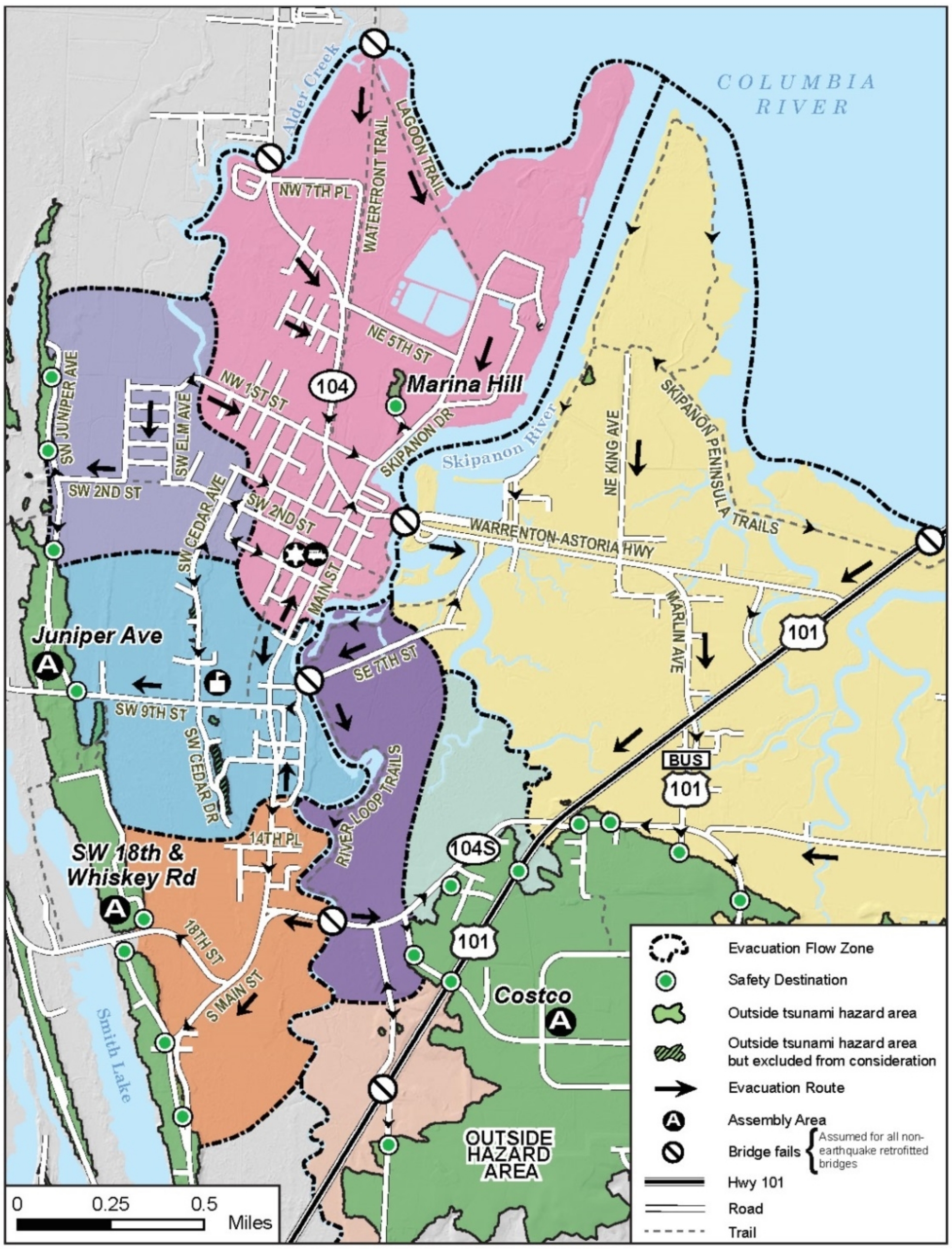
Figure 3-2 confirms that evacuation in a few areas on the Clatsop Plains will be extremely challenging if not impossible such that vertical evacuation or alternative route construction are the only options available to save lives. Identified problem areas include:

- The south end of the Alder Creek area (**Figure 3-2C**) in the region of NW 9th Street immediately north of the Highway 104 bridge. BTW modeling indicates that residents must ***"sprint"*** (travelling at a minimum speed of 8.2 mph) to reach their nearest evacuation point of safety, located near Ridge Road, south of Hammond. Given these speeds, it is probable that elderly residents and children living in this area would not survive a local XXL1 Cascadia tsunami;
- Parking lot D at the distal end of Jetty Road, on Clatsop Spit (**Figure 3-2A**). Visitors to this site will not survive the tsunami as the time required to reach safety is too long relative to when the tsunami arrives. Furthermore, southward evacuation is effectively eliminated at ~ 20 minutes just south of the turnoff to lot C due to early wave arrival. The required evacuation speeds are ~ 12–14 mph, which is only achievable with the aid of a vehicle;
- BTW speeds at parking lot C (**Figure 3-2A**) and the viewing platform adjacent to the south Columbia River jetty are comparable to lot D. Thus, visitors at this site are unlikely to survive the event;
- On the beach south of parking lot A (**Figure 3-2A**). Visitors to this site are unlikely to survive the event as the time required to reach safety is too long given the early wave arrival;
- On the beach, midway between Delaura Beach Road and Peter Iredale Road (**Figure 3-2A**). Visitors to this site are unlikely to survive the event as the time required to reach safety is too long relative to early wave arrival.

3.1 Warrenton

Figure 3-3 presents the least cost (path) distance modeling for the community of Warrenton. Recall that the purpose of this type of modeling is to identify and define detailed evacuation routes, which are used to define the evacuation corridors or flow zones in each community. Each of the evacuation flow zones defines the area being evacuated and the nearest destination points of safety (green circles), that is, those areas outside of the tsunami inundation zone and hence safe from a maximum considered XXL1 local tsunami event, as well as assembly areas outside the tsunami hazard area (black circles labeled with "A").

Figure 3-3. Least cost (path) distance modeling for the community of Warrenton showing evacuation flow zones assuming non-retrofitted bridges failure throughout the area.



As can be seen in **Figure 3-3**, the Warrenton area has eight evacuation flow zones, and each zone has 1-2 evacuation destinations. For example, people located in the cyan-colored polygon adjacent to SW 9th Street would evacuate due west onto Juniper Road located directly west of town (**Figure 3-3**). Residents located near S Main Street (orange zone) at the south end of town evacuate southwest along S. Main Street and then up either N or S Whiskey Road (**Figure 3-3**). On the other hand, evacuees on the northwest side of the Skipanon River would converge on a piece of high ground called "Marina Hill," located near the south center of the rose colored polygon, adjacent to NE Skipanon Drive and near the Daniel Knight Warren House (**Figure 3-3**).

Once evacuation flow zones had been defined, we calculated BTW speeds for the Warrenton area (**Figure 3-4**). Because tsunami wave arrival times for the Warrenton area are on the order of ~ 34–40 minutes and evacuation destinations (i.e., safety) are close by, the modeled BTW speeds indicate that much of the area is characterized with ***minimum*** evacuation speeds that range from ***"slow walk"*** to ***"walk."*** To better understand the potential effect of bridge failure and loss of certain evacuation destinations, we define three scenarios based on the following:

1. 10-minute delay taken from the beginning of the earthquake. All bridges are considered undamaged and remain intact, allowing for safe evacuation across them (**Figure 3-4A**);
2. 10-minute delay taken from the beginning of the earthquake. Only bridges that have been seismically retrofitted to survive a > Mw 9.0 earthquake remain intact. Bridges that have not been retrofitted are considered to fail such that evacuation routes at these locations are cut off (**Figure 3-4B**); and,
3. As above, but with "Marina Hill" removed as an evacuation destination (**Figure 3-5**).

3.1.1 Warrenton scenario 1: 10-minute delay, bridges remain intact

Figure 3-4A indicates that visitors walking the Skipanon peninsula trails located next to the Skipanon and Columbia Rivers will have to move rapidly in order to reach safety, at speeds considered to be mainly a ***"fast walk"*** to ***"slow jog."*** Furthermore, those trail walkers near the distal end of the peninsula trail will have to travel the fastest, with one section of the peninsula requiring ***"run"*** speeds for survival. Because of the higher speeds required in these areas, we anticipate that the elderly and young children would struggle to reach safety in time and hence would probably not survive the tsunami.

Although evacuation routes north of Alder Creek are not shown in **Figure 3-4,** the nearest evacuation destination for those residents is "Marina Hill," located adjacent to Skipanon Drive. These evacuees must travel south over the OR 104 bridge in order to reach safety. This scenario assumes that the OR 104 bridge over the creek does not fail. As described in detail in section 3.2, the expected failure of the OR 104 bridge over Alder Creek in response to the earthquake shaking creates severe limitations on the survivability of those people located immediately north of Alder Creek.

All other BTW speeds in Warrenton are characterized with ***minimum*** evacuation speeds that range from ***"slow walk"*** to ***"walk."*** This is entirely due to their close proximity to evacuation destinations (safety, characterized by green and black circles in Figure 3.4).

Figure 3-4. "Beat the wave" speed modeling for the community of Warrenton. A) 10-min evacuation delay, bridges survive; B) 10-minute evacuation delay, non-retrofitted bridges fail. Not all evacuation flow zone boundaries are shown on this map; only the primary north-south divide (black dash-dot line) is shown to emphasize the effect of removing bridges.

A.

B.

3.1.2 Warrenton scenario 2: 10-minute delay, non-retrofitted bridges fail

In this scenario, all bridges in the Warrenton area *fail* during the earthquake shaking. As a result, evacuation across the bridges is eliminated and alternate evacuation routes must be used.

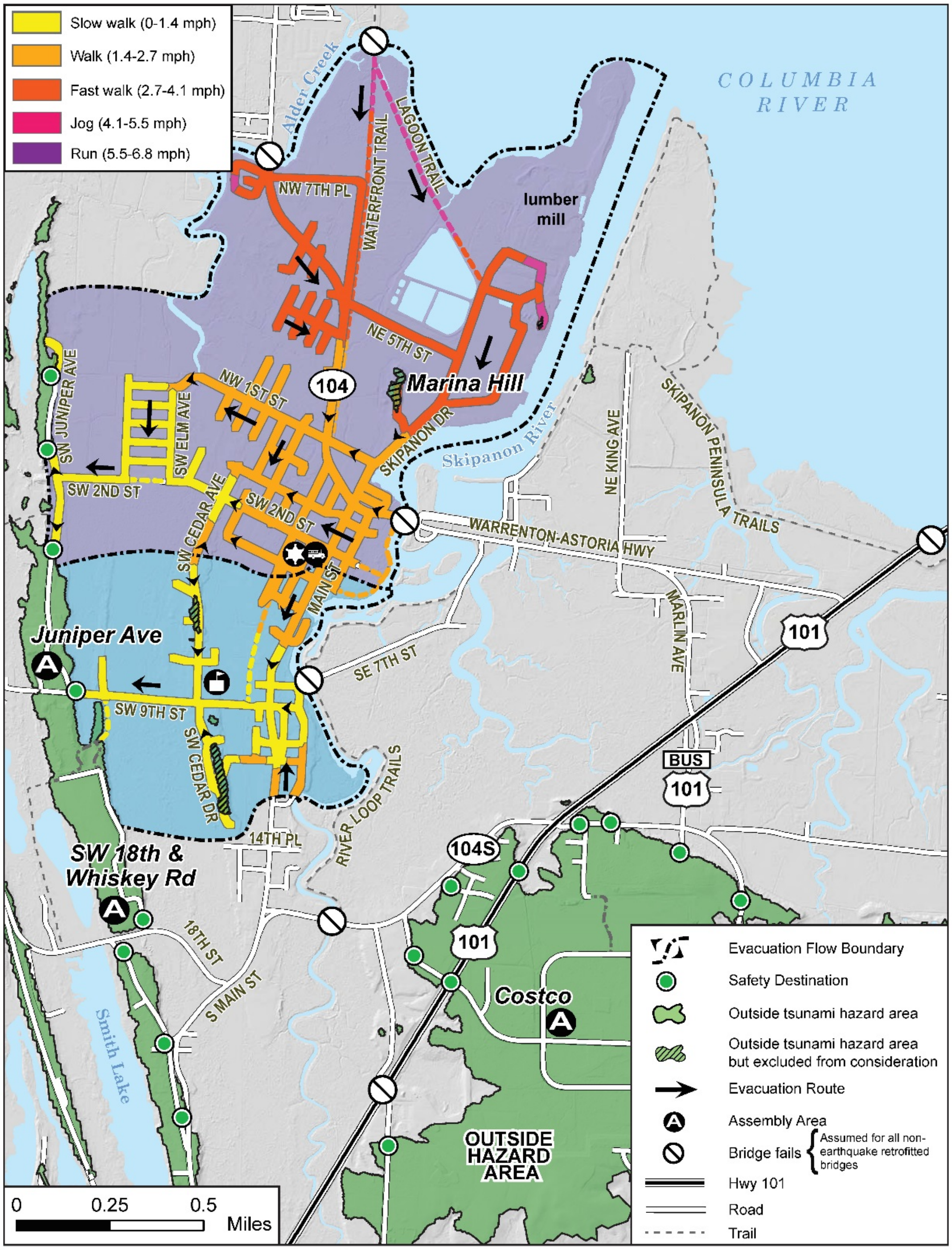
The main effect of bridge failure in Warrenton occurs adjacent to the OR 104 bridge over the Skipanon River. In this scenario, residents and businesses located on the east bank of the Skipanon River, must now evacuate east along the Warrenton-Astoria Highway (104), along Marlin Avenue, and then southwest along Highway 101 (**Figure 3-4B**). The required minimum speeds for residents and business located here are identified as ***"fast walk/slow jog."*** As a result, evacuation of the elderly and impaired adults would likely be challenging. All other areas throughout Warrenton remain essentially unchanged. See Appendix B for a complete map of the evacuation route arrows and flow zones for Warrenton scenario 2.

3.1.3 Warrenton scenario 3: 10-minute delay, non-retrofitted bridges fail, Marina Hill excluded as an evacuation destination

We modeled a third scenario for the Warrenton community that assumes that "Marina Hill" is unavailable as an evacuation destination. **Figure 3-5** presents the combined evacuation flow zones and modeled BTW speeds. For comparison, the original evacuation flow zones in this area can be seen in **Figure 3-3**, while BTW speeds are presented in **Figure 3-4**.

In this scenario, people in downtown Warrenton who would have evacuated to "Marina Hill," must now evacuate due west toward 2nd Street and onto SW Juniper Avenue to reach safety. People east of 3rd and Main Street must now evacuate due west along SW 9th Street to Juniper Avenue. In addition, due to the increased evacuation distances, the ***minimum*** speeds required to reach safety increase significantly from ***"slow walk"/"walk"*** to speeds that range from ***"fast walk"*** to ***"jog."*** The most important of these changes occurs in the north along Lagoon trail and in the northeast by the lumber mill. This scenario would have the greatest effect on the elderly and impaired. From the model results, removal of "Marina Hill" as a viable evacuation destination could lead to an increase in loss of life during a Cascadia event. We encourage the City of Warrenton to work with the owners of this property to ensure its availability for evacuation purposes prior to an actual event.

Figure 3-5. "Beat the wave" speed modeling and evacuation flow zone in Warrenton assuming "Marina Hill" is not available as an evacuation destination.

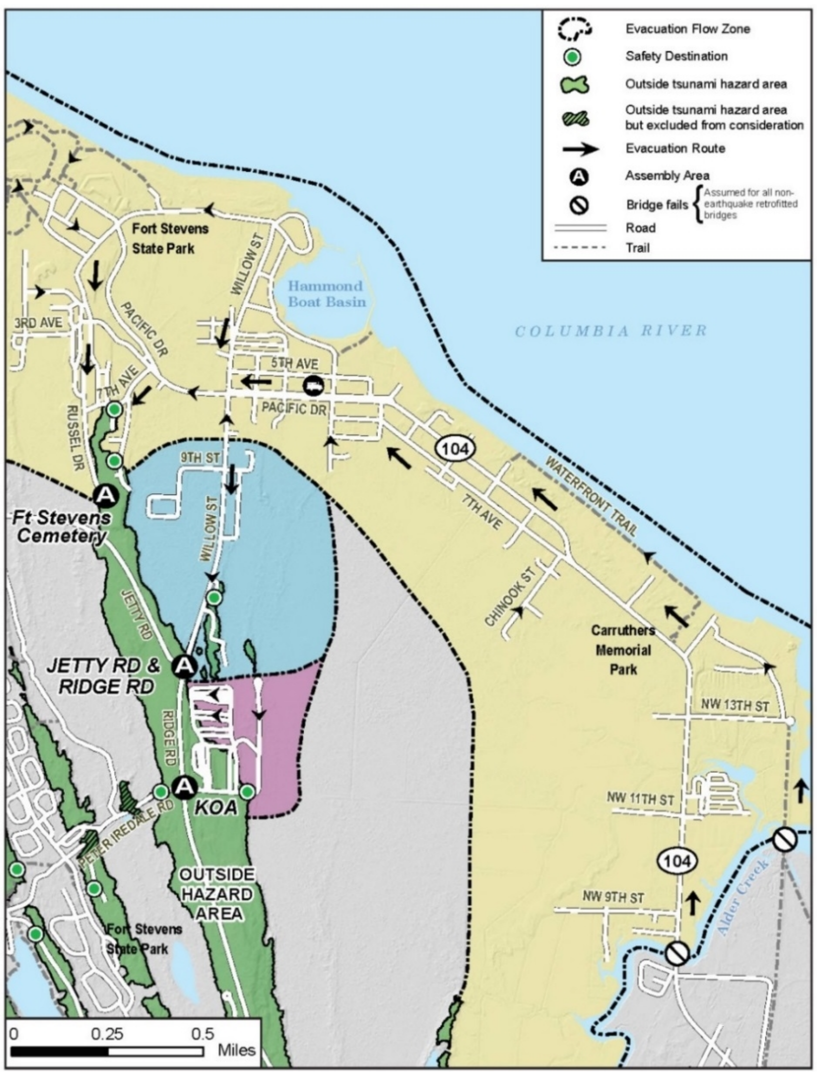


3.2 Hammond/Alder Creek

Figure 3-6 defines least cost (path) distance modeling for the community of Hammond. As noted previously, this analysis is used to identify and define detailed evacuation routes, which are used to delineate the evacuation corridors or flow zones in each community. **Figure 3-6** indicates that the Hammond area has three evacuation flow zones. These include two small zones associated with the KOA campground and a portion of Willow Street; both are located just south of the town of Hammond. Furthermore, both areas have evacuation destinations that are located very close to residents, enabling potentially easier evacuation during a local Cascadia tsunami event.

The third and largest flow zone encompasses all of Hammond and extends down to Alder Creek. From our modeling we identify the nearest evacuation destination located at the intersection of Quinnat Street and 7th Avenue; a second destination is located up Peacock Street, which intersects with 7th Avenue (green dots in Figure 3-6). Fort Stevens Historical Area also has a designated assembly area nearby at Soldiers Cemetery on Russell Drive. As noted previously (section 3.1.1), because of the combination of large evacuation distances and wave arrival times, residents living adjacent to Alder Creek will face significant challenges reaching safety.

Figure 3-6. Least cost (path) distance modeling for the community of Hammond showing evacuation flow zones.



Having defined the evacuation flow zones, we then modeled BTW speeds for the Hammond/Alder Creek area. These data are presented in **Figure 3-7** and **Figure 3-8** based on four scenarios:

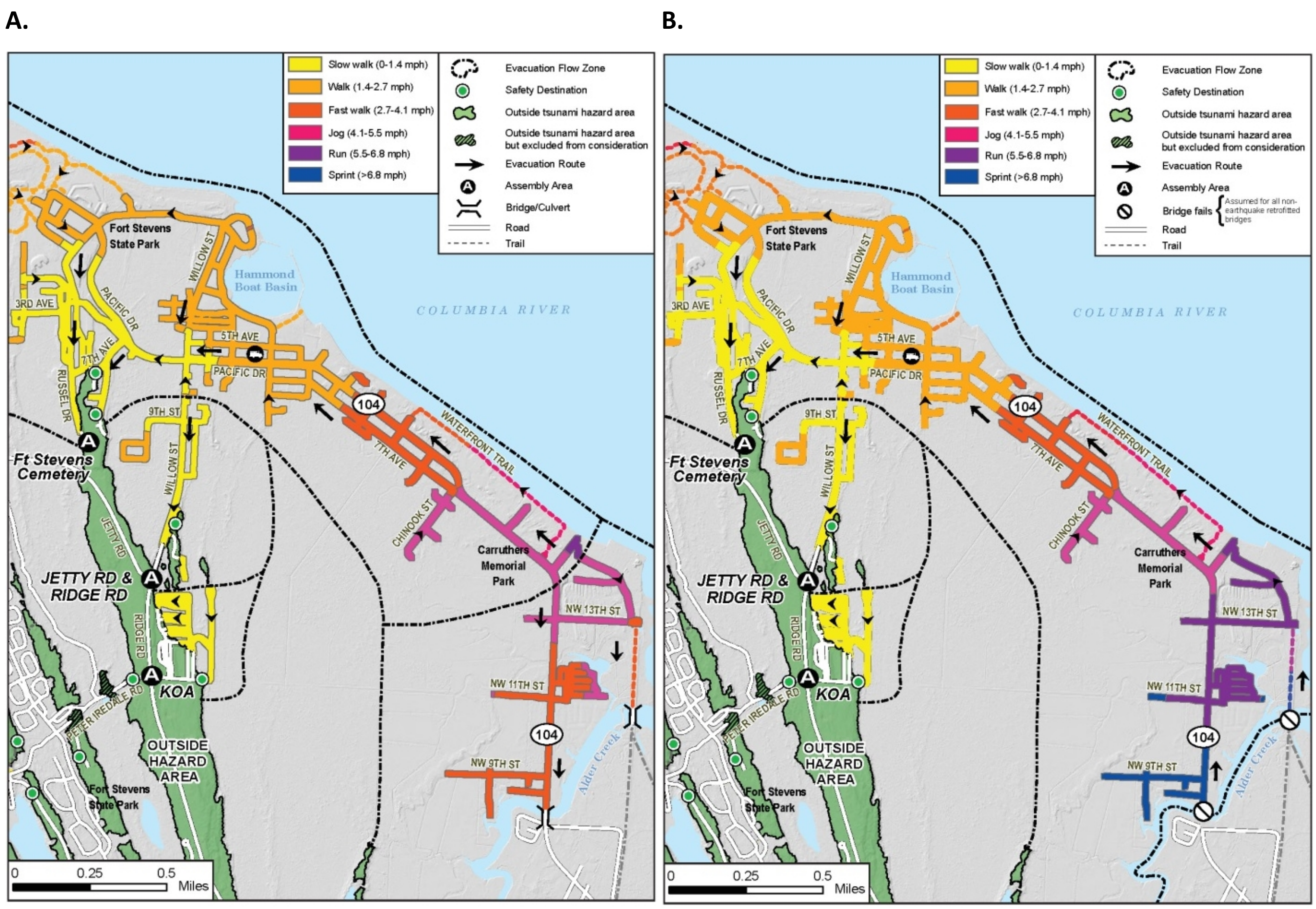
1. 10-minute delay taken from the beginning of the earthquake. All bridges are considered undamaged and remain intact allowing for evacuation across them (**Figure 3-7A**);
2. 10-minute delay taken from the beginning of the earthquake. Only bridges that have been retrofitted to survive a > Mw 9.0 earthquake remain intact. Bridges not retrofitted are expected to fail such that evacuation routes at these locations are eliminated (**Figure 3-7B**);
3. As above, but with the inclusion of a hypothetical extension to NW 11th Street, enabling a westward evacuation directly to the KOA campground located adjacent to NW Ridge Road (**Figure 3-8A**); and,
4. As above in 2, but with the building of a hypothetical vertical evacuation structure constructed at Carruthers Memorial Park (**Figure 3-8B**).

3.2.1 Hammond scenario 1: 10-minute delay, bridges remain intact

Figure 3-7A reveals that residents in the immediate vicinity of the town of Hammond (west of Pacific Drive and Fleet Street), must travel at speeds considered to be a ***"walk"*** to ***"slow walk"*** in order to reach safety. For these residents, evacuation to safety is attainable. However, with distance to the east evacuation difficulty increases. As can be seen in **Figure 3-7A**, in this scenario with bridges intact, the larger Hammond evacuation flow zone actually ends just east of NW 15th Street. Northwest of this separation point, residents and businesses would travel northwest toward the evacuation destination at the intersection of Quinnat Street and 7th Avenue. Required ***minimum*** speeds are defined as a ***"slow jog,"*** that must be maintained along the entire length of the evacuation route. The exception to this is a small section at the distal end of NW 15th Street where the BTW speeds increase to a ***"run."***

In contrast, residents southeast of NW 15th Street and including the Alder Creek area travel south over the Alder Creek Highway 104 bridge toward "Marina Hill" located in Warrenton (**Figure 3-3** and Figure 3-4**A**) The modeled ***minimum*** evacuation speeds for these residents range from a ***"slow jog"*** to ***"fast walk."***

Figure 3-7. "Beat the wave" speed modeling for the community of Hammond and Alder Creek: *A)* 10-min evacuation delay, bridges survive; *B)* 10-min evacuation delay, non-retrofitted bridges fail.



3.2.2 Hammond scenario 2: 10-minute delay, non-retrofitted bridges fail

With bridge failure over Alder Creek, evacuation difficulty increases appreciably for residents living immediately north of the Alder Creek Highway 104 bridge (**Figure 3-7B**). With the loss of the bridge, southward evacuation to "Marina Hill" is no longer an option, such that the nearest evacuation destination is now at the intersection of Quinnat Street and 7th Avenue, ~ 2.8 miles away by Hammond (**Figure 3-7B**). Our modeling indicates that the required ***minimum*** evacuation speed to reach safety is 8.2 mph, which equates to running at ~ 7.3 min/mile pace. Such a speed is classified as a ***"sprint"*** that must be maintained along the entire length of the evacuation route. Although achievable for fast runners, such a speed would almost certainly be impossible for the majority of the population and especially the elderly, impaired, and families with children, especially infants. As a result, under this scenario we would expect to see a significant loss of life in the Alder Creek neighborhood as a result of being caught by the tsunami. This is especially the case given the strong likelihood that the routes will almost certainly have significant debris on them that could potentially serve to slow ability to travel quickly. Appendix C presents a complete map of evacuation route arrows and flow zones for Hammond scenario 2.

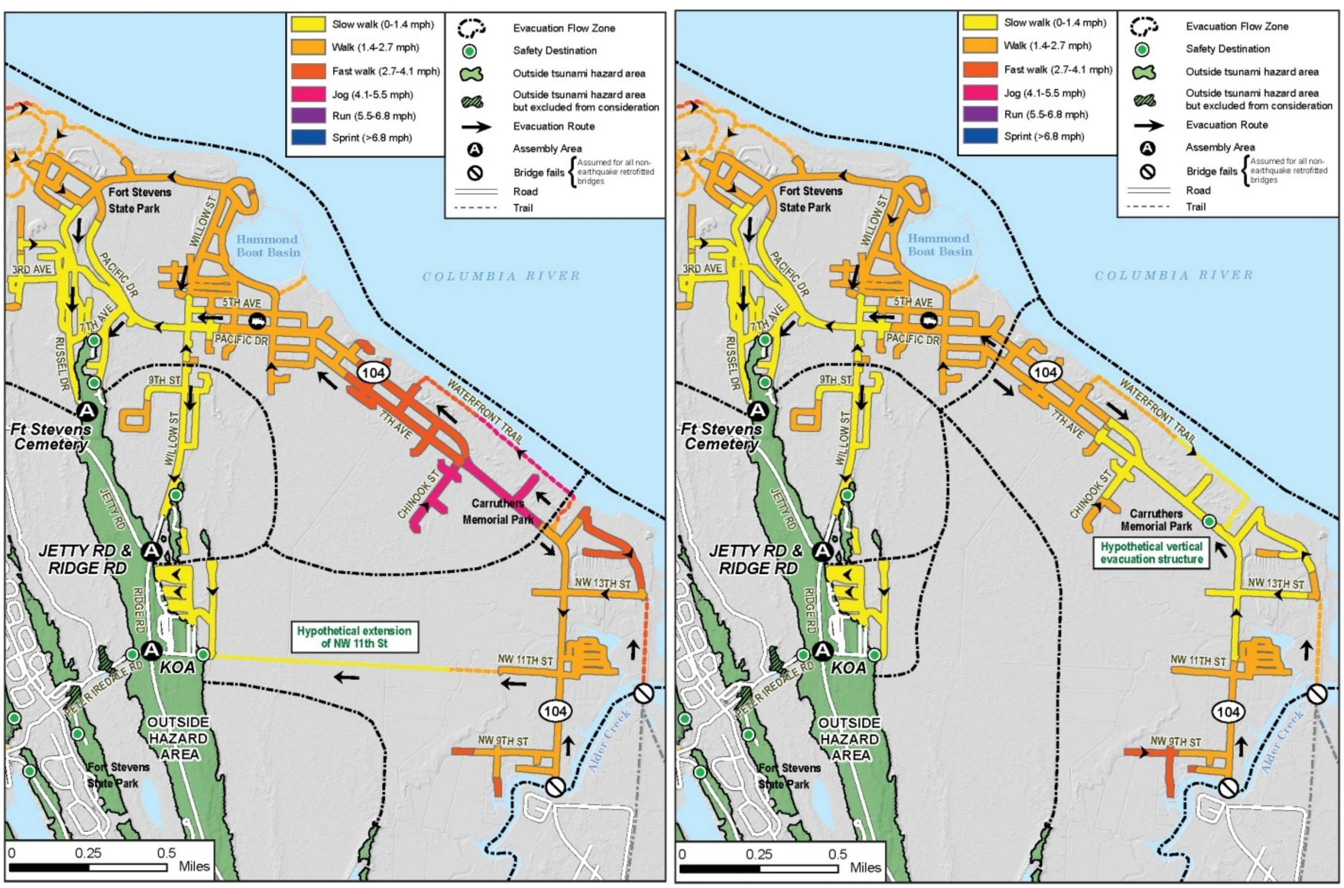
3.2.3 Hammond scenario 3: 10-minute delay, non-retrofitted bridges fail, hypothetical extension to 11th Street

With the sobering reality that residents in the Alder Creek area would probably not survive a maximum considered XXL1 local tsunami, we modeled a hypothetical case that reflects a westward extension and hardening of NW 11th Street, allowing it to connect with NW Ridge Road near the KOA campground. Such a road would need to be constructed to withstand possible liquefaction since much of this area crosses a wetland.

The model results for this scenario are presented in **Figure 3-8A**. With this new addition, evacuation of the Alder Creek community becomes attainable. BTW evacuation speeds are reduced significantly such that they now fall into the ***"fast walk"*** to ***"walk"*** categories, compared with a ***"sprint"*** as identified in **Figure 3-7B**. Under these circumstances, an XXL1 tsunami would be survivable. The modeling results also indicate little change to the area around NW 15th Street. As a result, residents in this area continue to evacuate to the west to the intersection of Quinnat Street and 7th Avenue at a ***"jog."***

Figure 3-8. BTW speeds for Hammond/Alder Creek based on two hypothetical scenarios: *A)* the westward expansion of NW 11th Street so that it merges with NW Ridge Road, and *B)* construction of a vertical evacuation berm at Carruthers Memorial Park.

A. **B.**



3.2.4 Hammond scenario 4: 10-minute delay, non-retrofitted bridges fail, hypothetical construction of a vertical evacuation structure

An alternative option to the westward expansion and hardening of NW 11th Street is the construction of a vertical evacuation structure at Carruthers Memorial Park, located between NW 15th Street and NW 17th Avenue and next to the Warrenton-Astoria Highway 104. Such a structure could be of the form of a hardened berm and would need to be designed to an elevation exceeding ~ 8.5 m (~ 28 ft). This is based on a maximum tsunami flood elevation of ~ 5.7 m, plus a 50% safety margin. See Appendix G for a complete map of maximum flow depths for the study area. Furthermore, the structure would need to be of a sufficient size to accommodate a large enough group of people. Should this option be explored in the future, we recommend additional modeling to assess the engineering requirements needed to construct a safe structure.

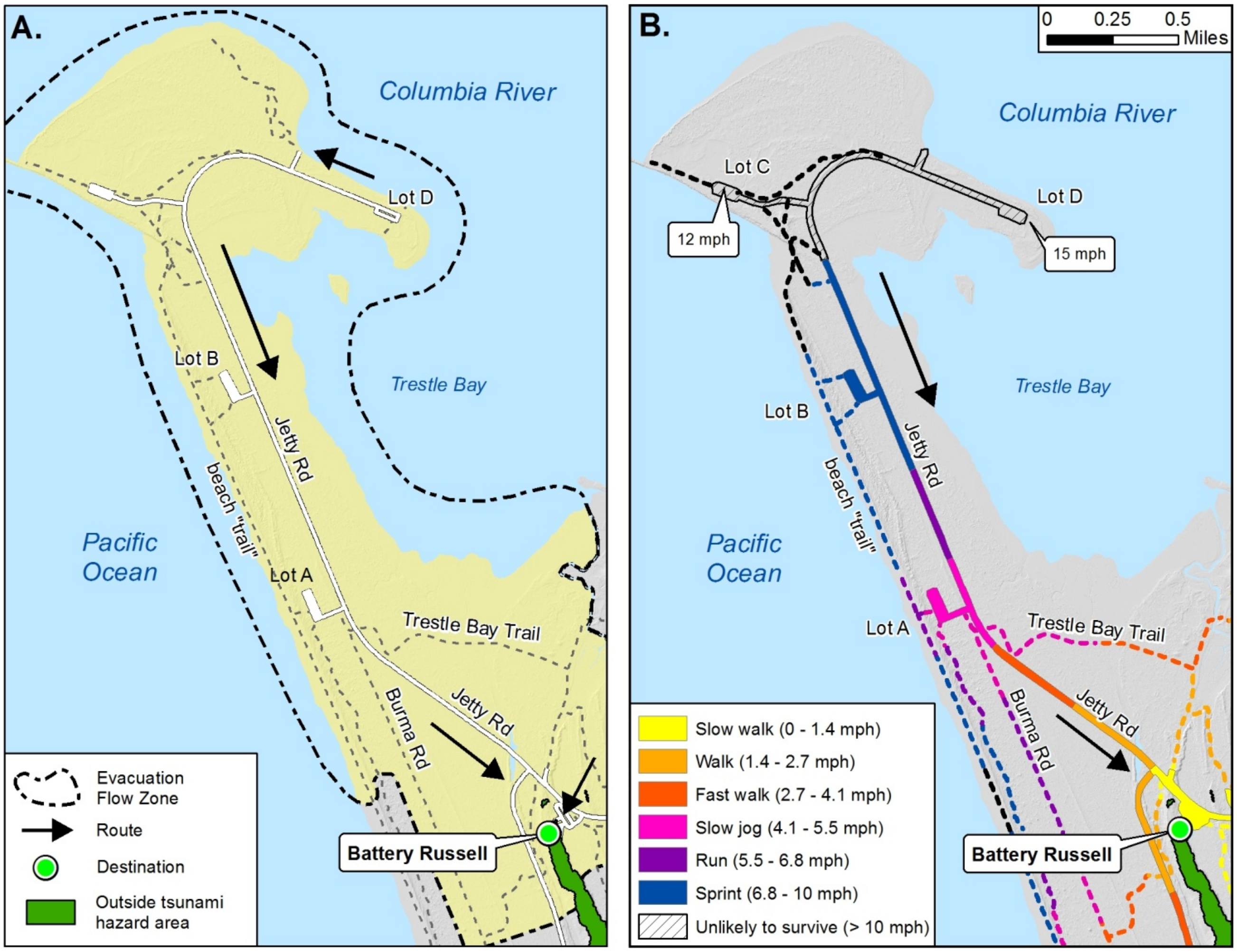
Our model results (**Figure 3-8B**) clearly demonstrate the benefits of building such a structure in this community, with the required ***minimum*** evacuation speeds having been reduced from a ***"sprint"*** (**Figure 3-7B**) to a ***"fast walk"*** at the south end of NW 9th Street, while most speeds are now closer to a ***"walk"*** to ***"slow walk"*** (**Figure 3-8A**). As with our Hammond scenario 3, evacuation of the Alder Creek community becomes attainable with this approach. Importantly, building a vertical evacuation structure at Carruthers Memorial Park benefits a much broader area when compared with the westward expansion of NW 11th Street. This is clearly evident by the reduction of the BTW speeds for those residents located on 7th Avenue, Highway 104, and on the Warrenton waterfront trail, effectively increasing their survivability. As a result, the construction of such a structure benefits a much larger community when compared with the expansion of NW 11th Street and of the two scenarios is the better long-term solution for this community.

3.3 Clatsop Spit

Figure 3-9A defines the evacuation flow zone and ***minimum*** "beat the wave" (BTW) speeds identified for Clatsop Spit. Detailed evacuation route arrows and flow zones can be found in Appendix D. As can be seen in the figure, the nearest evacuation destination is located at Battery Russell, ~ 4 miles to the south. Modeled BTW speeds are presented in **Figure 3-9B** and highlight a number of challenges facing evacuees in this area. These include the following:

- Evacuees in the vicinity of parking lots D and C out at the distal end of Jetty Road (**Figure 3-9B**) would probably not survive the tsunami as the speeds required to reach safety are too fast to be sustained on foot and only achievable in a vehicle. Given that much of the road surface would be affected by liquefaction, travel by vehicle is likely to be challenging. As a result, we expect a complete loss of life for anyone present in this area at the time of the earthquake;
- At parking lot B, the BTW speeds are categorized as a ***"sprint."*** ***Minimum*** speeds at lot B were determined to be ~ 8 mph (7.5 min/mile pace). As a result, evacuation from this location is survivable though both older and younger evacuees would probably be caught by the approaching wave;
- At parking lot A, BTW speeds are defined as ***"run"*** such that the majority of people in this area would probably survive the event, reaching Battery Russell before the tsunami caught them; and,
- Evacuees located out on the beach south of parking lot A would also be required to travel at speeds classified as a ***"sprint"*** in order to reach safety. Again, close inspection of the actual minimum speeds required to beat the wave and survive the event were found to be ~ 10.9 mph, akin to running at a 5.5 min/mile pace. From this, it is highly likely that the overwhelming majority of people located out on the beach in this area would be caught by the tsunami and killed.

Figure 3-9. ***A)*** **Least cost (path) distance modeling for Clatsop Spit showing the evacuation flow zone to Battery Russell;** ***B)*** **"Beat the wave" speed modeling for the spit after accounting for a 10-minute delay prior to evacuating.**



3.3.1 Clatsop Spit scenario 1: 10-minute delay, hypothetical construction of a vertical evacuation structure

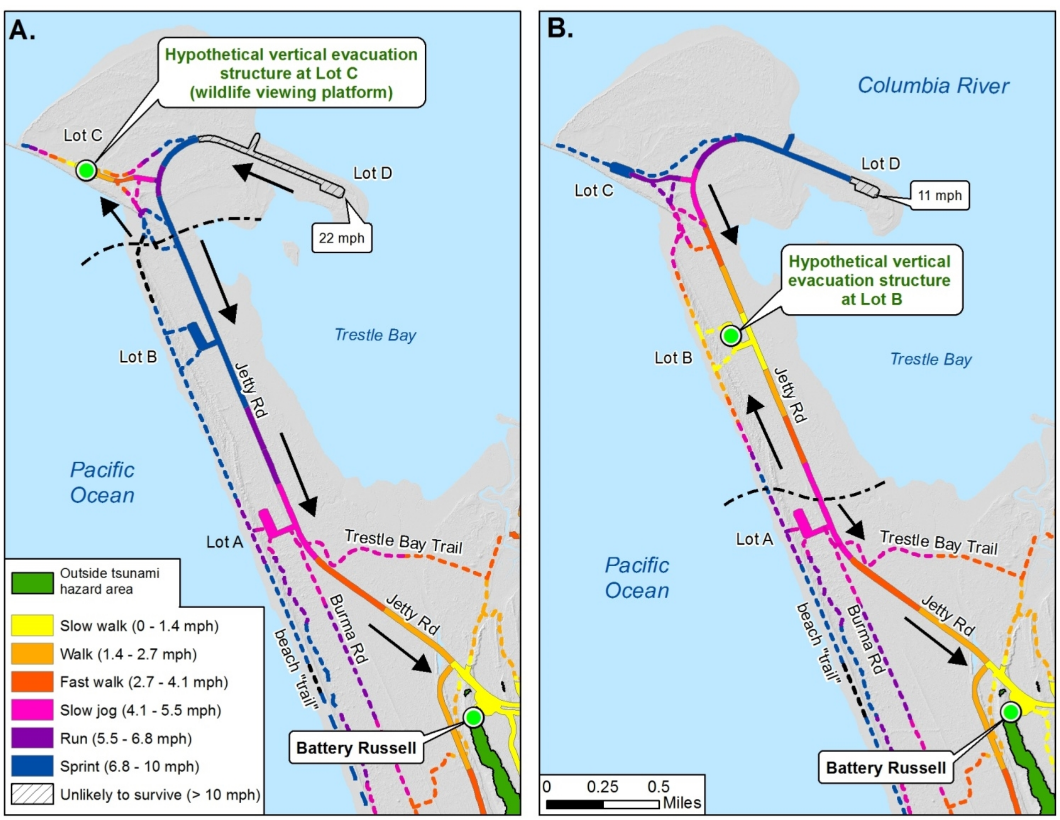
Given that visitors to Clatsop Spit would likely be killed by a maximum considered XXL1 tsunami, we examined the benefits of constructing a vertical evacuation structure at two locations: in parking lot C and at parking lot B. Such a structure could be of the form of a hardened berm or an engineered structure capable of withstanding the large tsunami forces. An initial estimate of the height of such a structure based on modeled flow depths in the lot C parking lot suggest that the structure would need to be exceed ~ 9–12 m (~ 30–39 ft). This is based on a maximum tsunami flood elevation of ~ 6-8 m in the parking lot, plus a 50% safety margin. See Appendix G for a complete map of maximum flow depths for the study area. Similar heights were identified for parking lot B to the south. In both cases, such a structure would need to be of adequate size to accommodate a sufficiently large group of people.

BTW evacuation speed results for parking lot C are presented in **Figure 3-10A**. The dashed line denotes the break point, where the LCD analyses splits the evacuation distances between heading north to lot C, versus heading south to Battery Russell. The results indicate that the benefits of such a vertical evacuation structure in lot C are confined to a very limited area. This is largely because the tsunami wave arrives very early at the site (~ 15 minutes). Factoring in a 10-minute delay (the time it takes to get moving) means that people in the surrounding area have ~ 5 minutes to get to the structure, effectively limiting the areal coverage to ~ 0.3 miles around the structure. Even at lot D the speeds required to reach safety (~ 22 mph) indicate that people would not reach the structure in time. In contrast, because there is no early wave arrival to the south, the speed required to reach safety for everyone south of the boundary (black dash-dot line) is considerably lower.

In contrast, we find that a hypothetical vertical evacuation structure built in parking lot B to the south (**Figure 3-10B**) greatly improves the chance of surviving the tsunami, while also benefitting visitors in a much wider area of the spit, including visitors recreating on the beach. As can be seen in the figure, the required ***minimum*** BTW speed at the distal ends of Jetty Road drops by 50% to 11 mph (16.2 fps; 5.4 min/mile pace). At this speed, and even using a shorter delay time of just 5 minutes, visitors to lot D would likely not make it to the structure in time.

As is shown in the figure, BTW speeds for the lot B option are significantly reduced everywhere in comparison to the lot C option. Additional modeling could be implemented in order to further refine the choice of potential vertical evacuation sites on the spit, especially if the goal is to identify a site where survivability at the distal end of Jetty Road in parking lot D becomes feasible.

Figure 3-10. "Beat the wave" (BTW) speeds for Clatsop Spit based on two hypothetical scenarios: *A)* construction of a vertical evacuation structure at parking lot C, and *B)* construction of a vertical evacuation structure at parking lot B. For each case, the BTW speed modeling assumes a 10-minute delay before evacuating.

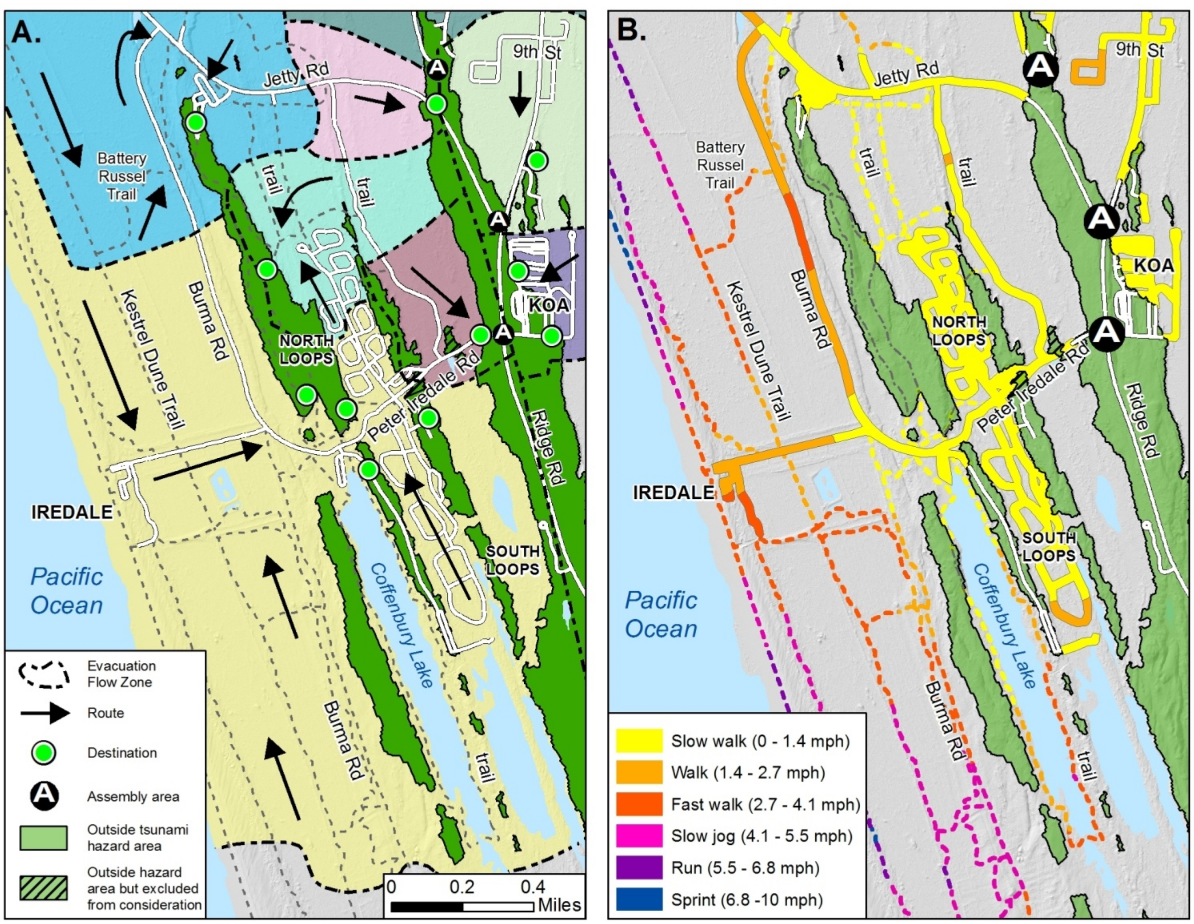


3.4 Fort Stevens State Park

Figure 3-11A defines the least cost (path) distance and BTW modeling for the Fort Stevens campground and day use area, which has multiple evacuation flow zones. Of these, the larger, pale yellow colored zone is probably of greatest interest to park officials. Evacuation destinations in the park include a number of potential sites: at least two sites on Peter Iredale Road, sites by Coffenbury Lake, and on the high dune near the north loop camp sites. Other evacuation destinations include "Battery Russell," which serves the Clatsop Spit evacuation flow zone (described previously), the KOA campground site, and Ridge Road. Given the prevalence of high ground, we did not consider any hypothetical vertical evacuation structures for Fort Stevens State Park. Detailed evacuation route arrows and flow zones can be found in Appendix E.

Minimum "beat the wave" (BTW) speeds identified for Fort Stevens State Park are presented in **Figure 3-11B**. These results indicate that much of the camp ground is classified with speeds in the ***"slow walk"*** category. Farther west out on the beach and on the park trails, the ***minimum*** evacuation speeds increase to a ***"fast walk"*** to ***"jog"*** category. The exceptions are a few areas out on the beach and most seaward trails, where the required ***minimum*** speeds increase to a ***"run."*** From these data it is apparent that reaching safety is possible for the majority of people camping at Fort Stevens. As with other sites, as ev**acuation speeds increase above a** *"walk"* **the e**lderly and those who may be mobile impaired are most affected.

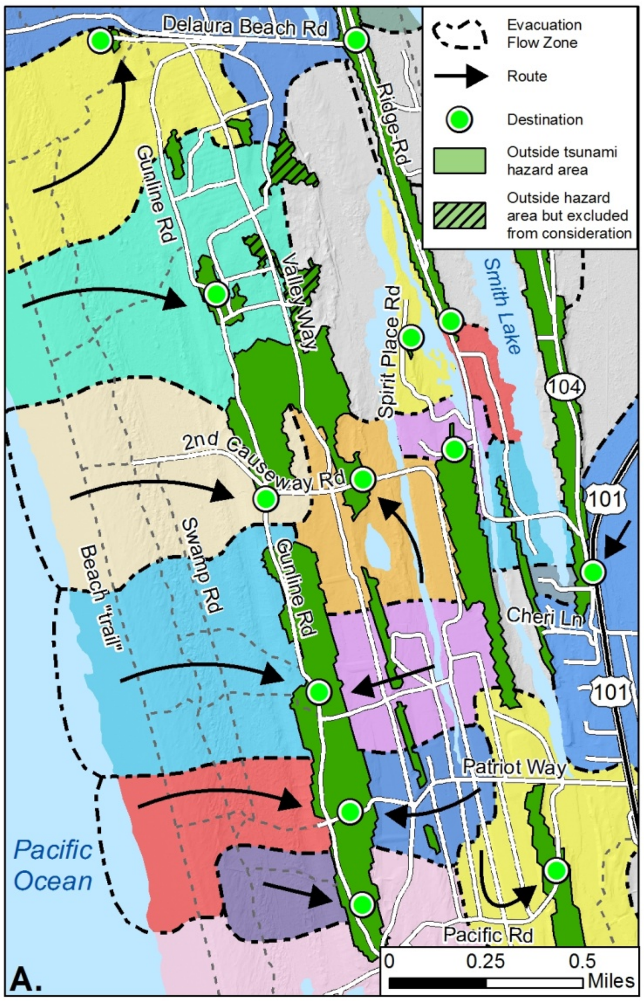
Figure 3-11. ***A)*** **Least cost (path) distance modeling for Fort Stevens State Park showing the evacuation flow zones to multiple evacuation destinations;** ***B)*** **"Beat the wave" speed modeling for the park after accounting for a 10-minute delay prior to evacuating.**

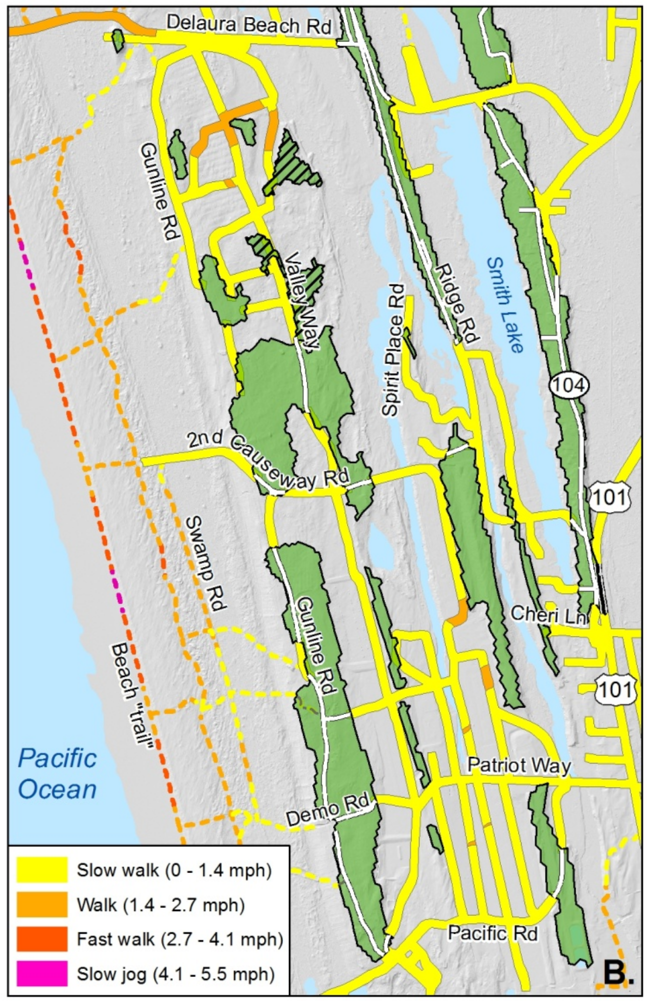


3.5 Camp Rilea

As shown in **Figure 3-12A**, the Camp Rilea military training area has over a dozen easily achievable safety destination sites. From our BTW speed modeling (**Figure 3-12B**), it can be seen that the bulk of the area is characterized with BTW speeds in the "slow walk" category. As a result, reaching an evacuation destination point and surviving the tsunami is possible throughout much of this area. Given the prevalence of high ground, we did not consider any hypothetical vertical evacuation structures for the Camp Rilea area. Detailed evacuation route arrows and flow zones can be found in Appendix F. Not surprisingly, the most challenging areas for evacuation purposes are out on the beach, where the minimum evacuation speeds to reach safety increase to a ***"fast walk."***

Figure 3-12. ***A)*** **Least cost (path) distance modeling for Camp Rilea showing the evacuation flow zones to multiple evacuation destinations;** ***B)*** **"Beat the wave" speed modeling for Camp Rilea after accounting for a 10-minute delay prior to evacuating.**





4.0 "BEAT THE WAVE" MAPS

Finally, we present a refined BTW map for the Warrenton and Hammond areas (**Figure 4-1** and **Figure 4-2**). These figures reflect the most conservative scenario with non-retrofitted bridges removed from the modeling as these are not expected to survive the earthquake shaking. Although we modeled the effect of excluding "Marina Hill" as an evacuation destination in Warrenton (discussed in section 3.1.3), we chose to include it in the final BTW map because this site remains a viable area for assembly during a tsunami event. We encourage the city of Warrenton to pursue discussions prior to a disaster taking place with the owners of the property to ensure that this location can be used as an evacuation destination site. Exclusion of this site would greatly impact the survivability of residents and visitors, especially the elderly, at the distal ends of the evacuation flow zones.

The final BTW maps depict with arrows and evacuation flow zones the most efficient evacuation routes. Evacuation flow zone boundaries, defined by the black dash-dot boundary lines, are especially useful because they clarify evacuation routes (i.e., which bridges to cross) and depict break points between two equally efficient routes to safety. Evacuation destinations (points of safety) are characterized by the green and black circles. Flow zones and the direction arrows to the evacuation destinations thus provide valuable guidance, even without the BTW speed information (**Figure 4-1** and **Figure 4-2**).

As discussed previously, estimates of needed speed to "beat the wave" for the maximum considered XXL1 tsunami in Warrenton (**Figure 4-1**) indicate that people in much of this area are able to evacuate to high ground, with ***minimum*** speed characterized in the ***""slow walk"*** to ***"walk"*** categories. Nevertheless, previous studies have found that the elderly are able to maintain speeds of ~ 2–4 fps for only short distances (Fraser and others, 2014). Langlois and others (1997) observed that ~ 0.5 percent of 72-year-old and older pedestrians in a sample of 989 people could cross an 8-ft course at ≥ 4 fps (81.1 percent could walk at only 1–3 fps). This would suggest that survival for these people is possible for much of Warrenton. This assumes that evacuation routes are easily travelled after the earthquake and, importantly, are well signposted. In contrast, elderly residents living at the north end of Warrenton adjacent to Alder Creek, or those visiting the Skipanon Peninsula trails or based on the east side of the Skipanon Highway 104 Bridge near downtown Warrenton, would likely not survive the event due to the higher speeds required to "beat the wave."

Removing the Alder Creek Highway 104 bridge has been shown to severely compromise evacuation for those residents located immediately north of and adjacent to the creek (**Figure 4-2**). Our analyses demonstrate that adding a vertical evacuation structure at Carruthers Memorial Park (**Figure 3-8B**) greatly enhances evacuation in the Alder Creek area. Notwithstanding that, a vertical evacuation structure built at Carruthers benefits a much broader region than would an extension to NW 11th Street, significantly increasing the survivability throughout this area, especially those with limited mobility and the elderly.

Although the speeds presented in **Figure 4-1** and **Figure 4-2** imply that people in most areas of the Clatsop Plains could evacuate in time following a local Cascadia event, it is inevitable that after the earthquake other factors will contribute to slow or impede actual evacuation travel times. Accordingly, ***evacuees should maintain the overarching goal of immediately evacuating following the earthquake, and moving as rapidly as possible in order to ensure they reach safety with ample time to spare***. The speeds presented in **Figure 4-1** and **Figure 4-2** should be viewed only as minimum values such that faster travel remains the best approach for surviving such an event.

Figure 4-1. Final "beat the wave" map for the community of Warrenton.

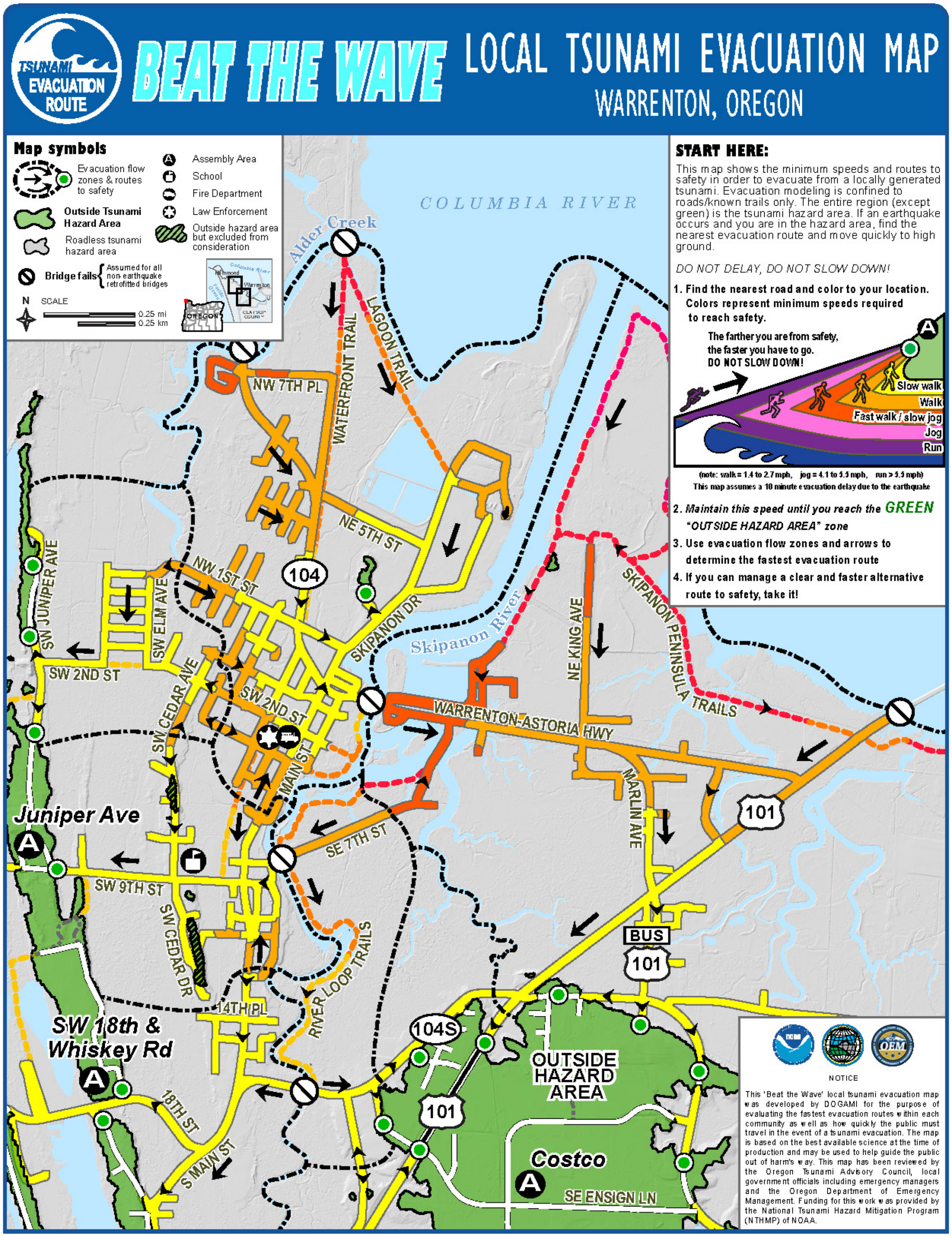
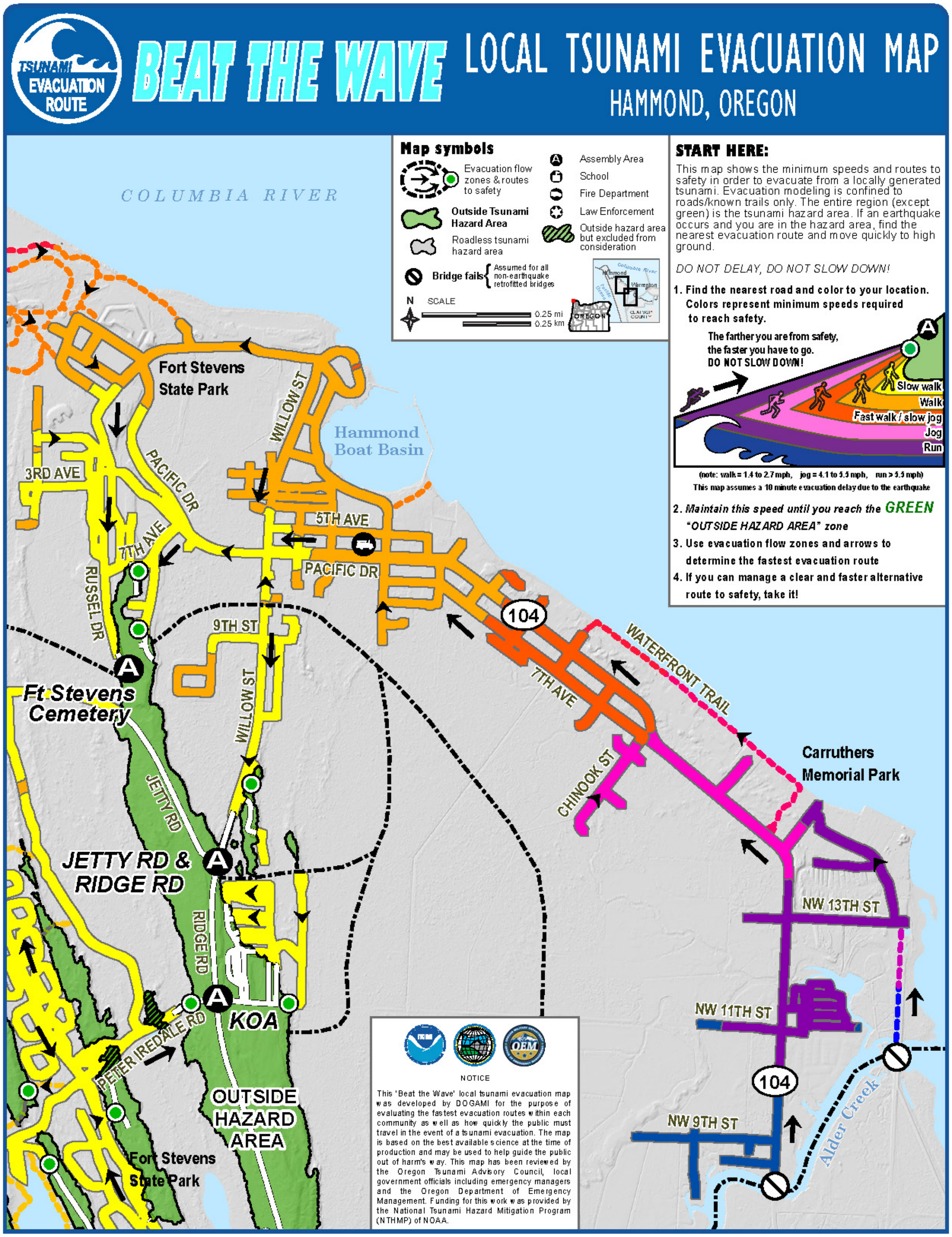


Figure 4-2. Final "beat the wave" map for the community of Hammond and Alder Creek.



5.0 DISCUSSION

5.1 Key findings

By depicting minimum speeds to reach safety from every part of a study area, the BTW approach to analyzing evacuation difficulty accomplishes in a single map what would take many maps using a single evacuation speed to estimate evacuation time (e.g., Wood and Schmidtlein, 2012). Unlike the single-speed approach, BTW analysis takes into account early tsunami arrivals at waterways and lowlands that can catch evacuees before they reach safety. Examination of the tsunami wave front advance across the study area is thus a critical first step in identifying where the tsunami may arrive early along some routes relative to what would be expected for normal dry land inundation. For example, on Clatsop Spit just south of parking lot C, wave arrivals times at 20 minutes could potentially impact evacuation from parking lot D, effectively cutting off escape to Battery Russell (**Figure 3-9** and **Figure 3-10**). Similarly, early wave arrival times in the Hammond boat basin could potentially affect those evacuating from north of Alder Creek, compromising their chance of reaching safety. Minimum speeds to safety must therefore be adjusted upward to make sure that these critical points can be crossed by those evacuating toward them (Priest and others, 2015a,b). Our analyses have accounted for these effects and are included in the BTW modeling results presented for the northern Clatsop Plains.

Because bridges over Alder Creek have not been retrofitted to withstand such a large earthquake, we expect that they will collapse during the shaking, effectively cutting off evacuation to "Marina Hill" in the south. This loss critically affects people north of Alder Creek, such that their only form of escape will be to the northwest toward Hammond. However, our analyses demonstrate that the speeds required to successfully "beat the wave" are on the order of 12 fps (akin to a 7 min/mile pace), limiting evacuation success to only a few very fit adults. As a result, a portion of the population on the north side of Alder Creek would not be able to reach safety in time and would be killed en route by the tsunami.

Mitigation techniques for addressing sites where evacuation speeds are too high include installing vertical evacuation structures, providing more lateral evacuation routes, and/or reinforcing bridges expected to fail during a major earthquake. These techniques are especially important when accounting for the fact that most elderly are unable to sustain speeds of ~ 2-4 fps (**Table 3-1**) for very long (Wood and others, 2015).

In addressing such challenges, we explored several options in the Warrenton, Hammond/Alder Creek, and Clatsop Spit areas that target improvements in evacuation routes (e.g., the westward expansion of NW 11th Street) or focus on the construction of vertical evacuation structures. These analyses presuppose that any vertical evacuation structures have adequate capacity for the population served and are designed and constructed to remain intact and accessible after the earthquake shaking while also resisting tsunami forces and scour. With these assumptions in mind, our analyses clearly validate the benefits of building vertical evacuation structures at Carruthers Memorial Park in Hammond and at parking lot B on Jetty Road at the tip of Clatsop Spit. In both examples, the hypothetical installation of such structures was found to <u>*significantly*</u> improve evacuation times, thereby reducing the required <u>***minimum***</u> evacuation speeds to "beat the wave" and reach safety. These results demonstrate the power and utility of the least cost distance and BTW modeling approaches for examining and refining the locations of hypothetical mitigation techniques. In contrast, the Wood and Schmidtlein (2012) single-speed approach is really aimed at answering a simple question: which parts of a community can and cannot be evacuated at a single nominal walking speed such as 4 fps for unimpaired adults? The BTW map answers that question more accurately by binning output into multiple speeds, with the resultant evacuation opportunity map providing the yes-no answer at a glance.

In addition to consideration of vertical evacuation structures, retrofitting existing bridges throughout the Warrenton area remains another option for hardening evacuation routes. Our "with" and "without" model runs over these bridges demonstrate the importance of the bridges for evacuation purposes. However, as seen in Seaside, Oregon (Priest and others, 2015a,b) the benefit of retrofitting bridges to withstand such a large earthquake may be far smaller than the benefit obtained by building a well-sited vertical evacuation structure. Although these types of comparisons were not implemented for Warrenton, they remain an option should the city decide to further evaluate evacuation alternatives.

Regardless of mitigation considerations, good wayfinding is the key to survival. Even in areas where safety is nearby and all populations appear likely to survive based on BTW speeds alone, confusion about where to go can make the difference between life and death. The Clatsop Plains are characterized by low-lying areas covered with stabilized dunes (some densely vegetated) that create "islands" of high ground. It is not necessarily intuitive which direction to travel in order to reach the nearest high ground, especially when compared to communities with less complicated topography where high ground is fairly obvious (i.e., Astoria or Garibaldi). Clear and visible signage placed in key locations is extremely important, especially for areas containing high numbers of visitors such as Fort Stevens State Park and at some of the major stores along Highway 101 (i.e., Fred Meyer, Staples, etc.).

5.2 Uncertainties and potential improvements

BTW modeling for this study relied on a skilled analyst to examine wave front advance data to determine where evacuation routes might be compromised by early tsunami arrivals (i.e., establishment of intermediate critical points). An algorithm for placing intermediate critical points would eliminate human error. Likewise, the current BTW method has no algorithm that integrates the tsunami wave front arrival times as a cost in the LCD analysis. For example, the flow zone boundaries are established strictly on the basis of minimum distance to safety without regard to tsunami wave arrivals. If there were a quantitative way to assign costs to wave arrivals along every potential path, both minimum distance and least likelihood of being caught by the tsunami would influence location of flow zone boundaries.

This issue can be visualized using the hypothetical vertical evacuation structure scenarios for Clatsop Spit discussed in section 3.3. BTW results for a structure at Lot B initially yielded a flow zone boundary resulting in some people evacuating north to the structure instead of south to high ground at Battery Russell even if it required a slower speed to head south. If every potential path considered both distance and time, those kinds of inconsistencies could be removed.

In this approach, BTW speeds are limited to paths from the back shore to roads and trails, but starting at points between roads and trails will take longer than from points on roads and trails, so nearest BTW speeds will slightly underestimate or overestimate speed for evacuees starting between roads and trails. In Warrenton, distance to a road is generally less than or equal to about half the separation between city streets (approximately 100 ft or 30 m), which creates a 2% error for the western parts of town that are approximately 1 mile (1.6 km) from safety. For evacuees that may have high ground nearby but require travel over natural areas, BTW speeds may be overestimated by constraining evacuees to roads. These sources of error could be eliminated by running the model for all areas between streets and trails, but this would complicate demarcation of evacuation arrows and pathways by requiring more detailed land cover mapping (e.g., fences) and possibly resulting in pathways that run through private property.

Future BTW mapping could also focus on better characterization of the evacuation landscape after the initial earthquake. Required evacuation speeds are likely to be increased above model values by ground failures, such as earthquake-induced liquefaction, lateral spreading, and landslides or development of sinkholes from broken water mains. With respect to landslides, an initial effort could simply be to identify those evacuation routes that could be compromised by earthquake-triggered landslides by using the Statewide Landslide Information Database of Oregon (SLIDO) and landslide susceptibility maps developed by Burns and others (2016). Although there remain many uncertainties about ability to travel over such earthquake-disrupted terrain, these types of first-order analyses remain valuable from the standpoint of simply identifying potential obstacles that could compromise rapid and safe evacuation (Wood and others, 2016). In addition, downed power lines that may or may not be live as well as debris on roads are likely to slow or impede evacuation travel. Lowland areas of Warrenton and Hammond are on Holocene sand and silt, which are variably prone to liquefaction and lateral spreading (Madin and Wang, 1999). This is especially the case because of the close proximity of the water tables throughout this area, which is conducive to liquefaction. We did not include cost factors for these hazards in the LCD analysis, because of the highly site specific nature of the hazards and high uncertainty of their effect on evacuation speed. Recognition and mitigation of these hazards on key evacuation routes would be a useful means of decreasing this source of uncertainty in the evacuation modeling.

The BTW approach provides ***minimum*** speeds to safety for routes defined by the LCD approach, but the BTW apprach does not directly evaluate whether those speeds can be maintained along an entire route, for example in sand and up steep hills. One approach for dealing with this might be to incorporate into the BTW results additional safety factors that increase speeds to account for the length of path in difficult terrain. Furthermore, current BTW modeling does not account for human characteristics (age, gender, physical disabilities, etc.) that may be present in a local population. Thus, more refined modeling could be directed toward better evaluation of such social characteristics.

Research devoted to better understanding evacuee behavior is another area for future work. In our case study, 10 minutes is subtracted from the actual tsunami wave arrivals to account for delay of evacuation from earthquake shaking and behavioral factors, but this assumption is highly uncertain. The origin time for the tsunami wave arrival time data is the beginning of slip on the CSZ megathrust fault. Once slip begins, there is a variable but potentially significant amount of time required for the natural evacuation signal to arrive in the form of strong shaking. Departure will be additionally delayed by the shaking itself. In the magnitude 9.0 March 11, 2011, Tohoku earthquake, strong shaking lasted about 3–5 minutes (USGS, 2012), and, while coseismic slip on this earthquake was similar to that assumed for the XXL1 scenario (Witter and others, 2011), fault rupture width was larger and length shorter than estimated for a Cascadia event. There are little empirical data on how long it takes people to begin evacuation, but it is reasonable to assume that, as a minimum, walking would be difficult during the 3–5 minutes of strong shaking, but there is more uncertainty about the time needed to start evacuation after the shaking. The mean of 7 minutes found in the surveys by the Mas and others (2013) of La Punta, Peru is highly uncertain, as it is not based on data collected immediately following an event. This source of uncertainty could be decreased by systematic collection of behavioral data from modern local tsunami events and promotion of quick, instinctive evacuation through ongoing education programs with a focus on regular community-wide evacuation drills (e.g., Connor, 2005).

BTW analysis is more complex and time consuming than evacuation analyses that determine evacuation times from single speeds (e.g., Wood and Schmitdtlein, 2012; Wood and others, 2016). This is especially the case in more complicated communities such as in Seaside and Warrenton, where early wave arrival could compromise evacuation. Unlike single-speed methods, BTW studies require careful demarcation of intermediate critical points and separate LCD models for every critical point. BTW studies also require detailed information on tsunami wave arrival. If rapid analysis of large regions is the objective or if wave arrival times are not available, single-speed methods may be more practical, especially if the primary objective is to compare relative evacuation difficulty among a suite of communities rather than detailed guidance within one community.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This investigation accomplished the primary objective: to provide a quantitative assessment of evacuation difficulty on the northern Clatsop Plains, including the communities of Warrenton and Hammond. The investigation implemented the BTW ("beat-the-wave") approach to evacuation analysis developed by Priest and others (2015a,b), with a major refinement in that we can now account for variable speeds along a route due to differences in the route characteristics (e.g. flat vs steep, sand vs paved). As a result, the BTW approach accomplishes in a single map what would require multiple maps in previous approaches such as that of Wood and Schmidtlein (2012). In contrast, the simpler single-evacuation-speed approach of Wood and Schmidtlein (2012) is more practical for regional analyses.

The results of this study show that evacuation from much of the Clatsop Plains in response to a maximum considered XXL1 tsunami is possible. The exceptions are several distinct areas that include: north of Alder Creek; out at the tip of Clatsop Spit; and on the open coast beaches west of "Battery Russell." Without suitable mitigation techniques in these areas, we anticipate complete loss of life because the time required to "beat the wave" to safety is too long relative to arrival time of the wave.

To address the evacuation difficulty identified in these areas, vertical evacuation options are likely to be critical for successful evacuation, especially for those with limited mobility. Construction of more earthquake resistant bridges across the Skipanon River and over Alder Creek (the Astoria-Warrenton Highway 104) would also increase evacuation efficiency in Warrenton, but the area positively impacted by each bridge is small relative to that of a local vertical evacuation structure. Westward extension and hardening of NW 11th Street, north of Alder Creek, to the KOA campground on Ridge Road was found to be a less effective means of increasing efficiency of lateral evacuation of residents in the Alder Creek area.

7.0 ACKNOWLEDGMENTS

This project was funded by the National Oceanic and Atmospheric Administration (NOAA) through the National Tsunami Hazard Mitigation Program under award #NA14NWS4670048. We are especially grateful to Dr. Nathan Wood, U.S. Geological Survey who reviewed the report and provided many helpful suggestions and comments. We also thank Mr. Matt Williams (DOGAMI) who reviewed the geospatial information system (GIS) database files. Finally, we would like to acknowledge the City of Warrenton for their assistance and comments throughout the study.

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9.0 APPENDICES

- Appendix A: Seaside “beat the wave” (BTW) Ground Truth Test
- Appendix B: Detailed evacuation routes for Warrenton
- Appendix C: Detailed evacuation routes for Hammond
- Appendix D: Detailed evacuation routes for Clatsop Spit
- Appendix E: Detailed evacuation routes for Fort Stevens State Park
- Appendix F: Detailed evacuation routes for Camp Rilea
- Appendix G: Illustration of XXL1 tsunami maximum flow depths for northwest Clatsop County

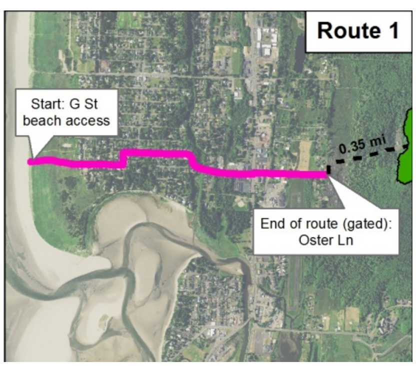
Appendix A: Seaside "beat the wave" (BTW) ground truth test

A small experiment was conducted in Seaside to evaluate the validity of the evacuation speed bins chosen (2, 4, 6, 8, and 10 ft/sec) and to assess the difficulty in actually maintaining a constant minimum speed over the course of an entire evacuation route. Five key routes were walked by the authors of this report. They recorded average speed along the route and when they reached critical locations (bridges, low areas, and safety). Each route is discussed in detail in Table A-1; both actual and expected wave arrival times are shown, that is, if the walker "beat the wave."

Overall, the results show that when traveling at the speed identified in the BTW map, an evacuee will reach safety ahead of the tsunami. Difficulties occurred only when the walker traveled slower than necessary.

Table A-1. Detailed description of each route walked including expected and observed walking speeds, time to critical locations including bridges, low points and safety, and a brief discussion of the results. Orange paths indicate a route requiring a "fast walk to a slow jog" (4-6 ft/sec) according to beat the wave data for Seaside; pink paths indicate a "jog" (6-8 ft/sec) (Priest and other, 2015b). Values with an asterisk indicate estimated data due to missing data. An explanation is provided for those instances. Blue text in the "Difference" column indicates a positive results – safety was reached ahead of the wave. Red text indicates the walker did not reach safety ahead of the wave (or did not travel at the pace requested by the map).

		BTW Speed and Wave Arrival Time	Actual Speed and Time	Difference (red = too slow, blue = survived)
Route 1	Speed	6-8 ft/sec	7.5 ft/sec	**within range**
1.22 miles	Speed category	Jog	Jog	**within range**
	Time to end of route (gate prevented reaching safety)	29.0 min	14.1 min	**14.9 min**
	Time to safety (Oster Lane)	33.3 min	18.4 min*	**14.9 min***



Discussion:
Route 1 starts on a sandy beach trail adjacent to Avenue G in Gearhart. The route heads due east toward Oster Lane. Safety was not reached due to a gated private property however it can still be concluded from the distance covered that the walker was well ahead of the wave, by nearly 15 minutes, when traveling at a speed consistent with the map (jog).

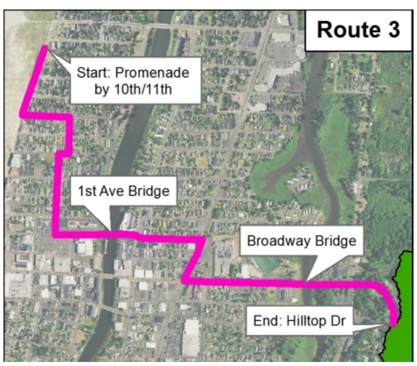
(table continued on next page)

(Table A-1, continued)

		BTW Speed and Wave Arrival Time	Actual Speed and Time	Difference (red = too slow, blue = survived)
Route 2	Speed	6-8 ft/sec	5.1 ft/sec	**0.9 ft/sec**
1.13 miles	Speed category	Jog	Walk	**too slow**
	Time to 1st bridge (12th St over Neawanna)	25.3 min	22.0 min	**3.3 min**
	Time to safety (Skyline Drive)	33.3 min	20.0 min	**13.3 min**

Discussion:
Route 2 starts at the mouth of the Necanicum River at the intersection of 26th Ave and Oregon St. The route heads south along Holladay Dr and Hwy 101 before crossing Neawanna Creek on the 12th St Bridge. The route then heads east along Ocean Ave and ends on Skyline Dr. The route requires a "jog" speed"; however, the walker only walked. In spite of moving slower than thought necessary, the walker beat the wave at Neawanna Creek by 3.3 minutes and at safety by 13.3 minutes. The narrow escape at Neawanna Creek is no surprise as early arrivals over both bridges proved to be critical to all seaward evacuation routes (Priest and others, 2015b).

Route 3	Speed	6-8 ft/sec	5 ft/sec	**1 ft/sec**
1.55 miles	Speed category	Jog	Walk	**too slow**
	Time to 1st bridge (1st Ave over Necanicum)	21.3 min	11.9 min	**9.4 min**
	Time to 2nd bridge (Broadway over Neawanna)	27.3 min	21.6 min	**5.7 min**
	Time to safety (Hilltop Drive)	32.7 min	26.8 min	**5.9 min**

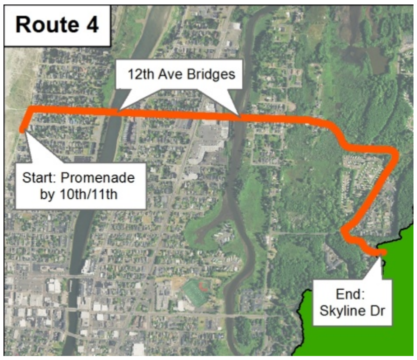


Discussion:
Route 3 starts on the Promenade between 10th and 11th St. The route heads south along the Prom and Downing St before heading east across the Necanicum River on the 1st Ave Bridge and Neawanna Creek on the Broadway Bridge. The route ends at Hilltop Dr. The route requires a "jog" speed; however, the walker only walked. In spite of moving slower than thought necessary, the walker beat the wave at all critical junctures.

(table continued on next page)

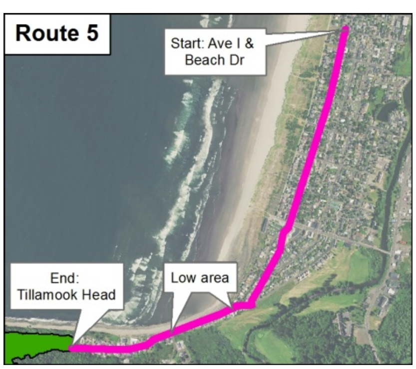
(Table A-1, continued)

		BTW Speed and Wave Arrival Time	Actual Speed and Time	Difference (red = too slow, blue = survived)
Route 4	Speed	4-6 ft/sec	5 ft/sec	within range
	Speed category	Fast walk to slow jog	Walk	within range
1.58 miles	Time to 1st bridge (12th St over Necanicum)	20.0 min	6.0 min	14.0 min
	Time to 2nd bridge (12th St over Neawanna)	25.3 min	12.0 min	13.3 min
	Time to safety (Skyline Drive)	33.3 min	28.0 min	5.3 min



Discussion:
Route 4 starts on the Promenade between 10th and 11th St. The route heads east along 12th St across the Necanicum River and Neawanna Creek. The route then continues east along Ocean Ave and ends on Skyline Dr. The walkers speed exactly matched the required speed and it can clearly be seen that the walker beat the wave at all critical junctures.

		BTW Speed and Wave Arrival Time	Actual Speed and Time	Difference (red = too slow, blue = survived)
Route 5 (walk)	Speed	6-8 ft/sec	5.1 ft/sec	within range
	Speed category	Jog	Walk	within range
1.43 miles	Time to Ocean Vista Drive (start of low area on route)	18.0 min	16.5 min	1.5 min
	Time to end of straight cobble beach (end of low area)	18.0 min	19.9 min	1.9 min
	Time to safety (Tillamook Head)	36.7 min	24.9 min	11.8 min
Route 5 (jog)	Speed	6-8 ft/sec	11 ft/sec	7 ft/sec
	Speed category	Jog	Jog	within range
1.43 miles	Time to Ocean Vista Drive (start of low area on route)	18.0 min	8.5 min*	9.5 min*
	Time to end of straight cobble beach (end of low area)	18.0 min	10.3 min*	7.7 min*
	Time to safety (Tillamook Head)	36.7 min	12.9 min	23.8 min

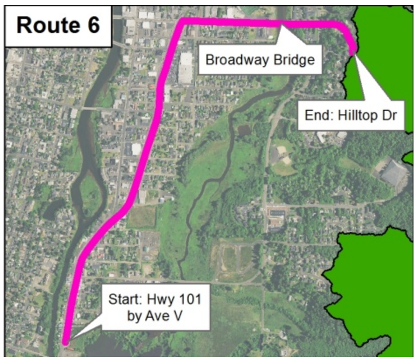


Discussion:
Route 5 starts at Avenue I, heading south along Beach Dr and Ocean Vista Dr toward Tillamook Head, passing a critical early wave arrival along Ocean Vista Dr. The route requires a "jog" speed; however, the walker only walked. While that pace was enough to reach safety with nearly 12 minutes to spare, it was not fast enough to get past the low area. The walker then retraced the route, moving at the correct pace (jog), and that time made it past the low area with several minutes to spare. One caveat – the walker did not note when he reached the low area on the second pass – these values are estimates based on a constant rate of speed and the total route duration.

(table continued on next page)

(Table A-1, continued)

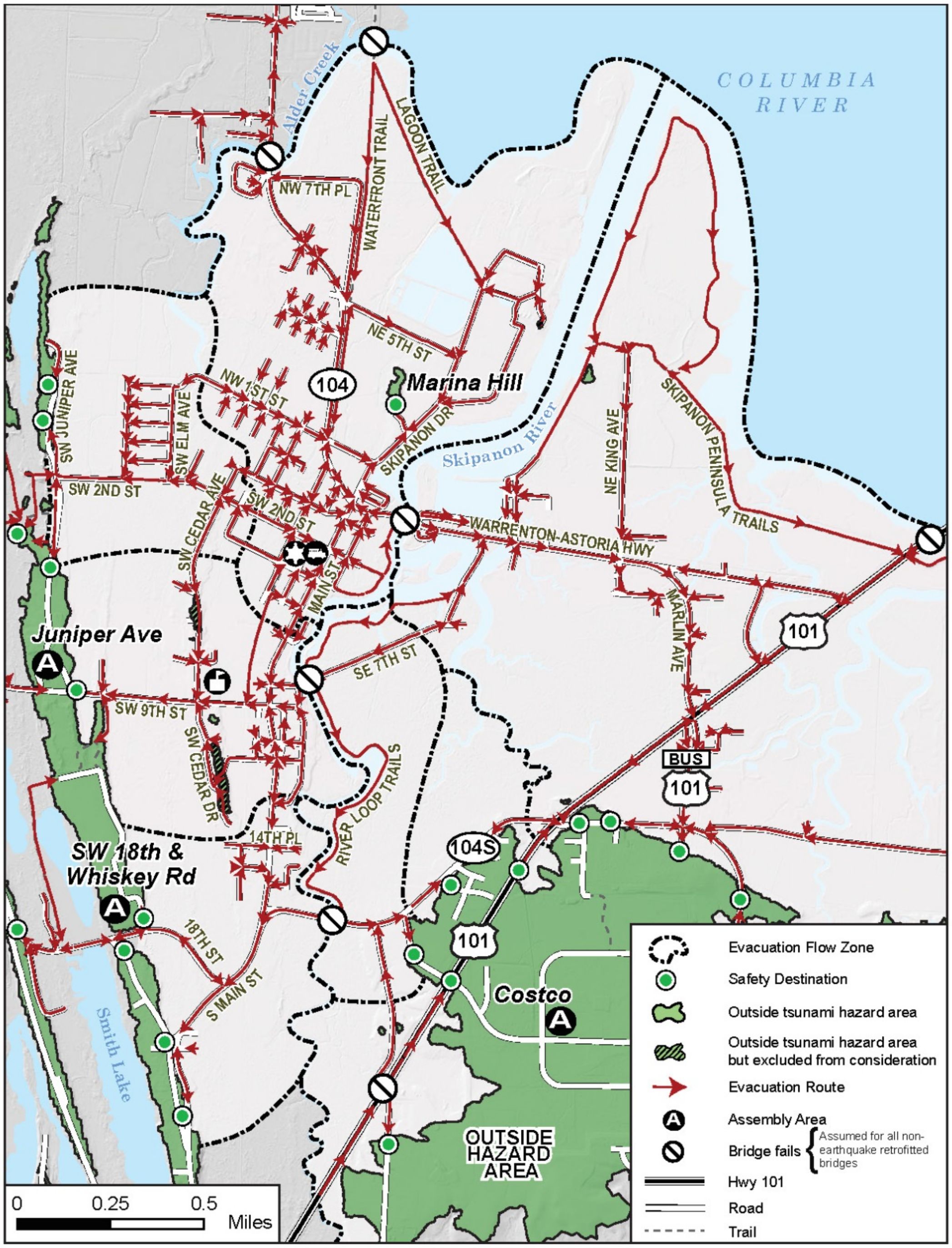
		BTW Speed and Wave Arrival Time	Actual Speed and Time	Difference (red = too slow, blue = survived)
Route 6	Speed	6-8 ft/sec	5 ft/sec	**1 ft/sec**
	Speed category	Slow jog	Walk	**too slow**
1.58 miles	Time to 1st bridge (Broadway over Neawanna)	27.3 min	22.0 min	**5.3 min**
	Time to safety (Hilltop Drive)	32.7 min	27.0 min	**5.7 min**



Discussion:
Route 6 starts on Hwy 101 near Avenue V. The route heads north along Hwy 101 before heading east across Neawanna Creek on the Broadway Bridge. The route ends at Hilltop Dr. The route requires a “jog” speed; however, the walker only walked. In spite of moving slower than thought necessary, the walker beat the wave at both critical junctures.

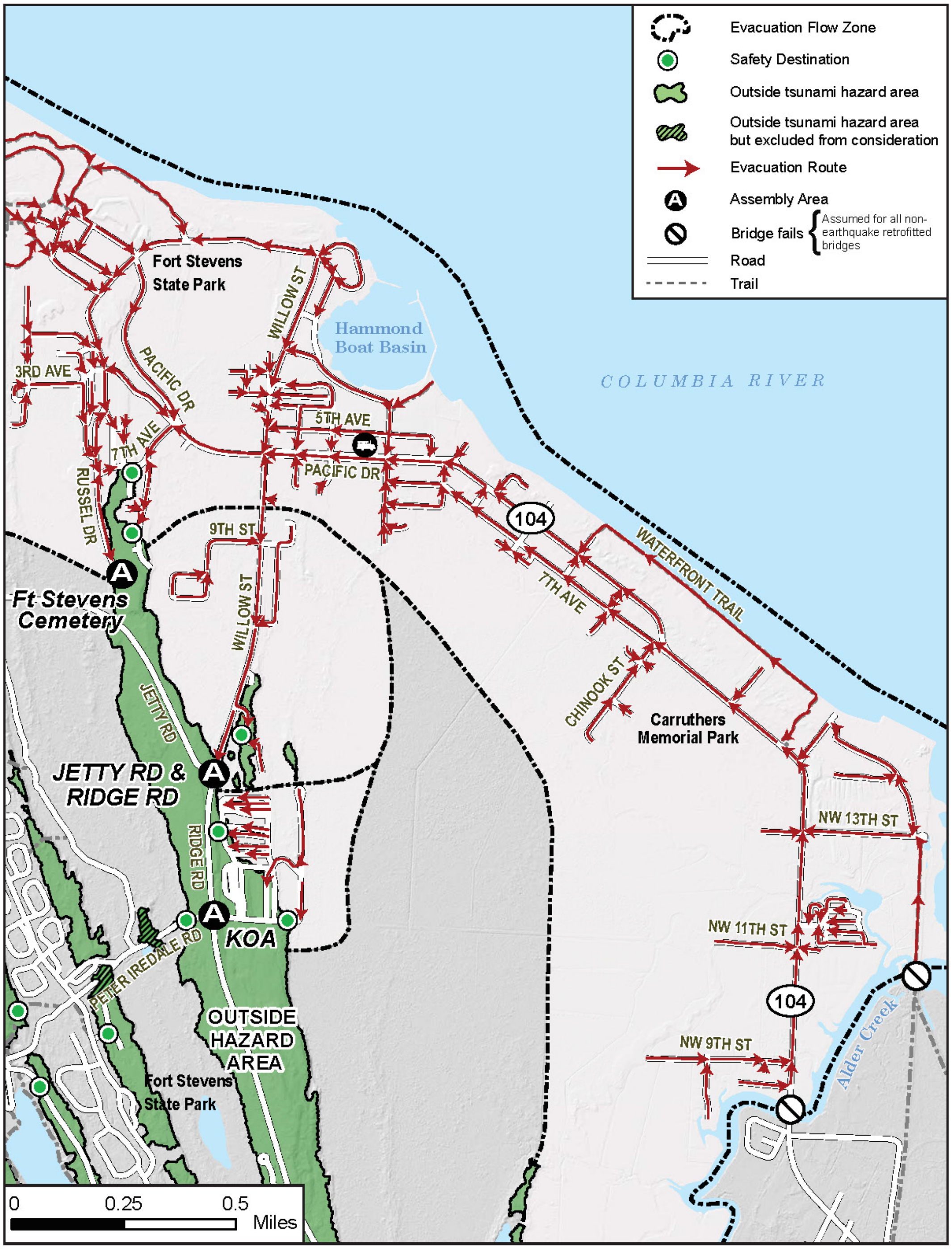
Appendix B: Detailed evacuation routes for Warrenton

Figure B-1. Least cost (path) distance modeling for the community of Warrenton showing evacuation flow zones and detailed evacuation routes for the scenario assuming all non-retrofitted bridges fail during the earthquake and are unavailable for evacuation.



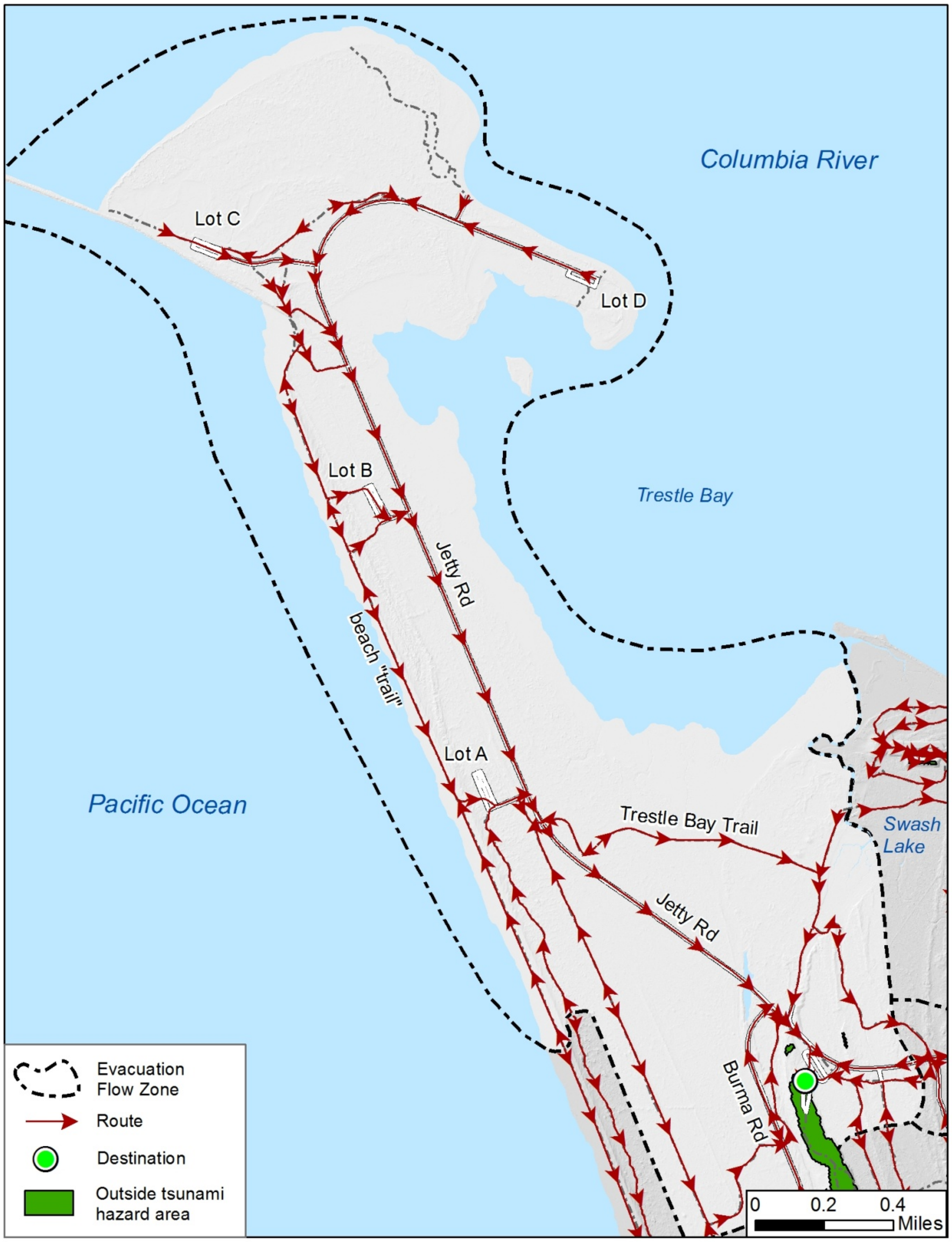
Appendix C: Detailed evacuation routes for Hammond

Figure C-1. Least cost (path) distance modeling for the communities of Hammond and Alder Creek showing evacuation flow zones and detailed evacuation routes for the scenario assuming all non-retrofitted bridges fail during the earthquake and are unavailable for evacuation.



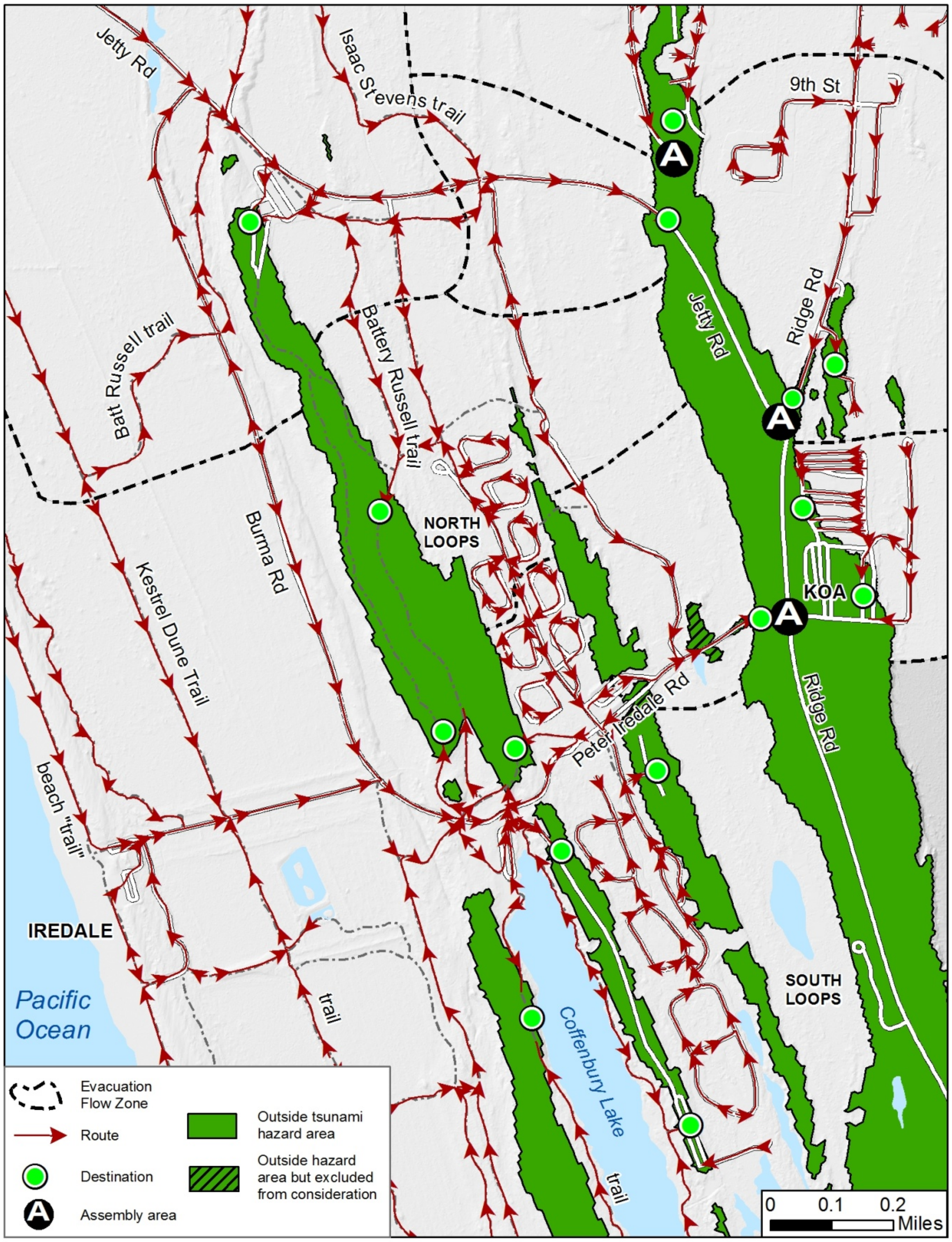
Appendix D: Detailed evacuation routes for Clatsop Spit

Figure D-1. Least cost (path) distance modeling for the Clatsop Spit showing evacuation flow zones and detailed evacuation routes.



Appendix E: Detailed evacuation routes for Fort Stevens State Park

Figure E-1. Least cost (path) distance modeling for Fort Stevens State Park showing evacuation flow zones and detailed evacuation routes.



Appendix F: Detailed evacuation routes for Camp Rilea

Figure F-1. Least cost (path) distance modeling for Camp Rilea showing evacuation flow zones and detailed evacuation routes.

Appendix G: Illustration of maximum-considered Cascadia subduction zone tsunami (XXL1) maximum flow depths for northwest Clatsop County

Figure G-1. Illustration of XXL1 maximum flow depths (in feet) after a Cascadia subduction zone earthquake: *A)* on the Clatsop Plains; *B)* Warrenton inset *[next page]*; ***C)* Hammond inset** *[next page]*.

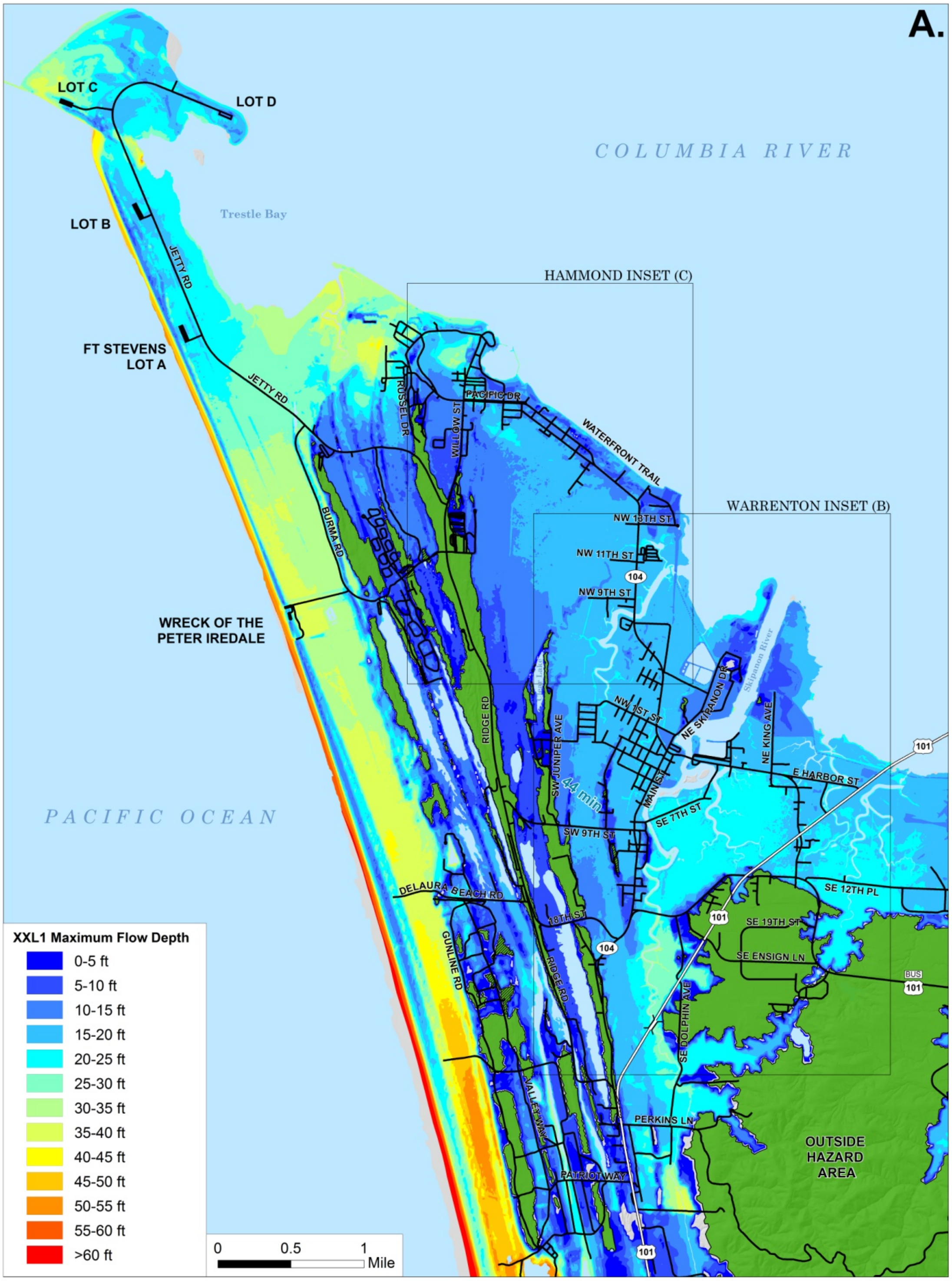


Figure G-1, continued**. **A) **Illustration of XXL1 maximum flow depths (in feet) after a Cascadia subduction zone earthquake on the Clatsop Plains; *B)* Warrenton inset; *C)* Hammond inset.**