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LOCAL TSUNAMI EVACUATION ANALYSIS OF ROCKAWAY BEACH, TILLAMOOK COUNTY, OREGON

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2017

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GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.

Geodatabase is Esri® version 10.5 format. Metadata is embedded in the geodatabase and is also provided as separate .xml format files.

Rockaway_Tsunami_Evacuation_Modeling.gdb:

feature classes:

BTW_XXL1_ExistingRoadNetworkIntact_10minDelay_Roads (polygon)
BTW_XXL1_ExistingRoadNetworkIntact_10minDelay_Trails (polyline)
BTW_XXL1_ExistingRoadNetworkIntact_EvacuationFlowZones (polygon)
BTW_XXL1_ExistingRoadNetworkIntact_EvacuationRoutes (polyline)
BTW_XXL1_NonRetroBridgesOut_10minDelay_Roads (polygon)
BTW_XXL1_NonRetroBridgesOut_10minDelay_Trails (polyline)
BTW_XXL1_NonRetroBridgesOut_EvacuationFlowZones (polygon)
BTW_XXL1_NonRetroBridgesOut_EvacuationRoutes (polyline)

Metadata in .xml file format:

BTW_XXL1_ExistingRoadNetworkIntact_10minDelay_Roads.xml
BTW_XXL1_ExistingRoadNetworkIntact_10minDelay_Trails.xml
BTW_XXL1_ExistingRoadNetworkIntact_EvacuationRoutes.xml
BTW_XXL1_ExistingRoadNetworkIntact_EvacuationFlowZones.xml
BTW_XXL1_NonRetroBridgesOut_10minDelay_Roads.xml
BTW_XXL1_NonRetroBridgesOut_10minDelay_Trails.xml
BTW_XXL1_NonRetroBridgesOut_EvacuationRoutes.xml
BTW_XXL1_NonRetroBridgesOut_EvacuationFlowZones.xml

ABSTRACT

We evaluated difficulty of pedestrian evacuation in the communities of Rockaway Beach (including Nedonna Beach), Twin Rocks, and Barview, Tillamook 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 (defined as ~20 ft beyond the inundation limit) for a moderate walking speed of 4 fps (feet per second, 22 min/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.

To estimate whether pedestrians can stay ahead of a tsunami along entire routes, we produced maps of:

- Tsunami wave advance for an XXL1 event,
- LCD walking time (at 4 fps),
- Detailed evacuation routes for the XXL1 scenario, and
- “Beat-the-Wave” (BTW) for the XXL1 scenario.

The BTW maps depict the **minimum evacuation speed** required to stay ahead of the wave given a variety of scenarios that will increase evacuation difficulty. The primary scenario uses the existing road network and includes a 10-minute delay from start of earthquake before beginning evacuation. Additional challenges to evacuation are discussed and include the failure of non-retrofitted bridges and the possibility of road closures due to landslides. In all cases, **the identified minimum speeds must be maintained for the entire time it takes to evacuate from the inundation zone.** Given the model limitations defined in the Methods section (i.e. liquefaction, fenced yards, etc.), results show that evacuation of the entire region (here referred to as “the greater Rockaway Beach area”) is achievable at a moderate walking speed (4 fps) assuming the existing road and bridge network remains available. Even for those with mobility limitations (i.e., those traveling at speeds greater than 4 fps), safety can be reached ahead of the wave from all parts of town, again assuming the existing road and bridge network remains available. LCD and BTW scenarios showed that failure of one or both bridges in the area (Highway 101 by Lake Boulevard and NE 12th Avenue) introduces evacuation challenges for evacuees starting from areas west of Lake Lytle and Crescent Lake. Landslide-induced road closures also introduce evacuation difficulties in several locations throughout the area.

Possible mitigation options include increasing the number of evacuation routes by constructing more earthquake-hardened bridges (built or remodeled to withstand shaking from a major earthquake); adding new evacuation routes that allow for bypassing landslide-prone routes; and/or installing a tsunami refuge, otherwise known as a vertical evacuation structure, along Highway 101 west of Lake Lytle.

1.0 INTRODUCTION

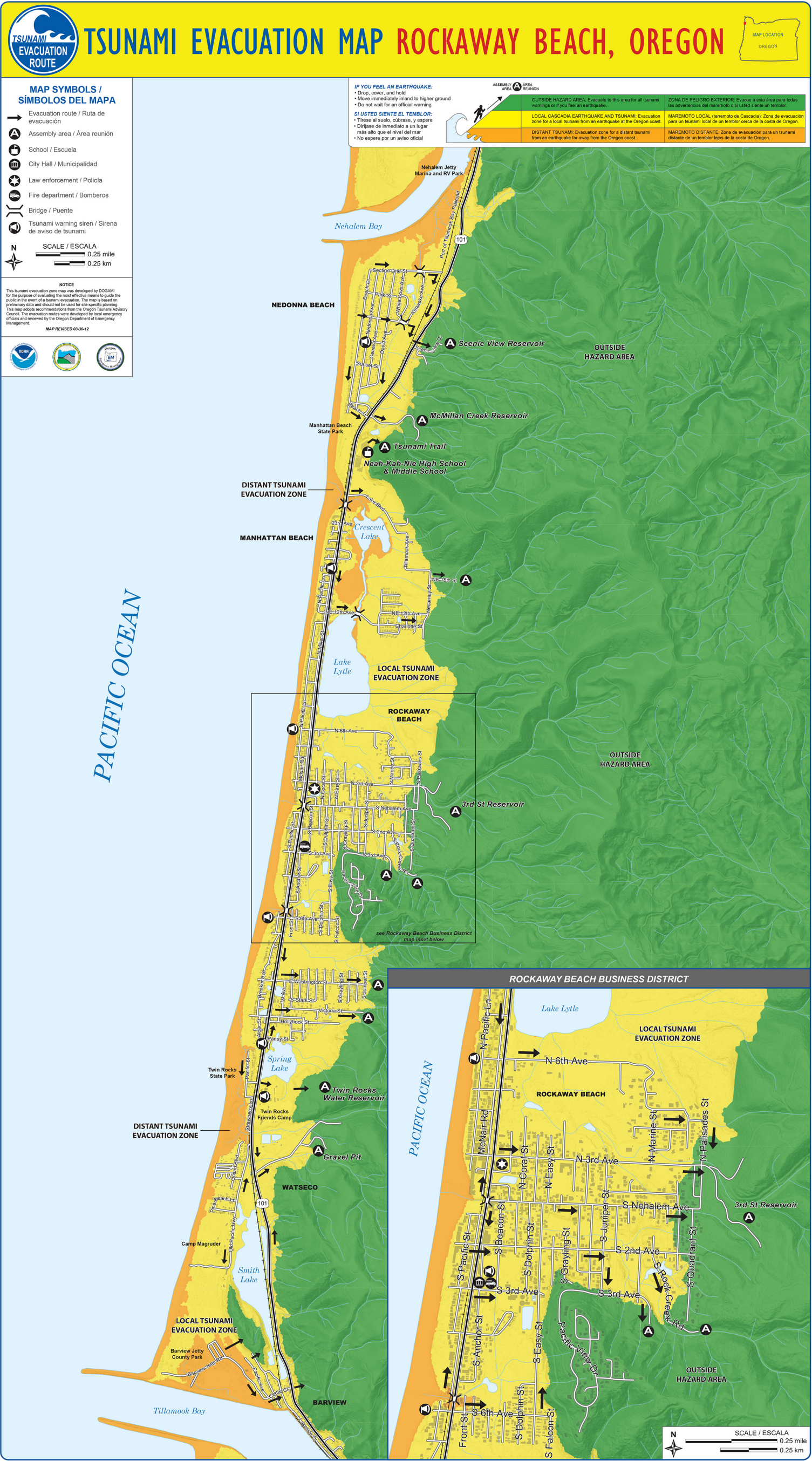
A locally generated tsunami from a Cascadia subduction zone (CSZ) earthquake will inundate the Oregon coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). Spontaneous evacuation on foot would likely be the only effective means of limiting loss of life for the majority of the population, as vehicle evacuation would be quickly compromised by traffic congestion and road blockages. CSZ earthquakes affecting northern Oregon will likely be of magnitudes 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%), 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 region (depicted as the extent of the yellow area in the evacuation map, [Figure 1-1](#)). Further complicating evacuation in the area is reliance of evacuation routes on bridges over the outlets of Lake Lytle and Crescent Lake ([Figure 1-1](#)) as well as the possibility of landslides. The objective of this study is to provide local government with a quantitative assessment of the difficulty of evacuating the greater Rockaway Beach area 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 Schmidlein (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 all the way to safety to stay ahead of the tsunami (Priest and others, 2015a). We then summarize which parts of the region are most in need of tsunami hazard mitigation.

Figure 1-1. DOGAMI (2012) tsunami evacuation map for Rockaway Beach showing geographic information; inundation for a maximum-considered Cascadia subduction zone (CSZ) tsunami scenario (XXL1) is designated yellow, while the maximum considered distant tsunami scenario (AKMax) is shown in orange (Note: the Cascadia scenario encompasses BOTH the yellow and orange zones.) High ground outside the XXL1 hazard area is 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 pedestrian walking speed under optimal conditions (e.g., a nearly flat paved street that has a slight downward decline), increasing or decreasing that speed (by increasing the effective distance to safety) to account for changes in slope and other ground conditions. Generally speaking, a positive slope (upward) produces slower speeds, as does a negative steep slope (downward), while a slight decline (<3 degrees) in the slope reflects the optimal speed and no costs. We used the LCD model of Wood and Schmittlein (2012) because we wanted to understand the spatial distributions of evacuation times in the Rockaway Beach area, 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), which is listed as a moderate walk by Wood and Schmittlein (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 Schmittlein (2012) approach these difficulty or cost values are categorized as speed conservation values (SCV). Horizontal cost values represent land cover types across the landscape; vertical costs are a function of slope and account for the effort required to traverse hills. Horizontal and vertical costs are both considered when calculating least-cost routes. Vertical SCVs will be discussed further in Section 2.3. 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, field verified, and then 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 excluded (i.e., undeveloped areas, water, etc.). 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. Due to the nature of the beach in this area, modeling extends only to the seaward end of beach access pathways (i.e., no modeling on the beach). However, travel times on those paths 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., exiting a building, navigating fenced yards) and after the earthquake (e.g., fallen debris). The modeling approach thus produces minimum evacuation speeds to evacuate from the inundation zone. The land cover SCV values used are presented in [Table 2-1](#).

Table 2-1. Land cover 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

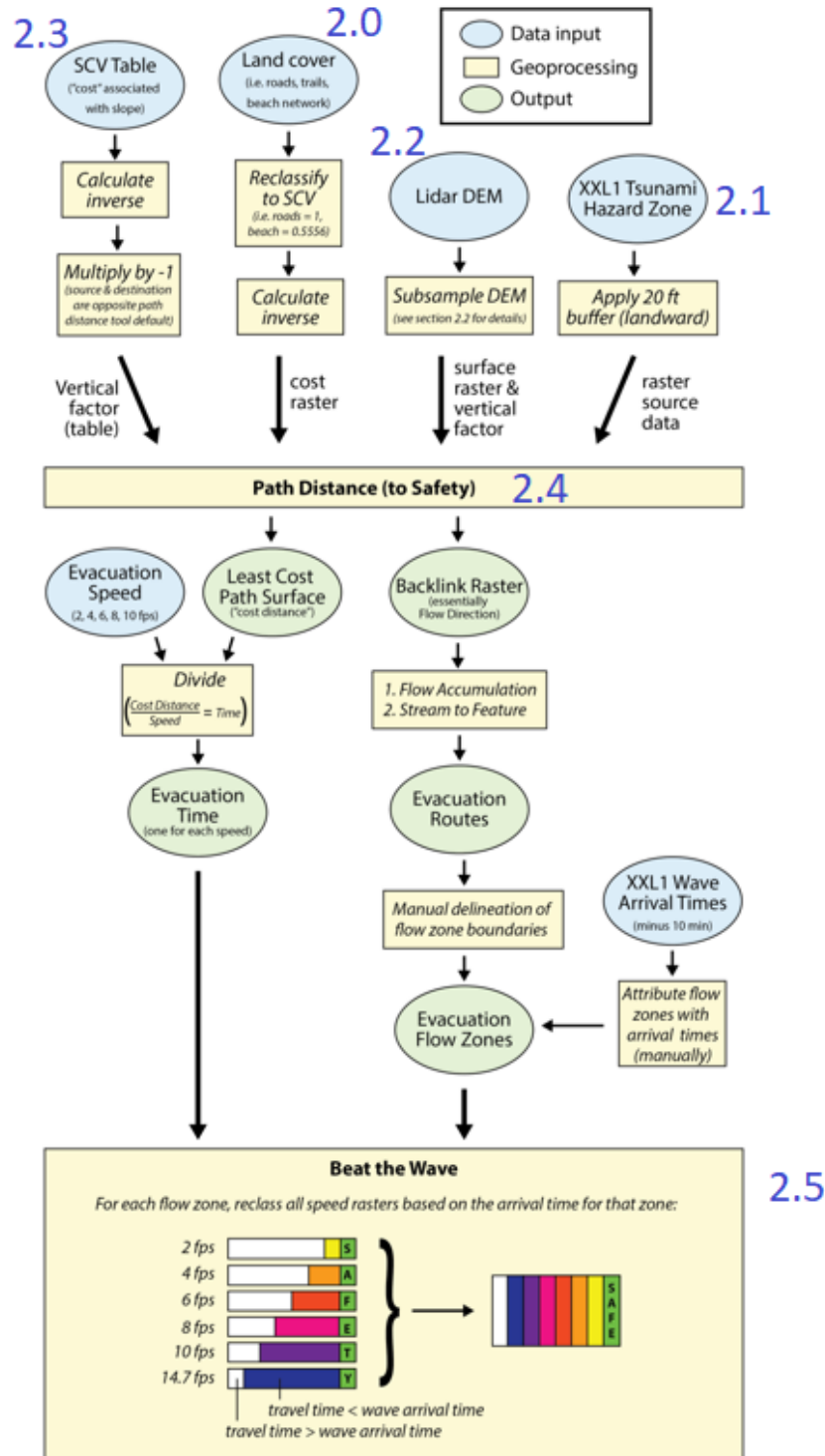
*Speed conservation values (SCV) are derived from Wood and Schmidtlein (2012).

**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; therefore slides, liquefaction (e.g., water-saturated sand turning to quicksand), and lateral spreading are likely to occur during an earthquake. These hazards will damage roads and reduce walking speeds by significant but uncertain amounts. Because assigning cost values to areas prone to liquefaction and lateral spreading remains highly uncertain, and because slowing of pedestrian speed will likely be highly site specific, we did not model their effect on evacuation difficulty. In contrast, due to the steep slopes and evident landslide terrain that border several key evacuation routes in the Rockaway area, we evaluated several additional scenarios in which certain roads were closed based on local geology, slope, and proximity to known landslides (as documented in DOGAMI's Statewide Landslide Inventory Database for Oregon, (SLIDO, Burns and others, 2016), <http://www.oregongeology.org/sub/slido/index.htm>). Such an approach is a first-order attempt to identify potential evacuation routes that could be vulnerable to landslides, which may lead to further investigations of the hazard.

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 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 for tsunami evacuation modeling from Wood and Schmidtlein (2012) and Wood and others (2016). SCV is speed conservation value, DEM is digital elevation model (Priest and others, 2015b). XXL1 is the maximum-considered Cascadia subduction zone (CSZ) tsunami scenario, covering 100 percent of potential CSZ tsunami inundation (Witter and others, 2011, Priest and others, 2013b). Unit fps is feet per second. Blue numbers indicate sections in this paper.



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 zone covers 100 percent of potential CSZ inundation (Witter and others, 2011).

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 the lidar highest hit data to define the bridge walking surface. The grid was further smoothed as it became clear that the slope profiles were too noisy, introducing slope artifacts of significant amplitude (e.g., a 3-inch elevation difference between cells 1 foot apart yields 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 attributed those points with elevation values from the native 3-foot-cell lidar DEM. We chose this interval because of work by Priest and others (2015a, b), who performed trials at 25, 50, and 100 feet; they found that 50 feet achieved the best compromise between accuracy and smoothness. Final sampling interval was ~50 feet for straight paths and somewhat less for curved paths in order to accurately depict curvatures. We then interpolated 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 the slope noise.

2.3 Vertical speed conservation value (SCV) slope table

We created a table that associates slopes with a specific SCV value (see [Table 2-2](#) for example values). 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:

$$\text{walking speed (fps)} = 5.5e^{-3.5 \times \text{abs}(\text{slope}+0.05)}$$

where slope is equal to the tangent of the slope angle. This formula is based on empirical data of Imhof (1950, as cited by Tobler, 1993) and predicts that speed is fastest (5.5 fps) on gentle (−3%) downslopes. This table is used to determine the vertical cost of each cell along a least-cost path towards safety based on the slope (determined from the DEM).

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

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

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

2.4 Path distance modeling

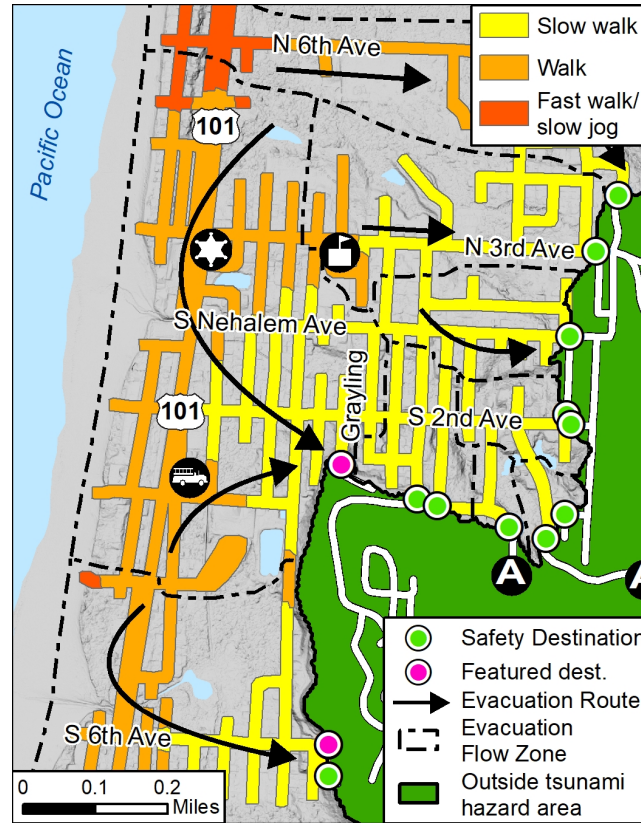
The output of the LCD model is a path distance surface showing the least-cost distance to safety from each pixel. The least-cost distance includes the actual surface distance plus extra to account for walking difficulty due to land cover and slope. We also calculated an LCD backlink raster that shows, 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 ArcGIS 10.2 and the backlink raster to extract a “stream” network to visualize the paths depicting the most efficient pedestrian flow for evacuation. These paths represent the shortest efficient distances to safety. The pixel value for cost distance is the actual surface distance, along the least-cost path, from the pixel to the point where the path intersects safety plus additional distance added in to account for difficulty in walking due to land cover and slope. For example, from city hall/fire station complex (fire truck symbol in [Figure 2-2](#)), the actual surface distance to safety on South Grayling Street is 1,900 feet while the least-cost path distance is 2,800 feet. This difference is due to the model having accounted for variations in slope and land cover along the entire route. The resulting direction of travel on each path is depicted in GIS as arrows along streets. Locations with opposing arrows are where one could travel to safety on two equal alternative paths and define boundaries of evacuation flow toward critical points such as the nearest safety location and are directly analogous to watershed boundaries or drainage divides in hydrologic modeling (see [Figure 1-1](#), inset, for example flow arrows in opposite directions near bridges).

These boundaries are particularly important in Rockaway Beach, where the majority of the population is along or west of Highway 101 and must choose whether to head north or south along the highway before reaching a road heading east toward 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 (corridors), 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 scenarios and mitigation options including:

- the collapse of two bridges not retrofitted to withstand a Cascadia subduction zone earthquake;
- landslide-induced road closures; and,
- a hypothetical vertical evacuation structure.

Figure 2-2. Example of the network of evacuation paths from the least-cost distance analysis limited to trails and streets. Evacuation flow zones (corridors) are highlighted for the two main safety destinations in the downtown area (white background, pink dots). Additional destinations for the neighborhood to the east are also shown (white background, bright green dots). 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).



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, written 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 that many more would be needed to fully explore an array of evacuation speeds appropriate for specific populations (e.g., elderly or small children versus able-bodied adults). This is explored further in the next section where we discuss the development of tsunami wave front advance maps and integrating 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

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. To better understand the complexities of tsunami wave advance over land, 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 interpolated those arrival data to create a continuous map showing wave arrival times (**Figure 2-3**). We then examined data profiles 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 bottom of bridge spans, considering that 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 beaches ~16–18 minutes after the start of the earthquake, inundates much of the community in ~20–24 minutes, and reaches the hills behind town in ~26–30 minutes. **Figure 2-4** illustrates early wave arrivals along two routes that cross over low lying areas (creek outlets). These latter data were used to assess the potential for early wave arrival, which could cut off parts of the evacuation route thereby stranding the public in those areas.

The next step in the BTW analysis is to divide the landscape into evacuation flow zones and assign wave arrival times to each zone. Flow zone polygons are drawn manually 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 Hydrology toolset. However, we found this latter method to be useful as a guide only and not as functional data. Wave arrival times are assigned based on the time when the first wave reaches the point of safety for each zone. Ten minutes is 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 being in 1974. We therefore simulate a delay of 10 minutes mainly for earthquake shaking (the minimum of 3 minutes for shaking plus 7 minutes based on the La Punta survey).

After creating flow zone corridors, the path distance surface is divided by pre-determined evacuation speeds to yield multiple evacuation time maps of the region (cost distance divided by speed equals time). These time maps are then clipped twice: once to separate flow zones and again based on the unique wave arrival time for each zone. For each evacuation speed within a flow zone, the surface is clipped at the point where the time to reach safety is greater than the wave arrival time. These clipped grids are then mosaicked together, with the minimum speed for each cell having been maintained. These steps are described graphically in **Figure 2-1**.

Potential early wave arrival locations are treated as unique flow zone corridors (the low point is the effective destination) and the resulting BTW speeds are compared to that of the flow zone as a whole to determine if BTW speeds need to be adjusted upwards in order to “beat the wave” at all points along a route. In both 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 will not always be 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 examined the effect of bridge collapse, by performing scenarios initially with all bridges intact, followed by eliminating one or two of the key bridges in the Rockaway area. This approach yielded two scenarios with increasing evacuation difficulty for Rockaway Beach:

- 1) Existing road network intact (i.e., all bridges intact), 10-minute delay from start of earthquake before starting evacuation; and,
- 2) Failure of non-seismically retrofitted bridges, 10-minute delay; these failures will have no effect on evacuation from Nedonna Beach, Twin Rocks and Barview.

In addition to bridge failure, we examined the potential for landslides to cut off certain roads. This was done by examining the local geology, SLIDO, and the proximity of established roads to known landslides. Similar to the bridge-out scenarios, we incorporate a 10-minute evacuation delay in the landslide scenarios.

Actual travel speeds on any evacuation route 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 more difficult terrain (e.g., steep slopes or sand).

Binning of evacuation speeds was initially limited to five categories, which is typically the maximum number that the public 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-**). The ranges of speeds for these groups at one standard deviation (the last two rows of **Table 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 can 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-**). After examining the range of BTW speeds for Seaside (Priest and others, 2015b) and reviewing a number of references describing speed categories (Paul, 2013; Margaria, 1968), we settled on the following five speed bins:

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

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

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

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

individual, effectively killing them. This limited test of the BTW data suggests that they are reasonable guides to minimum evacuation speeds necessary to reach safety ahead of the tsunami.

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

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

fps is feet per second.

Figure 2-3. Illustration of XXL1 tsunami arrival times after a Cascadia subduction zone earthquake in the greater Rockaway Beach area; A) Nedonna Beach; B) Rockaway Beach; C) Twin Rocks/Barview.

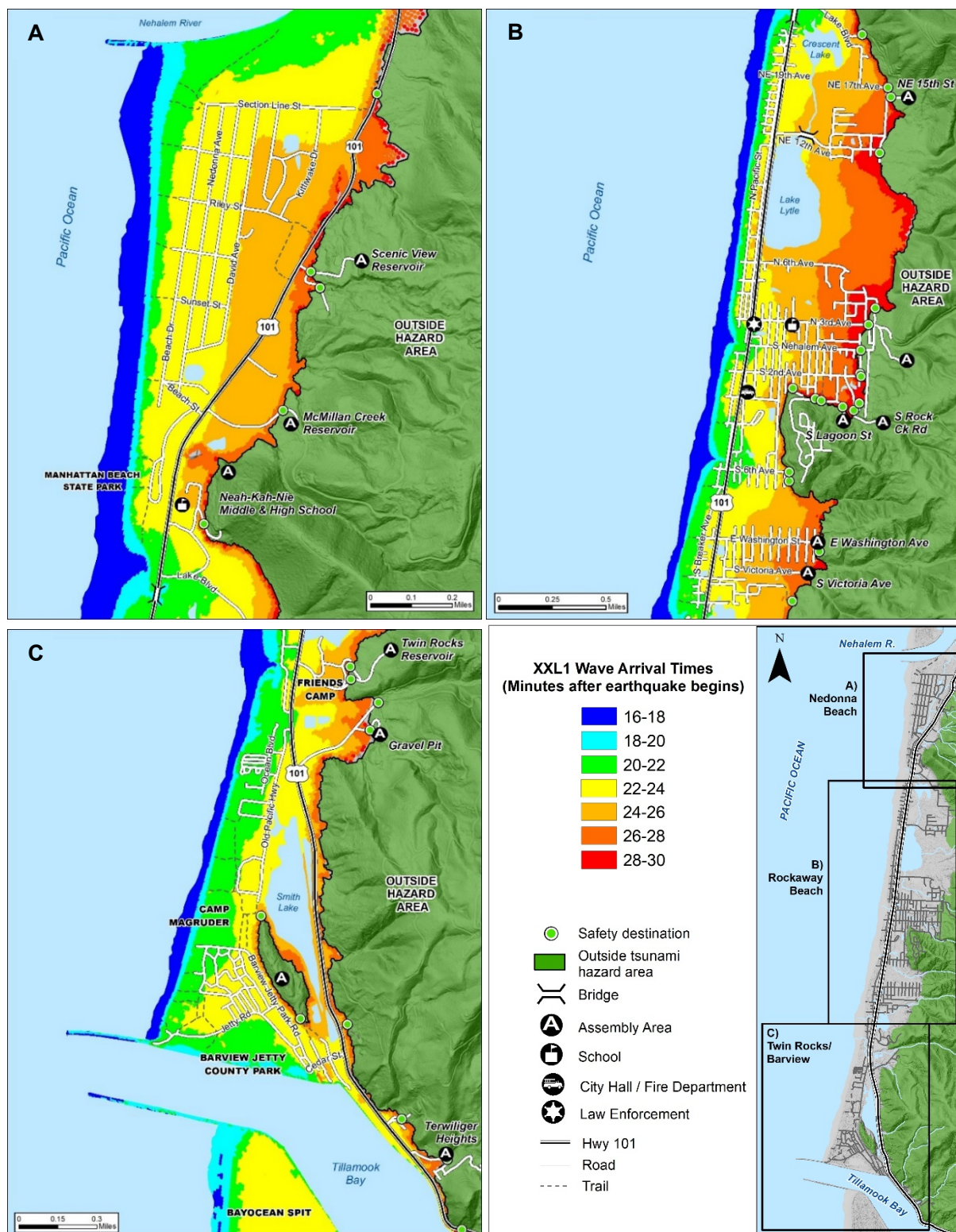
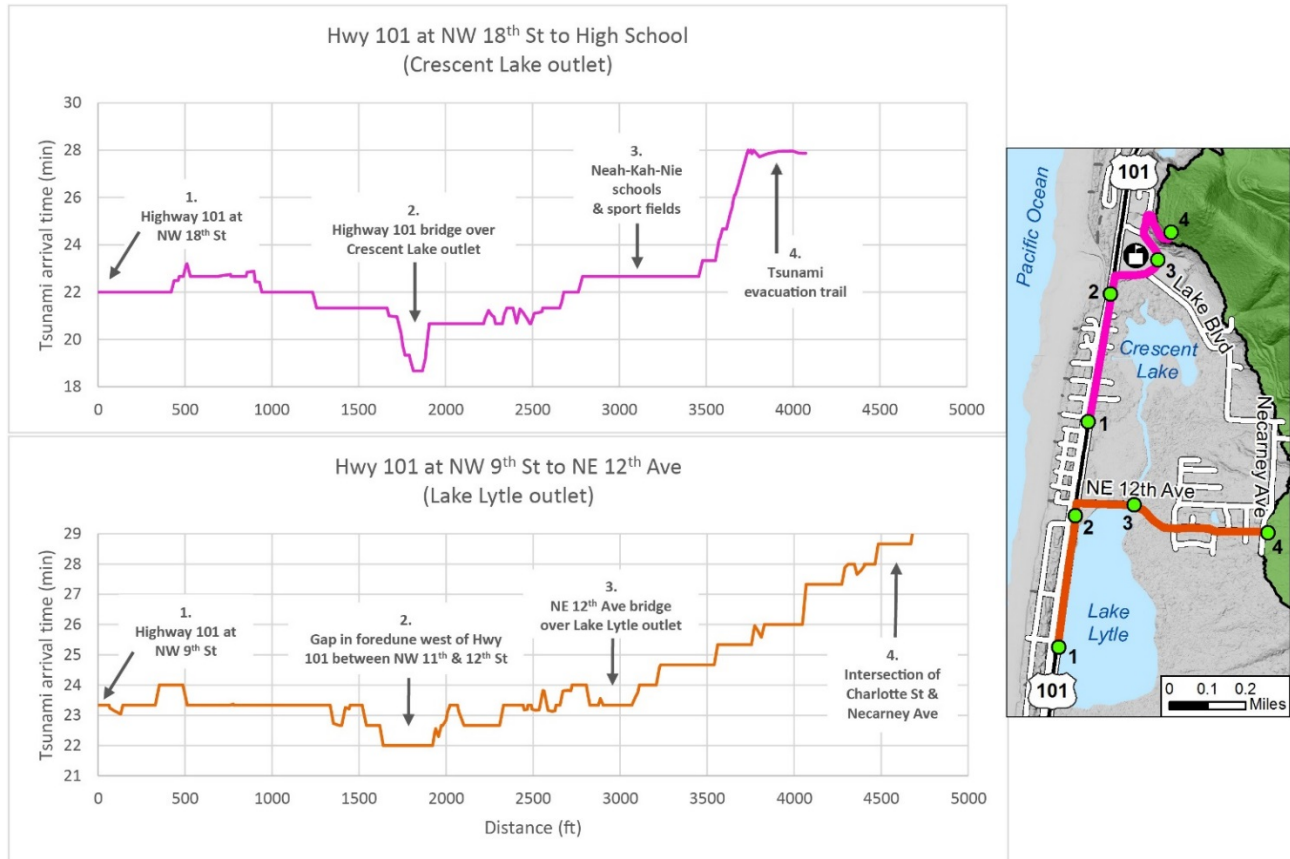


Figure 2-4. Time after the XXL1 earthquake when simulated tsunami flow depth exceeded 0.5 ft for selected evacuation routes in Rockaway Beach. Early tsunami wave arrival at the outlets to Crescent Lake (pink profile and map route) and Lake Lytle (orange) were examined to see if they were critical points for setting the minimum times for evacuation of the entire evacuation flow zone seaward of each point. In both cases we found that the early wave arrivals were not critical and the speeds required to reach safety were fast enough to enable evacuees to get past these low points before the tsunami arrived. Note that although tsunami wave arrival times are reduced by 10 minutes for BTW mapping in order to incorporate delay in evacuation from the effects of earthquake shaking, the times shown here reflect the actual wave arrival times



3.0 RESULTS

In general we find that unimpaired adults should be able to escape a maximum-considered Cascadia tsunami from all but a few critical beach front areas of greater Rockaway Beach. In this section we examine the broader regional findings, as well as evacuation modeling results for three areas: Nedonna Beach, Rockaway Beach, and Twin Rocks–Barview.

Figure 2-3 demonstrated the range of tsunami wave arrival times for an XXL1 local tsunami that inundates the area. As described previously, these arrival times are as little as 16 minutes on the beaches; ~20–24 minutes to inundate each community; and 30 minutes for the tsunami to reach its maximum runup limits. Using an average pedestrian evacuation speed of 4 fps (classified as a **walk**) and identified path distances, we present modeled pedestrian evacuation times based on intact and unimpeded routes in **Figure 3-1**. For the purposes of this map, we assume bridges that have not been retrofitted to withstand a > Mw 9.0 earthquake will fail and are not available for evacuation. Pedestrian evacuation times are generally about 10–25 minutes (yellow/orange colors) across much of the area because many routes are relatively close to areas outside the hazard zone; “safety” is designated as green and dashed lines indicate trails in this and in all subsequent figures. Along Highway 101 between Lake Boulevard and North 8th Avenue (and side streets), the default **walk** evacuation times increase significantly, from 30 to 55 minutes (**Figure 3-1**) due to the hypothetical bridge failures. This is the only area within the region where we believe that evacuation to safety will be challenging. This assumes that the public will walk at the modeled speed of 4 fps. Regardless, these results highlight several challenges for evacuation at these locations.

Modeled “Beat the Wave” (BTW) speeds for the region are presented in **Figure 3-2**. 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.

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

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 the public following the severe earthquake shaking, and the time required to exit buildings. **Table 3-1** presents a summary of the range of speeds and their various conversions that will be used throughout the remainder of this report.

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

Description	Feet per Second (fps)	Miles per Hour (mph)	Minutes per Mile
Slow walk	0–2	0–1.4	44
Walk	2–4	1.4–2.7	44–22
Fast walk / 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 in Fraser and others, 2014).

As can be seen in **Figure 3-2**, our modeled BTW results confirm that most of the region is classified with minimum speeds characterized as a **slow walk** (yellow roads) or **walk** (light orange roads). This suggests that evacuation to safety is achievable for much of the area. However, it is inevitable that following a disaster other factors will almost certainly contribute to impede the public's travel times. At this point, our modeling does not account for these potential ancillary effects. As a result, **the public 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 (i.e., reduce the 10-minute delay assumed in this analysis).**

Figure 3-1. Modeled pedestrian evacuation times assuming a 4 fps speed during an XXL1 local tsunami event in the greater Rockaway Beach area: A) Nedonna Beach, B) Rockaway Beach, C) Twin Rocks-Barview.

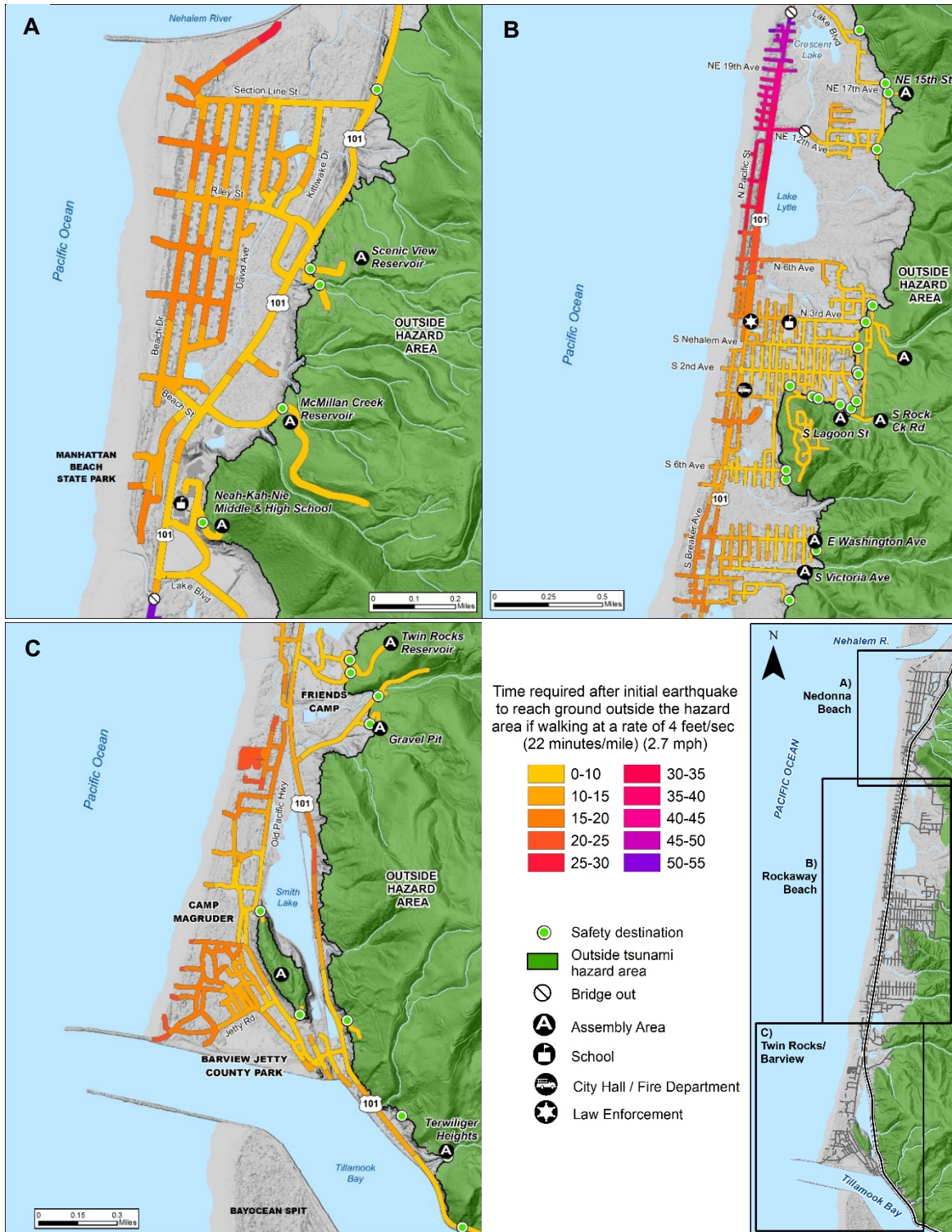


Figure 3-2. Modeled “Beat the Wave” speeds for XXL1 local tsunami event in the greater Rockaway Beach area; A) Nedonna Beach; B) Rockaway Beach; C) Twin Rocks–Barview. The speed indicated at the start of an evacuation route must be maintained the entire way to safety (averaged along entire route), i.e., an evacuee cannot slow down as he/she gets closer to safety.

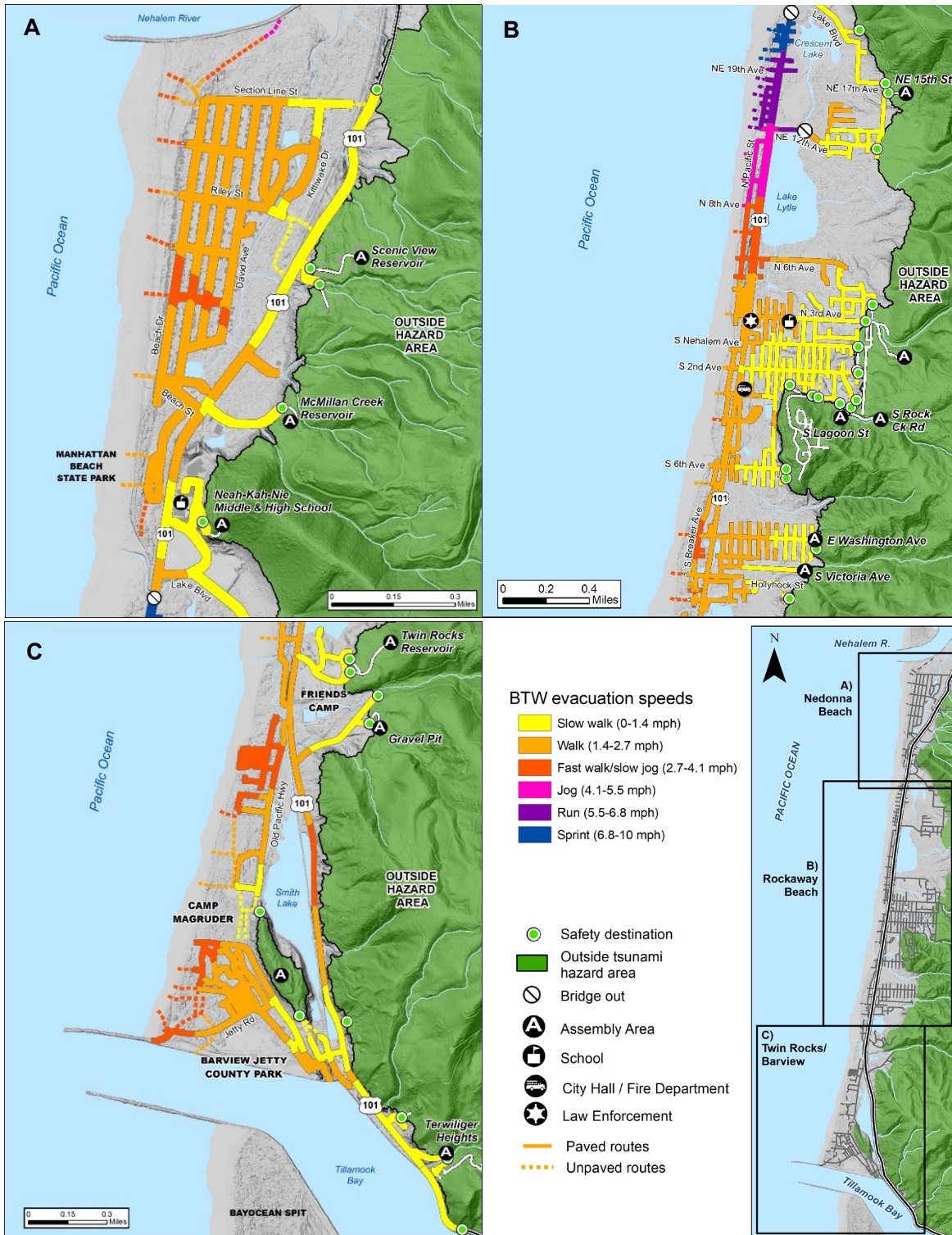


Figure 3-2 confirms that evacuation for much of the area is achievable with the exception of a portion of downtown Rockaway Beach along Highway 101 (and side streets) between Lake Boulevard and North 8th Avenue where evacuation will be more challenging due to route dependence on crossing non-retrofitted bridges (**Figure 3-2B**). Options such as vertical evacuation or hardening of bridges could be considered in this area to save lives. Landslides may further complicate evacuation in several areas, as discussed below.

3.1 Nedonna Beach

Figure 3-3 defines the least-cost (path) distance modeling for the Nedonna Beach neighborhood. Recall that the purpose of this type of modeling is to identify and define the detailed evacuation routes, which we then use to define the evacuation flow zones (corridors) in each community. Each of the evacuation flow zones effectively defines the area being evacuated and the associated nearest destination points of safety (defined by the green and black circles) located outside of the inundation zone. The solid green color delineates areas outside the tsunami inundation zone and hence safety from a maximum considered XXL1 local tsunami event.

Figure 3-3 reveals that the Nedonna Beach area is characterized with three evacuation community flow zones (corridors). The entire neighborhood is separated from Highway 101 and high ground to the east by a thin stretch of low-lying marsh and has only one road in and out (Beach Street). However, there are at least two trails (dashed lines) connecting the neighborhood to Highway 101. People located in the northern end of the neighborhood (purple polygon in **Figure 3-3**) would evacuate due east along Section Line Street, continue up a trail, cross the Tillamook railway line (which runs parallel to Highway 101 on the west side), and move north along Highway 101 to the safety destination. Those residents and visitors in the central part of the neighborhood (blue-green region in **Figure 3-3**) would evacuate due east along Riley Street and its adjoining footpath, cross Highway 101 and head up to the Scenic View Reservoir. People in the south end of the neighborhood (salmon-colored region in **Figure 3-3**), including those visiting Manhattan Beach State Park, would evacuate toward Highway 101 along Beach Street. East of Highway 101 they would head uphill to the McMillan Creek Reservoir.

Having defined the evacuation flow zones, we modeled BTW speeds for the Nedonna Beach area (**Figure 3-4**). Because tsunami wave arrival times for the neighborhood are ~22–26 minutes (**Figure 2-3**) and most locations are relatively close to evacuation destinations (i.e., safety), the modeled BTW speeds indicate that the bulk of the area is characterized by minimum evacuation speeds that range from **slow walk** to **walk**. To better understand the potential effects of impediments to evacuation and possible mitigation options, we defined three scenarios based on the following (all scenarios include a 10-minute delay taken from the beginning of the earthquake):

1. Existing road and trail network remains intact (**Figure 3-4**);
2. All three safety destinations are unreachable due to hypothetical landslide activity, forcing evacuation to the high school (**Figure 3-5A**);
3. As above in 2, but with the inclusion of the northernmost safety destination on Highway 101, assuming the route will be hardened to survive the earthquake (**Figure 3-5B**).

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

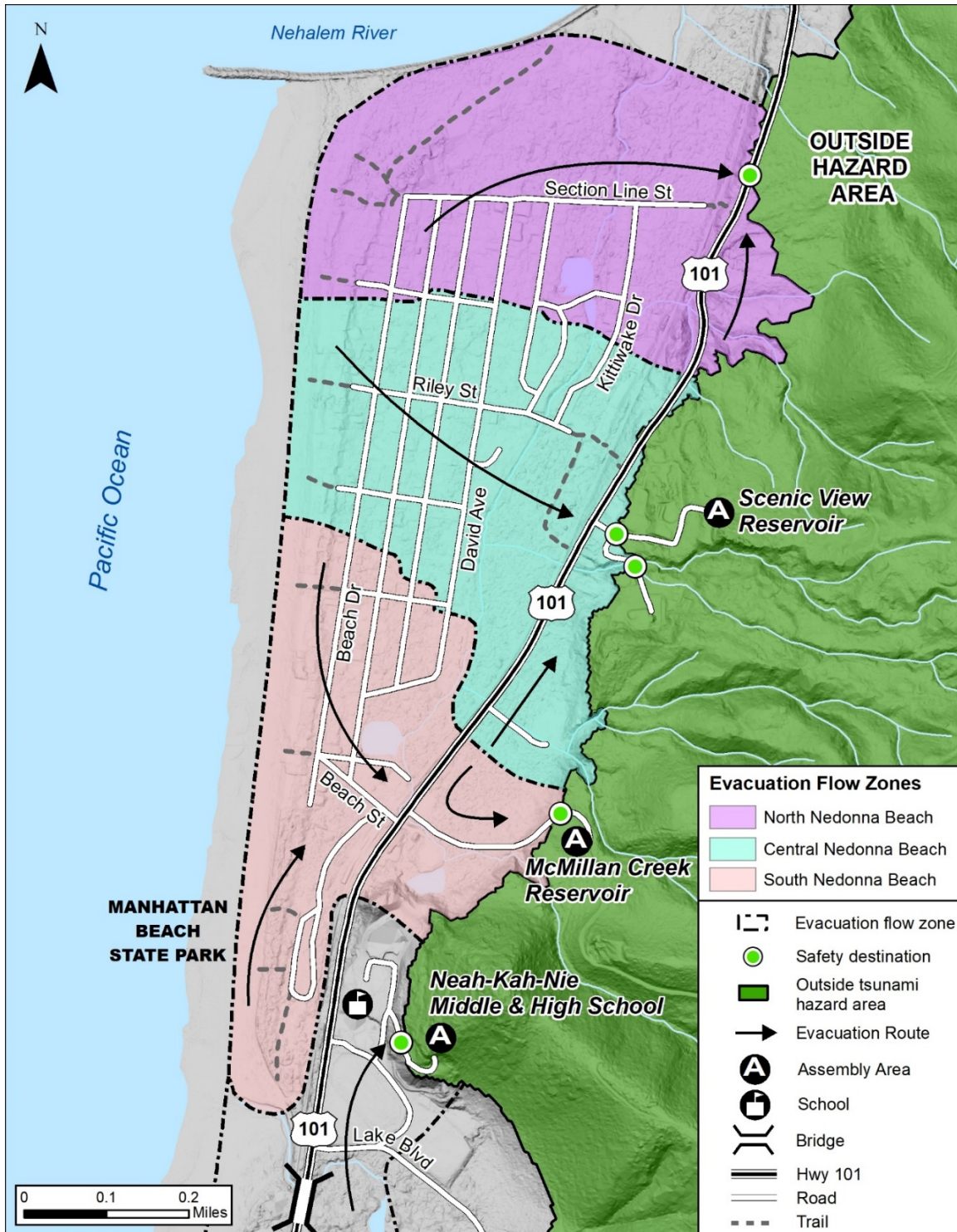
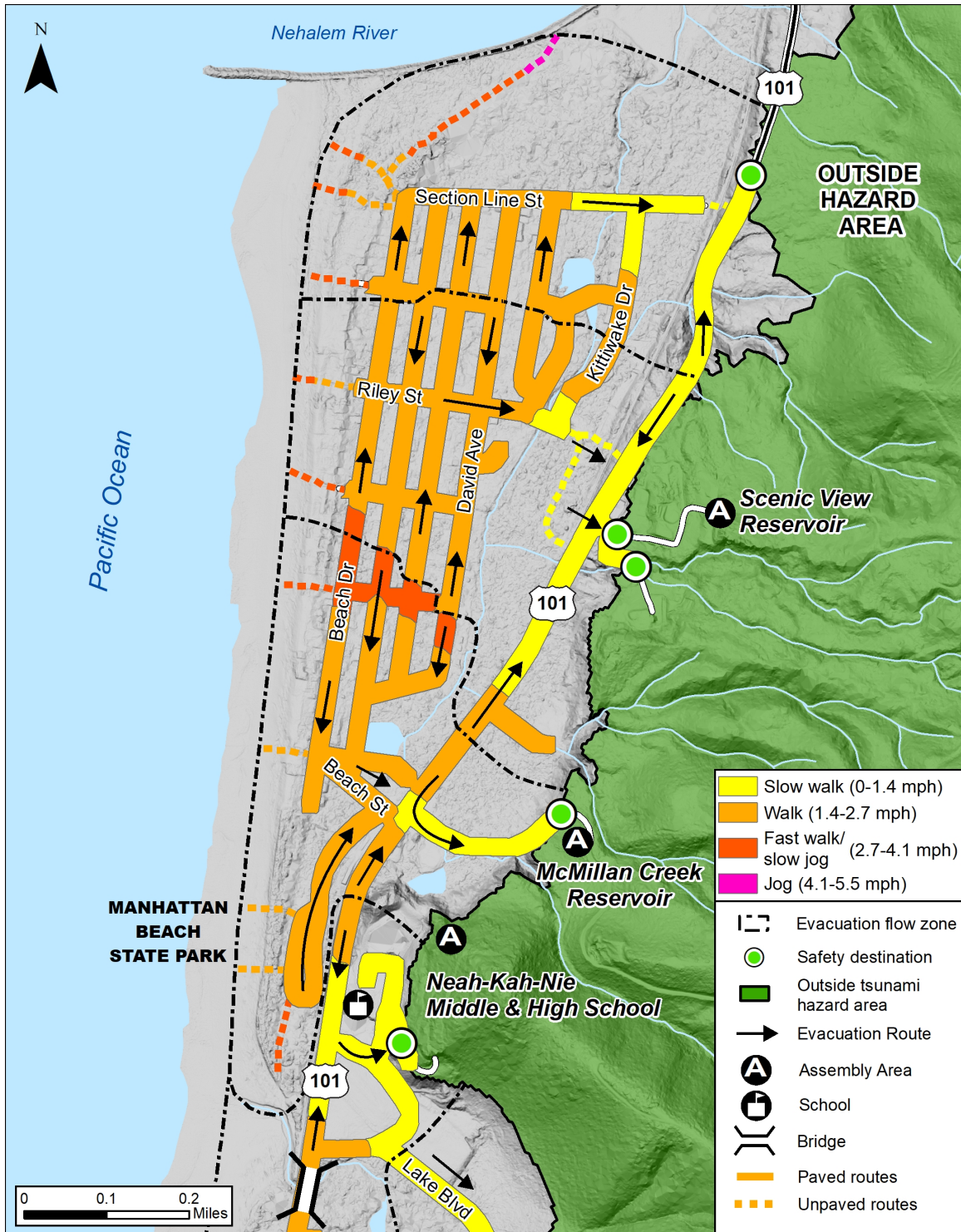


Figure 3-4. “Beat the Wave” speed modeling for the community of Nedonna Beach including 10-minute evacuation delay.



3.1.1 Nedonna Beach Scenario 1 — Existing road network remains intact

Figure 3-4 reveals that residents in the Nedonna Beach neighborhood must travel at speeds considered to be a **slow walk** to a **walk** in order to reach safety, assuming the existing road and trail network remains intact and passable. For nearly all residents, evacuation to safety is attainable under this scenario. A map showing detailed evacuation routes and flow zone corridors for this scenario is provided in Appendix A.

3.1.2 Nedonna Beach Scenario 2 — Multiple landslide failures north of Nea-Kah-Nie School

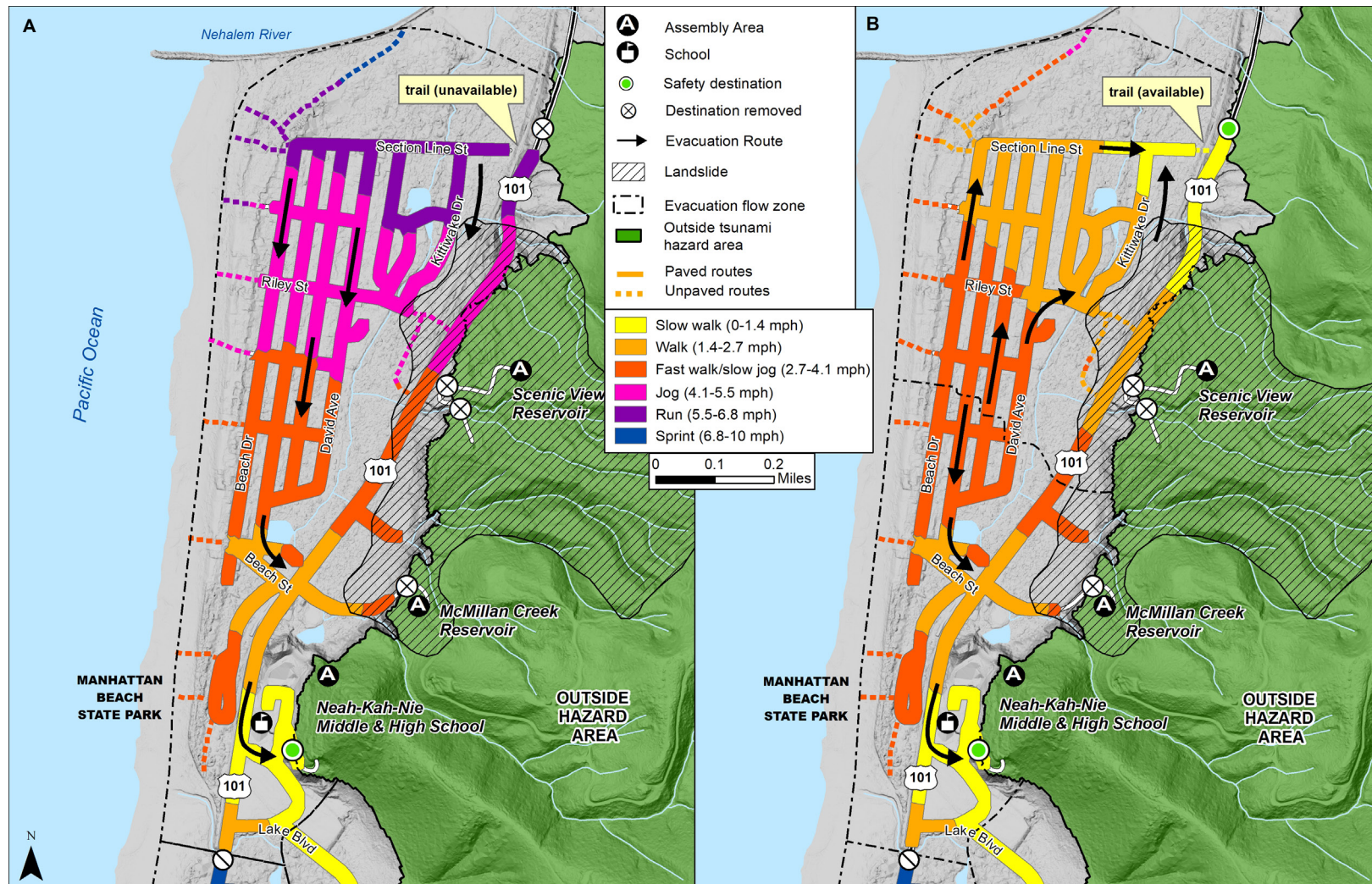
The hashed polygons in **Figure 3-5** represent terrain identified as landslide prone. Two of the three main safety destinations rely on routes that are directly in the path of what could be a significant landslide triggered by a Cascadia subduction zone earthquake. Although safety on Highway 101 for the northernmost watershed is not in a designated landslide area, the trail connecting Section Line Street to Highway 101 is steep, is composed of loose boards, and could conceivably fail during the earthquake. Because the terrain is relatively steep, using this trail could be a significant challenge for the public. As will be demonstrated below, maintaining and potentially earthquake-hardening this trail further is considered to be important for the Nedonna Beach community.

If all safety destinations north of Nea-Kah-Nie School become compromised by landslide activity, everyone in Nedonna Beach and Manhattan Beach State Park would have to evacuate southward to the Nea-Kah-Nie High and Middle Schools tsunami trail (**Figure 3-5A**). As can be seen in **Figure 3-5A**, landslide activity significantly increases evacuation difficulty for everyone, but particularly for residents living at the north end of Nedonna Beach who must now **run** (equates to ~6 mph or a 10 minute/mile pace) to reach safety. Even residents nearest to the high school experience an increase in their required minimum evacuation speed, which increases to a **fast walk/slow jog** (referred to as **fast walk** for the remainder of the report). These travel speeds must be maintained along the entire length of the evacuation route. Although achievable for fast runners, such speeds would almost certainly be challenging and perhaps impossible for certain age groups, including the elderly, physically impaired, and families with children and infants. Thus, with this scenario we would expect to see some loss of life in the Nedonna Beach neighborhood as a result of being caught by the tsunami. This is especially the case given the strong likelihood that the routes will have significant debris on them that could further slow travel.

3.1.3 Nedonna Beach Scenario 3 — Landslide failure constrained to the McMillan Creek and Scenic View Reservoirs

In the previous scenario, the north end of Nedonna Beach is the most vulnerable because of the greater distance to safety. To better understand the implications of this site we modeled a second landslide scenario that affects the McMillan Creek and Scenic View Reservoirs, while allowing for safe evacuation in the north along the Section Line Street and trail. This scenario assumes that this trail is hardened sufficiently to withstand the earthquake shaking and potential collapse of parts of the trail. The model results for this scenario are presented in **Figure 3-5B**. With one of the “original” safety destinations reinstated, evacuation of the Nedonna Beach community becomes more attainable. BTW evacuation speeds are reduced significantly such that they now fall into the **walk** to **fast walk** categories, compared with **slow jog** and **run** as identified in **Figure 3-5A**. Under these circumstances, an XXL1 tsunami would be survivable for many more people. These findings highlight the importance of maintaining and hardening the Section Line Street trail system to Highway 101 for evacuation purposes.

Figure 3-5. “Beat the Wave” speeds for Nedonna Beach based on two hypothetical landslide scenarios: A) All safety destinations north of the high school are unavailable due to landslides (hatched area), and B) hardening of the trail at Section Line Street allows evacuation to the north, although both reservoir safety destinations remain unavailable due to landslides. Both scenarios include a 10-minute evacuation delay.



3.2 Rockaway Beach

Figure 3-6 presents the least-cost (path) distance modeling for the community of Rockaway Beach. As noted previously, this analysis is used to identify and define detailed evacuation routes, which we then use to delineate the evacuation corridors or flow zones in each community.

As can be seen in **Figure 3-6**, the Rockaway Beach area is characterized with 14 evacuation flow zones (corridors), with each zone having one or two evacuation destinations (assuming non-retrofitted bridges are out). For example, people located in the pink colored polygon west of Crescent Lake and Lake Lytle would evacuate south along Highway 101 and then east along North 6th Avenue (**Figure 3-6**). Individuals located in the downtown area (yellow zone) would make their way south and east to South Grayling Street (north side of the Pacific View neighborhood) (**Figure 3-6**). Residents in the south end of the area would head east via any number of east-west streets: South 6th Avenue (salmon-colored polygon), East Washington Avenue (pink), South Victoria Avenue (teal), or Hollyhock Street (lilac) (**Figure 3-6**).

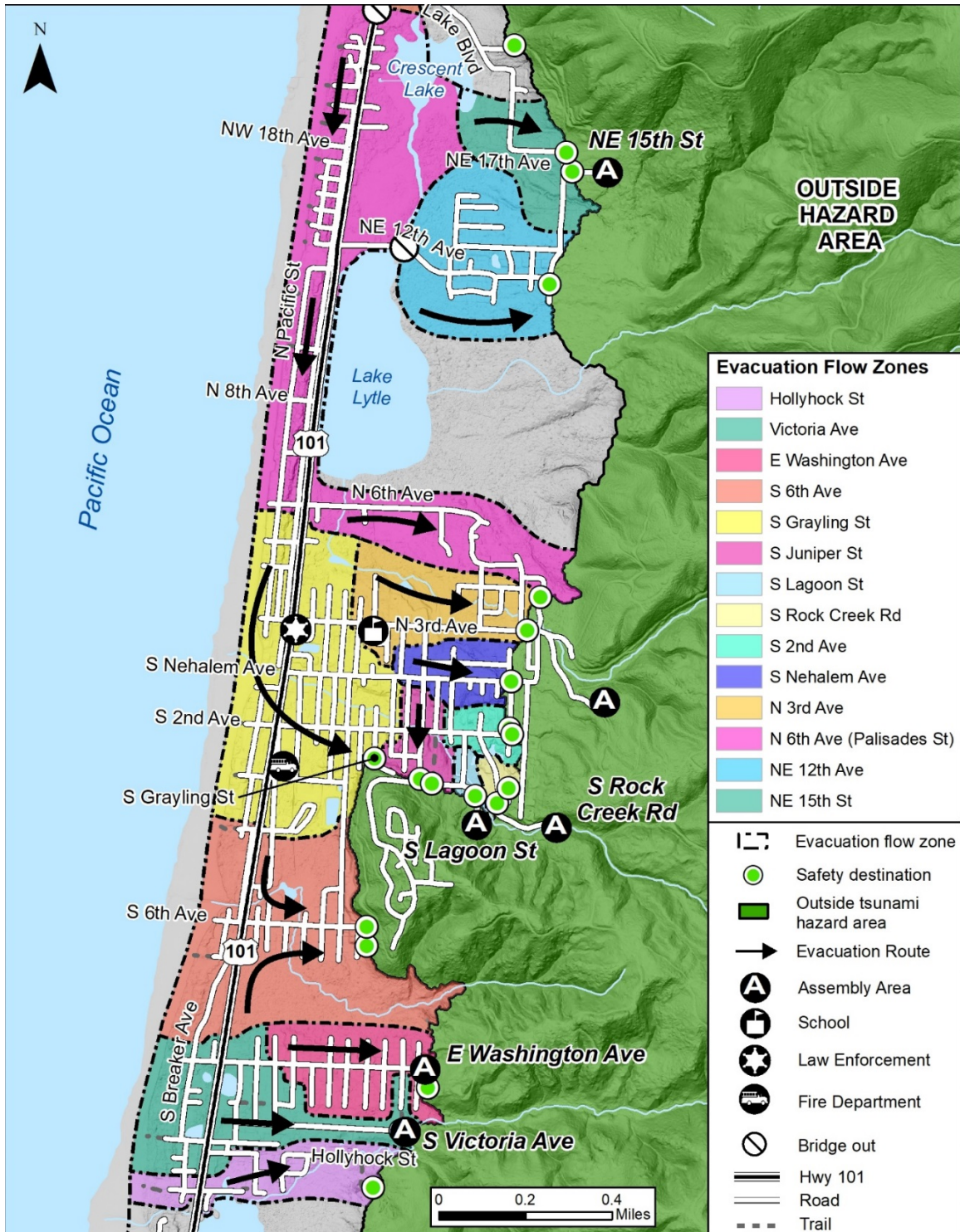
Having defined the evacuation flow zones, we calculated BTW speeds for the Rockaway Beach area (**Figure 3-7**). Because tsunami wave arrival times for Rockaway Beach are ~22–26 minutes and most locations are relatively close to evacuation destinations (i.e., safety), the modeled BTW speeds indicate that much of the area is characterized by minimum evacuation speeds that range from **slow walk** to **walk**. One notable exception is the area west of Crescent Lake and Lake Lytle where multiple bridge failures are expected to occur; bridge failures would result in much longer travel distances to safety, meaning higher minimum evacuation speeds that could reach a **fast walk** to a **sprint** (**Figure 3-8**).

To understand the effects of various potential impediments to safe and rapid evacuation, including possible mitigation options, we define seven scenarios based on the following:

1. The existing road and trail network is available for safe evacuation including all bridges, which are considered undamaged (**Figure 3-7**);
2. Bridges that have not been retrofitted to survive a > Mw 9.0 earthquake are considered to fail such that evacuation routes at these locations are cut off. This applies to the Highway 101 bridge by Lake Boulevard and NE 12th Avenue over the Lake Lytle outlet (**Figure 3-8**);
3. As above, in 2, but with the Highway 101 bridge hypothetically hardened to survive the earthquake shaking, allowing for safe evacuation across the bridge to the north (**Figure 3-9A**);
4. As above in 2, but with the NE 12th Avenue bridge hypothetically hardened to survive the earthquake shaking enabling evacuation to the east (**Figure 3-9B**);
5. As above in 2, but with the building of a hypothetical vertical evacuation structure at Highway 101 and NW 11th Street (**Figure 3-9C**);
6. As above in 2, but with all safety destinations on the north side of the Pacific View neighborhood unreachable due to hypothetical landslide activity (**Figure 3-10A**); and,
7. As above in 5, but with an additional destination removed on the west side of the Pacific View neighborhood (South 6th Avenue) (**Figure 3-10B**).

Each of these scenarios include a 10-minute delay taken from the beginning of the earthquake that accounts for shock associated with the earthquake, and the time required to mobilize and exit buildings.

Figure 3-6. Least cost (path) distance modeling for the community of Rockaway Beach showing evacuation flow zones. (Watershed polygons are shaded for the purpose of identification only, no meaning in the actual colors.)



3.2.1 Rockaway Beach Scenario 1 — Existing road network remains intact

Figure 3-7 indicates that BTW speeds throughout the area are characterized with minimum evacuation speeds that range from **slow walk** to **walk** with small areas of **fast walk**, mostly west of Lake Lytle. This includes a 10-minute delay to the start of evacuation and is entirely due to close proximity to evacuation destinations (safety, characterized by the green and black circles). Although still a manageable **fast walk**, BTW speeds west of Lake Lytle are the highest for this scenario; this highlights the fact that even in the best case, this is the area farthest from safety and merits additional consideration with respect to possible mitigation options.

3.2.2 Rockaway Beach Scenario 2 — Non-retrofitted bridges fail

In this scenario, both the Highway 101 and NE 12th Avenue bridges fail during the earthquake shaking. As a result, evacuation across the bridges is eliminated and alternate evacuation routes must be used. The primary effect of bridge failure in Rockaway Beach is to force evacuees to travel significantly farther to their nearest safety destination, now located to the south.

Under this scenario, residents, visitors, and businesses on Highway 101 (and side streets) between Lake Boulevard and North 8th Avenue must evacuate south along Highway 101 and then east along North 6th Avenue (**Figure 3-8**) as opposed to heading east on NE 12th Avenue or north to the high school (just north of the map extent), assuming that bridges survive (**Figure 3-7**). In addition, due to the increased evacuation distances, the minimum speeds required to reach safety increase significantly from a **walk/fast walk** to speeds that range from **jog** to **sprint**. As a result, safe evacuation for the elderly, physically impaired, and families with children would likely be challenging under this scenario. All other areas throughout Rockaway Beach remain unchanged. A map showing detailed evacuation routes and flow zone corridors for scenario 2 is provided in Appendix B.

Figure 3-7. “Beat the Wave” speed modeling for the community of Rockaway Beach including a 10-minute evacuation delay with all bridges intact; detailed routes can be found in the digital data.

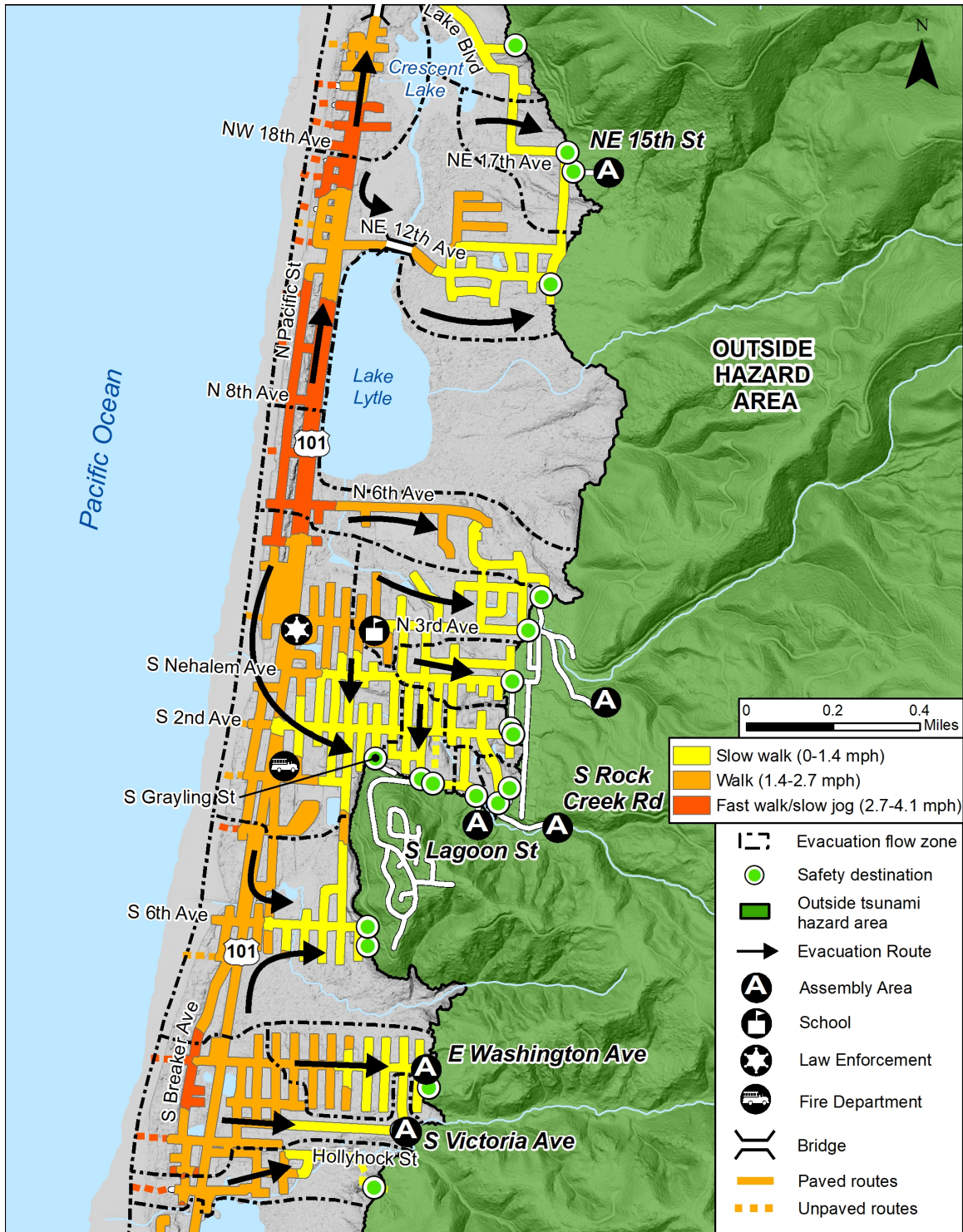
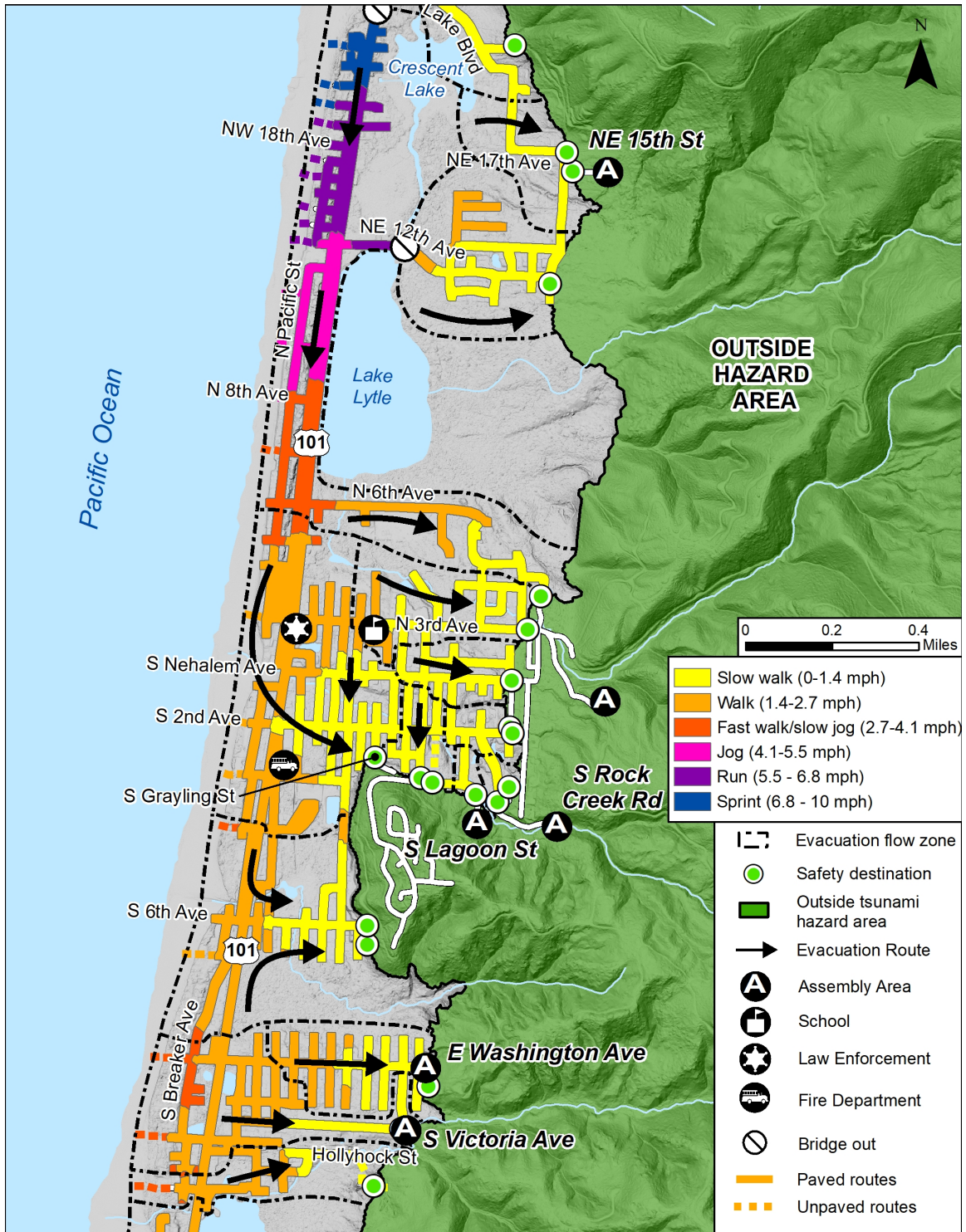


Figure 3-8. “Beat the Wave” speed modeling for the community of Rockaway Beach including a 10-minute evacuation delay with non-retrofitted bridges unavailable for evacuation. See Appendix B and digital data for detailed routes.



3.2.3 Rockaway Beach Scenario 3 — Highway 101 bridge hardening

With the sobering reality that residents and visitors on Highway 101 between Lake Boulevard and NE 12th Avenue would probably not survive a maximum considered XXL1 local tsunami, we modeled a hypothetical case that reflects hardening of the Highway 101 bridge, allowing more people in the vulnerable area to evacuate north to the high school (**Figure 3-9A**). With this change, evacuation throughout this area becomes attainable for more people (compared with the bridges-out scenario in **Figure 3-8**). BTW evacuation speeds are reduced significantly such that they now fall into the **walk** to **slow jog** categories, compared with a worst-case **sprint** as shown in **Figure 3-8**. Under these circumstances, an XXL1 tsunami would be survivable for the majority of residents, visitors, and business persons located in this evacuation community.

3.2.4 Rockaway Beach Scenario 4 — NE 12th Avenue bridge hardening

Scenario 4 considers the case for hardening of the NE 12th Avenue bridge instead of the Hwy 101 bridge. **Figure 3-9B** shows that keeping this bridge passable for evacuation purposes significantly reduces the required BTW evacuation speeds needed to reach safety, particularly when compared with the previous scenario that results in hardening of the Highway 101 bridge (**Figure 3-9A**).

From these model results, we believe further investigations exploring hardening existing bridge routes is warranted, because these options clearly demonstrate the potential to decrease loss of life during a Cascadia event.

3.2.5 Rockaway Beach Scenario 5 — Construction of a vertical evacuation structure

In some localities, safe and effective evacuation to high ground may not be feasible due to terrain challenges (high ground is too far away), or due to the potential failure of critical evacuation infrastructure such as bridges. Given these circumstances, communities may want to explore the construction of a vertical evacuation structure, designed to withstand the forces directed at it by the tsunami. Such structures include soil berms, multi-story parking garages, community facilities, commercial facilities (e.g., hotels), and schools (Applied Technology Council, 2012). In the United States, the first vertical evacuation structure was built at the Ocosta Elementary School on the Westport Peninsula in Washington State. The structure is the school's new gymnasium and has unrestricted (open) access to its rooftop where school children and residents may congregate during a tsunami evacuation; the vertical evacuation structure was opened in June 2016.

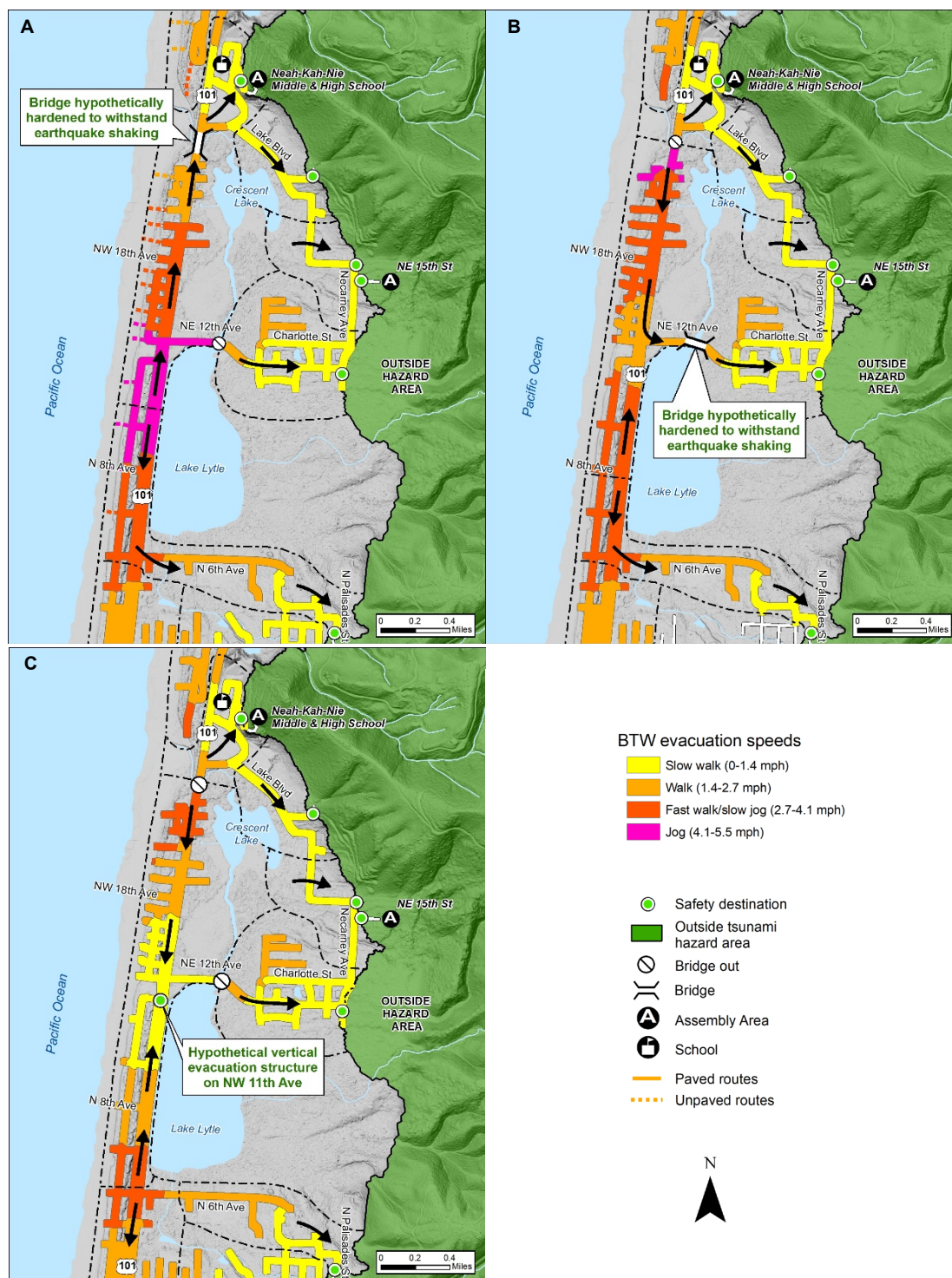
Here we explore the placement of a vertical evacuation structure along the west side of Lake Lytle, at the intersection of Highway 101 and NW 11th Street, due to it being centrally located to areas requiring high BTW speeds (**Figure 3-9C**). Further, ground level at this location is slightly higher than the surrounding area, making it potentially more desirable from an engineering/cost standpoint. As can be seen in **Figure 3-9C**, building a vertical evacuation structure at this location would significantly decrease the required evacuation speeds needed to reach safety — reduced from a **sprint** to predominantly **walk** and **fast walk**. These changes provide a striking visual argument for the benefits of such a structure centrally located to a vulnerable population.

As noted previously, a vertical evacuation structure could be designed in a variety of ways, some of which could add significant economic benefit to the area. Importantly, such a structure would need to be designed to exceed the maximum flow depth in this area and would need to be able to withstand the forces directed at it. Using our XXL1 model results used for evacuation purposes, we estimate that the design elevation must exceed the maximum tsunami flood elevation of ~19 m (62 ft) (a maximum flow depth of ~14 m [46 ft]) (see Appendix D for XXL1 maximum flow depths for the study area). Furthermore, the

structure would need to be of a sufficient strength to withstand the tsunami current flow and be large enough to accommodate the estimated number of evacuees in the immediate area (defined as the flow zone surrounding the structure in **Figure 3-9A**).

From these model results, we believe further investigation into the building of a vertical evacuation structure is warranted, because the numbers of people saved could be much larger compared with hardening bridges. The significant height of the structure, potential large foot print, and large cost are likely to be a deterrent. Costs versus benefits must be carefully evaluated among all these options, including the possibility of designing a structure based on a smaller tsunami scenario, i.e., an L1 (Large) instead of an XXL1 scenario, which experiences significantly smaller flow depths.

Figure 3-9. “Beat the Wave” evacuation speeds for three hypothetical mitigation scenarios for Rockaway Beach. A) The Highway 101 bridge is hardened to survive the earthquake and is available for evacuation, B) the NE 12th Avenue bridge is hardened to survive the earthquake, and C) the construction of a vertical evacuation structure near the intersection of Highway 101 and NW 11th Avenue. All scenarios include a 10-minute evacuation delay.



3.2.6 Rockaway Beach Scenario 6 — Landslide failure on the north side of the Pacific View neighborhood

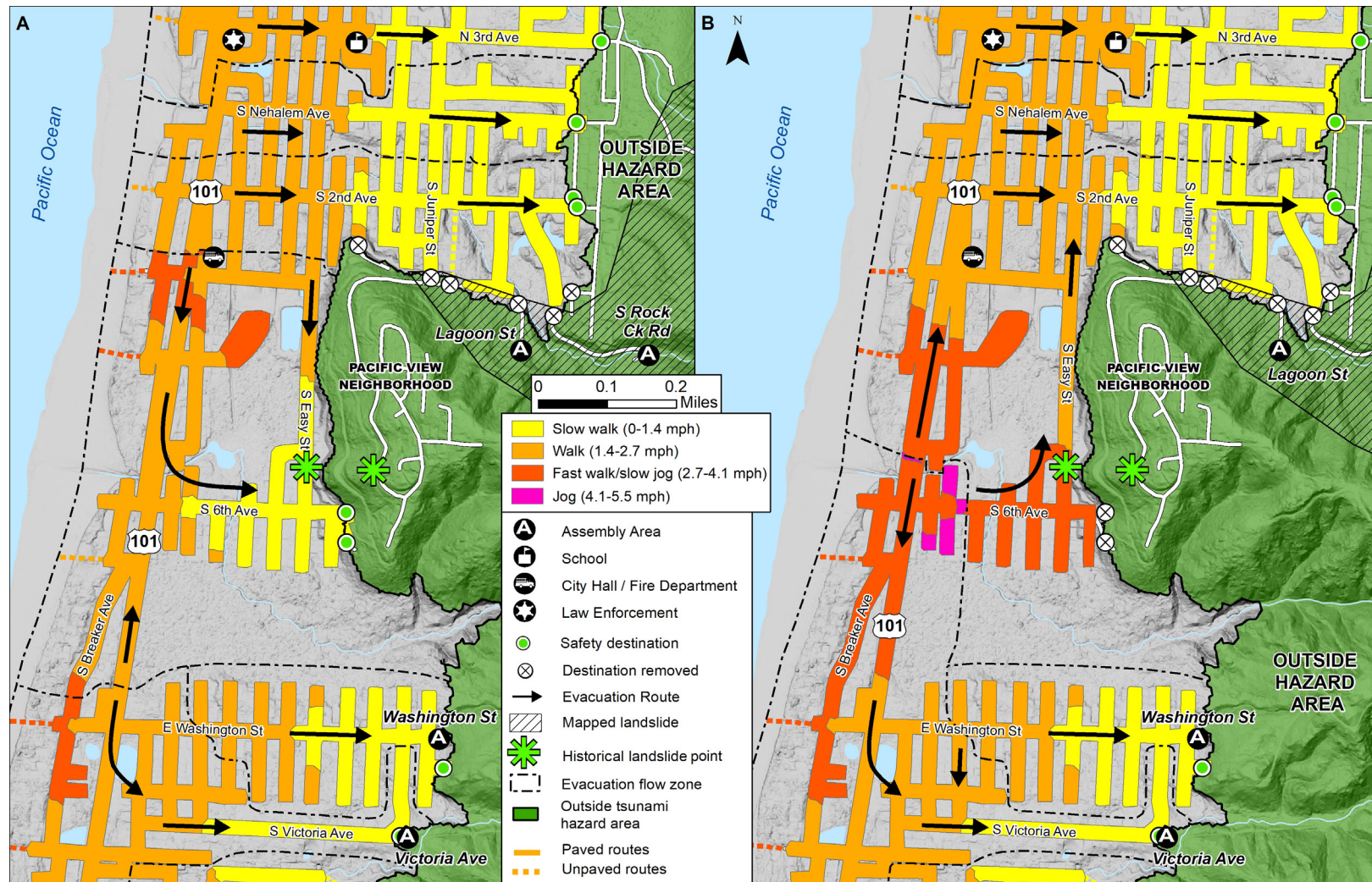
Steep slopes and landslide terrain adjacent to the Pacific View neighborhood have the potential to remove several safety destinations in the heart of Rockaway Beach. To test the importance of roads at risk of becoming impassable, we generated BTW speeds and evacuation flow zones for a scenario with all safety destinations along the north side of the Pacific View neighborhood removed. This includes the following streets adjacent to South 2nd Avenue: Grayling Street, Juniper Street, Keel Street (grassy easement, not paved), Neptune Street, and Rock Creek Road ([Figure 3-10A](#)). Overall, evacuees can still reach high ground via South 2nd Avenue with a minimum evacuation speed of **walk** to **slow walk**. There is a small increase in the number of residents that must **walk** as opposed to **slow walk**, and on SE 4th Avenue (Rockaway Beach RV Park) minimum evacuation speed increases from **walk** to **fast walk**.

3.2.7 Rockaway Beach Scenario 7 — Landslide failure on the north and west sides of Pacific View neighborhood

Although there are no mapped landslides at the east end of South 6th Avenue, SLIDO reports that the hillside experienced a landslide (roughly 200 ft long by 90 ft wide) during the February 1996 storms ([Figure 3-10](#)). In addition to this historical landslide along the evacuation route, the hillside above the path reaches a slope of 45°, well beyond the angle of repose for the underlying sandstone bedrock. These facts suggest that it would not be surprising if some sort of slope failure occurred in response to a major Cascadia earthquake that could prevent people from reaching safety. Therefore we ran an additional landslide scenario in this area, removing the safety destinations on the west side of the Pacific View neighborhood in addition to those in the north ([Figure 3-10B](#)).

As expected, people on South 6th Avenue end up having to travel much farther to reach safety. Minimum evacuation walking speeds correspondingly increase from **slow walk** and **walk** to **fast walk**. Flow zone boundaries show that there is a new decision point that results from the removal of safety at South 6th Street: many evacuees who would have evacuated up South 6th Avenue would now head north to South 2nd Avenue while the remainder would head south to Victoria Avenue. These findings highlight the importance of establishing sufficient wayfinding information along core evacuation routes, while recognizing that other routes may become impassable. Furthermore, residents in certain community evacuation corridors need to plan for potential scenarios where one route is eliminated due to a landslide, while other routes remain open.

Figure 3-10. “Beat the Wave” evacuation speeds for two hypothetical landslide scenarios for Rockaway Beach. A) Earthquake-induced landslides prevent evacuation on the north side of the Pacific View neighborhood, and B) As in scenario A but with the addition of another closure at the east end of South 6th Avenue. Both scenarios include a 10-minute evacuation delay.



3.3 Twin Rocks and Barview

Figure 3-11 defines the least-cost (path) distance modeling for Twin Rocks and Barview. The area is characterized with six community evacuation flow zones (corridors). Visitors at the Barview County Jetty Park would evacuate up “sand hill” in the southwest (yellow polygon), while residents at Camp Magruder and Old Pacific Highway (red polygon) would evacuate up “sand hill” from the north side within Camp Magruder. Shorewood RV Park and the northern end of Old Pacific Highway (blue polygon) would evacuate east across Highway 101 toward the Gravel Pit. Pacific Street and Shand Avenue (purple polygon) would evacuate to Twin Rocks Friends Camp and up to the reservoir. The public located on Highway 101 (pink polygon) would evacuate inland up a number of unnamed side roads located on the east side of the highway. There are no homes in this area, so we expect these to be generally unused with the exception of the Harborview Drive community (Terwilliger Heights flow zone, orange polygon in **Figure 3-11**).

BTW speeds have been modeled for the Twin Rocks and Barview areas for the six flow zones. These data are presented in **Figure 3-12** based on two scenarios assuming the previously mentioned 10-minute delay before evacuation starts:

1. Existing road and trail network remains intact (**Figure 3-12A**); and
2. Hypothetical landslides block safety destinations along Highway 101 (**Figure 3-12B**).

3.3.1 Twin Rocks–Barview Scenario 1 — Existing road network remains intact

Similar to Nedonna Beach, the Twin Rocks and Barview region has ample high ground located nearby. The required minimum evacuation travel speeds for this area ranges from a **walk** to **fast walk** in order to reach safety (**Figure 3-12A**). For many people, evacuation to safety is possible. The west end of the county park, closest to the north Tillamook jetty, and Shorewood RV Park are the farthest locations from safety; the minimum evacuation speed is a **fast walk** in order to “beat the wave.” As previously discussed, this speed may be difficult for certain populations to maintain. A map showing detailed evacuation routes and flow zone corridors for this scenario is provided in Appendix C.

3.3.2 Twin Rocks–Barview Scenario 2 — Landslides block routes to safety east of Highway 101

Landslide terrain adjacent to Highway 101 will likely restrict evacuation along the highway and could exclude some safety destinations from consideration. **Figure 3-12B** reveals little change to the overall evacuation flow zone corridor boundaries and minimum evacuation speeds for the area. As a result of this modeling, we believe the area of Twin Rocks and Barview does not need to consider landslide-induced evacuation mitigation options. Although we did not model a vertical evacuation structure in this region, such a structure might merit further evaluation, given the **fast walk** speed required to reach safety from the Shorewood RV Park.

Figure 3-11. Least cost (path) distance modeling for the communities of Twin Rocks and Barview showing evacuation flow zones.

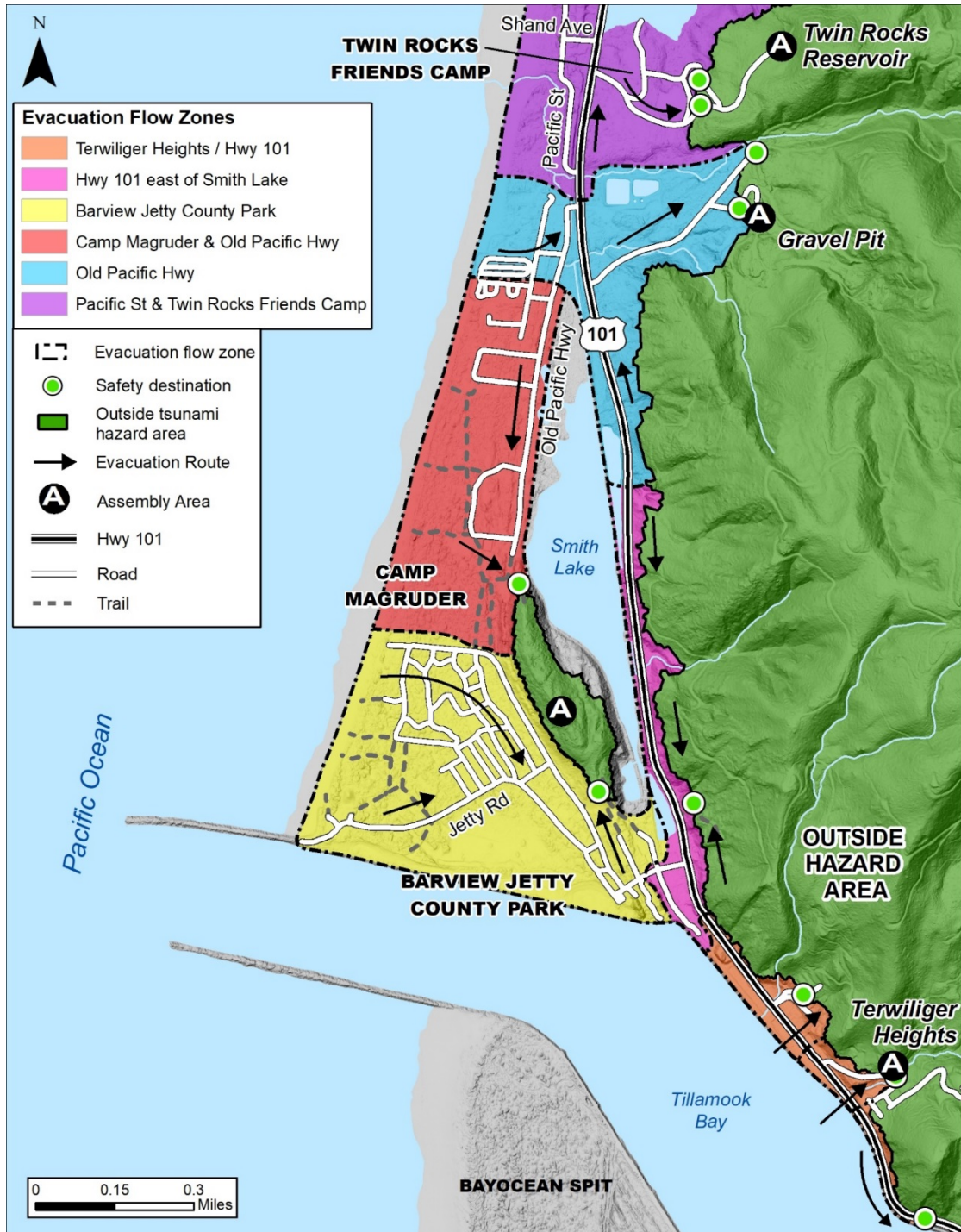
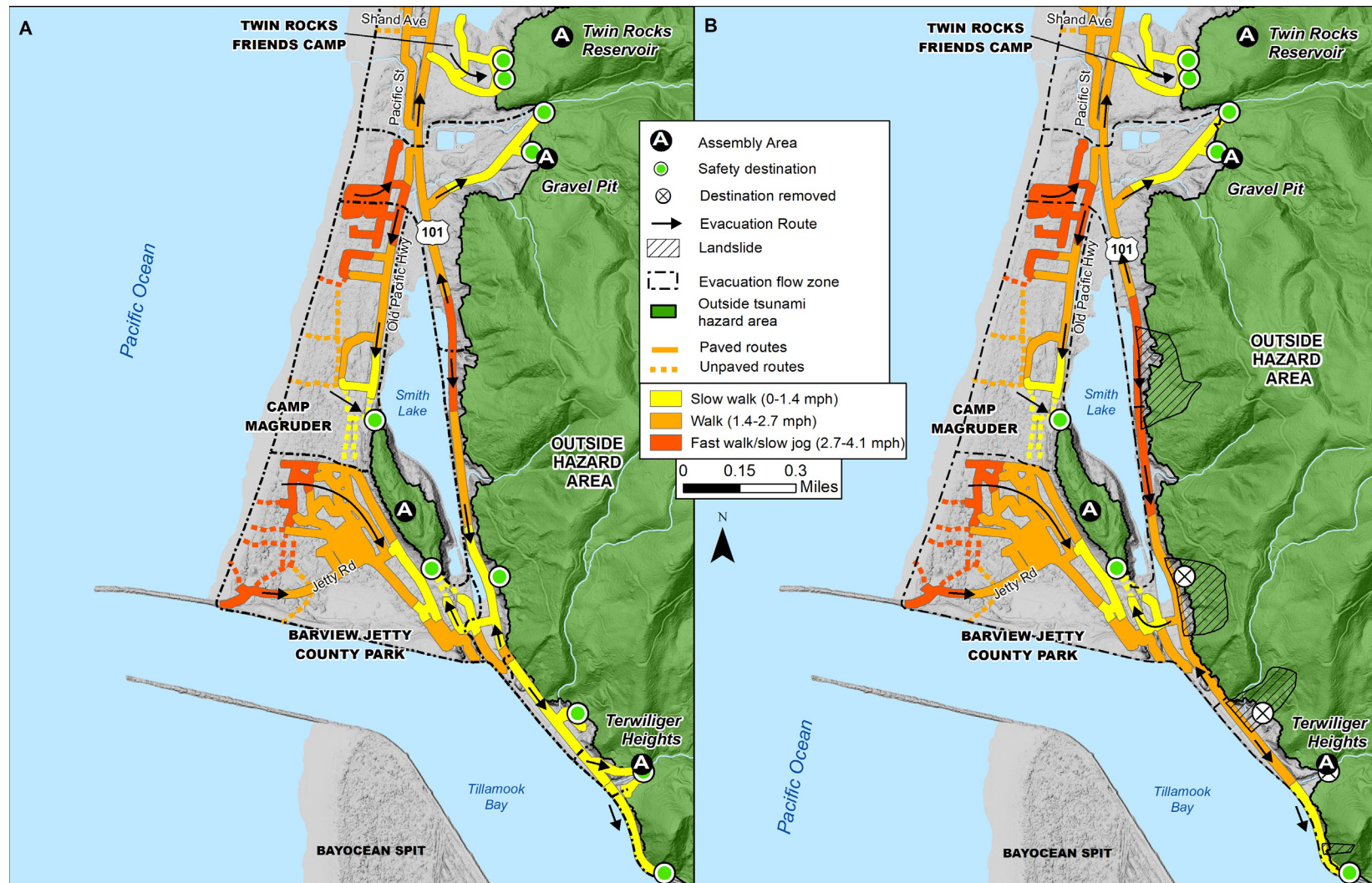


Figure 3-12. “Beat the Wave” speeds for Twin Rocks and Barview: A) existing road and trail network remains intact, and B) landslides eliminate safety in three locations along Highway 101, requiring evacuees in that area to travel further to reach safety. Due to the close proximity of other safety destinations, however, BTW speeds are barely affected. Both scenarios include a 10-minute evacuation delay.



4.0 “BEAT THE WAVE” MAPS

“Beat-the-Wave” (BTW) maps for the greater Rockaway Beach area are presented in [Figure 4-1](#), [Figure 4-2](#), and [Figure 4-3](#). These figures reflect the most conservative scenario with non-retrofitted bridges removed from the modeling. Landslide-induced road closures were not included due to uncertainty over where they might occur and how they might impact pedestrian evacuation.

The BTW maps depict with arrows and evacuation flow zones the most efficient evacuation routes along streets and trails. Evacuation flow zone boundaries, defined by the black dash-dot boundary lines, are especially useful because they help clarify evacuation community routes and depict break points between two equally efficient routes to safety. Evacuation destinations (points of safety) are characterized by the green and black circles. Evacuation flow zone corridors and the direction arrows to the evacuation destinations thus provide valuable guidance, regardless of BTW speed information.

As discussed previously, estimates of needed speed to “beat the wave” for the maximum considered XXL1 tsunami in the greater Rockaway Beach area indicate that people in much of this area would be able to evacuate to high ground, with minimum speeds in the **walk** category (2–4 fps). 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 years 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 observation suggests that survival for older residents is attainable for much of the area. This assumes that the evacuation routes are easily traveled after the earthquake and, importantly, are well signposted. One notable exception is the Shorewood RV Park, which is far enough from its nearest safety destination to require a faster minimum evacuation speed (characterized as a **fast walk**, which may not be attainable for older residents living in that community ([Figure 4-3](#)).

Removing the Highway 101 and NE 12th Avenue bridges has been shown to severely compromise evacuation for residents located west of Lake Lytle and Crescent Lake ([Figure 4-2](#)). Our analyses demonstrate that hardening the Highway 101 bridge ([Figure 3-5A](#)) or adding a vertical evacuation structure at NW 11th Street and Highway 101 ([Figure 3-5B](#)) would greatly enhance evacuation and thus survivability for this area. However, a vertical evacuation structure built in this vicinity benefits a much broader area than would a retrofitted bridge, significantly increasing the survivability of the public throughout this area, especially those with limited mobility or the elderly.

Although the speeds presented in [Figure 4-1](#), [Figure 4-2](#), and [Figure 4-3](#) imply that people in much of the area 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, **the public 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](#), [Figure 4-2](#), and [Figure 4-3](#) should be viewed 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 Nedonna Beach.

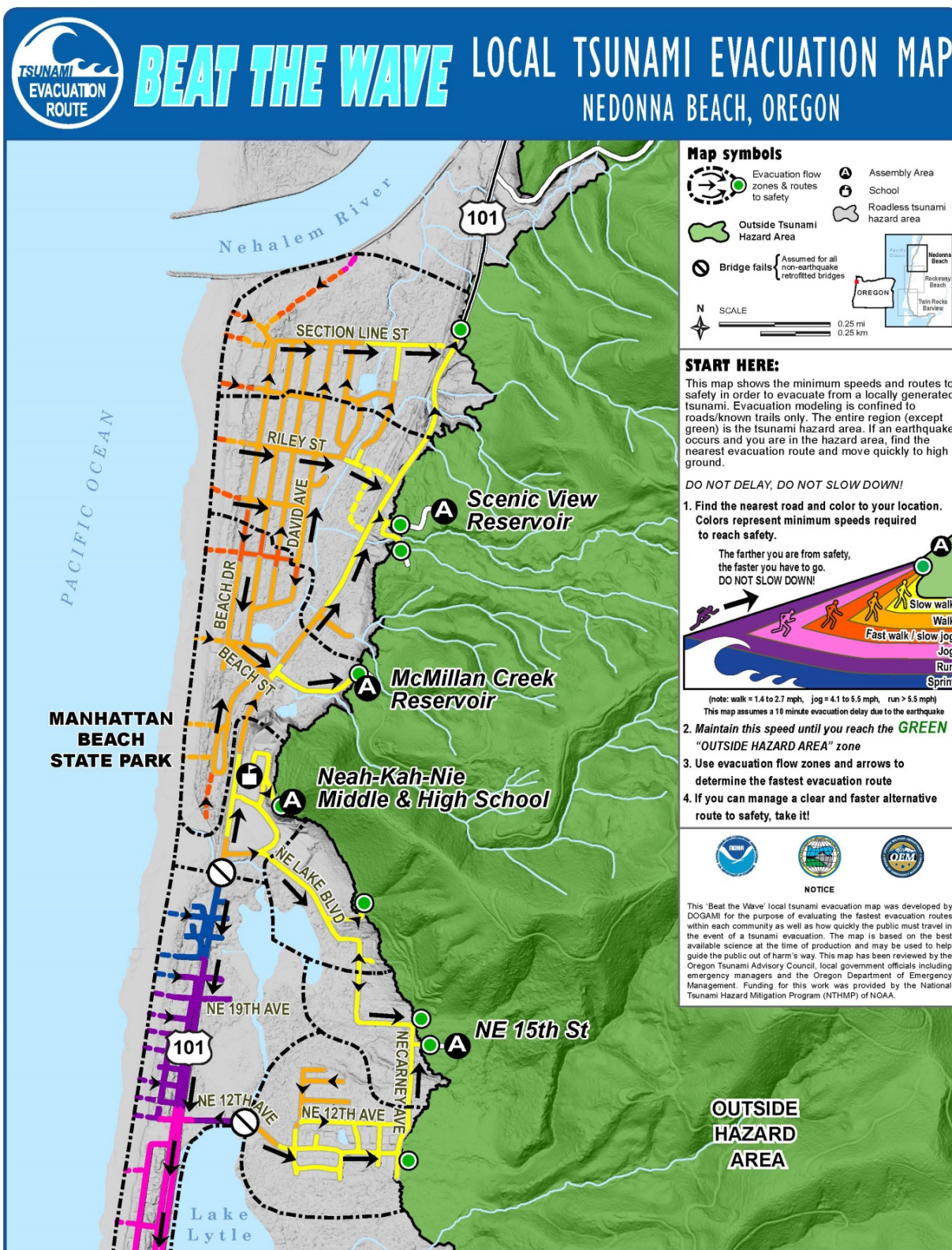


Figure 4-2. Final “Beat the Wave” map for the community of Rockaway Beach.

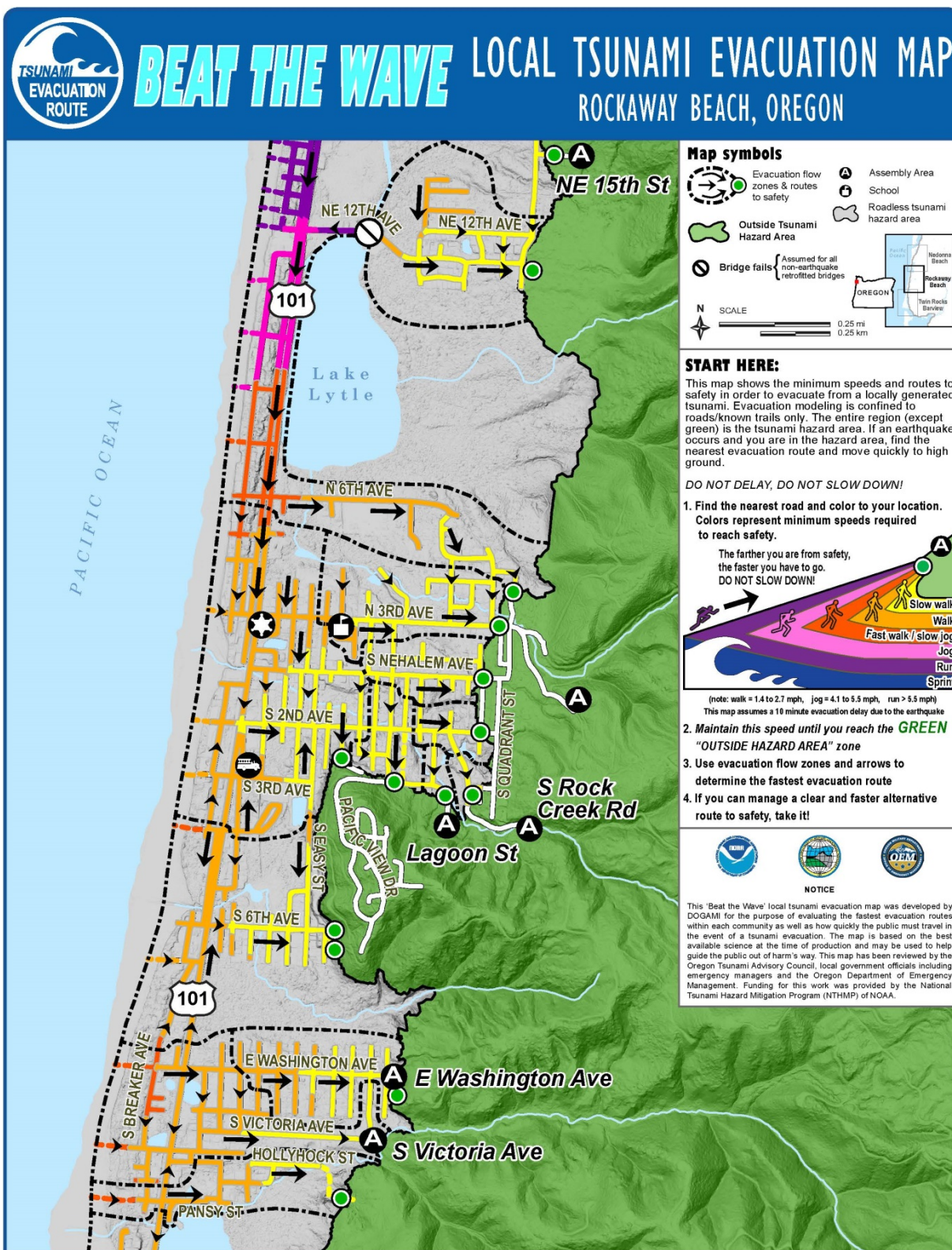
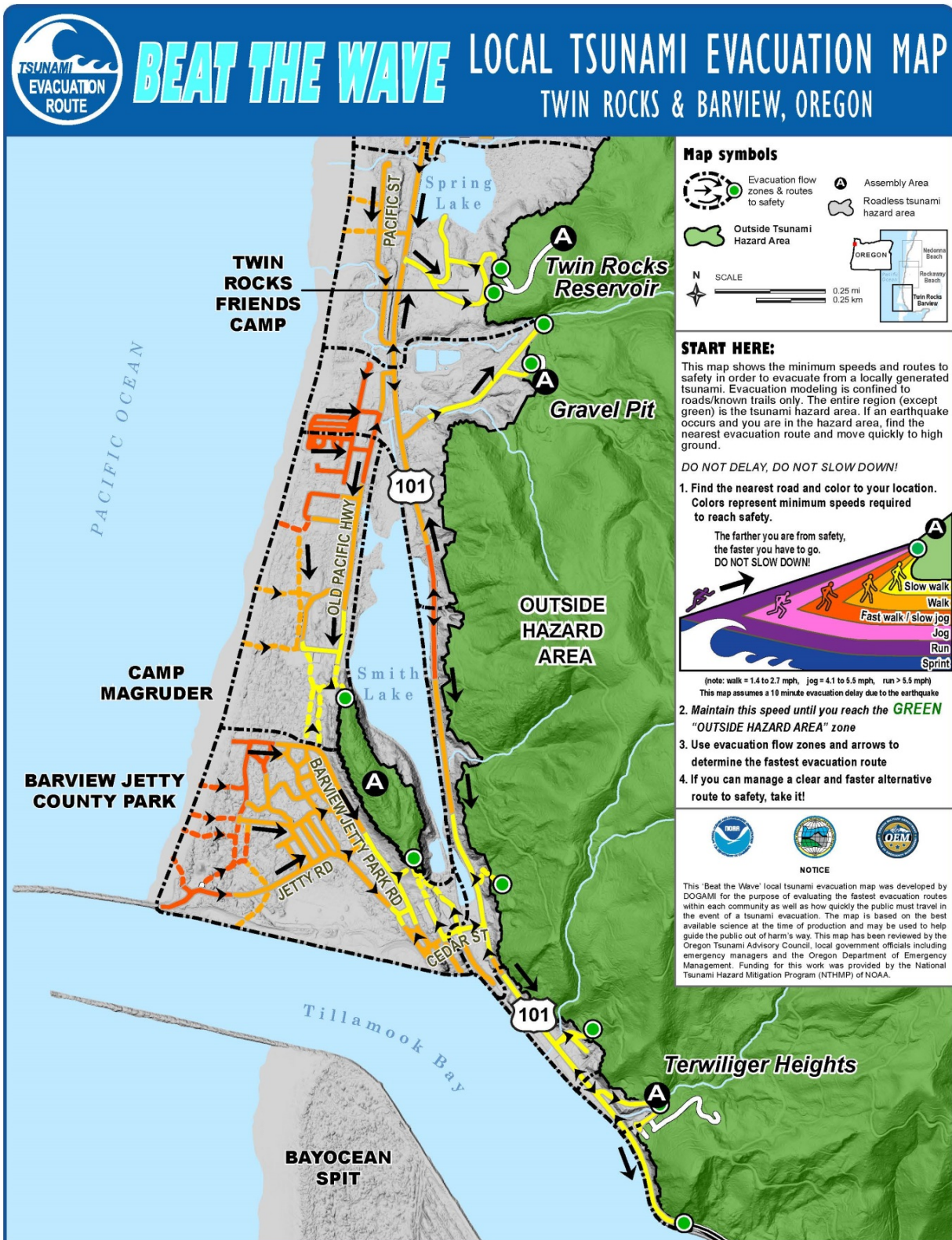


Figure 4-3. Final “Beat the Wave” map for the communities of Twin Rocks and Barview.



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 reaching safety. Examination of the modeled 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. Although there are several early wave arrivals in the greater Rockaway Beach area, they are minor and result in no impact to the modeled evacuation speeds (**Figure 4-2**).

Because bridges over Lake Lytle and Crescent Lake outlets have not been retrofitted to withstand an ~Mw 9.0 earthquake, it is possible that they will collapse during the shaking, effectively cutting off evacuation to the high school in the north and along NE 12th Avenue to the east (**Figure 3-7B**). This loss critically impacts residents living on and adjacent to Highway 101 between Lake Boulevard and North 8th Street, such that their only way of escape is now to the south along North 6th Avenue. Our analyses demonstrate that the speeds required to successfully “beat the wave” in this area are on the order of 10–12 fps (akin to a 7.3–8.8 min/mile pace), limiting evacuation success to only a few very fit adults. As a result, a portion of this population would not be able to reach safety in time and would be killed by the tsunami while evacuating.

Mitigation techniques for addressing sites where evacuation speeds are too high include installing vertical evacuation structures and/or reinforcing those bridges expected from engineering analysis 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 that target improvements in evacuation routes (e.g., the retrofitting of one or both bridges) or focus on 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 demonstrate the benefits of building a vertical evacuation structure along Highway 101 near NW 11th Street in Rockaway Beach. The establishment of such a structure would significantly decrease the public’s evacuation times and the minimum evacuation speeds (**Figure 3-9C**) to reach safety.

In addition to consideration of vertical evacuation structures, retrofitting existing bridges remains another option for hardening evacuation routes. Our “with” and “without” model runs over these bridges serve to reinforce the importance of the bridges for evacuation throughout the area (**Figure 3-7**). **Figure 3-8A** and **Figure 3-8B** highlight how hardening just one of the two bridges could have a significant impact on reducing evacuation difficulty and hence the required minimum travel speeds needed to reach safety. Of the two scenarios, our analyses suggest that at a minimum, hardening the NE 12th Avenue bridge would produce the best response, yielding the lowest required travel speeds in the area. Although the areas benefitting from retrofitting bridges to withstand such a large earthquake may be smaller than the area impacted by a vertical evacuation structure, the required height of such a structure in Rockaway Beach would pose a significant challenge with respect to land use planning objectives (e.g., viewsheds) and cost.

Although landslide and slope stability analyses were not performed for this study, “what if” analyses assuming worst case slope failures are valuable for identifying the severity of their potential effect on evacuation (Wood and others, 2016). Our results show that, if landslides do obstruct evacuation, such slides may play a pivotal role in preventing people from reaching safety in certain parts of the community, most notably Nedonna Beach and to a lesser extent Rockaway Beach adjacent to the Pacific View neighborhood. We suggest that slope stability analyses and related mitigation recommendations be considered to guide decision makers.

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 Schmidlein (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 for unimpaired adults such as 4 fps? The BTW map answers that question definitively by binning output into multiple speeds which can be directly correlated to maximum walking speeds of particular populations (e.g., an unimpaired adult walking at 4 fps can evacuate from all yellow and light orange areas but cannot evacuate from dark orange, pink, purple and blue areas).

Regardless of mitigation considerations, wayfinding through adequately spaced signage, battery operated lighting, and other means is essential to survival. Even in areas where safety is nearby and all populations appear likely to survive, confusion about where to go will make the difference between life and death. Although Rockaway Beach is relatively “simple” in its topography (the tsunami advances from the west, safety lies to the east and is generally visible from a distance), it can still be tricky to reach high ground. Much of town is separated from safety by low-lying marsh terrain and not all east-west roads extend all the way to the safety. Clear and visible signage placed in key locations is extremely important, especially for areas likely to experience large numbers of visitors such as Manhattan Beach State Park, downtown Rockaway Beach, and Barview Jetty County Park.

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 became apparent while modeling evacuation of Clatsop Spit (Gabel and Allan, 2016) where BTW results for a hypothetical vertical evacuation structure initially yielded a flow zone boundary resulting in some people evacuating to the structure instead of high ground even though high ground could be reached at a slower speed. If every potential path considered both distance and time, those kinds of inconsistencies could be removed. Because there were no significant early wave arrival issues in Rockaway ([Figure 4-2](#)), this issue can be effectively ignored for this area.

Existing modeling of BTW speeds is 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 the greater Rockaway Beach area, 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 4% error for the western parts of town that are approximately 0.5 mile (0.8 km) from safety. For evacuees that may have high ground nearby but require travel over natural areas, then 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. However, such an approach would complicate the identification 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. Although there remain many uncertainties about the public's 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 are on Holocene sand and silt, which are variably prone to liquefaction and lateral spreading (Madin and Wang, 1999). This is especially the case in the Rockaway area because of the close proximity of the water tables throughout this area, which is conducive to causing 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 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, the existing 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 few empirical data on how long it takes people to begin evacuation, but it is reasonable to assume that walking would be difficult during the 3–5 minutes of strong shaking, and hence there is some uncertainty about the time needed to start evacuation after the shaking. The mean of 7 minutes found in the surveys of Mas and others (2013) in La Punta, Peru, remains untested, 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).

6.0 CONCLUSIONS AND RECOMMENDATIONS

The investigation accomplished the primary objective: to provide a quantitative assessment of evacuation difficulty in the greater Rockaway Beach area, including the communities of Nedonna Beach, Rockaway, Twin Rocks, and Barview. The investigation implemented the “Beat-the-Wave” (BTW) 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 other 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 demonstrate that evacuation of much of the greater Rockaway Beach area in response to a maximum considered XXL1 tsunami is attainable with one notable exception. The exception is Highway 101 and corresponding side streets between Lake Boulevard and North 8th Street (the area west of Crescent Lake and Lake Lytle) where bridges are expected to fail during the earthquake, potentially eliminating two key evacuation routes. Without suitable mitigation efforts directed at reinforcing at least one of the bridges, we anticipate some potential loss of life because the time required to “beat the wave” to safety in this area is too long relative to the arrival time of the tsunami. Of the two bridge scenarios examined in this study, where modeling maintains one route while eliminating the other due to expected bridge failure, we recommend further evaluation of at least the NE 12th Avenue bridge. This is because our BTW model results strongly point to this site providing the best gains with respect to reducing the evacuation speeds required to reach safety. If this option is not achievable, than retrofitting the Highway 101 bridge remains a viable option, though the gains in improved evacuation speeds were found to be slightly less than would be gained by strengthening the 12 Avenue bridge.

Of additional concern is the risk of landslide activity that could potentially block access to several of the safety destinations in the Rockaway Beach and Nedonna Beach areas. However, due to uncertainty in how the landscape might respond during a major earthquake, we cannot say for certain where and whether earthquake-induced landslides will affect established evacuation routes. Instead, we can offer general guidance based on the assumption that previously mapped slide locations could fail and block evacuation. To that end, our analyses have shown that consideration of earthquake-induced landslides is important in a few discrete areas; in these areas landslides potentially pose a significant barrier to safe evacuation, and care should be taken to plan accordingly for such a hazard.

To address evacuation difficulties identified in a few areas in the Rockaway Beach area, a vertical evacuation structure remains another viable option, especially as a refuge for those with limited mobility. Such a structure could consist of a large berm, tower, or commercial building. However, this option would need to be carefully weighed (cost/benefit) against options such as hardening bridges. A large enough structure (e.g., a berm or building) capable of holding the estimated number of people in the relevant evacuation flow zone would need to be built to a sufficient height. A structure would need to exceed an elevation of ~19 m (64 ft), and exceed ~14 m (46 ft) above the ground surface in order to provide protection against the maximum considered XXL scenario. We recommend further evaluation in order to assess the cost/benefits of each of these options.

7.0 ACKNOWLEDGMENTS

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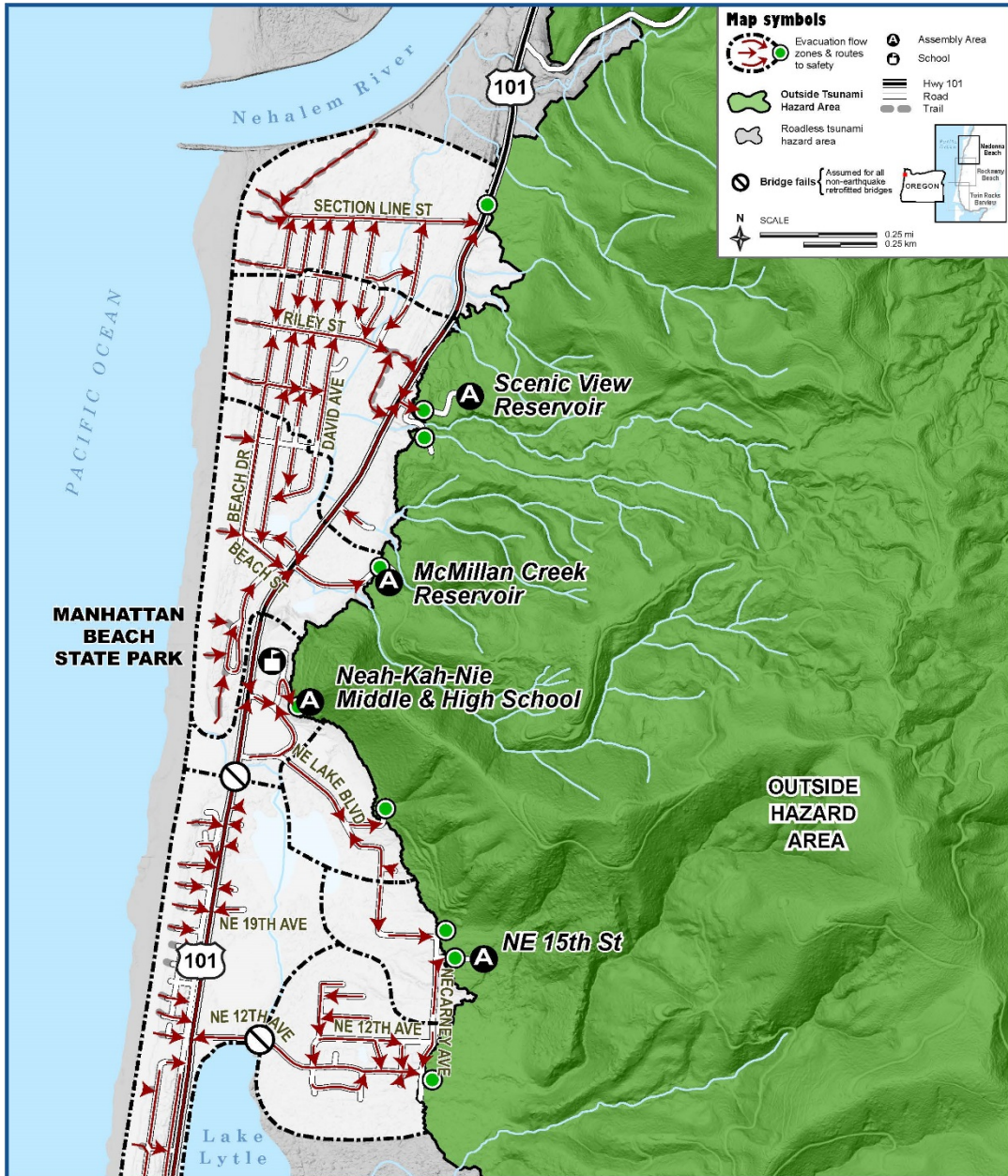
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9.0 APPENDICES

- Appendix A: Detailed evacuation routes for Nedonna Beach
- Appendix B: Detailed evacuation routes for Rockaway Beach
- Appendix C: Detailed evacuation routes for Twin Rocks and Barview
- Appendix D: Illustration of XXL1 tsunami maximum flow depths for the greater Rockaway Beach area

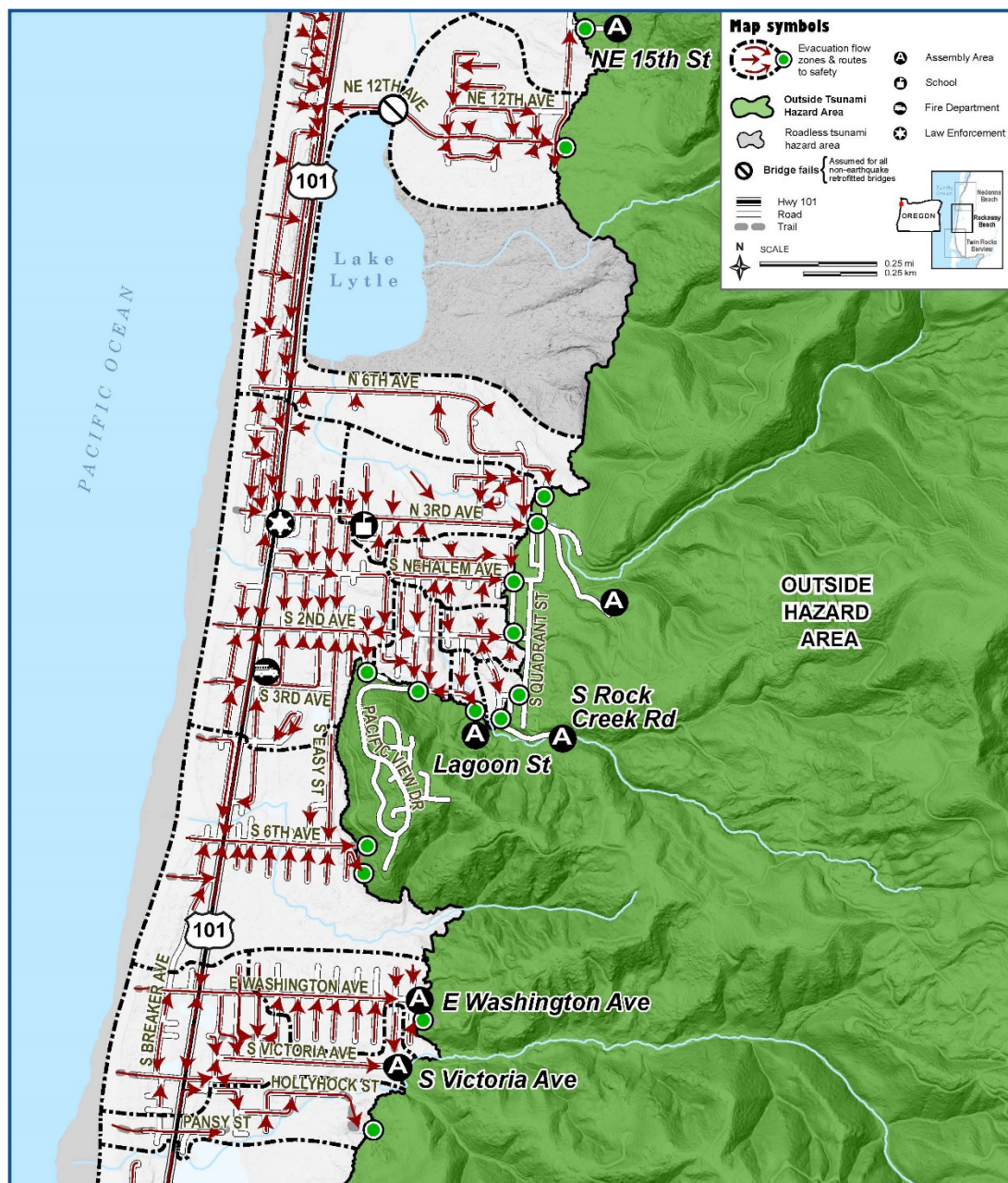
9.1 Appendix A: Detailed evacuation routes for Nedonna Beach

Figure 9-1. Least cost (path) distance modeling for the community of Nedonna Beach 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.



9.2 Appendix B: Detailed evacuation routes for Rockaway Beach

Figure 9-2. Least cost (path) distance modeling for the community of Rockaway Beach 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.



9.3 Appendix C: Detailed evacuation routes for Twin Rocks and Barview

Figure 9-3. Least cost (path) distance modeling for the communities of Twin Rocks and Barview showing evacuation flow zones and detailed evacuation routes for the scenario assuming the existing road and trail network remains intact.

