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VERTICAL STRUCTURES AND OTHER TSUNAMI EVACUATION IMPROVEMENT OPTIONS IN SEASIDE AND CANNON BEACH, CLATSOP COUNTY, OREGON

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DISCLAIMER

WHAT'S IN THIS REPORT?

This report describes the methods and results of pedestrian tsunami evacuation modeling of present-day routes and possible mitigation measures for Seaside and Cannon Beach, Clatsop County. This information can help communities plan and prepare for the next Cascadia Subduction Zone earthquake and tsunami.

Cover photograph: Aerial view of Seaside (beach and the promenade) during the annual beach volleyball tournament. Tsunami evacuation from this location requires crossing the Necanicum River, seen at the top of the photo. Of the four bridges shown, only one is expected to survive earthquake shaking.
Photo credit: Erica Harris, 2011.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This project is about helping communities evaluate ways to move people out of the tsunami zone in the shortest amount of time possible between the start of earthquake shaking and the arrival of the tsunami. During 2023 and 2024, the Oregon Department of Geology and Mineral Industries (DOGAMI) evaluated pedestrian evacuation routes for a local tsunami generated by an earthquake on the Cascadia Subduction Zone (CSZ) in Seaside and Cannon Beach, Clatsop County, Oregon. To assist communities in identifying and prioritizing mitigation projects, we produced the following maps and tables:

- Pedestrian evacuation speed maps and survivor estimates for present-day evacuation routes
- Pedestrian evacuation speed maps and survivor estimates for hypothetical mitigation scenarios, including one or more vertical evacuation structures (VES) and seismic bridge retrofits
- Tsunami wave arrival maps
- Permanent- and temporary-resident population distributions within the tsunami zone

Beat the Wave tsunami pedestrian evacuation analyses calculate minimum speeds required to stay ahead of the tsunami for each scenario, which include present-day conditions as well as hypothetical improvements such as the inclusion of one or more VES and bridge retrofits. *Beat the Wave* uses least-cost distance (LCD) modeling combined with knowledge of route characteristics (e.g., flat versus steep terrain) and wave arrival times. Evacuation paths were limited to established roads, trails, and pedestrian pathways designated by local government reviewers as the most likely routes. The model also includes a 10-minute delay from the start of an earthquake before beginning evacuation to account for the time in which earthquake shaking takes place (3 minutes–5 minutes), disorientation, shock, and collecting family members and go bags, and the time required to evacuate buildings and reach the nearest road (navigating fallen debris, exiting building, crossing a fenced yard, etc.).

Survivability is defined as being able to leave a tsunami-hazard zone before wave arrival and is determined through the selection of a maximum speed, using the assumption that faster speeds may not be realistic for some people, especially given roadway conditions (e.g., debris on road, downed power lines, and broken asphalt). We chose 4 feet per second (fps) (2.7 mph) to represent a realistic maximum speed that vulnerable populations such as impaired adults and the elderly can maintain for the entirety of their route. It is worth noting that while results are heavily dependent on the speed threshold chosen, the power of this analysis lies in the *relative* difference between scenarios. It should also be noted that evacuation modeling results assume clear roads and do not reflect the influence of road debris or other impediments that are potentially generated by the preceding earthquake.

Results in Seaside demonstrate that a significant portion of the city cannot reach natural high ground given the present-day road and bridge network. Evacuation routes are as long as ~1.5 mi and require travel speeds of up to 10 fps (6.8 mph) to successfully evacuate before wave arrival. We estimate 25% of permanent and temporary residents (~4,200 people) within the tsunami zone will survive. A hypothetical scenario simulating a seismic retrofit of every bridge in Seaside yields a 1% increase in survival, a stark demonstration of the ineffectiveness of this mitigation solution. Alternatively, a single VES placed at the Convention Center parking lot results in the hypothetical survival of 50% of the total population in the modeled tsunami-hazard zone (~8,500 people). Our population model does not incorporate day visitors, which can increase the number of temporary residents in Seaside by as much as 9,000 people–16,000 people and in Cannon Beach by as much as 6,000 people. A large majority of these people will be near the ocean beaches and dense downtown areas, placing them at the highest risk from tsunamis. Scenarios

incorporating a second, third, and fourth VES further increase life safety to 66%, 74%, and 85% of the total population, respectively.

We estimate 90% of the total population in Cannon Beach will survive due to the prevalence of high ground adjacent to most neighborhoods. One exception to this encouraging result is the downtown district, which is cut off from its nearest high ground by Ecola Creek. The creek and its broad marshy banks can only be crossed via the Fir Street Bridge, which is not expected to survive earthquake shaking. Instead, people in this heavily trafficked area must travel up to 1 mi south to alternative high ground at travel speeds of up to 8 fps (5.5 mph). We estimate 2% of the total *downtown* population will survive. A hypothetical seismic retrofit of the Fir Street Bridge saves the lives of 77% of the downtown population and brings the citywide survivability estimate to 97%. Four VES scenarios were modeled; three downtown sites and city hall, farther to the south. Two of the three downtown locations are estimated to save 100% of the residents. The third downtown location saves 82% of residents, with the reduction due to its position close to the highest density of residents as well as its placement within the Ecola Creek floodplain. The city hall location does not improve life safety over current conditions.

In both communities, tsunami evacuation modeling is designed to aid in community planning, raise awareness of tsunami hazards and preparedness, and to support emergency management and land use planners to make informed life-safety decisions. These results may be used to identify, prioritize, and justify funding for infrastructure mitigation projects such as VES and seismic bridge retrofits or rebuilds. Maps and estimated survivor count for current conditions and hypothetical mitigation scenarios are intended to provide an overview of evacuation challenges facing a community; they do not replace site-specific analyses and are not intended to be interpreted as a literal expectation of how a tsunami evacuation will unfold.

1.0 INTRODUCTION

1.1 Purpose

The purpose of this study is to help the communities of Seaside and Cannon Beach in Clatsop County (**Figure 1-1**) prepare for the next CSZ earthquake and tsunami by quantitatively assessing potential barriers to successful evacuation. Importantly, this study highlights areas of evacuation improvement which may be used by the communities to identify and prioritize mitigation projects that will help reduce potential loss of life in the next CSZ tsunami. This is accomplished by comparing the number of estimated survivors for various mitigation scenarios utilizing DOGAMI's *Beat the Wave* tsunami evacuation analysis method, in conjunction with a spatially explicit population model that details where locals and visitors are located within the tsunami zone.

The study provides a quantitative assessment of current tsunami evacuation routes and compares them against various mitigation scenarios, including seismic bridge retrofits and vertical evacuation structures (VES). Maps identifying those areas where the likelihood of surviving the tsunami are low are provided to better understand which neighborhoods and routes need further attention. Tables and charts comparing the number of survivors for different mitigation scenarios provide straightforward comparisons to aid in the prioritization and justification of future mitigation projects. Maps of tsunami wave arrival times and permanent- and temporary-population distributions are also included to help demonstrate needs.

A steering committee was formed at the outset of the investigation to provide oversight on the project's overall direction and strategy. Committee members include Nate Wood (U.S. Geological Survey), Meg Reed and Rhiannon Bezore (Department of Land Conservation and Development), Althea Rizzo (Oregon Emergency Management), Monica Ward (former Curry County Emergency Management), Tiffany Brown (Lane County Emergency Management, formerly with Clatsop County Emergency Management), Felicia Olmeta Schult (Oregon Sea Grant), Liz Safran (Lewis & Clark College), and Derrick Tokos (City of Newport). As a pilot study, the project could only include two communities. The committee first assisted in the selection of those communities. This was accomplished by establishing a multi-criteria decision analysis framework to ensure that a thorough evaluation of risk factors affecting Oregon's coastal communities were considered. These factors included: the number of vulnerable people inside the tsunami zone, residents over 65 years of age and children under five, tourists, and a growing Spanish-speaking community (e.g., Wood, 2007; Allan and others, 2020). Other risk factors of critical importance included aged infrastructure not expected to survive earthquake shaking, distance to a major metropolitan city (i.e. rural representation), and high numbers of people with long evacuation routes. DOGAMI was then able to reach out to the communities identified as high risk to ascertain their level of interest and ultimately move forward with Seaside and Cannon Beach. The committee provided invaluable guidance on our overall approach to ensure that our input data, methods, and results were accurate, clear, and meaningful.

Figure 1-1. Map of Clatsop County showing the Seaside and Cannon Beach study areas.

1.2 Hazard Overview: Cascadia Subduction Zone (CSZ)

The destructive and life-threatening forces of tsunamis are well known globally, as demonstrated by the 2011 Tōhoku, Japan, event that resulted in 15,899 killed and another 2,526 missing (as of March 10, 2021; National Police Agency of Japan, 2021). Most of the deaths in the event were due to drowning (Mori and Takahashi, 2011). The Oregon Coast is similarly exposed to large megathrust subduction zone earthquakes, capable of generating catastrophic tsunamis (Witter and others, 2011). A locally generated tsunami from a CSZ earthquake will inundate the Oregon Coast within tens of minutes (Priest and others, 2009; Witter and others, 2011). For most of the coastal population, spontaneous evacuation on foot will be the only effective means of limiting loss of life, because vehicle evacuation will be quickly compromised by traffic congestion and road blockages.

The CSZ geologic record contains evidence of at least 19 earthquakes >8.5 M_W over the past 10,000 years (Goldfinger and others, 2012, 2017; Priest and others, 2009; Satake and others, 2003; Walton and others, 2021; Witter and others, 2012). The most recent tsunami generated on the CSZ occurred on January 26, 1700 (Atwater and others, 2005). Goldfinger and others (2017) estimated the conditional probability of an earthquake on the CSZ at ~16–22% in the next 50 years; a partial rupture of the CSZ impacting the southern Oregon Coast has a conditional probability of ~37–43% (Goldfinger and others, 2012).

To evaluate CSZ tsunami impact, Witter and others (2011) used a logic tree approach to produce a suite of deterministic scenarios that represent uncertainty in earthquake magnitude and fault characteristics. One of those characteristics is the length of the fault rupture. Rupture describes the two tectonic plates slipping past one another. A full-margin rupture refers to a CSZ earthquake that slips along its entire 600-mi length, from Cape Mendocino, California, in the south to Vancouver Island, British Columbia, in the north. A partial rupture describes a CSZ event where only a portion of the plate boundary slips. Partial ruptures may still generate large earthquakes and tsunamis. However, the geographic extent of the resulting tsunami's impact may be less than that of a full-margin rupture. Full-margin ruptures on the CSZ that trigger tsunamis are estimated to occur on the order of 480 to 505 years, with partial ruptures on the southern Oregon Coast occurring more frequently (~220 years, Goldfinger and others, 2017). Even though the next CSZ event is more likely to be a smaller, partial rupture, we focus on full-margin ruptures to capture the largest possible tsunami inundation for life-safety purposes.

Five size classes (Small, Medium, Large, Extra-Large, XX-Large) represent the range of full-margin earthquake magnitudes experienced on the CSZ in the past ~10,000 years. Each scenario has a potential likelihood of being the size of the next Cascadia event, but the frequency of previous events can provide insight on which scenarios may be more likely. For example, 26% of past tsunamis were no larger than the Small scenario. This suggests that there is a 26% chance that the next full-margin CSZ event will be analogous to the size Small scenario or smaller. Conversely, 74% of tsunami events in the geologic record have been larger than the Small scenario. For comparison, if partial ruptures are included in this calculation, there is a 58% chance that the next CSZ event will be size Small or smaller. XXL describes a hypothetical full-margin scenario slightly larger than the largest tsunami in the 10,000-year historical record and therefore 100% of past tsunamis were smaller than this scenario. This implies that the XXL scenario encompasses the maximum possible tsunami that could occur (Priest and others, 2013b).

1.3 Risk Reduction: How to Increase Community Resilience

Education and outreach, wayfinding signage (Neis and others, 2014), personal preparedness, and evacuation drills have been proven to save lives in countries with a more recent history of subduction zone earthquakes and tsunamis, such as Japan (e.g., Nakaya and others, 2018; Sun and Katsuya, 2018) and Chile. For many coastal communities, such outreach efforts may be sufficient to save most lives. However, several communities on the Oregon coast have a much higher exposure risk to tsunami hazards, with the potential for mass casualties due to having large numbers of people in the tsunami zone, long distances to high ground, and aging bridge infrastructure that could collapse during an earthquake. For these communities, other forms of mitigation may be required to improve successful evacuation, including the construction of new roads and trails that shorten evacuation routes, hardening key routes against liquefaction and other coseismic (earthquake) hazards, moving power lines underground, and seismically retrofitting bridges. If natural high ground is simply too far away and evacuation is not realistically achievable, then the only other solution is to construct vertical evacuation structures (VES). All options should be carefully evaluated to determine which approaches will maximize lives saved.

A VES is a building, tower or berm designed to survive the earthquake and the tsunami and provide refuge for people that otherwise could not reach safety (ATC, 2012). VES construction is a challenging endeavor due to their size, design requirements, time of construction, and need for sustained maintenance. Only three exist in the United States at the time of this publication: two in Washington and one in Oregon (**Figure 1-2, top row**). Three additional VES and one bridge evaluation have been approved and funded in Oregon and Washington but not yet completed (**Figure 1-2, bottom row**). Two of the three existing VES are schools, highlighting the dual uses that can be incorporated into the design. Parking structures, nature observation platforms, and public parks are other examples of potential dual roles for VES.

The first VES constructed in the United States was an elementary school in Ocosta, Washington. Washington local and state agencies have long recognized the need for numerous VES and have been working closely with community leaders for more than 15 years to understand what it will take to meet the needs of coastal Washington (El-Anwar and others, 2011, and Freitag and Gomez, 2021). It is now understood that ~80 VES are needed to save the lives of everyone who lives at and visits the Washington Coast (personal communication with Washington State Emergency Management Division, 2024). A similar analysis of the total number of VES needed in Oregon has not been completed, however we estimate that no more than five coastal communities (including state parks) need this level of assistance with perhaps 10-15 VES needed in total.

Figure 1-2. VES in the United States. (top) Completed structures in use today. From left to right: Ocosta Elementary School (Ocosta, WA), Gladys Valley Marine Studies Building, Oregon State University Hatfield Marine Science Center (Newport, OR), and the Auntie Lee Vertical Evacuation Tower (Tokeland, WA). (bottom) Structures that have been funded but not yet completed.

Photo credits:
Ocosta, WA: Degenkolb Engineers, accessed 2024 https://degenkolb.com/work/ocosta-elementary-school-tsunami-vertical-evacuation-building/
Newport: Laura Gabel, 2022
Tokeland: Washington State Emergency Management Division, 2022 https://mil.wa.gov/news/celebrating-nations-first-tsunami-vertical-evacuation-tower
Astoria, OR: Columbia Memorial Hospital, 2023 https://www.columbiamemorial.org/health-compass-newsletter/issues/fall-2023/building-a-state-of-the-art-facility/
Westport, WA: City of Westport VES Feasibility Study and Cost Estimate, 2020
Ocean Shores, WA: Degenkolb Engineers, accessed 2024 https://degenkolb.com/work/city-of-ocean-shores-tsunami-evacuation-tower-ocean-shores-wa/

1.4 Study Area

1.4.1 City of Seaside

Seaside is a popular tourist town in Clatsop County that sits along the open coast on a low-lying coastal plain, with the Necanicum River estuary to the north and Tillamook Head to the south. Almost the entire city is inside the tsunami zone, as well as 93% of permanent residents (Allan and others, 2020). The nearest high ground for most people is in the hills east of Highway 101, or south toward Tillamook Head. **Figure 1-3** and **Figure 1-4** present *Beat the Wave* maps for North and South Seaside, respectively. They show the inundation zone for an XXL tsunami along with key evacuation routes and minimum travel speeds needed to reach safety ahead of the tsunami. Reaching safety for much of the city requires crossing the Necanicum River and Neawanna Creek, which are two waterways running north-south along the entire length of the city. Six bridges cross the Necanicum River and four cross Neawanna Creek. Of these 10 bridges, only four were built with CSZ seismic shaking loads incorporated into their design. There is a high likelihood that the other six bridges will fail during the earthquake shaking and will not be available for evacuation.

The Venice Park neighborhood (24th, 25th, and 26th Ave) is notably reliant upon an aging bridge. The closest safety destination is ~1 mile east on Lewis and Clark Rd, however it can only be reached by crossing the Highway 101 bridge over Neawanna Creek. This bridge is not currently expected to survive earthquake shaking due to its age. As demonstrated in **Figure 1-3** by the dark purple ***run*** arrow, without this bridge, evacuees must travel an extra ~0.8 miles south to the 12th St bridge before heading east to high ground.

The highest concentrations of people in Seaside are visitors, who tend to concentrate in the downtown area west of the Necanicum River (Priest and others, 2015; Allan and others, 2020). As a result, many Seaside visitors will have the longest and potentially most confusing routes to safety as they must navigate narrow streets to find available bridges over the Necanicum River and Neawanna Creek.

As a community-driven project, engagement with city officials was key to our community selection. The city of Seaside has long recognized the need to pursue evacuation improvements; the city's five-year preparedness goals include prioritizing the development of a VES, which may be leveraged, and potentially combined with, the need for a parking structure.

Figure 1-3. ***Beat the Wave*** **map for north Seaside showing the XXL tsunami zone and key evacuation routes. Minimum speeds necessary to reach safety ahead of the tsunami are indicated by the shade of purple on route arrows. High resolution BTW maps can be downloaded at www.OregonTsunami.org.**

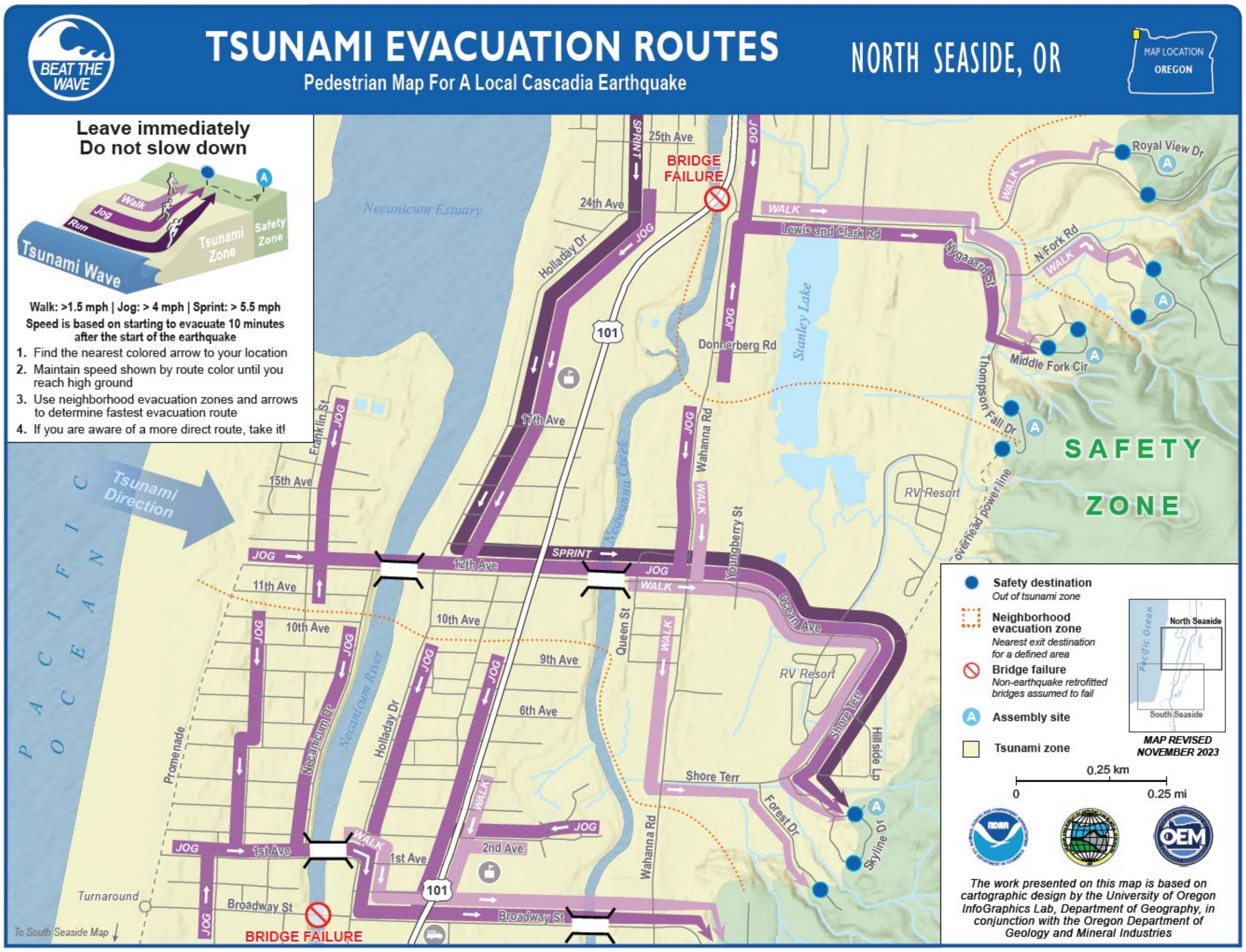
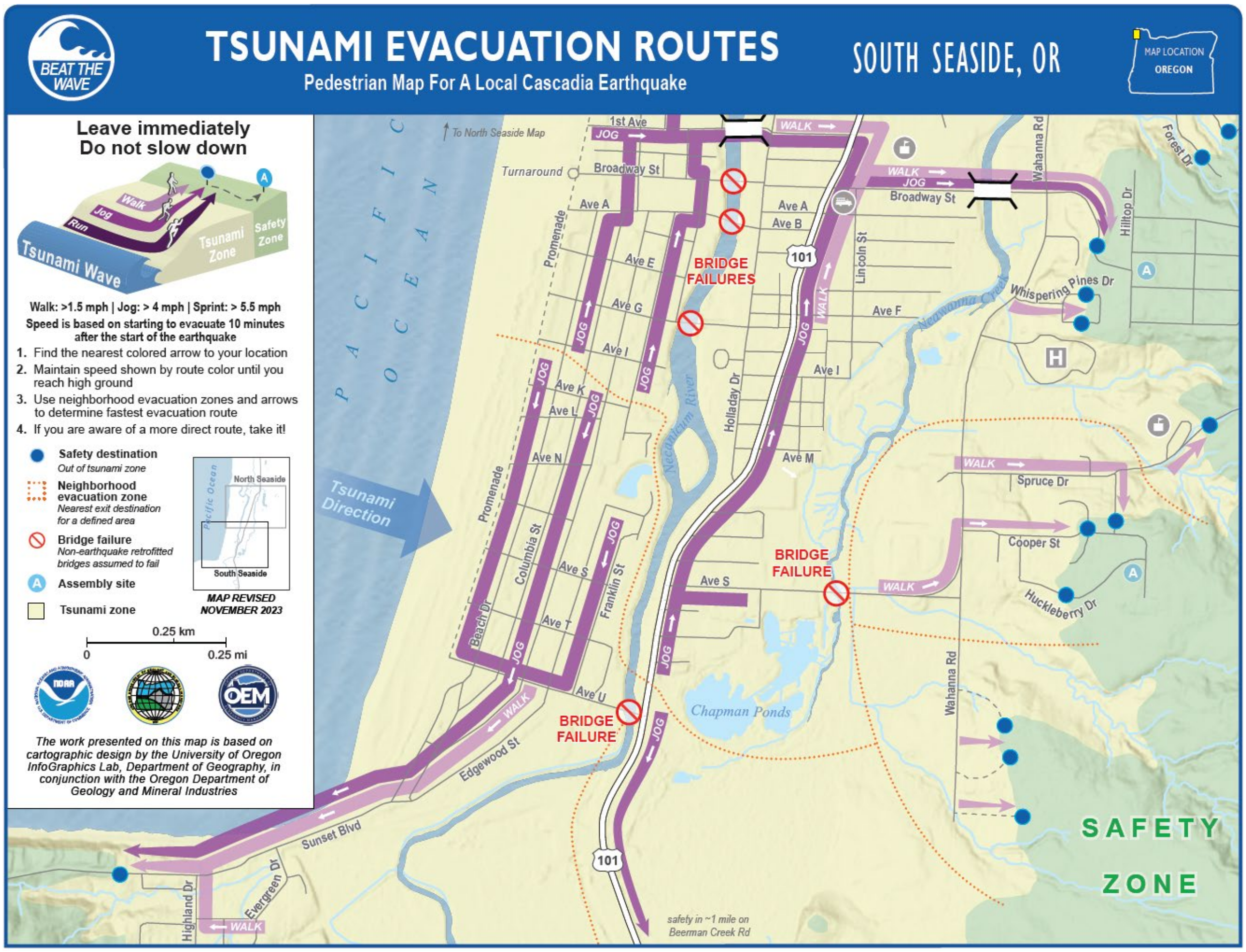


Figure 1-4. *Beat the Wave* map for south Seaside showing the XXL tsunami zone and key evacuation routes. Minimum speeds necessary to reach safety ahead of the tsunami are indicated by the shade of purple on route arrows. High resolution BTW maps can be downloaded at www.OregonTsunami.org.



1.4.2 City of Cannon Beach

Cannon Beach is a popular tourist town in Clatsop County located south of Tillamook Head. Much of the city is inside the tsunami zone, as well as 87% of permanent residents (Allan and others, 2020). **Figure 1-5** and **Figure 1-6** present *Beat the Wave* maps for North and South Cannon Beach, respectively (Gabel and others, 2022). They show the inundation zone for an XXL tsunami along with key evacuation routes and minimum travel speeds needed to reach safety ahead of the tsunami. North Cannon Beach is almost entirely inside the XXL tsunami zone. It is bisected by Ecola Creek as it makes its way to the Pacific Ocean. The area north of Ecola Creek is referred to as Chapman Point. High ground is relatively close for this neighborhood: northward toward Ecola State Park and east toward Highway 101. Immediately south of Ecola Creek is the downtown district. Continuing south is a residential area referred to as the "Presidential Streets" neighborhood. This part of Cannon Beach sits on a marine terrace ~40 ft above sea level. High ground for downtown Cannon Beach and the Presidential Streets neighborhood can only be found to the south in the S Curves neighborhood; Ecola Creek borders this part of Cannon Beach to the east. South Cannon Beach, also known as "Tolovana", is also predominantly inside the tsunami zone. However, it is a narrow zone and high ground can be reached at or just past Highway 101, just east of the community.

The closest high ground for downtown Cannon Beach is to the north toward the Highway 101 on-ramp, however it can only be reached by crossing Ecola Creek on the Fir Street Bridge (**Figure 1-7**). Notably, this bridge was pulled off its foundations and carried 1,000 feet upstream during the 1964 distant tsunami originating in Alaska. Having been rebuilt that same year, well before seismic loads were incorporated into bridge designs, it is not expected to survive earthquake shaking and unlikely to be available for evacuation. Therefore, evacuees (primarily visitors) in the downtown Cannon Beach area must navigate a much longer route southward. This is likely to confuse people who think they need to be traveling east, away from the ocean and oncoming tsunami. The City of Cannon Beach has also recognized this need and was awarded a $480,000 FEMA Hazard Mitigation Grant Program grant in 2023 to evaluate the current Fir Street Bridge, which is a precursor to a future seismic retrofit or rebuild.

Figure 1-5. ***Beat the Wave*** **map for north Cannon Beach showing the XXL tsunami zone and key evacuation routes. Minimum speeds necessary to reach safety ahead of the tsunami are indicated by the shade of purple on route arrows. High resolution BTW maps can be downloaded at www.OregonTsunami.org.**

Figure 1-6. *Beat the Wave* map for south Cannon Beach showing the XXL tsunami zone and key evacuation routes. Minimum speeds necessary to reach safety ahead of the tsunami are indicated by the shade of purple on route arrows. High resolution BTW maps can be downloaded at www.OregonTsunami.org.

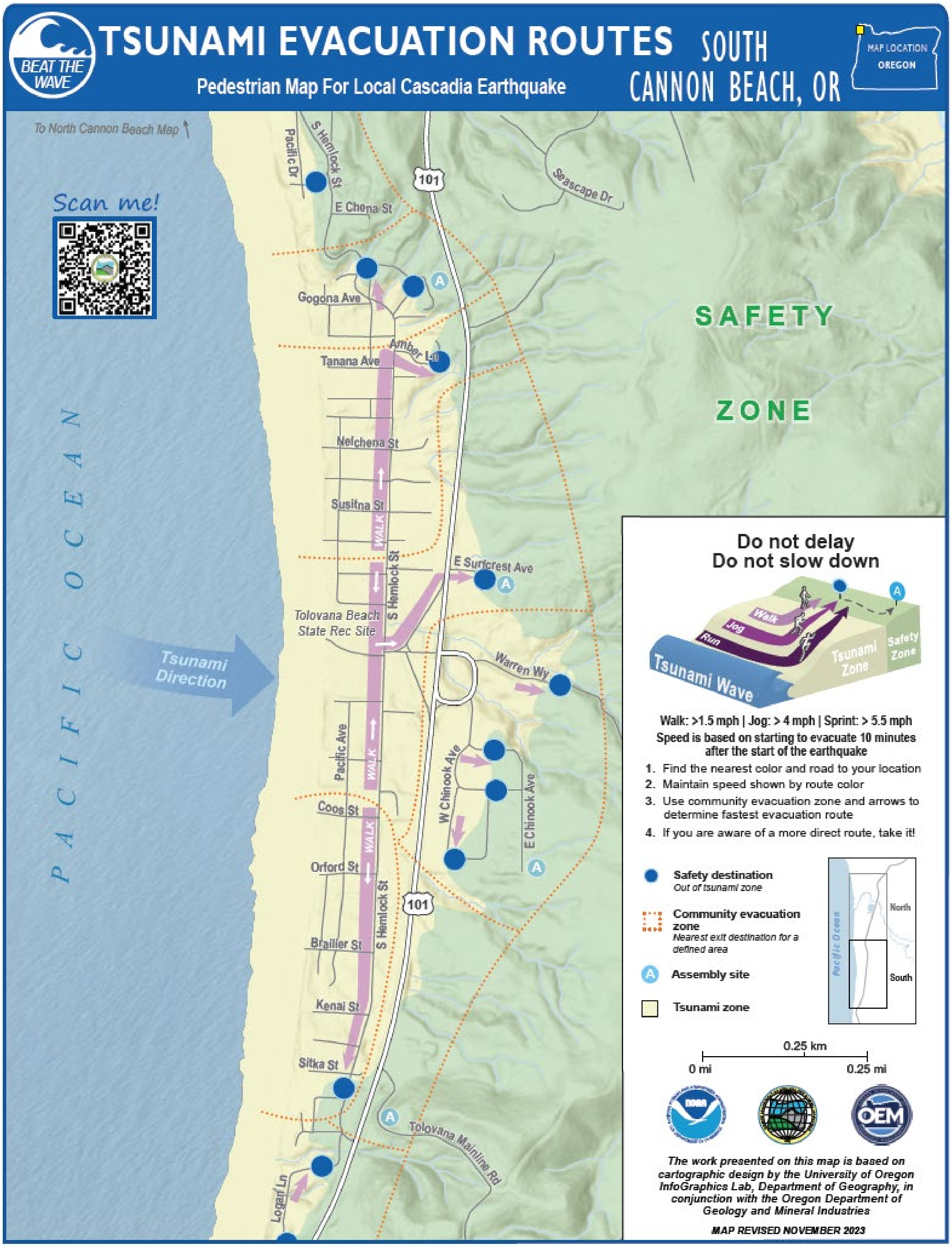
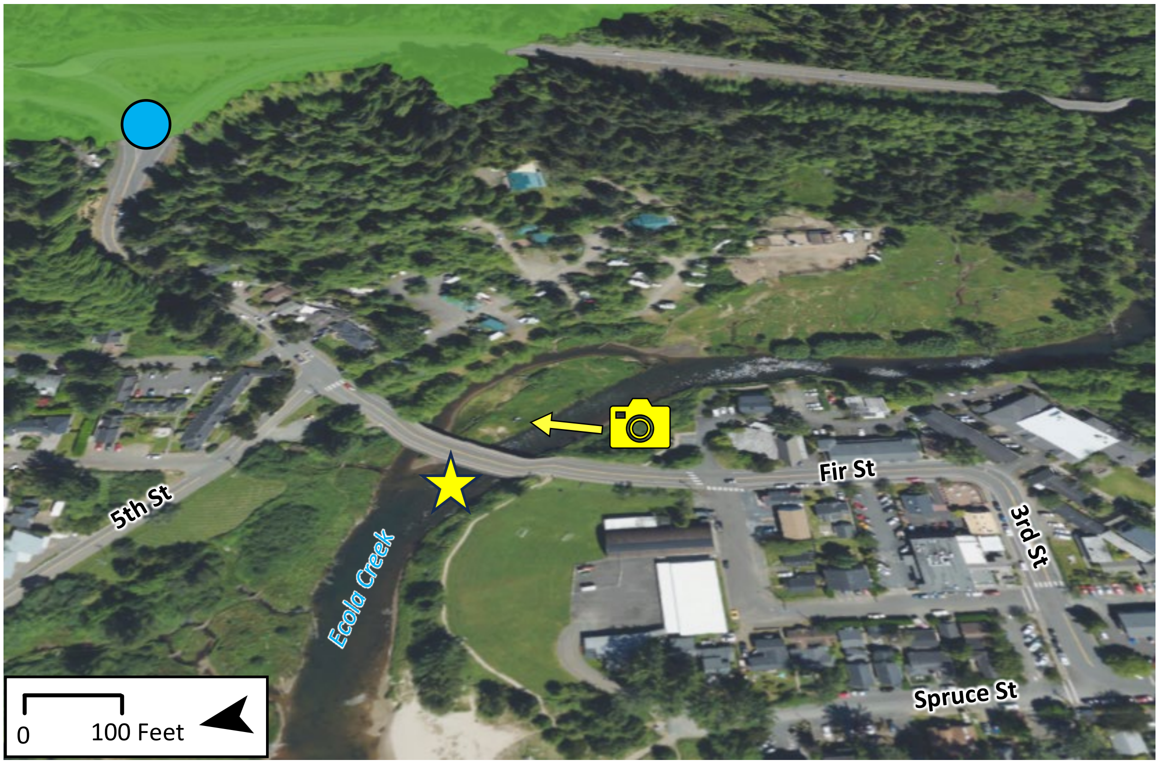


Figure 1-7. Fir Street Bridge over Ecola Creek. (top) Oblique aerial image looking east, bridge marked with yellow star near center of image. Downtown is to the right (south) and the nearest high ground is in the top left (northeast), marked with a blue circle and green overlay. Base map is 2022 NAIP imagery. (bottom) As seen from the ground. Location and direction of photo marked in aerial image with camera icon. Photo credit: Rick Hudson.



1.5 Tsunami Evacuation Modeling

The overall approach presented here follows comparable tsunami evacuation analyses undertaken over the past decade for all of Oregon's coastal communities (e.g., Gabel and others, 2022). *Beat the Wave* studies evaluate tsunami evacuation difficulty using an approach developed by Priest and others (2015, 2016). It uses the least-cost distance (LCD) approach of Wood and Schmidtlein (2012) and Wood and others (2016), which provides estimates of evacuation travel times to safety assuming a constant travel speed. *Beat the Wave* expands on this by incorporating wave arrival times, which can vary widely within a community and result in different minimum speeds needed to reach safety ahead of the tsunami in different areas. This study also incorporates a spatially explicit population model developed by Allan and others (2020), allowing us to quantify *Beat the Wave* results and better ascertain which mitigation efforts will be the most effective.

Landslides, lateral spreading, and liquefaction are site-specific hazards associated with earthquake shaking that are likely to further challenge evacuation. Downed power lines and trees may also impede swift travel toward safety. We did not model the effect of these hazards on evacuation difficulty in this study. Instead, this study focuses on comparing the relative improvement of different mitigation scenarios and assumes all other variables, including factors like liquefaction, are consistent across scenarios. We recommend site-specific evaluations along all key evacuation routes to ensure they remain accessible after the earthquake.

2.0 METHODS

This study uses *Beat the Wave* pedestrian tsunami evacuation modeling method to investigate the cost-benefits of various mitigation strategies, including retrofitting bridges and the construction of VES. The overall approach integrates a robust geospatial population model to provide quantitative comparisons of the various scenarios to help decisionmakers direct and prioritize future mitigation efforts.

Agent-based and LCD modeling are the two most common approaches for simulating pedestrian evacuation. Agent-based modeling focuses on the individual as the modeling unit of analysis and how their travel would most likely be impacted by localized effects in the landscape, such as congestion points at bridges (Yeh and others, 2009). As a result, agent-based evacuation models are constrained by initial assumptions of the distribution of at-risk individuals in a hazard zone. Given the high number of scenarios for where people may be during a tsunami, LCD-based evacuation modeling instead focuses on landscape conditions and evacuation difficulty across the entire landscape, which is influenced by both terrain slope and land-cover type (e.g., paved roads, trails, or wetlands). LCD modeling calculates the most efficient path to the tsunami inundation limit for every point in the inundation zone, artificially increasing distances as terrain conditions change (e.g., as slope increases, or a person travels across a wetland versus on pavement) and ultimately defining the most optimal evacuation routes. The number and location of people can then be added to these evacuation modeling results to determine survivability.

The pedestrian travel speed needed to reach safety ahead of the wave (e.g., ***walk***, ***jog***, or ***run***) can then be estimated by dividing the least-cost path by the time of wave arrival. We used the LCD model of Wood and Schmidtlein (2012) because we wanted to understand the spatial distributions of evacuation times throughout the region, without having to create the many scenarios for specific starting points required by agent-based models. *Beat the Wave* models integrate tsunami wave arrival data directly into the LCD analysis to produce maps of minimum evacuation travel speeds that must be maintained along the entire route to reach safety in time. Additional information on *Beat the Wave* methodology is provided by Priest and others (2015, 2016), Wood and others (2016), and Gabel and others (2023).

We can then quantitatively compare the effectiveness of various mitigation solutions (e.g., bridge retrofit versus VES) by estimating the number of survivors for each scenario. For this study, we chose 4 fps to represent a realistic maximum speed that vulnerable populations, such as impaired adults and the elderly, can maintain for the entirety of their route. Each person is assigned a minimum travel speed using *Beat the Wave* data, based on their location within the tsunami zone (specifically, which road segment they are adjacent to). We then calculate how many people can reach safety at 4 fps or less and classify them as survivors for a given scenario. People requiring faster minimum travel speeds are not likely to survive given the inherent difficulties that come with traveling a longer route at a faster speed (i.e., running), especially given roadway conditions (i.e., debris on road, broken asphalt). It is worth noting that while the results are heavily dependent on the speed threshold chosen, the power of this analysis lies in the relative difference between scenarios.

2.1 Road and Trail Network

We considered only roads and clearly designated paths as evacuation pathways (all other land-cover classes were excluded). This removes the complication of crossing private property and reflects the reality that most people will tend to follow established roads to high ground rather than strike out cross-country. Restricting evacuation to pathways also enables us to make more informative maps. Geospatial data representing roads and pedestrian paths were generated from existing road data. Adjustments were made to the base dataset to reflect a realistic network of paths available to pedestrians, including the addition of trails (e.g. path across a golf course) and the removal of incorrect road segments. These adjustments were made through manual classification of imagery (lidar and aerial photographs) and field verification, and then reviewed by local officials. We chose to ignore travel time from buildings or other parts of urban areas to the roads, because there is large uncertainty in conditions contributing to the time it will take an evacuee to reach the nearest road. For example, reaching the nearest road may require crossing a fenced yard. In addition, after the earthquake, there will likely be fallen debris and other impediments. Because of these assumptions and factors, the modeling approach represents minimum travel speeds that are maintained for the duration of an evacuation to safely get out of the inundation zone.

2.2 Hypothetical Scenarios

The evacuation landscape was first characterized using the existing road, trail, and bridge network. An inventory of infrastructure at risk of failure during the earthquake was collected, and a suite of scenarios was developed to investigate and compare evacuation route improvements, including seismically retrofitting bridges, constructing new pedestrian and/or car bridges, and VES. Multiple review sessions with community officials ensured local needs and concerns were addressed by the hypothetical scenarios.

Bridge failure was simulated by removing that section of the road network, effectively forcing the model to recalculate routes that originally relied on bridge connectivity. Which bridges to remove for the simulations was based on discussion with public officials and information about bridge age, a measure of whether it has been designed to withstand significant seismic forces. Bridge failure typically results in longer distances to safety, either by requiring a longer route to the original safety destination or by rerouting to a completely different destination. Our standard modeling process begins with a scenario that includes all bridges, for comparison to scenarios without them. This highlights which bridges are important for evacuation and can be useful when prioritizing those bridges in need of a retrofit or to construct as part of a long-term transportation resilience plan.

VES are incorporated into *Beat the Wave* modeling by editing the tsunami hazard zone to include a small polygon of safety at the location of the hypothetical structure. This results in a complete recalculation of routes in the vicinity of the structure, often much shorter than the original safety destination.

In coastal towns, landslide-prone slopes and saturated sandy soils are common; therefore landslides, liquefaction (**Figure 2-1, left**), and lateral spreading (**Figure 2-1, right**) are likely to occur during an earthquake (Madin and Wang, 1999; Madin and Burns, 2013; Madin and others, 2021). These hazards can damage roads and will reduce walking speeds by significant, but indeterminate, amounts. Because knowing where to remove routes remains highly uncertain and site specific, we did not model the effect of these hazards on evacuation difficulty in this study. Instead, this study focuses on comparing the relative improvements for different mitigation scenarios and assumes all other variables, including factors like liquefaction, are equal.

Figure 2-1. Photos of liquefaction and lateral spreading in Christchurch, New Zealand following the February 2011 earthquake. Water-saturated sand can turn to quicksand during strong shaking, forming sand boils, ponding, and sunken roads. (A) Extensive liquefaction along River Road. (B) Lateral spreading along one of many roads constructed next to waterways. During a CSZ event, such processes could compromise tsunami evacuation routes, as well as the time and speed to safety in areas prone to liquefaction. (Photo credits: Martin Luff, licensed under CC BY-SA 2.0)

2.3 Population Model

To quantitively compare different mitigation strategies, we need to know who is inside the tsunami zone and where they are. The underpinning of the population model used in this study is a building inventory originally developed by Williams and others (2020) and updated by Allan and others (2020). This dataset identifies all buildings that can be considered a residential facility, including traditional single-family residences, manufactured housing, multifamily residential buildings, condominiums, motels and hotels, dormitories, and assisted living facilities. RVs and campgrounds were also added. Occupancy type (e.g., single versus multifamily residence) as well as square footage are used to assign specific numbers of people to a particular building. See Figure 2-2 in Allan and O'Brien (2023) for latest information on the population model developed. The 2020 U.S. Census was used for population modeling (U.S. Census Bureau, 2022).

Because coastal communities experience significant temporal (daily, seasonal, and annual) population fluctuations, with large visitor influxes on weekends and in the summer, community planners have expressed strong interest in having our population model account for such variations, which could then be used to assist with identifying tsunami evacuation challenges and short-term sheltering needs. To better understand these effects, we follow the approach of Allan and others (2020) and distinguish two population groups:

- *permanent residents* (coastal residents in the tsunami zone)
- *temporary residents* (overnight visitors in the tsunami zone)

At night, temporary residents occupy residential facilities such as second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds; permanent residents typically occupy residential structures (Allan and others, 2020). During the day, permanent and temporary residents may occupy institutional, educational, commercial, and industrial buildings, along with residential buildings, or may be dispersed throughout the tsunami zone (e.g., at the beach) and thus may not be directly associated with any particular type of building. Project scope constraints dictated that we focus on a single temporary-population model. Discussion with community members by Allan and others (2020) led to us focusing our attention on a summer weekend 2 a.m. population model to maximize estimates of the temporary-population overnighting in the tsunami zone, providing a more conservative worst-case tsunami evacuation scenario.

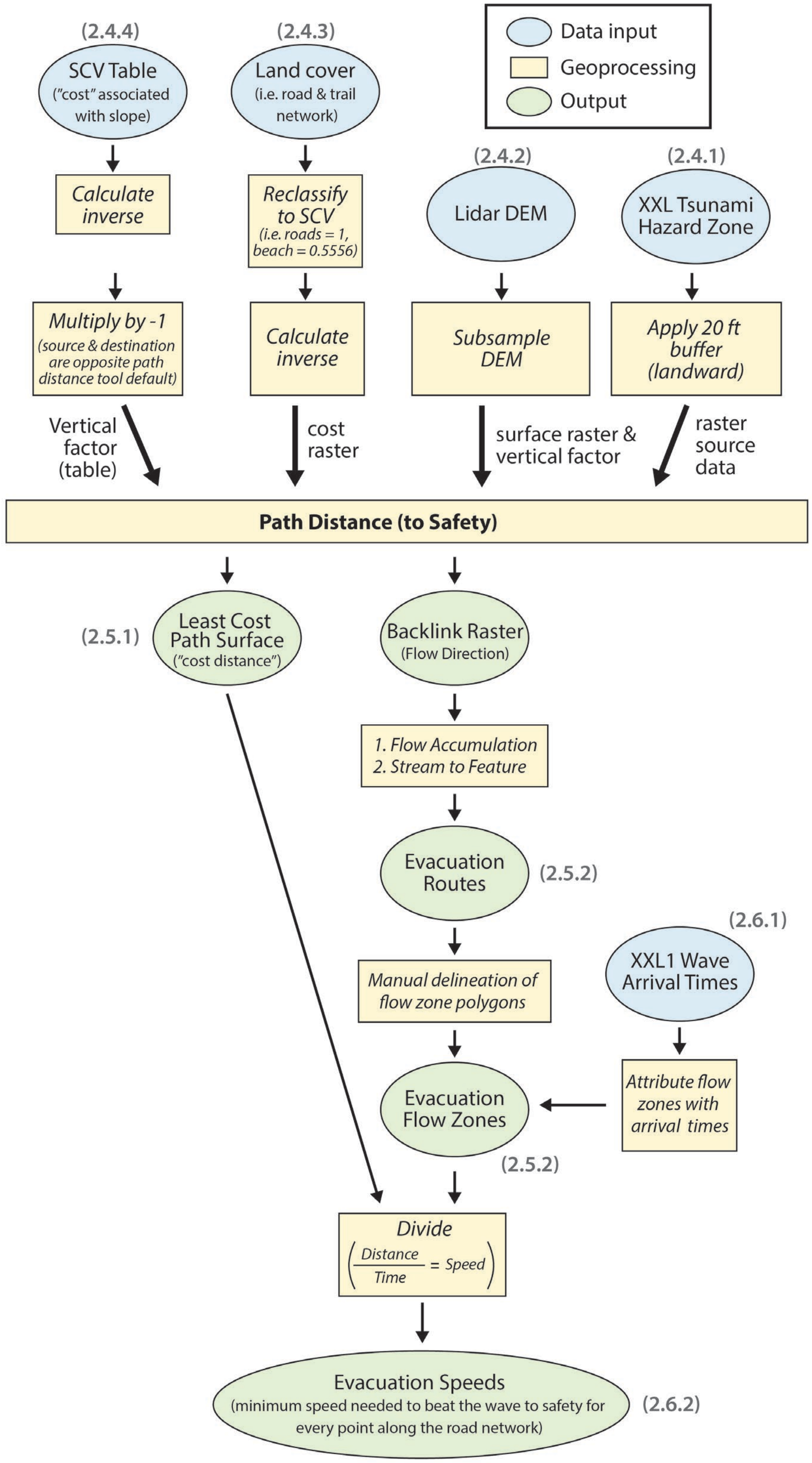
Due to the challenge of determining how many and precisely where day visitors are at the coast on any given day, we are presently not able to include this in our population modeling. Nevertheless, since the population model developed by Allan and others (2020) assumes maximum (100%) occupancy in second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds, they concluded that the population estimates are likely to be still somewhat conservative (i.e., upper bound). In contrast, planners can view the resident casualty estimates as a baseline (i.e., lower bound). Through conversations with local officials, it is understood that day visitors can easily double the population of Seaside and Cannon Beach on a summer weekend and most of those people will be in the tsunami zone where many of the community's recreational activities occur (e.g., visiting the beach and eating/shopping in the downtown districts). While day visitors are not included in the analysis, it is imperative that they be factored into any future discussions related to mitigation options, especially the capacity of VES.

2.4 Least-Cost Distance (LCD) Model Inputs

LCD modeling is based on four inputs: the XXL tsunami inundation limit, a digital elevation model (DEM), a land-surface cost raster, and a table relating slope to cost. The road and trail network are provided via the land-surface cost raster. The tsunami inundation limit serves as the destination for all evacuation routes. The DEM is used to determine actual distances and slopes. Slope data derived from the DEM, in conjunction with the slope table, are used to apply a cost reflecting evacuation difficulty due to slope changes. The land-cost raster contains a second set of cost values reflecting evacuation difficulty due to terrain (i.e., walking on a paved surface versus soft sand). A detailed discussion of all four inputs is presented in the following sections.

We implemented LCD modeling by using Esri® ArcGIS Pro® 3.2 software. The path-distance tool uses geospatial algorithms to calculate the most efficient route from each point in the evacuation zone to safety, defined as the maximum inundation limit, i.e., where the tsunami flow depth and velocity are effectively zero. The product of this tool is referred to as the least-cost path-distance surface, and it reflects an artificial distance to safety for every point in the evacuation zone that contains the difficulty of walking that route. **Figure 2-2** summarizes the steps and inputs into the path-distance tool as well as the subsequent *Beat the Wave* approach.

Figure 2-2. Model diagram of *Beat the Wave* tsunami evacuation methodology using the path-distance approach from Wood and Schmidtlein (2012) and Wood and others (2016). The methodology was first detailed by Priest and others (2015, 2016). Gray numbers indicate sections in this report where a step is discussed in detail.



2.4.1 Tsunami hazard zone

The inundation zone used in this study is XXL1, originally derived from digital data of Priest and others (2013a,b) and updated by Allan and others (2021). This zone covers 100% of potential CSZ inundation (Witter and others, 2011), and reflects the zone used for evacuation as shown in DOGAMI evacuation brochures (https://www.oregon.gov/dogami/tsuclearinghouse/Pages/pubs-evacbro.aspx) and online (http://nvs.nanoos.org/TsunamiEvac) for the entire Oregon Coast.

For the purposes of this study, safety is reached when an evacuee has walked to the limit of tsunami inundation. Safety is also referred to as "high ground" throughout the remainder of this report. Safety *destinations* represent the intersection of the road and trail network with the tsunami inundation limit. These locations were created by converting the inundation polyline into a raster data file.

Two "islands" of high ground in Cannon Beach were not included in this community-wide analysis as safety destinations due to their small size and the proximity of larger areas of contiguous high ground. The first is the Hallmark Resort off Hemlock Street, near Sunset Boulevard. The second is at Chapman Point, near the intersection of 5th Street and Laurel Street. Both islands are valid safety destinations, however neither can provide refuge for hundreds to thousands of people. The added fact that there are nearby alternative destinations that can accommodate the necessary volume of people reinforced the decision to exclude these islands from the analysis. Local decisionmakers were consulted before this decision was ultimately made.

2.4.2 DEM

Initially, we created a high-resolution DEM by interpolating lidar ground points into a 12-ft (3.6 m) resolution raster; in areas characterized by bridges, we used lidar highest-hit data to define the bridge walking surface. We smoothed the DEM grid, because generated slope profiles are too noisy, introducing slope artifacts of significant amplitude (e.g., a 3-in elevation difference between cells 1 ft apart yields a 14° slope) that add significantly more time to the total calculated time (Priest and others, 2015, 2016). To smooth the data, we created points at 50-ft (15.2 m) intervals along all evacuation paths, including major roads and at intersections, and we attributed those points with elevation values from the lidar DEM. Priest and others (2015, 2016) performed trials at 25, 50, and 100 ft and found that the 50-ft interval achieved the best compromise between accuracy and smoothness. The final sampling interval was ~50 ft on straight paths and somewhat less for curved paths to accurately depict the curvatures. We then interpolated those points using an Esri triangulated irregular network (TIN) and converted the TIN to a raster to produce a smoothed DEM (12-ft cell size) that closely emulated the actual elevation values of the lidar while dramatically reducing slope noise.

2.4.3 Land-cover raster

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

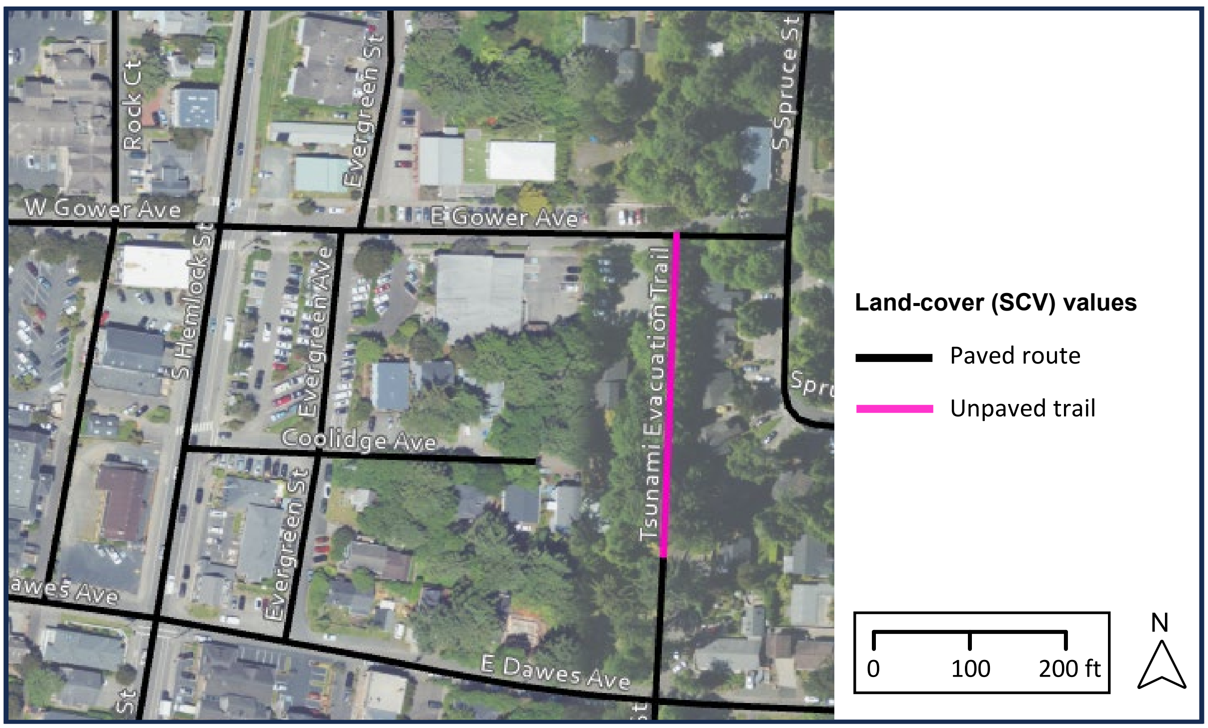
Table 2-1. SCVs used in modeling pedestrian evacuation difficulty in this study.

Feature Type	SCV*
Roads (paved surface)	1
Unpaved trails	0.9091
Everywhere else	0

*SCVs are derived from Soule and Goldman (1972).

GIS polylines representing all roads and trails in the project area were converted to polygons (40 ft (12.2 m) wide) and attributed with land-cover values (i.e., 1 for paved surfaces, 0.556 for packed sand, etc.). The polygons were then converted into a raster (12-ft (3.6-m) cell size) for input into the LCD model.

Figure 2-3. Example of a land-cover raster in Cannon Beach, which serves the dual purposes of defining the road and trail network and classifying it with land-cover values. Base map is 2022 National Agriculture Imagery Program (NAIP) imagery.



2.4.4 Speed Conservation Value (SCV) slope table

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

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

where slope is equal to the tangent of the slope angle. This formula is based on empirical data of Imhof (1950) and predicts that speed is fastest on gentle (−3°) downslopes. **Table 2-2** presents an example set of slope and SCV values. The actual table used includes slope values from −90° to +90° in 0.5° increments. A positive slope (upward) results in a slower walking speed and is assigned a larger cost. The same applies for a large negative slope (steeply downward), while a slight decline (~3°) in the slope reflects the optimal condition, i.e. no reduction in the selected maximum speed.

Table 2-2. SCVs used to calculate evacuation difficulty due to traversing hills, with slope determined for each pixel from the DEM.

Slope (degrees)	Tobler (1993) Walking Speed (fps)	SCV*
−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.

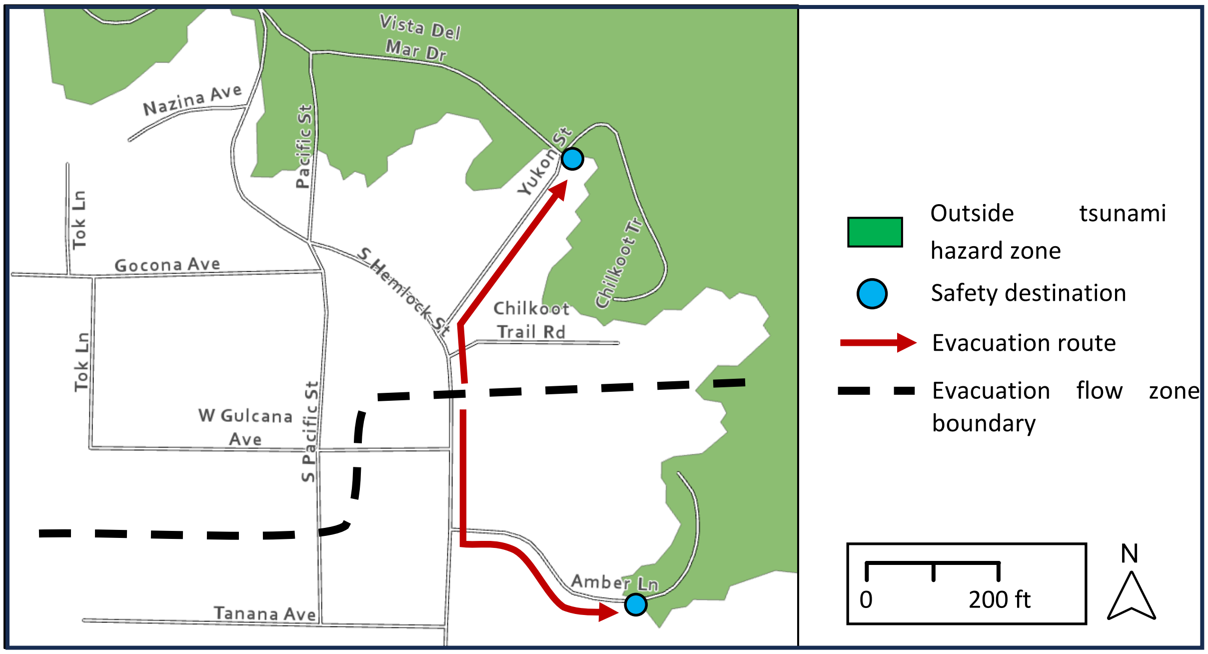
2.5 Least-Cost Distance (LCD) Model Outputs

Beat the Wave maps are created using outputs from the LCD model in ArcGIS. Results provide a path-distance surface showing effective distance to safety from each pixel and a flow-direction raster containing detailed route information. From these data we create maps visualizing evacuation routes, travel-flow directions and zones, and *Beat the Wave* minimum travel speeds.

2.5.1 Path-distance surface

The pixel values on the path-distance surface represent the effective distance, along the least-cost path, from the pixel to the point where the path intersects safety. For example (**Figure 2-4**), from the intersection of South Hemlock Avenue and Yukon Street, the actual distance to safety is ~330 ft (~101 m), while the least-cost path distance is ~500 ft (~152 m) (path distances not shown on map). This difference is due to the model accounting for variations in slope and land cover along the entire route (although in this case the entire route is paved, meaning the cost is entirely due to the significant slope on Yukon Street).

Figure 2-4. Example of a network of generalized evacuation flow zones and select evacuation route arrows from a least-cost-distance analysis limited to streets in Cannon Beach. The XXL inundation zone (inside the tsunami hazard area) on this and following figures is from Priest and others (2013b).



2.5.2 Evacuation routes and flow zones

The LCD backlink raster shows, for each cell, the direction to the next cell on the least-cost path. This raster makes it possible to trace the path to safety from any pixel and is equivalent to a flow-direction raster, which is the first step in hydrologic modeling of topographic surfaces. We use the hydrologic tools in ArcPro 3.2 and the backlink raster to extract a “stream” network to visualize the paths, depicting the most efficient pedestrian flow for evacuation on trails and roads. An example of evacuation flow zones with arrows depicting the nearest safety destination for a section of South Hemlock Street is shown in **Figure 2-4**. These paths represent the shortest effective distances to the nearest safety destination and are referred to as evacuation routes.

The routes can be simplified by identifying the boundaries of evacuation flow toward the nearest safety location. At these boundaries, one could travel in alternate directions to reach safety on separate paths that require equal amounts of effort (distance with slope and land-cover effects included). These evacuation flow zones are directly analogous to watershed boundaries or drainage divides in hydrologic modeling. As an example, **Figure 2-4** shows that the nearest safety destination for people on South Hemlock Street north of Chilkoot Trail is Yukon Street, while the nearest safety destination for people farther south on Hemlock Street is Amber Lane. The dashed black line delineates the evacuation flow-zone boundary.

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

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

2.6 *Beat the Wave* Modeling

Beat the Wave modeling integrates the results of the tsunami wave arrival times and the least-cost path-distance analyses to estimate the minimum speeds required over the duration of an evacuation to exit the inundation zone and avoid being caught by the approaching tsunami.

2.6.1 Wave arrival times

To understand the tsunami wave advance across the landscape, we extracted the time after the CSZ earthquake at which the XXL tsunami flow depth reached more than 6 in (15 cm) at each computational grid point and interpolated those arrival data to create a continuous map showing wave arrival time. More information on how arrivals are calculated can be found in Gabel and others (2020).

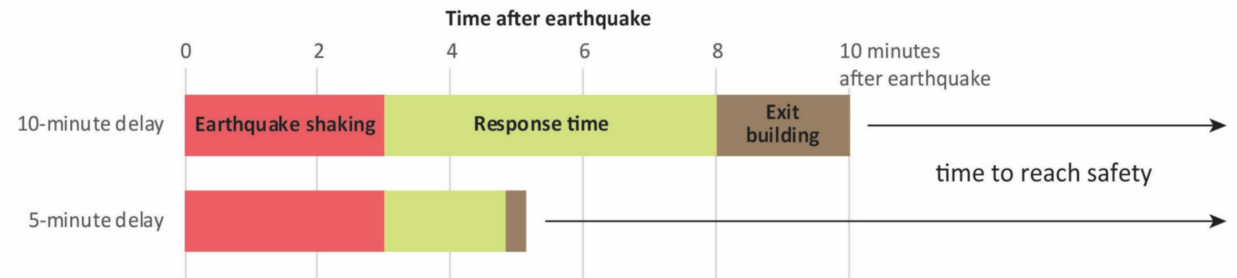
Wave arrival times were then assigned to each evacuation flow zone based on the time when the first wave reaches the *point of safety* for each zone. Depending on the safety destination, this time can be less than 15 minutes to more than 30 minutes after the tsunami first reaches land. We then subtracted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

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

Using the March 11, 2011, Tōhoku earthquake (Uchida and Bürgmann, 2021) as an analog to an XXL scenario, the minimum delay is probably ~3 minutes–5 minutes due to strong shaking for a ~Mw 9.0 event. There are few empirical data on how long it takes people to begin evacuation after shaking, but Mas and others (2013) determined a mean of 7 minutes in 2010 and 2011 surveys at La Punta, Peru, which has experienced several local earthquakes and tsunamis over the last ~400 years, the most recent in 1974. Makinoshima and Imamura (2024) analyzed evacuation surveys of more than 20,000 evacuees from 49 coastal cities in Japan to understand milling time for the 2011 Tōhoku tsunami. The range was quite large, depending on the region, with milling times of 3 minutes to 30 minutes and, in some areas, 44 minutes. These differences were presumed to be indicative of different early warning styles and different levels of tsunami awareness based on past experiences. **Figure 2-5** graphically describes how the three components of evacuation delay are related in this study. It is important to appreciate that the values adopted are not explicitly known because there are uncertainties associated with the length of the earthquake shaking, the human-response dimension (i.e., how quickly people respond and how organized they are [e.g., packing a bag, time spent searching for family members and pets]) and, lastly, how easy it may be to leave a building (e.g., digging out of rubble) and get underway.

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

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

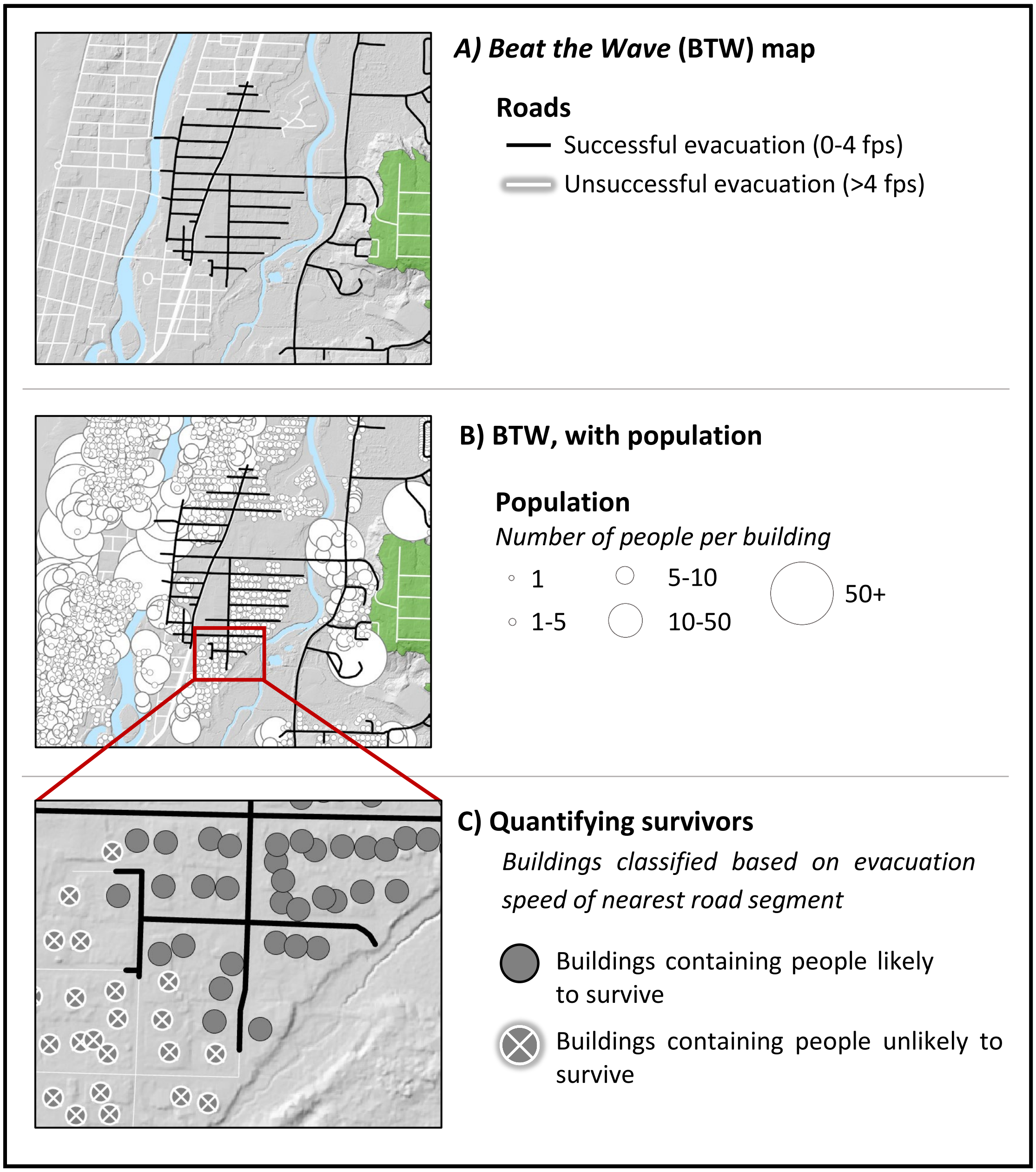


2.6.2 Beat the Wave maps

Minimum pedestrian travel speeds required to reach safety ahead of the tsunami are determined for every point along the road network by dividing the path-distance by its associated wave arrival time (distance ÷ time = speed). Locations from which evacuees can reach safety ahead of the tsunami at 4 fps or less are classified as survivable. Conversely, locations from which evacuees must travel faster than 4 fps are classified as unsurvivable. People are then classified as survivor or non-survivor based on their nearest road segment. These steps are depicted graphically in **Figure 2-6**.

We chose 4 fps (2.7 mph; 22 min/mi; 1.22 m/s), a pace listed as a moderate walk by Wood and Schmidtlein (2012), because it is the speed generally used for calculating curb-to-curb crossing light times at signalized intersections (Langlois and others, 1997; U.S. Department of Transportation, 2012) and in this case represents a realistic maximum speed that vulnerable populations, such as impaired adults and the elderly, can maintain for the entirety of their route (Fraser and others, 2014; Priest and others, 2015, 2016).

Figure 2-6. Demonstration of how *Beat the Wave* maps are used to measure survivability using a maximum speed threshold. A) *Beat The Wave* map demonstrating the estimated extent of survivability for a given scenario. Roads and trails that can reach safety at 4 fps or less are drawn in black; the remaining unsurvivable roads and trails are drawn in white. The green polygon is outside the tsunami hazard zone. B) Buildings containing people are added to the map, shown with white circles. C) Demonstration of how survivors are counted. Buildings are classified based on the evacuation speed of the nearest road segment (above or below 4 fps). The population within each building is then counted as survivors or non-survivors. Base map on this and subsequent figures is shaded relief from 2009 lidar data (Oregon Lidar Consortium North Coast Project, www.OregonGeology.org/lidar).



3.0 SEASIDE: RESULTS AND DISCUSSION

This section presents tsunami evacuation results for the City of Seaside with a quantitative comparison of various mitigation efforts, including bridge retrofits and one or more VES. **Figure 3-1** shows the inundation zone for an XXL tsunami in Seaside along with important natural and human-made features that play a role in tsunami evacuation. As discussed in section 1.4.1, there are 10 bridges over two bodies of water that play a role in evacuation. In total, there are five arterial (primary) evacuation routes that define the city's evacuation corridors (**Figure 3-1**), four of which rely on one or more of those bridges.

A CSZ tsunami will reach the ocean beaches ~10 minutes – 15 minutes after the start of earthquake shaking (**Figure 3-2**). The promenade is overtopped after ~20 minutes and Highway 101 is reached after ~17 minutes. In total, Seaside is fully inundated after ~30 minutes. The tsunami will enter the Necanicum Estuary and begin to travel up the Necanicum River and Neawanna Creek concurrently with the tsunami's eastward overland advance. Additional tsunami waves will continue to impact the open coast and enter the Necanicum River estuary, causing water levels to fluctuate for up to 12 hours after the earthquake.

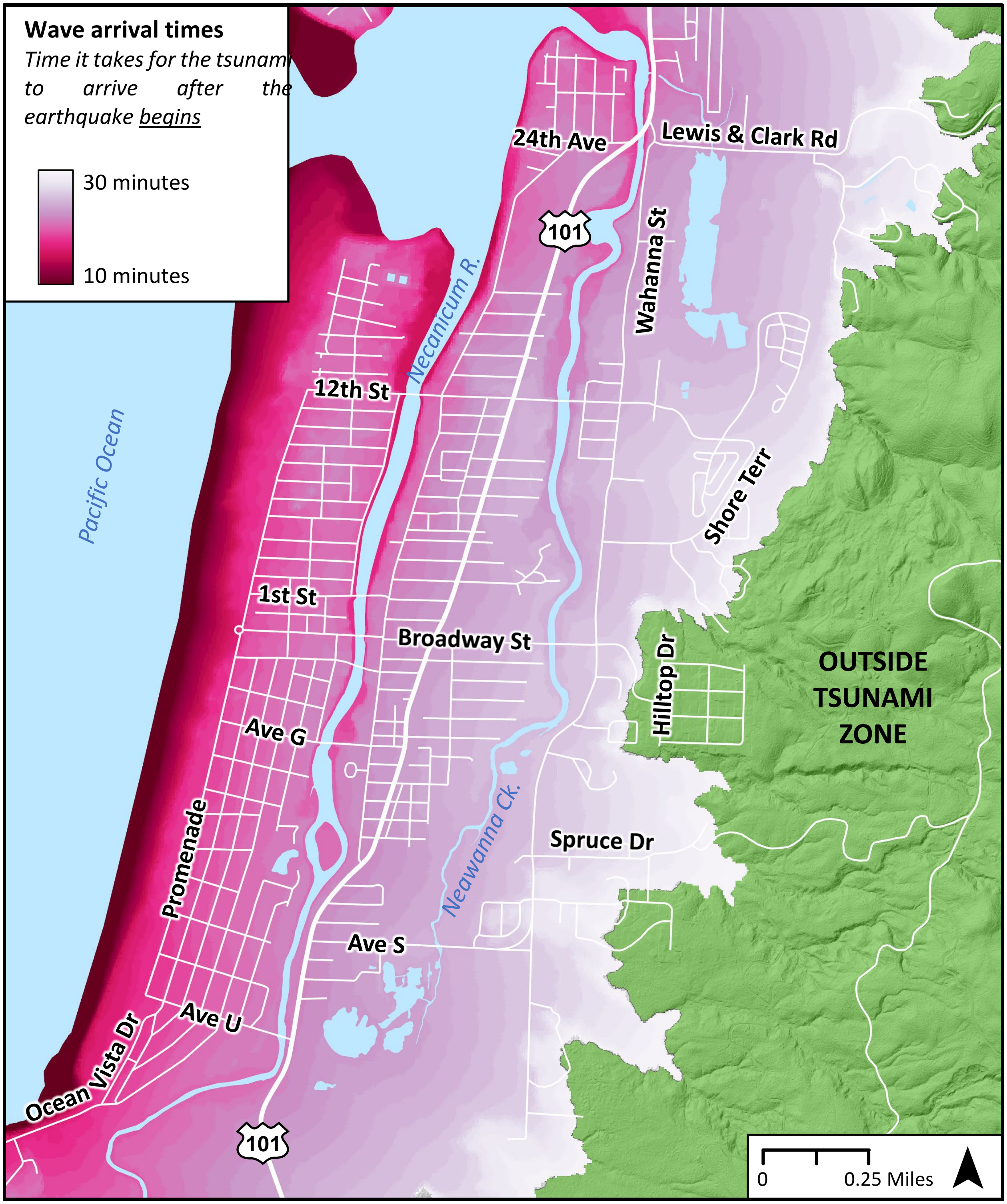
We first present the current conditions XXL scenario showing the minimum travel speeds required to reach safety using the existing road network, were evacuation to occur today. We then present a suite of hypothetical scenarios representing the following infrastructure improvements and compare them against the current conditions:

1. **Bridges-In:** Assumes all 10 bridges have been seismically retrofitted and will be available for evacuation
2. **Single VES scenarios** (letters equate to location on map in **Figure 3-1**):
   A) Convention Center (parking lot)
   B) Outlet Mall (parking lot)
   C) Goodman Park
   D) Former high school
   E) Cartwright Park
3. **Multiple VES scenarios**
   - 2 VES: Convention Center and Outlet Mall (A+B)
   - 3 VES: Convention Center, Outlet Mall, and Cartwright Park (A+B+E)
   - 4 VES: Convention Center, Outlet Mall, Cartwright Park, and Goodman Park (A+B+E+C)

All scenarios include a 10-minute delay before starting evacuation to account for the expected disoriented state of people following severe earthquake shaking and the time required to exit buildings (Mas and others, 2013, and Makinoshima and Imamura, 2024).

Figure 3-1. Detailed map of Seaside showing the XXL tsunami inundation zone (in gray), safety destinations (where roads reach the edge of the tsunami zone), and the five arterial (primary) evacuation routes. Hypothetical VES locations analyzed in this report are identified in capital red letters. Base map on this and subsequent figures is shaded relief from 2009 lidar data (Oregon Lidar Consortium North Coast Project, www.OregonGeology.org/lidar).

Figure 3-2. Illustration of tsunami wave arrivals after an XXL CSZ earthquake in Seaside. More information on how arrivals are calculated can be found in Gabel and others (2020).



3.1 Population

The number of people in Seaside fluctuates significantly due to the high number of tourists that visit year-round. As with many coastal communities, the distribution of permanent and temporary residents (aka visitors or tourists) is quite different both in terms of number and location. **Table 3-1** presents the permanent, temporary, and total population inside the tsunami zone for Seaside. Our results indicate ~6,700 residents and as many as ~10,200 overnight visitors. To account for variability and uncertainties in our population estimates, particularly amongst temporary residents, this report will round results (i.e. number of survivors for a given scenario) to the nearest hundred.

Table 3-1. Permanent, temporary, and total resident population inside the XXL tsunami zone in Seaside.

Permanent Population	Temporary Population*	Total Population**
6,700	10,200	16,900

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.

** Total population = permanent residents + temporary residents

Day visitors can significantly increase the population of Seaside, especially on summer weekends or during large events such as their annual beach volleyball tournament. We worked with Seaside's Visitor Bureau Director to better understand this important group using data they collect for tourism purposes. Datafy is a visitor analytics tool used to measure visitation to specific locations over time using cell phone data. Unfortunately, we were unable to incorporate these data into our population model because we could not constrain day visitor locations. However, we were able to infer that the city experiences influxes of as many as ~9,000 to 16,000 people on a single day. This range was calculated using Datafy estimates of the number of daily visitors on Saturdays in July and August from the years 2018, 2019, 2022 and 2023. Seaside began working with Datafy in 2018; 2020 and 2021 were omitted to remove anomalies due to the COVID-19 pandemic. DOGAMI's overnight population was subtracted from these results to isolate the day visitors. It remains imperative that day visitors be factored into any future discussions related to mitigation options, especially the capacity of VES.

Figure 3-3 presents the permanent- and temporary-population distributions for Seaside. At the request of Seaside officials, we will present results using the total population, which is simply the sum of permanent and temporary residents. **Figure 3-4** presents a map of the total population distribution in Seaside.

Figure 3-3. (left) Permanent and (right) temporary population distributions inside the tsunami zone in Seaside. Temporary population does not account for day visitors, which can increase the number of visitors in Seaside by ~9,000-16,000 people.

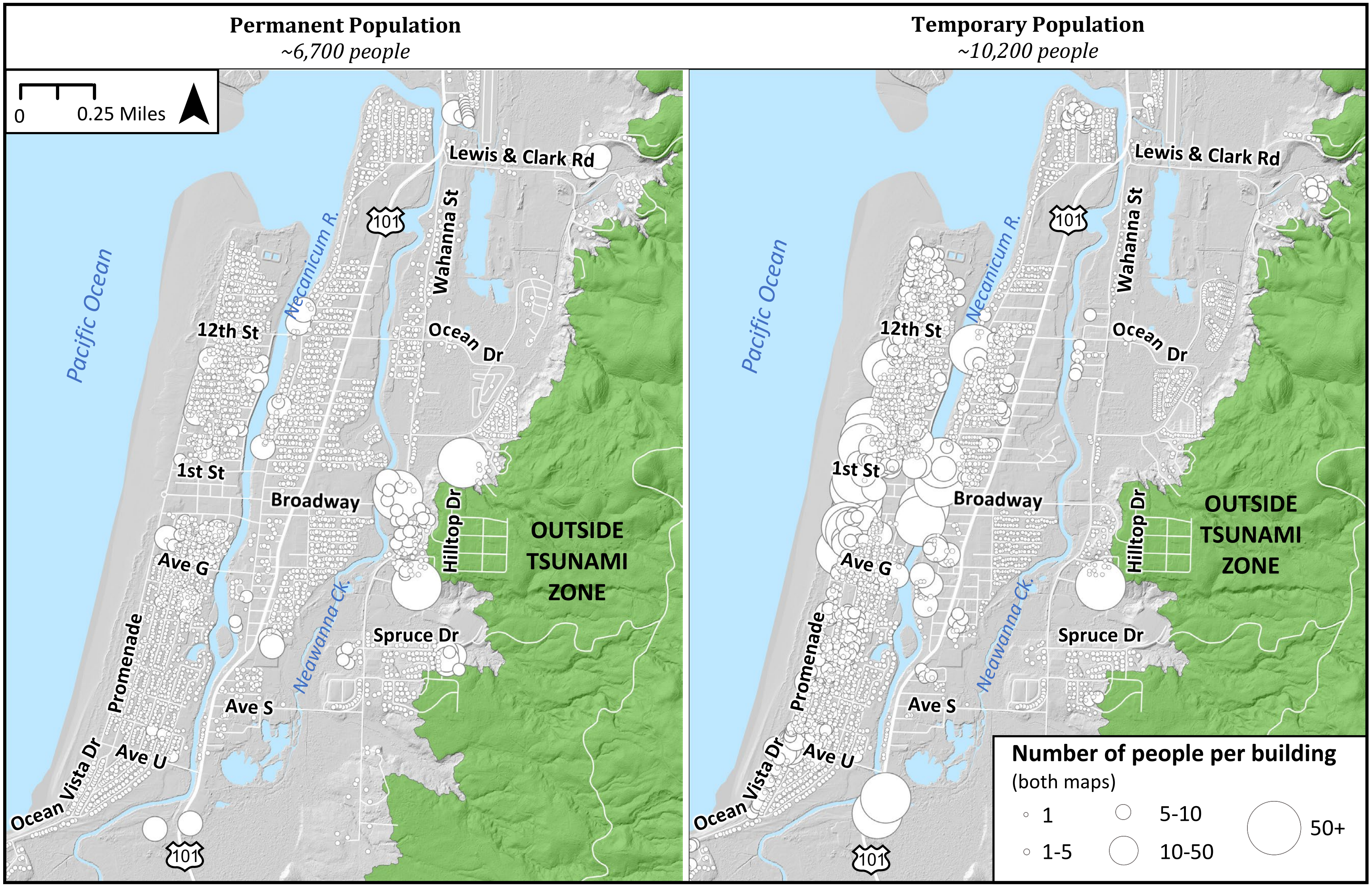
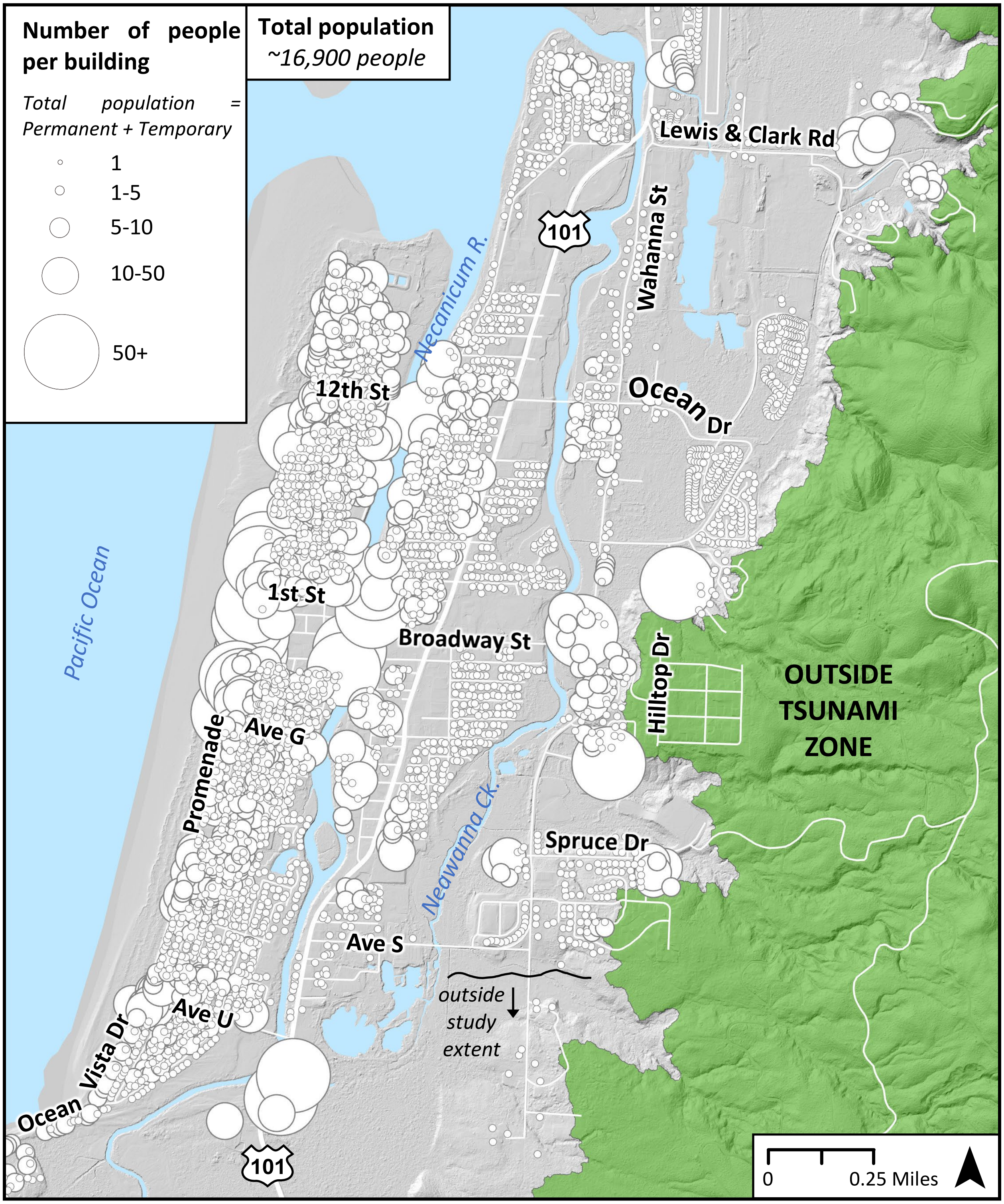


Figure 3-4. Total population distribution (permanent plus temporary residents) inside the tsunami zone in Seaside. Temporary population does not account for day visitors, which can increase the number of visitors in Seaside by ~9,000-16,000 people.



3.2 Current Conditions Scenario

Evacuation modeling results with a focus on which parts of the city are survivable at 4 fps or slower are presented in **Figure 3-5** and **Table 3-2**. We find that ~25% of the population (~4,200 people) can escape the tsunami at 4 fps or slower, assuming the four post-1995 bridges remain standing and can be used for evacuation. Of the estimated 4,220 survivors, 57% are permanent residents (2,421 people) and 43% (1,799 people) are temporary residents. No one west of the Necanicum River can reach safety in time, which explains the fact that roughly twice as many visitors are estimated to not survive in this scenario compared to permanent residents. In total, ~12,700 permanent and temporary residents are not expected to survive in this scenario.

The primary challenges to life safety in Seaside are the long distances people must travel to reach high ground and the reliance upon bridges. From the promenade, a very popular tourist destination that runs along the back edge of the beach, evacuation routes range from 1 mi to 1.5 mi. This challenge is compounded by the need to cross up to two bodies of water. Evacuees could lose precious time finding passable bridges or attempting to swim/wade across.

The only area not reliant upon bridges to reach high ground is in southwest corner of Seaside, where the nearest high ground is due south on Tillamook Head. Unfortunately, a low spot along the route experiences a significantly earlier tsunami wave arrival, which limits how much of southwest Seaside can expect to reach the Tillamook Head safety destination in time. This results in a longer route for a large swath of southwest Seaside that must travel north to the 1st Avenue bridge and then east on Broadway Street rather than south to Tillamook Head.

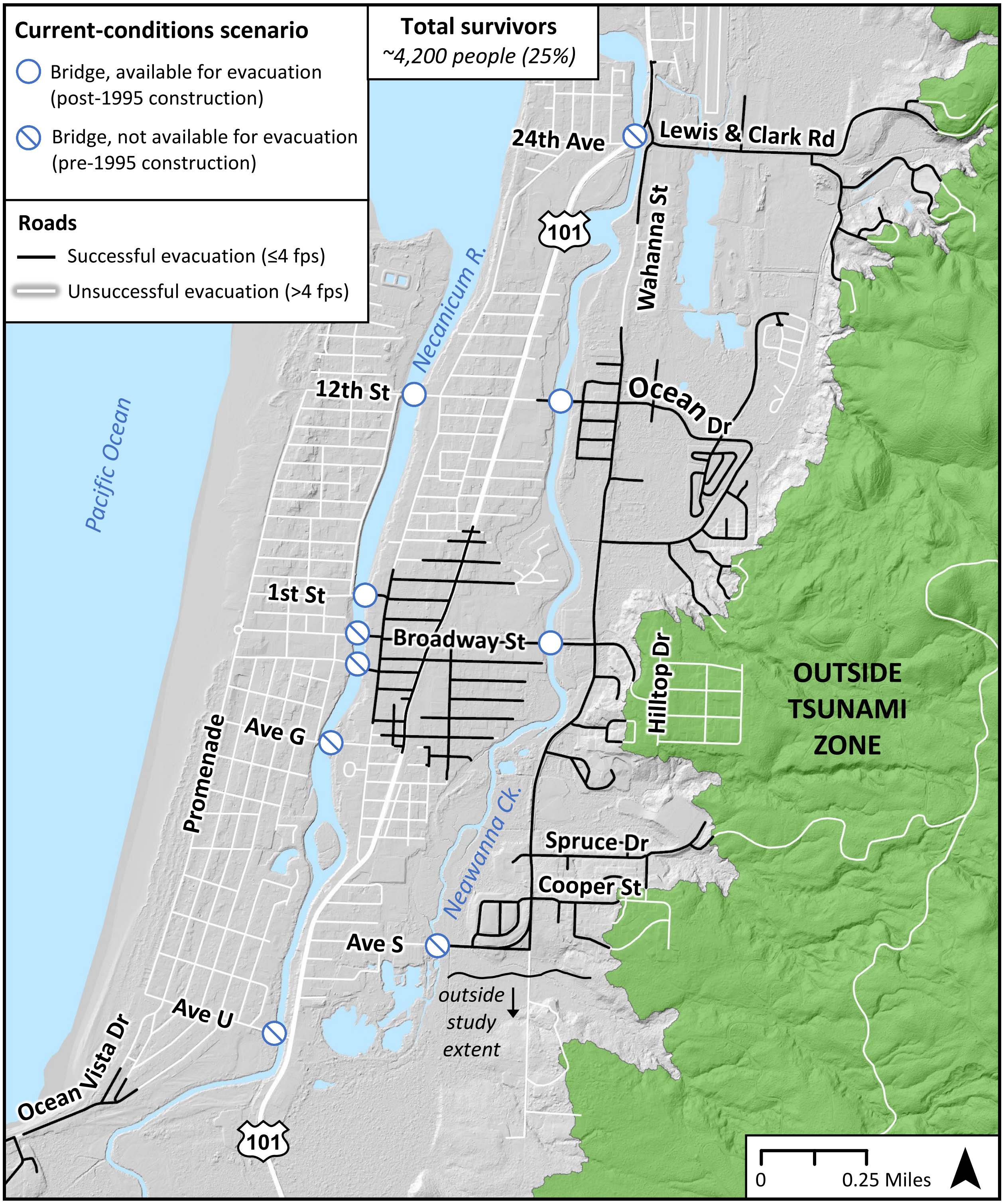
Table 3-2. Number of survivors for the XXL Current conditions scenario.

Scenario	Survivors			Non-Survivors		
	Permanent residents	Temporary residents*	Total population**	Permanent residents	Temporary residents*	Total population**
Current-conditions	2,400	1,800	4,200	4,300	8,400	12,700

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.

** Total population = permanent residents + temporary residents

Figure 3-5. Evacuation modeling in Seaside for the XXL Current conditions scenario depicting the existing road network and assuming all bridges constructed before 1995 are unavailable for evacuation. Road color reflects likelihood of survival based on travel speed that must be maintained along the route. Survivors are reported as a percentage of the total population (permanent + temporary residents) inside the tsunami zone.



3.3 Bridges-In Scenario

Our first hypothetical mitigation scenario was to seismically retrofit all 10 bridges in Seaside, simulating a mitigation scenario long thought to be the key to survivability in the city. **Figure 3-6** presents evacuation modeling results for this scenario along with a side-by-side map of the Current conditions scenario. Unexpectedly, this mitigation effort only yields a ~1% (~ 300 people) improvement in the number of lives saved (**Table 3-3** and **Figure 3-7**). Upon closer inspection of the results, it became clear that distances to high ground do not decrease appreciably with the inclusion of the six other bridges. While this result provides clear evidence that other, more drastic, solutions need to be sought to significantly improve life safety, it does not acknowledge the benefits that would still come from ensuring all bridges are available for evacuation. It would create more straightforward routes in some areas, especially the Venice Park neighborhood (area around 24th Ave, west of Lewis and Clark Road). The fewer choices people need to make during such a stressful time (i.e., multiple left/right turns to navigate to a particular bridge) the more successful they are likely to be in their evacuation. Nevertheless, if the bridges are reconstructed such that they survive the tsunami, they will greatly contribute to the city's post-event recovery.

Figure 3-6. Evacuation modeling in Seaside for the bridges-in scenario, which assumes all bridges are available for evacuation. The current conditions scenario is presented on the left for comparison. Road color reflects likelihood of survival based on travel speed that must be maintained along the route.

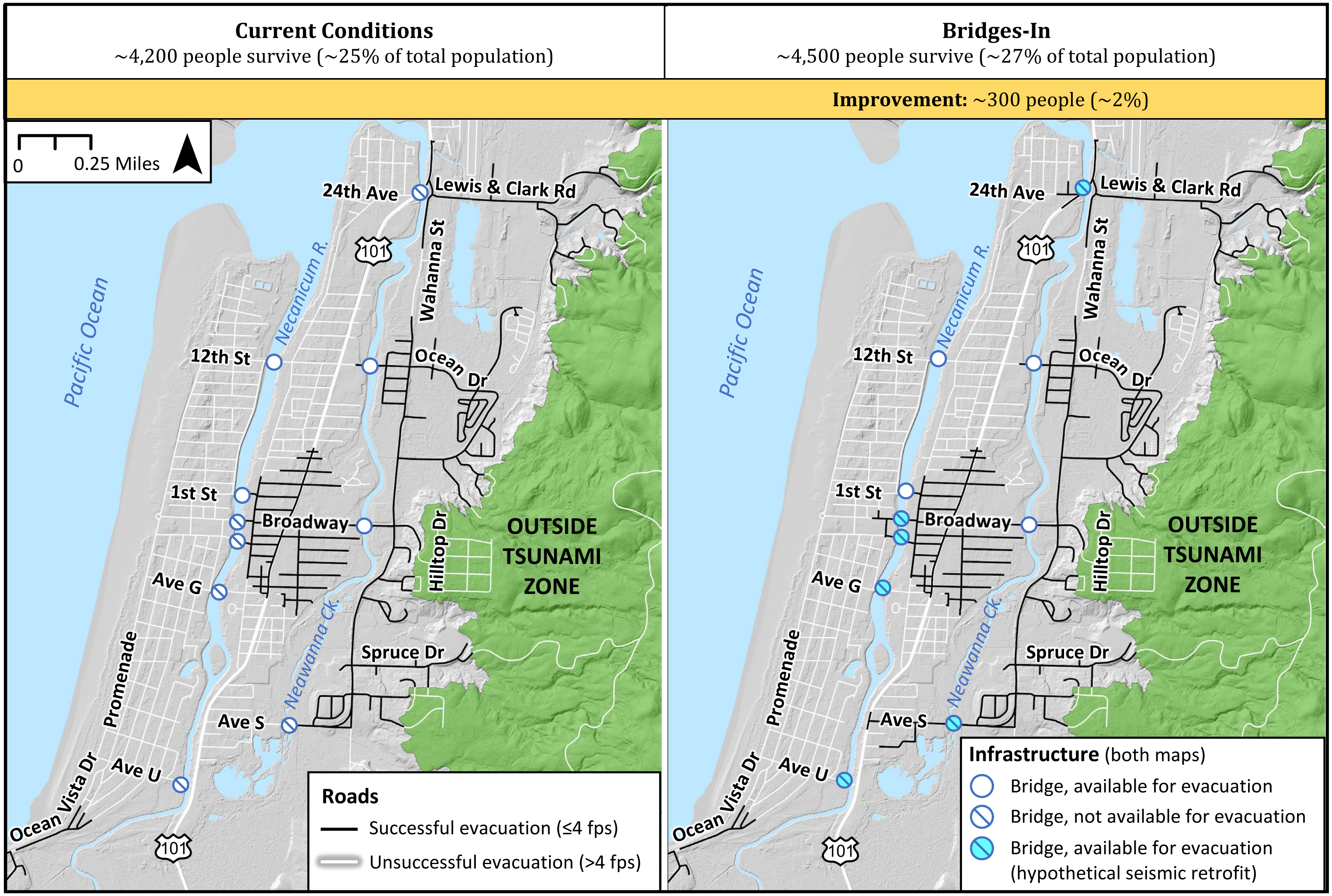
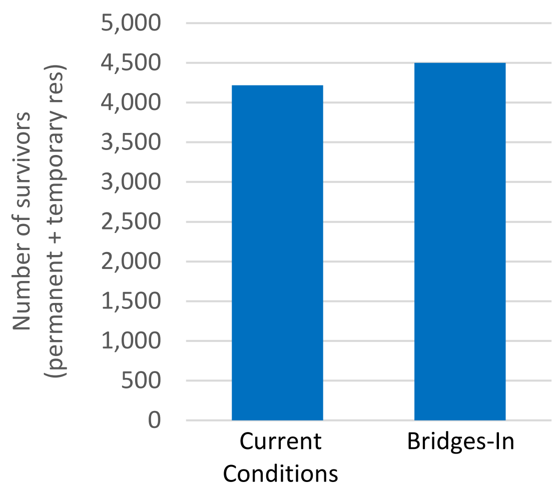


Table 3-3. Number of survivors for the Bridges-In scenario with Current conditions scenario for comparison.

	Survivors				Non-Survivors
Scenario	**Permanent residents**	**Temporary residents***	**Total population****	**Improvement from Current-conditions (Total pop)**	**Total population****
Current-conditions	2,400	1,800	4,200	-	12,700
All bridges in	2,500	2,000	4,500	300	12,400

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.
** Total population = permanent residents + temporary residents

Figure 3-7. Comparison of survivors for Current conditions and Bridges-in scenarios in Seaside using the total population (permanent plus temporary residents).

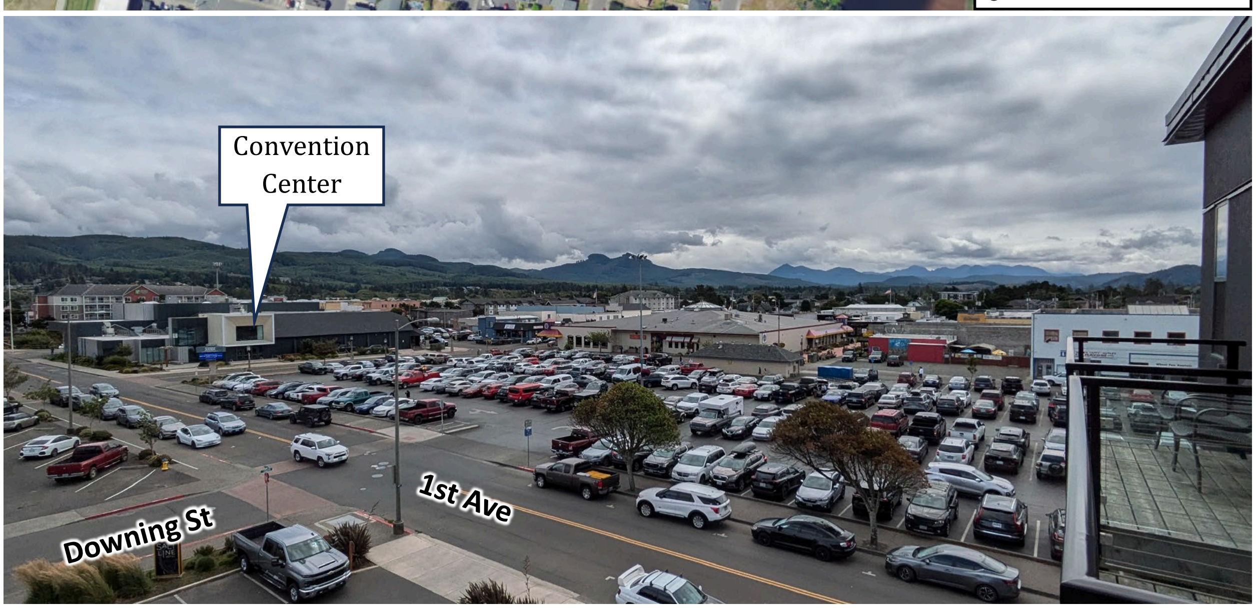


3.4 VES Scenarios

Five VES sites were selected in consultation with Seaside officials. Criteria included city-owned property, proximity to high-density clusters of people, distribution across the city, and dual uses (i.e., parking structure) (see **Figure 3-1** for locations):

A) Convention Center (parking lot) (see **Figure 3-8** for closer view of location)
B) Outlet Mall (parking lot)
C) Goodman Park
D) Former high school
E) Cartwright Park

Figure 3-8. Convention Center parking lot VES location. (top) Aerial image of downtown Seaside centered on the Convention Center and parking lot. (bottom) Oblique image of parking lot as seen from the fourth story of a nearby hotel. Location and direction of photo marked in aerial image with camera icon.



A VES at the Convention Center parking lot could serve as a new parking structure for the city's growing needs as well as a refuge during the next CSZ earthquake and tsunami. **Figure 3-9** present evacuation modeling results from this scenario along with a side-by-side map of the Current conditions scenario for comparison. A structure in this location could potentially save as many as 25% more lives (~4,300 additional residents), creating a 0.8-mile-long zone of survivability west of the Necanicum River. Of the 8,500 total survivors in this scenario (~50% of the total population inside the tsunami zone), 41% are permanent residents (~3,500 people) and 59% are temporary residents (~5,000 people) (**Table 3-4**).

We estimate ~4,000 permanent residents and overnight visitors seeking refuge at this hypothetical VES, which is more than any existing VES can securely hold. However, as noted previously, our analyses probably underestimate the number of people since we are unable to account for day visitors. It is safe to assume that a significant portion of the additional 9,000 to 16,000 visitors that may be in Seaside at the time of the earthquake would be in this general vicinity and seek refuge at this VES. Additional efforts are needed to resolve the size and number of structures required to meet the needs of downtown Seaside.

Results for the other four hypothetical VES sites considered in this report (Outlet Mall, Goodman Park, the former high school, and Cartwright Park) are provided in **Figure 3-10** and **Figure 3-11** as well as **Table 3-4**. The Outlet Mall and Goodman Park see notable reductions in fatalities that are comparable to a Convention Center VES (~22% and 25% improvement over current conditions, respectively), Cartwright Park is helpful but less so (14% improvement), and the former high school is the least effective (7% improvement).

In addition to individual VES scenarios, we ran three scenarios to investigate further improvements gained from having multiple (two, three, and four) VES in Seaside. In summary, having two VES at the Convention Center and the Outlet Mall yields a ~41% improvement (~6,900 additional people) over current conditions compared with 25% with a single VES. Adding a VES at Cartwright Park in the south yields a 49% improvement and finally, adding Goodman Park in the northwest yields a 60% improvement (~8,300 additional people). Survivor estimates for all VES scenarios along with current conditions, for comparison, are presented in **Table 3-4** and **Figure 3-12**. The three VES scenario results in survival of 85% of the total population. These results demonstrate the power of multiple VES in a community like Seaside.

Figure 3-9. Evacuation modeling in Seaside for VES at Convention Center scenario. The current conditions scenario is presented on the left for comparison. Road color reflects likelihood of survival based on travel speed that must be maintained along the route.

Current Conditions ~4,200 people survive (~25% of total population)	**VES at Convention Center** ~8,500 people survive (~50% of total population)
	Improvement: ~4,300 people (~25%)

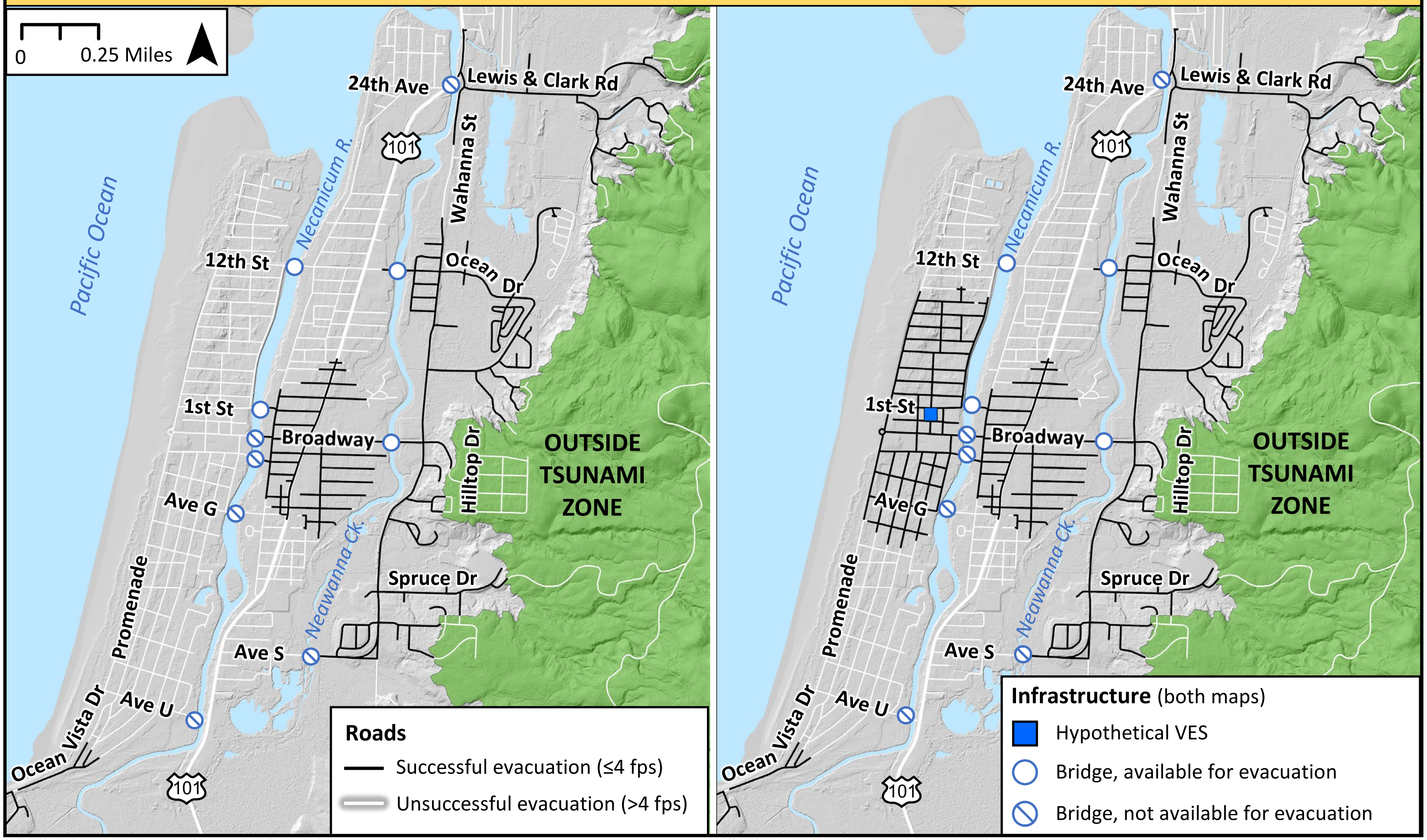


Figure 3-10. Evacuation modeling in Seaside for two VES scenarios: (left) VES at the Outlet Mall and (right) VES at Goodman Park. Relative improvement compared to the current conditions reported in the yellow bar.

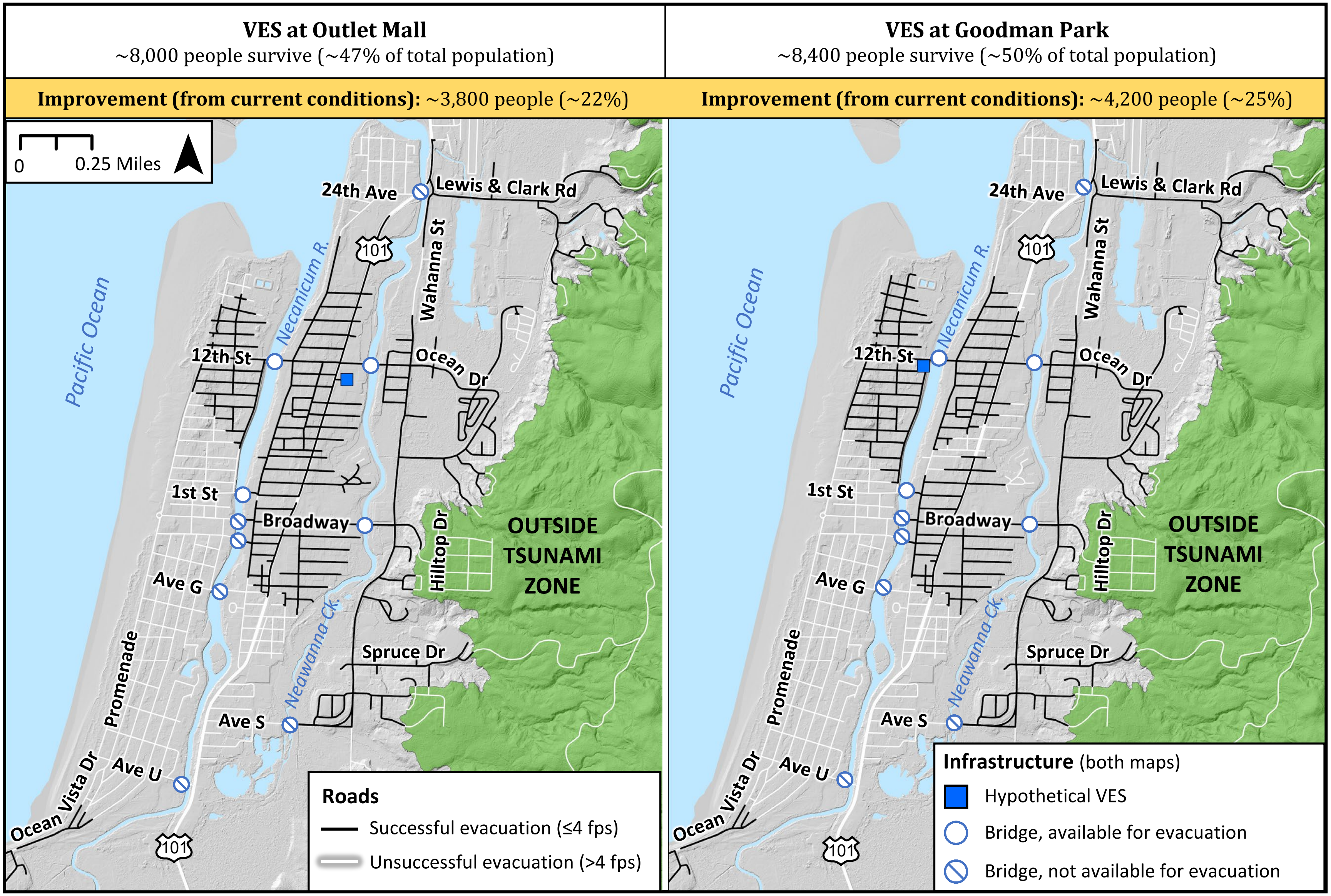


Figure 3-11. Evacuation modeling in Seaside for two VES scenarios: (left) VES at the former high school and (right) VES at Cartwright Park. Relative improvement compared to the current conditions reported in the yellow bar.

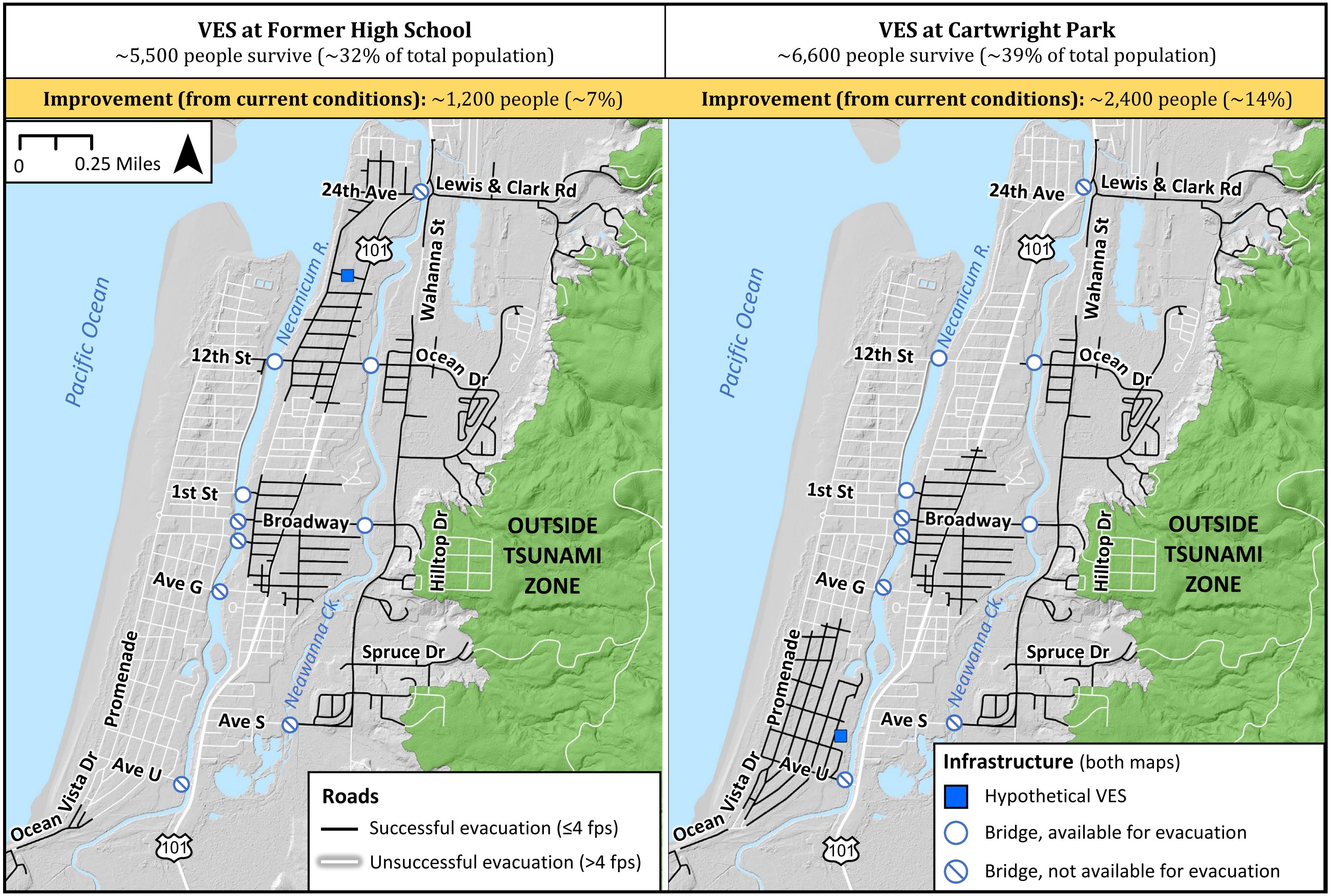


Table 3-4. Number of survivors for all VES scenarios with Current conditions scenario for comparison.

	Survivors				Non-Survivors
Scenario	**Permanent residents**	**Temporary residents***	**Total population****	**Improvement from Current-conditions (Total pop)**	**Total population****
Current-conditions	2,400	1,800	4,200	-	12,700
VES: Convention Center	3,500	5,000	8,500	4,300	8,400
VES: Outlet Mall	4,200	3,800	8,000	3,800	8,900
VES: Goodman Park	4,100	4,300	8,400	4,200	8,500
VES: Former high school	3,000	2,400	5,400	1,200	11,500
VES: Cartwright Park	3,000	3,600	6,600	2,400	10,300
2 VES: Convention Center & Outlet Mall	4,700	6,400	11,100	6,900	5,800
3 VES: Convention Center, Outlet Mall & Cartwright Park	5,000	7,500	12,500	8,300	4,400
4 VES: Convention Center, Outlet Mall, Cartwright Park & Goodman Park	5,600	8,700	14,300	10,100	2,600

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.
** Total population = permanent residents + temporary residents

Figure 3-12. Comparison of survivors for Current conditions and select VES scenarios in Seaside using the total population (permanent plus temporary residents).

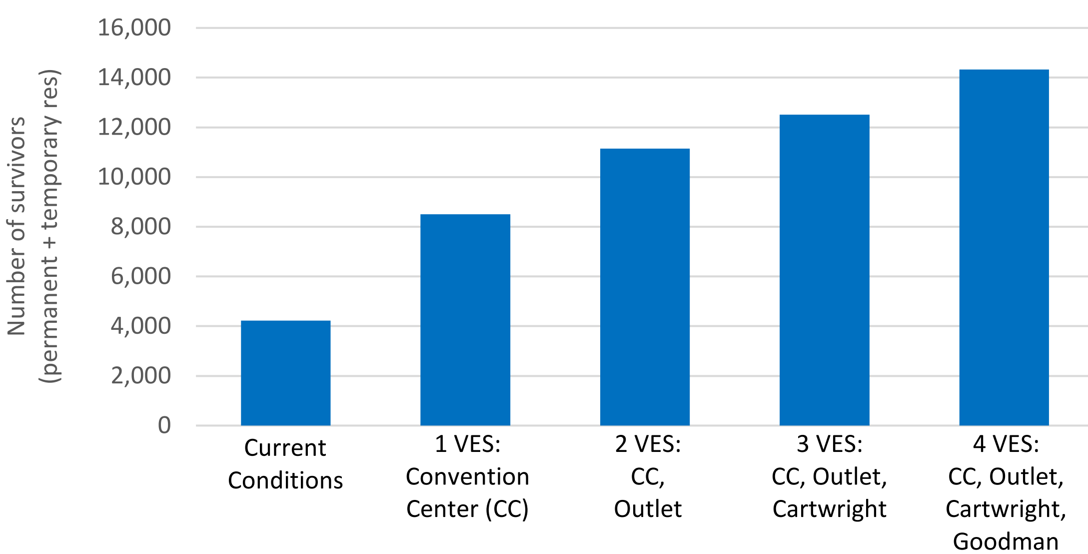


Table 3-5 reports the total number of people that will seek shelter at each hypothetical VES site along with maximum flow depths for three of DOGAMI's deterministic tsunami inundation scenarios (XXL, Extra-Large and Large), which can begin to inform decisionmakers about potential design heights of VES structures at each location. **Table 3-5** includes modeled flow depths for the Extra-Large tsunami inundation scenario because these depths are closest to what would be required under Oregon building codes (OBC). For engineering purposes, VES design must utilize tsunami modeling results and design standards produced by the American Society of Civil Engineers (ASCE, 2017). These design standards account for earthquake shaking, coseismic responses, and hydrodynamic forces of the tsunami on the structure including foundation scour effects, blowout walls and impact forces. For comparison, ASCE 7-16 is more conservative than DOGAMI's Extra-Large tsunami scenario, though the results vary along the coast (Priest and Allan, 2019).

Table 3-5. Number of survivors that will seek shelter at each hypothetical VES location in Seaside as well as maximum tsunami flow depths (XXL, X-Large, and Large tsunami scenarios).

	Required capacity for residents			Maximum tsunami flow depth (ft)		
VES site	**Permanent residents**	**Temporary residents***	**Total population****	**XXL tsunami scenario**	**X-Large tsunami scenario**	**Large tsunami scenario**
Convention Center	1,300	2,700	4,000	53	51	31
Outlet Mall	1,600	2,100	3,700	61	58	32
Goodman Park	1,500	2,400	3,900	49	47	28
Former high school	700	400	1,100	52	49	24
Cartwright Park	600	1,800	2,400	51	49	28

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.

** Total population = permanent residents + temporary residents

3.5 Comparison of Mitigation Scenarios

The number of total survivors have been tallied for each scenario and presented numerically in **Table 3-6** and graphically in **Figure 3-13**. **Figure 3-14** breaks these results down for permanent and temporary residents. A horizontal dashed line represents the number of survivors under current conditions and is intended to help visualize the extent to which each mitigation scenario improves life safety. Gray bars extend to the total population within the tsunami zone and allow the number of survivors for each scenario to be viewed as a proportion of the total population in addition to absolute numbers.

Table 3-6. Number of survivors for all scenarios in Seaside.

	Survivors				Non-Survivors
Scenario	**Permanent residents**	**Temporary residents***	**Total population****	**Improvement from Current-conditions (Total pop)**	**Total population****
Current-conditions	2,400	1,800	4,200	-	12,700
All bridges in	2,500	2,000	4,500	300	12,400
VES: Convention Center	3,500	5,000	8,500	4,300	8,400
VES: Outlet Mall	4,200	3,800	8,000	3,800	8,900
VES: Goodman Park	4,100	4,300	8,400	4,200	8,500
VES: Former high school	3,000	2,400	5,400	1,200	11,500
VES: Cartwright Park	3,000	3,600	6,600	2,400	10,300
2 VES: Convention Center & Outlet Mall	4,700	6,500	11,200	7,000	5,700
3 VES: Convention Center, Outlet Mall & Cartwright Park	5,000	7,500	12,500	8,300	4,400
4 VES: Convention Center, Outlet Mall, Cartwright Park & Goodman Park	5,600	8,700	14,300	10,100	2,600

* Results do not account for day visitors, which can increase the number of visitors in Seaside by ~9,000 people–16,000 people.

** Total population = permanent residents + temporary residents

Figure 3-13. Comparison of survivors for all scenarios in Seaside using the total population (permanent plus temporary residents). Top of gray bar indicates total population inside the tsunami zone for Seaside. Dashed horizontal line represents the number of survivors under current conditions; height of blue bars above this line represent the relative improvement of each mitigation scenario.

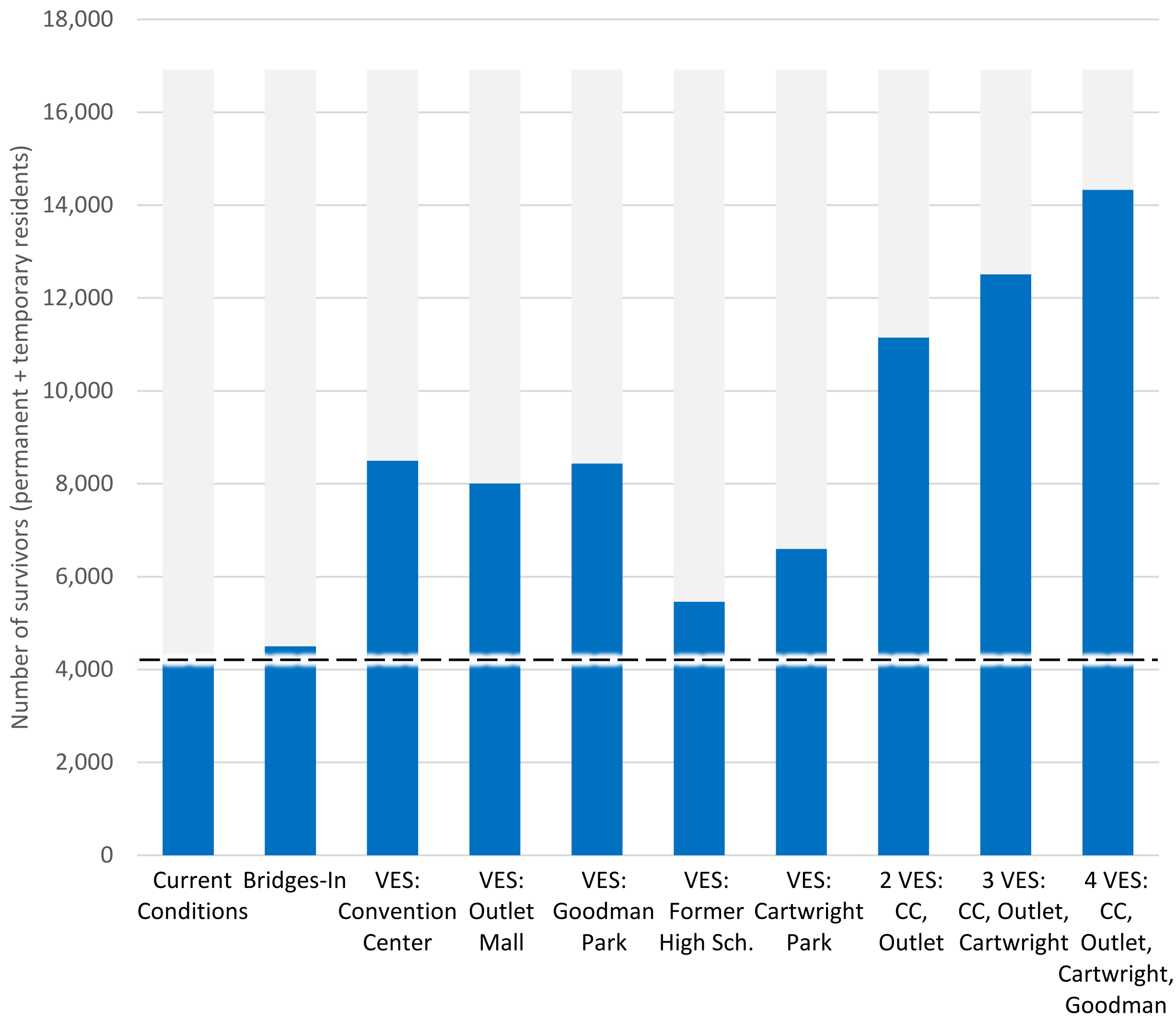
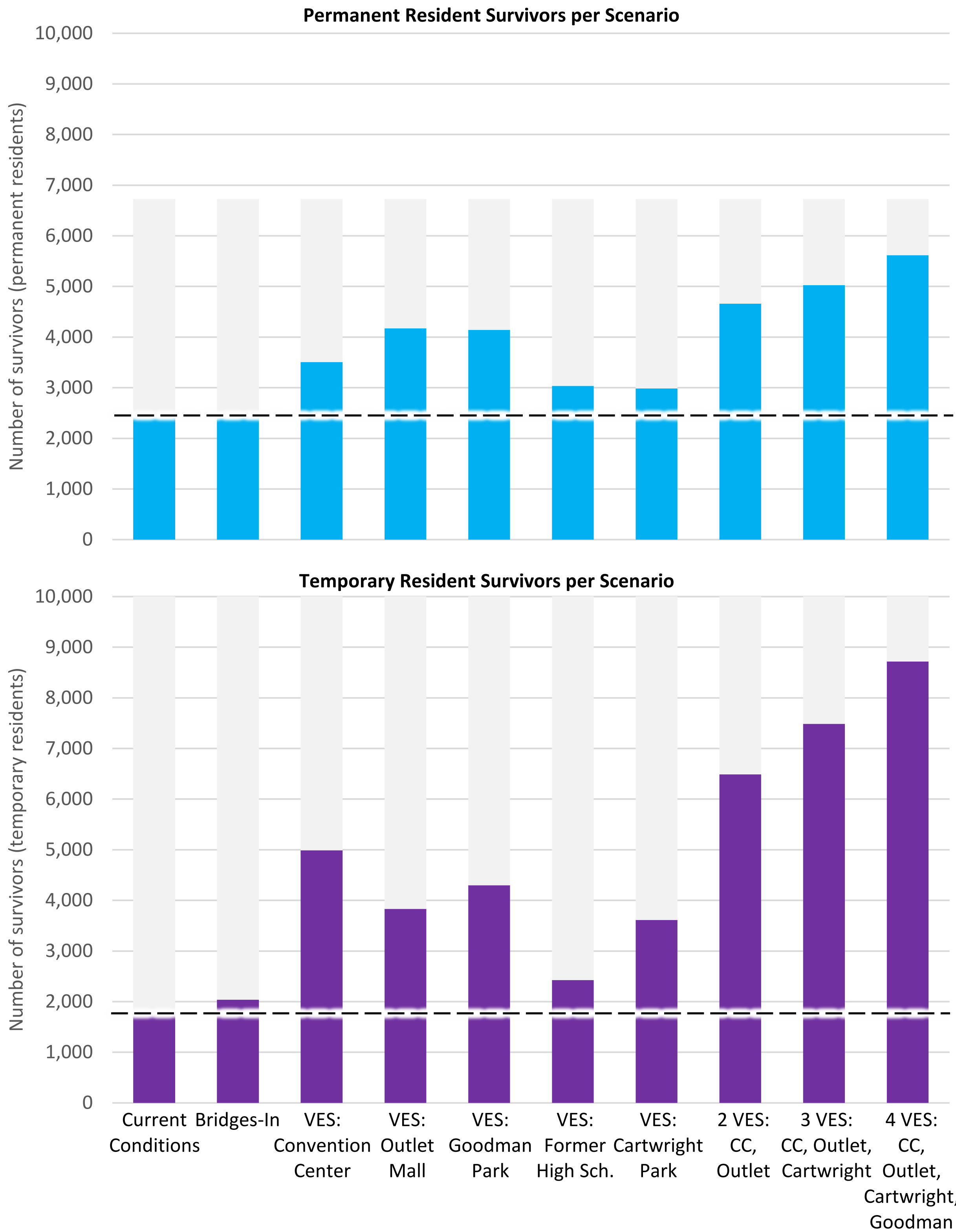


Figure 3-14. Number of (top) permanent and (bottom) temporary resident survivors for all scenarios in Seaside. Top of gray bar indicates total population (permanent and temporary, respectively) inside the tsunami zone. Dashed horizontal line represents the number of survivors under current conditions; height of bars above this line represents the relative improvement of each mitigation scenario.



4.0 CANNON BEACH: RESULTS AND DISCUSSION

This section presents tsunami evacuation results for the City of Cannon Beach with a quantitative comparison of various mitigation efforts, including a seismic retrofit of the Fir Street Bridge and several VES locations. **Figure 4-1** shows the inundation zone for an XXL tsunami in Cannon Beach along with important natural and human-made features that play a role in tsunami evacuation. As discussed in section 1.4.2, the Fir St Bridge over Ecola Creek is key to evacuation for downtown Cannon Beach. We will focus much of our results on downtown, which we define as the area between the Fir Street Bridge in the north to Washington Street in the south (**Figure 4-1**). The city can be naturally divided into a north and south region, separated by the "S Curves" neighborhood in the vicinity of Haystack Rock (**Figure 4-1**). Results will be discussed separately for each region.

Two "islands" of high ground in Cannon Beach were not included in our analyses due to their small size and the proximity of larger areas of contiguous high ground. The first is the Hallmark Resort off Hemlock Street, near Sunset Boulevard in the Presidential Streets neighborhood. The second is at Chapman Point, near the intersection of 5thStreet and Laurel Street. Both islands are valid areas of refuge and are included on all maps in this report. However, neither site is large enough to provide sufficient refuge for hundreds to thousands of people. The added fact that there are nearby alternative destinations that can accommodate large numbers of people reinforced the decision to exclude these islands from the analysis. Local decisionmakers were consulted before this decision was ultimately made.

The Highway 101 bridge over Ecola Creek was also not included in our analysis because this stretch of road does not contain any residential or commercial structures and therefore does not have an impact on evacuation. For this reason, we do not consider a hypothetical seismic retrofit of this bridge. As with the Fir Street Bridge, if the Highway 101 bridge is reconstructed such that it survives the earthquake and tsunami, it will greatly contribute to the city's post-event recovery.

A CSZ tsunami will reach the ocean beaches ~10 minutes after the start of earthquake shaking (**Figure 4-2**). The tsunami quickly enters the low-lying Ecola Creek floodplain, reaching downtown in another ~5 minutes. It takes another ~5 minutes for the tsunami to overtop the marine terrace south of downtown Cannon Beach. All of Cannon Beach's tsunami zone is inundated 30 minutes after the start of earthquake shaking. Additional waves will continue to impact the open coast and Ecola Creek for up to 12 hours after the earthquake.

Figure 4-1. Detailed maps of north and south Cannon Beach showing the XXL tsunami inundation zone (in gray), safety destinations (where roads reach the edge of the tsunami zone), and the primary neighborhoods. Hypothetical VES locations analyzed in this report are identified in capital red letters. Mitigation scenarios are compared for the downtown district in Section 4.5.

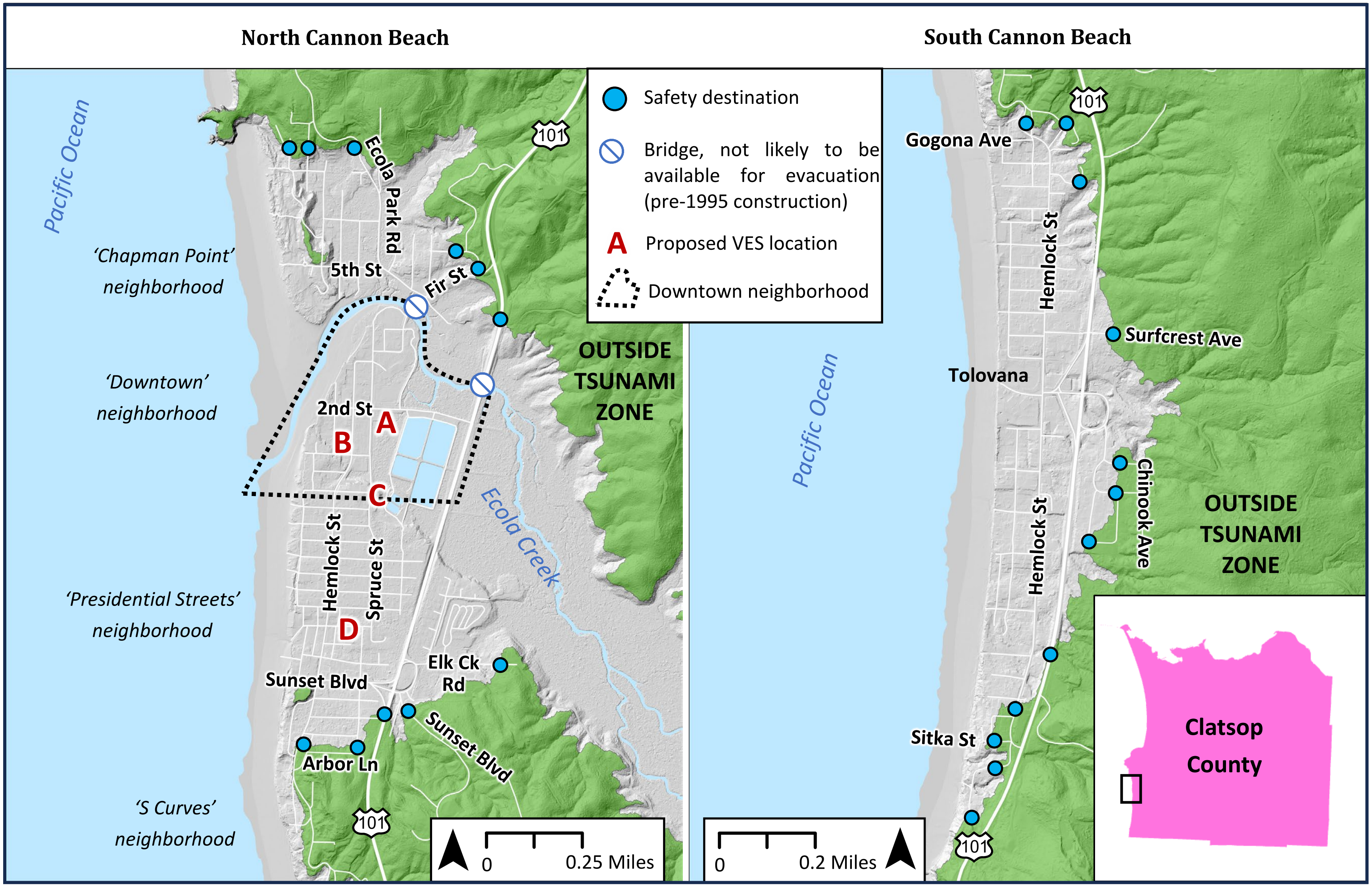
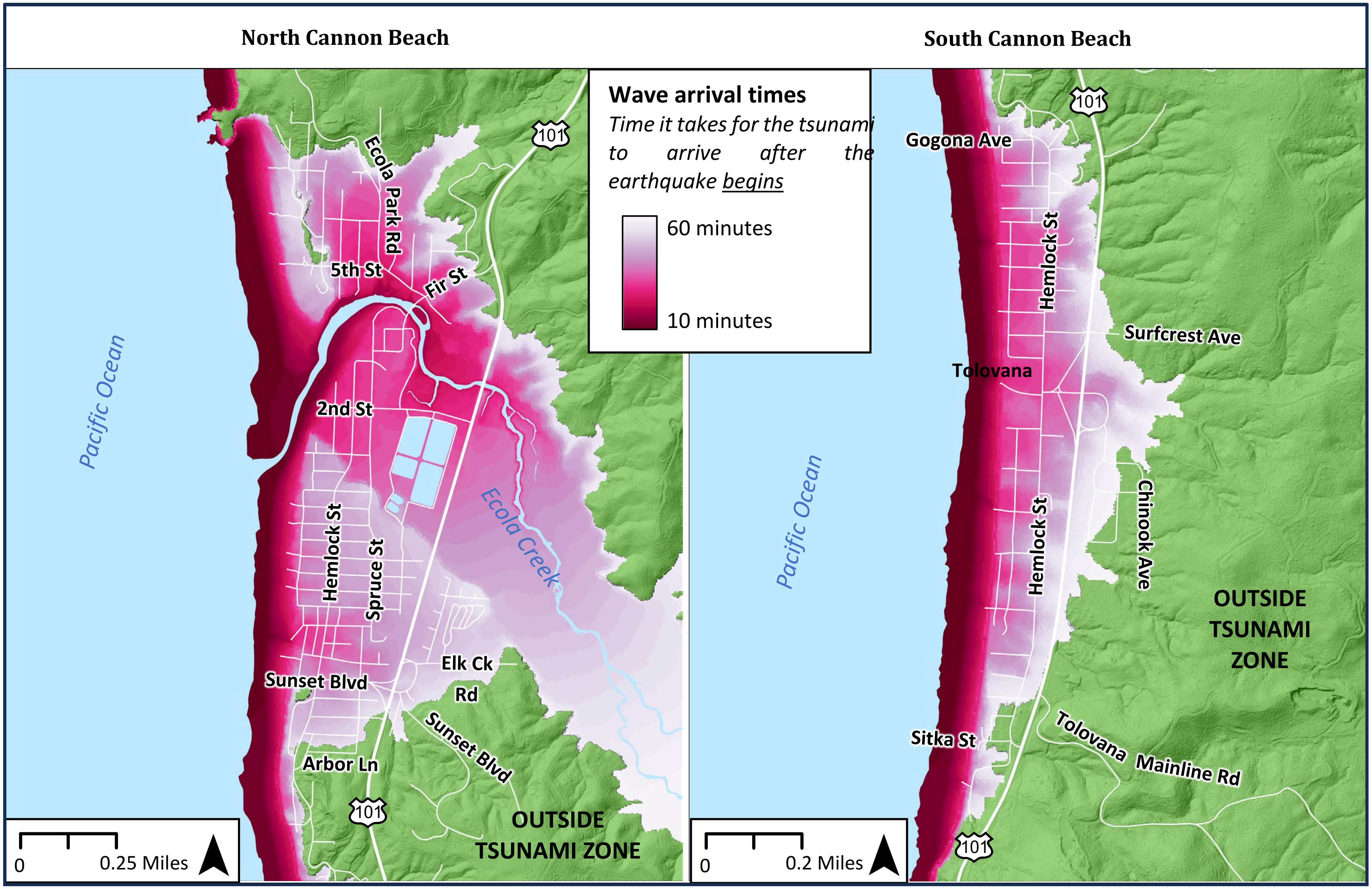


Figure 4-2. Illustration of tsunami wave arrivals after an XXL CSZ earthquake in north and south Cannon Beach. More information on how arrivals are calculated can be found in Gabel and others (2020).



We first present the current conditions XXL scenario showing the minimum travel speeds required to reach safety using the existing road network, were evacuation to occur today. We then present a suite of hypothetical scenarios representing the following infrastructure improvements and compare them against the current conditions:

1. **Bridge-in:** Assumes the Fir Street Bridge has been seismically retrofitted and will be available for evacuation
2. **VES scenarios** (letters equate to location on map in **Figure 4-2**):
   A) 2ndStreet and Spruce Street
   B) Larch Street and 1st Street
   C) Adams Street and Spruce Street
   D) City Hall

All hypothetical mitigation scenarios are focused on the downtown district because it is the area most in need of evacuation improvements. All scenarios include a 10-minute delay before starting evacuation to account for the expected disoriented state of people following severe earthquake shaking and the time required to exit buildings (Mas and others, 2013, and Makinoshima and Imamura, 2024).

4.1 Population

The number of people in Cannon Beach fluctuates significantly due to the high number of tourists that visit year-round. As with many coastal communities, the distribution of permanent and temporary residents (aka visitors or tourists) is quite different both in terms of numbers and locations. **Table 4-1** presents the permanent, temporary, and total population inside the tsunami zone for Cannon Beach. Our results indicate ~1,200 residents and as many as 7,400 overnight visitors. To account for variability and uncertainties in our population estimates, particularly amongst temporary residents, this report will round results (i.e. number of survivors for a given scenario) to the nearest hundred.

Table 4-1. Permanent, temporary, and total resident population inside the XXL tsunami zone in Cannon Beach.

Region	Permanent Population	Temporary Population*	Total Population**
North Cannon Beach	900	4,600	5,500
South Cannon Beach	300	2,900	3,200
Total	1,200	7,500	8,700

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

Day visitors can increase the population of Cannon Beach on a given day by as much as 6,000 people (personal communication with Cannon Beach Emergency Manager, 2024). Unfortunately, we were unable to account for this group in the analysis, because we could not constrain their locations. It remains imperative that day visitors be factored into any future discussions related to mitigation options, especially the capacity of VES.

Figure 4-3, **Figure 4-4**, and **Figure 4-5** present the permanent, temporary, and total population distributions for Cannon Beach, respectively.

Figure 4-3. (left) Permanent and (right) temporary population distributions inside the tsunami zone in north Cannon Beach. Temporary population does not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

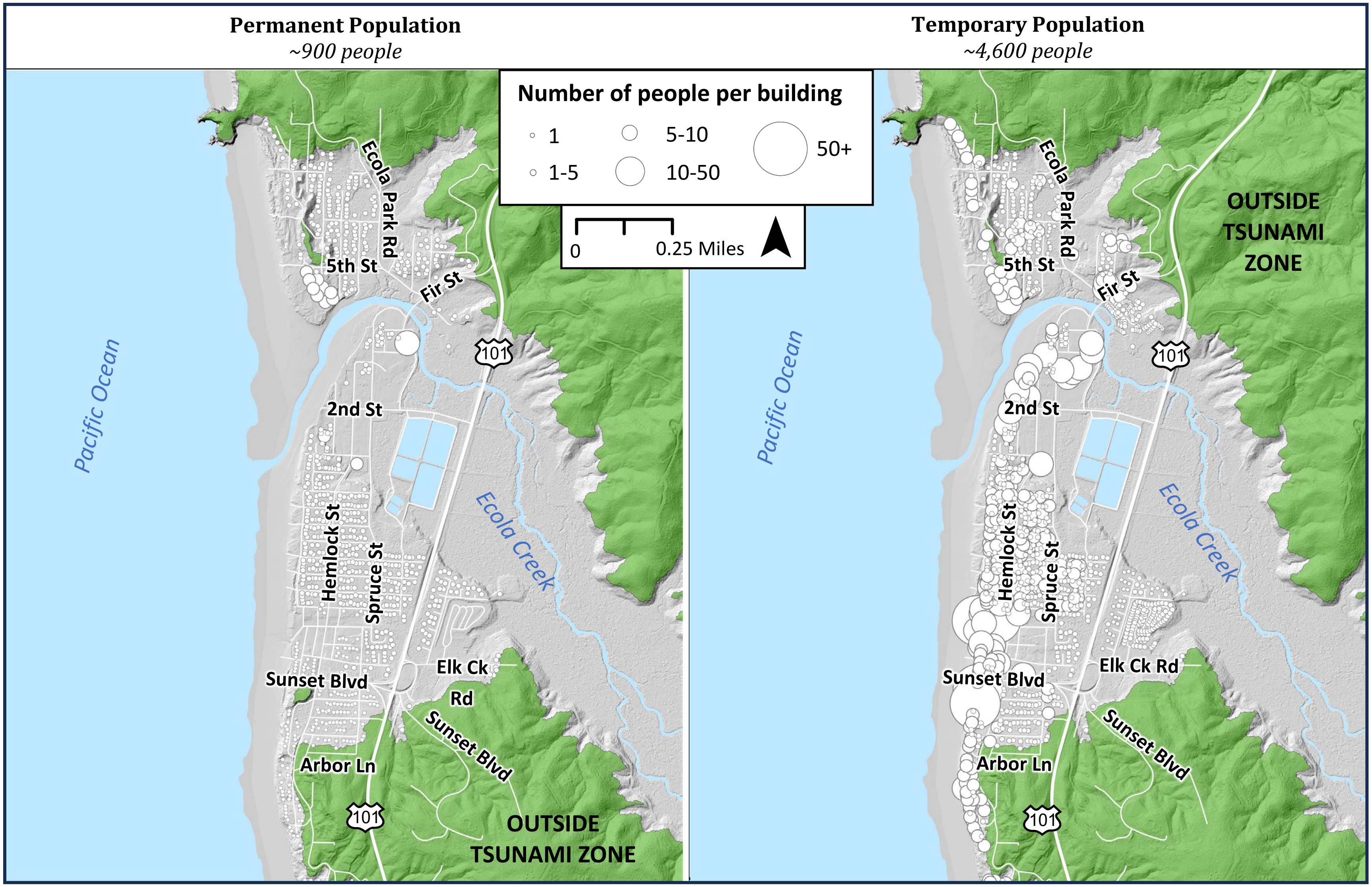


Figure 4-4. (left) Permanent and (right) temporary population distributions inside the tsunami zone in south Cannon Beach. Temporary population does not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

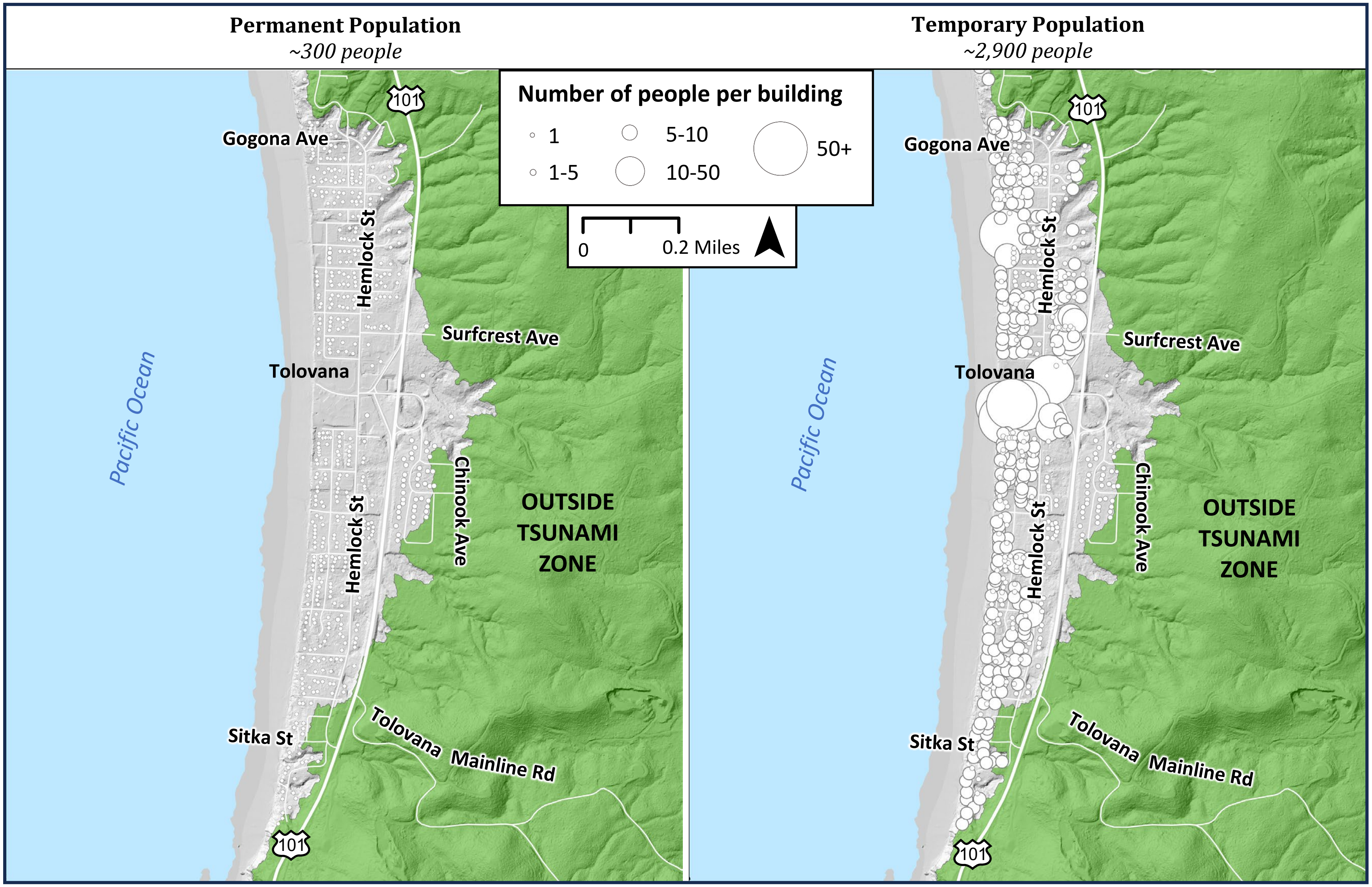
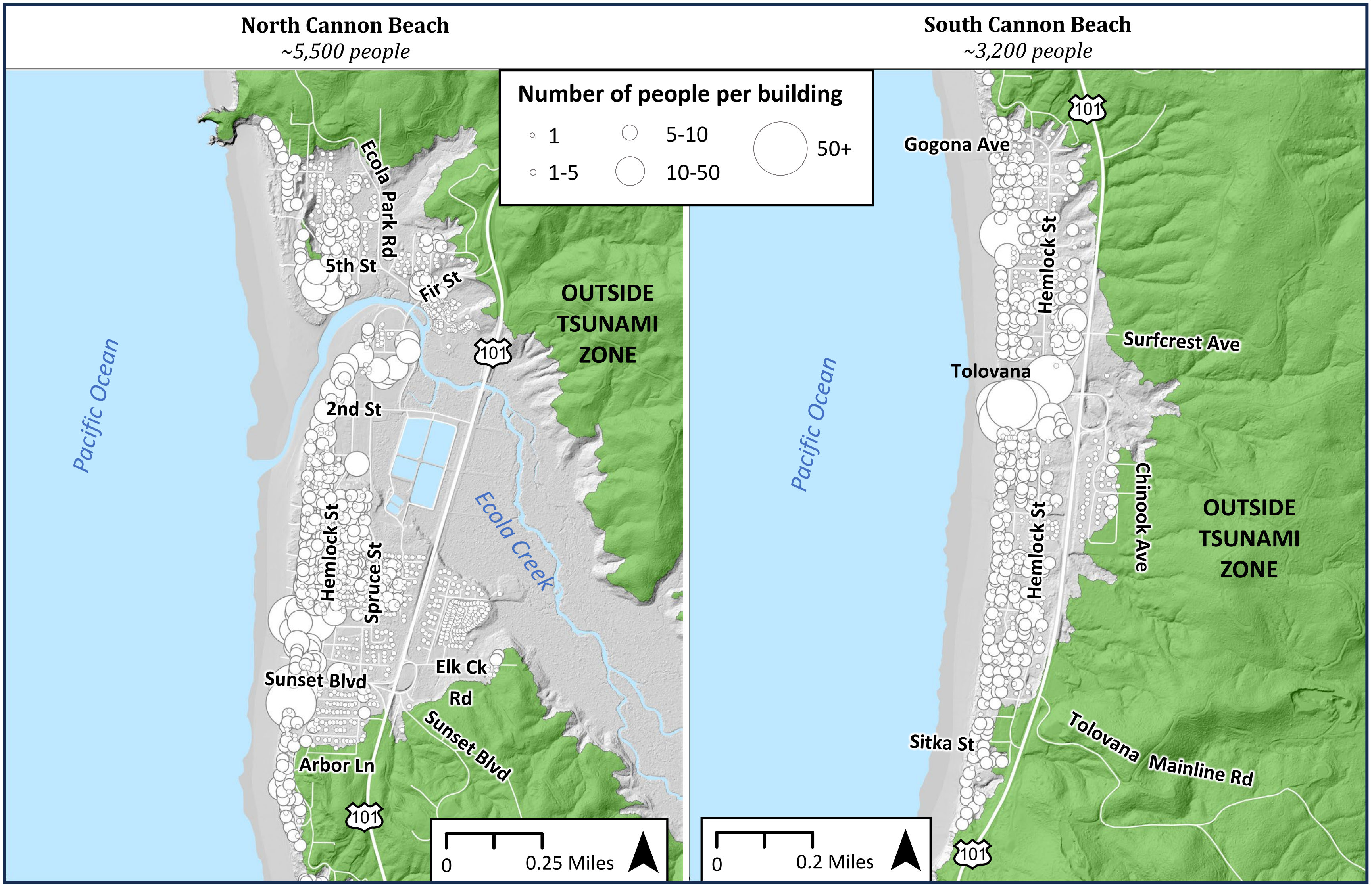


Figure 4-5. Total population distribution (permanent plus temporary residents) inside the tsunami zone in north and south Cannon Beach. Temporary population does not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.



4.2 Current Conditions Scenario

Evacuation modeling results with a focus on which parts of the city are survivable at 4 fps or slower are presented in **Figure 4-6** and **Table 4-2**. We estimate that ~85% of north Cannon Beach and 100% of south Cannon Beach can escape the tsunami at 4 fps or slower (4,636 and 3,169 people, respectively). Of the estimated ~7,800 survivors, 14% are permanent residents (1,067 people) and 86% (6,738 people) are temporary residents. In total, ~830 permanent and temporary residents are not expected to survive in this scenario, most of whom are visitors in downtown Cannon Beach. Therefore, mitigation scenario results will be tabulated exclusively for this neighborhood in addition to North Cannon Beach in its entirety. There will be no further discussion about South Cannon Beach due to the fact that 100% of the permanent and temporary residents survive for the current conditions scenario.

The primary challenge to life safety in downtown Cannon Beach is the lengthy distances people must travel to reach high ground, with evacuation routes as long as 1 mi. This is further compounded by the early tsunami wave arrival to Ecola Creek. Evacuees need to reach the marine terrace as quickly as possible while also advancing south toward high ground by the S Curves neighborhood.

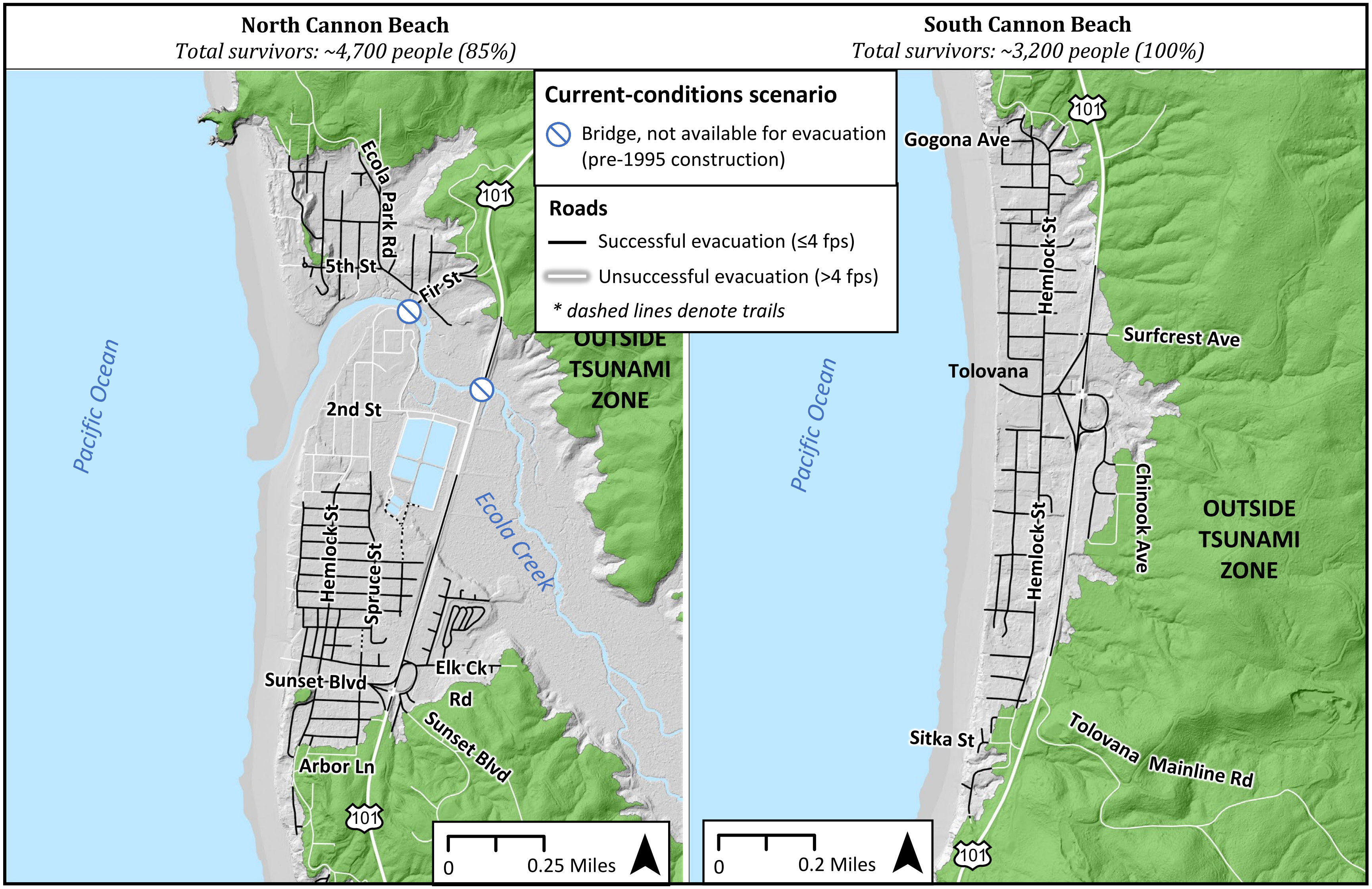
Table 4-2. Number of survivors for the XXL Current conditions scenario in north and south Cannon Beach.

Region	Survivors			Non-Survivors		
	Permanent residents	Temporary residents*	Total population **	Permanent residents	Temporary residents*	Total population **
North Cannon Beach	800	3,900	4,700	100	700	800
South Cannon Beach	300	2,900	3,200	0	0	0
Total	1,100	6,800	7,900	100	700	800

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

Figure 4-6. Evacuation modeling in north and south Cannon Beach for the XXL Current conditions scenario depicting the existing road network and assuming the Fir Street Bridge is unavailable for evacuation. Road color reflects likelihood of survival based on travel speed that must be maintained along the route. Survivors are reported as a percentage of the total population (permanent + temporary residents) inside the tsunami zone.



4.3 Bridges-In Scenario

Our initial mitigation scenario was to seismically retrofit the Fir Street Bridge, since this would significantly shorten downtown evacuation routes to the north. **Figure 4-7** presents evacuation modeling results for this scenario in north Cannon Beach along with a side-by-side map of the Current conditions scenario. Seismically retrofitting the Fir Street Bridge yields a ~11% improvement in the number of lives saved (~610 additional people) for all of north Cannon Beach, with ~96% of the total population now estimated to survive (**Table 4-3** and **Figure 4-8**). The map provides visible evidence that nearly all of downtown Cannon Beach could easily reach high ground at 4 fps or slower in this scenario.

Figure 4-7. Evacuation modeling in north Cannon Beach for the bridges-in scenario, which assumes the Fir Street Bridge is available for evacuation. The current conditions scenario is presented on the left for comparison.

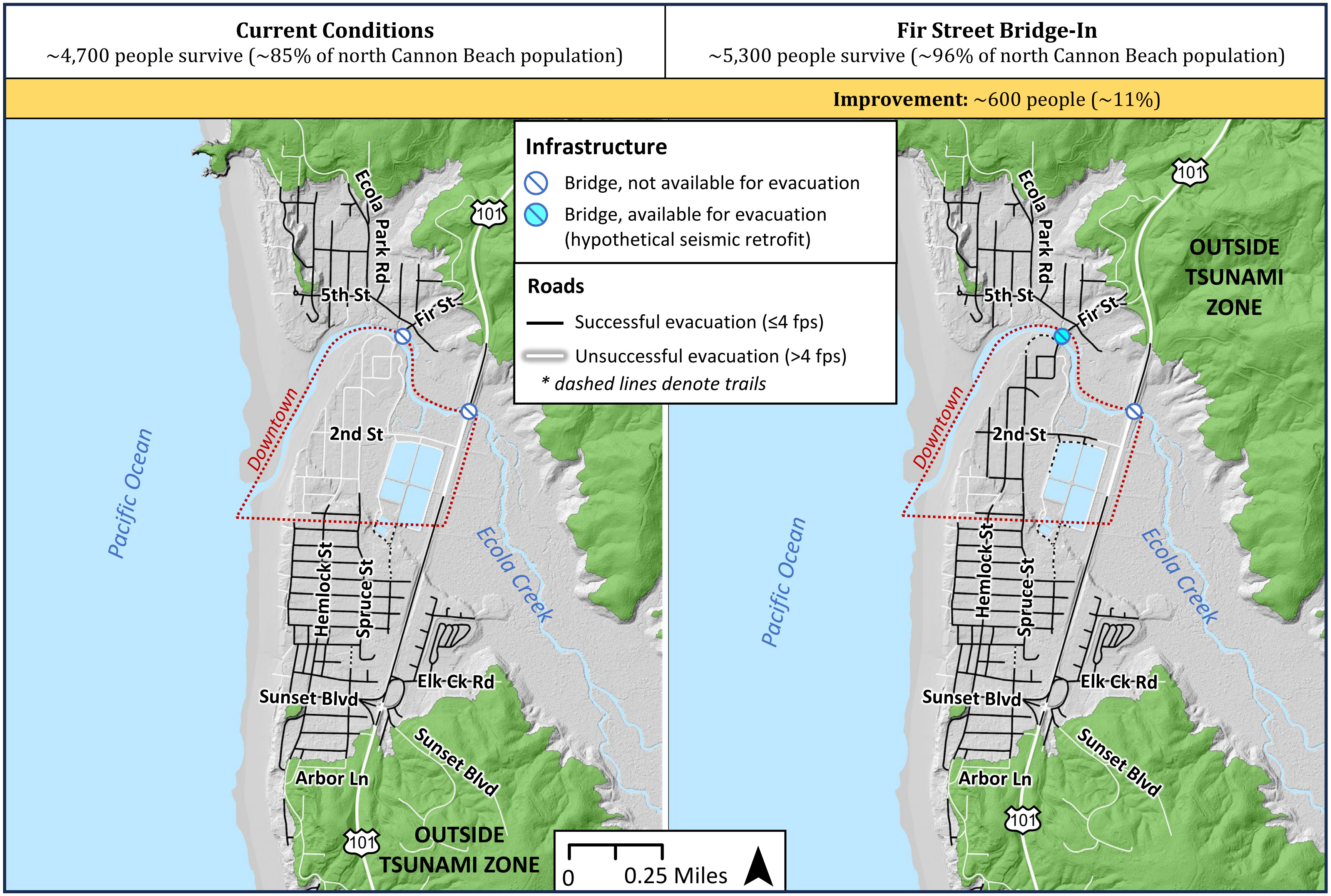


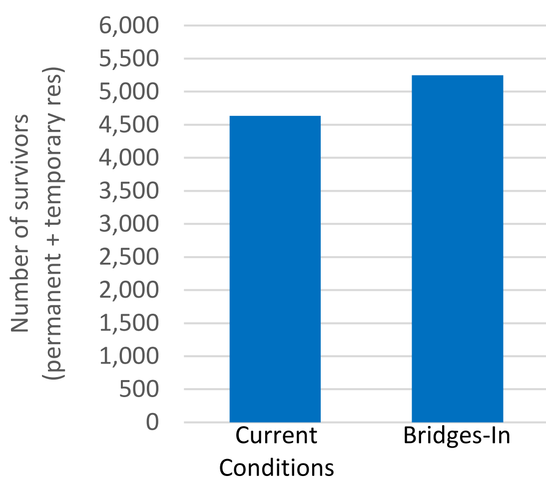
Table 4-3. Number of survivors in north Cannon Beach for the Bridges-in scenario with Current conditions scenario for comparison.

	Survivors				Non-Survivors
Scenario	**Permanent residents**	**Temporary residents***	**Total population**	**Improvement from Current-conditions (Total pop)**	**Total population**
Current-conditions	800	3,900	4,700	-	800
Fir St Bridge in	900	4,400	5,300	600	200

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

Figure 4-8. Comparison of survivors for Current conditions and Bridges-in scenarios in north Cannon Beach using the total population (permanent plus temporary residents).



4.4 VES Scenarios

While the Bridges-in scenario results provide convincing evidence that retrofitting the Fir Street Bridge is a worthwhile effort, we recognize the value in considering multiple mitigation efforts and therefore present results for four VES sites in the following section. The Fir Street Bridge is not available for evacuation in these scenarios. VES locations were selected in consultation with Cannon Beach officials. Criteria included city-owned property, proximity to high-density clusters of people, distribution across the city, and dual uses (i.e., wildlife viewing platform) (see **Figure 4-1** for all VES locations and **Figure 4-9** for a closer view of the three downtown locations):

A) 2nd Street and Spruce Street
B) Larch Street and 1st Street
C) Adams Street and Spruce Street
D) City Hall

Figure 4-9. Aerial image of downtown Cannon Beach showing 3 hypothetical VES locations.

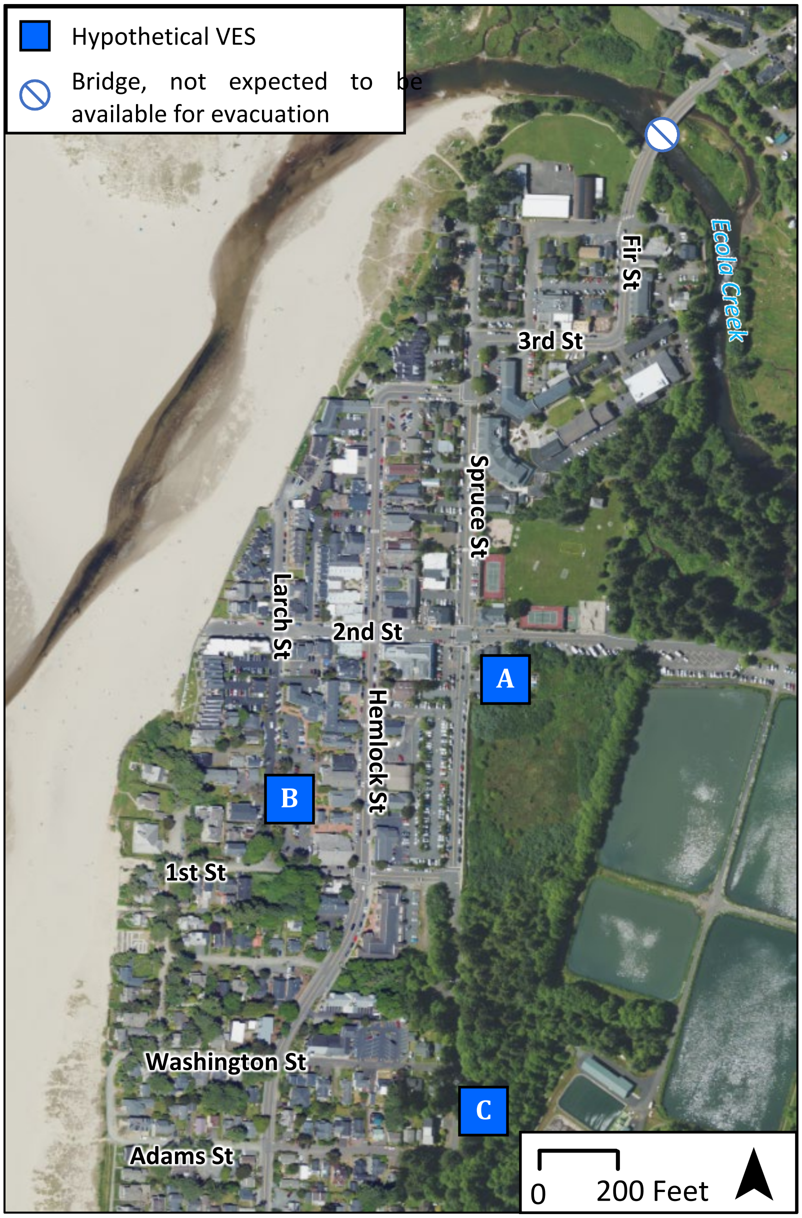


Figure 4-10 presents results for a VES at 2nd Street along with a side-by-side comparison with the current conditions scenario. We estimate that a structure in this location could save ~99% of the population in north Cannon Beach. The number of people who would seek refuge in this location is approximately 900 (**Table 4-5**), which matches the capacity of several existing VES constructed on the Washington and Oregon coast. However, a single structure is unlikely to meet all needs, since our population modeling excludes estimates of day visitors. As noted previously, Cannon Beach officials estimate that an additional 6,000 day visitors may recreate in downtown Cannon Beach or out on the beach and hence would potentially seek refuge at a VES. Accordingly, further efforts are needed to resolve the size and number of structures to meet the needs of downtown Cannon Beach.

Results for two additional VES sites are provided in **Figure 4-11**. Survival estimates for VES at Larch or Adams are similar to those for a VES at 2nd Street (~97% and 100% survival rate, respectively). We do not present a map of results for a VES at City Hall because it provides no improvement over the current conditions. This is because City Hall is too far south to help downtown and because of a slightly earlier wave arrival in the area. Survivor estimates for all four VES scenarios along with current conditions, for comparison, are presented in **Table 4-4** and **Figure 4-12**.

Because retrofitting the Fir Street Bridge or placing a VES in the downtown vicinity each bring survivability above ~96%, we do not present results for any VES-plus-bridge combinations. Nonetheless, each mitigation effort brings its own set of benefits that should be considered when prioritizing future projects. VES allow more access to high ground for those with limited mobility, even if natural high ground is reasonably close. And, if the bridge is reconstructed such that it will also survive the tsunami, it will greatly contribute to the city's post-event recovery.

Figure 4-10 Evacuation modeling in north Cannon Beach for the VES at 2nd Street and Spruce Street scenario. The current conditions scenario is presented on the left for comparison. Road color reflects likelihood of survival based on travel speed that must be maintained along the route.

Current conditions ~4,700 people survive (~85% of north Cannon Beach population)	**VES at 2nd St & Spruce St** ~5,500 people survive (~100% of north Cannon Beach population)
	Improvement: ~800 people (~15%)

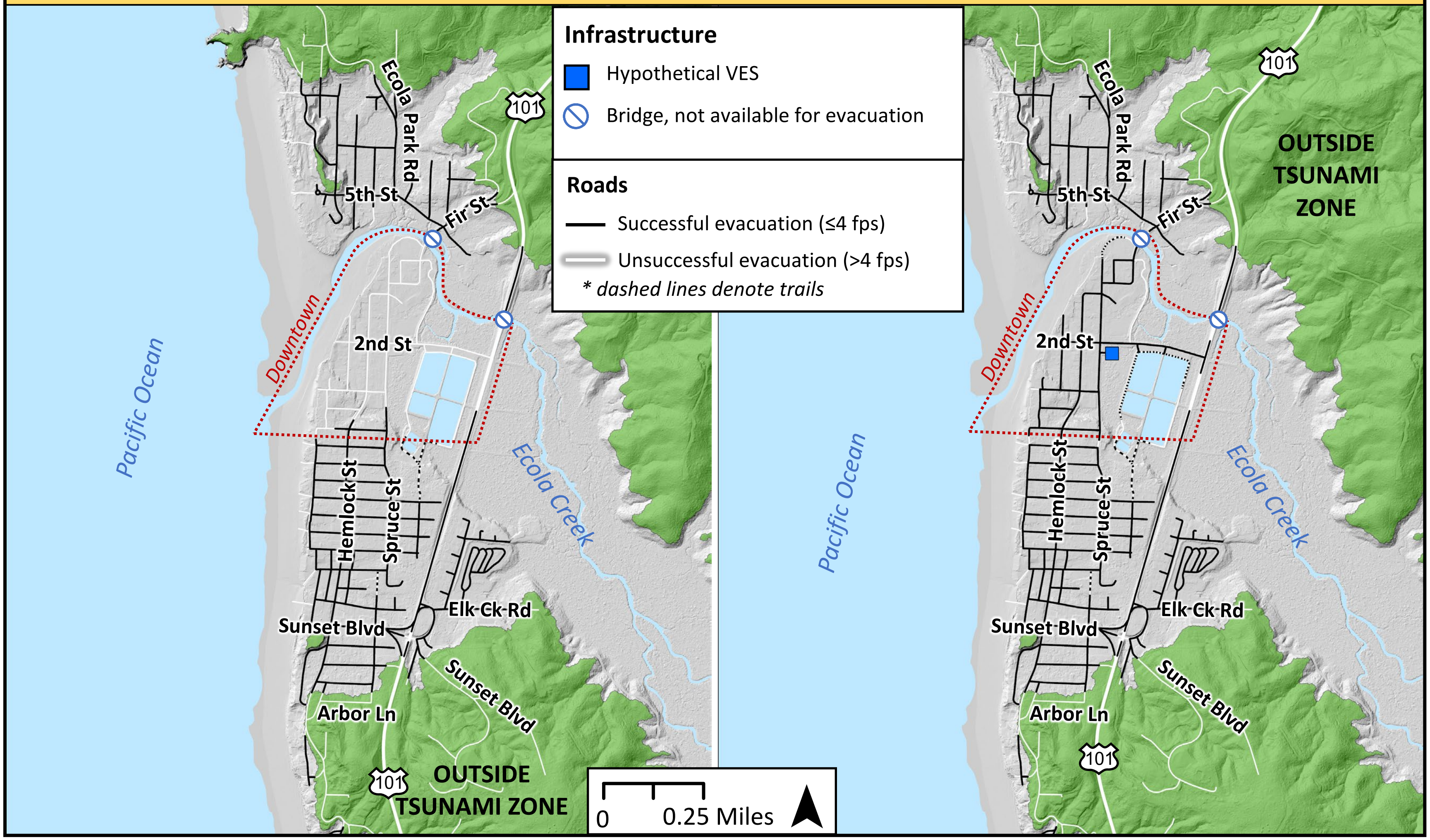


Figure 4-11. Evacuation modeling in north Cannon Beach for two VES scenarios: (left) VES at Larch Street & 1st Street and (right) VES at Adams Street & Spruce Street. Road color reflects likelihood of survival based on travel speed that must be maintained along the route.

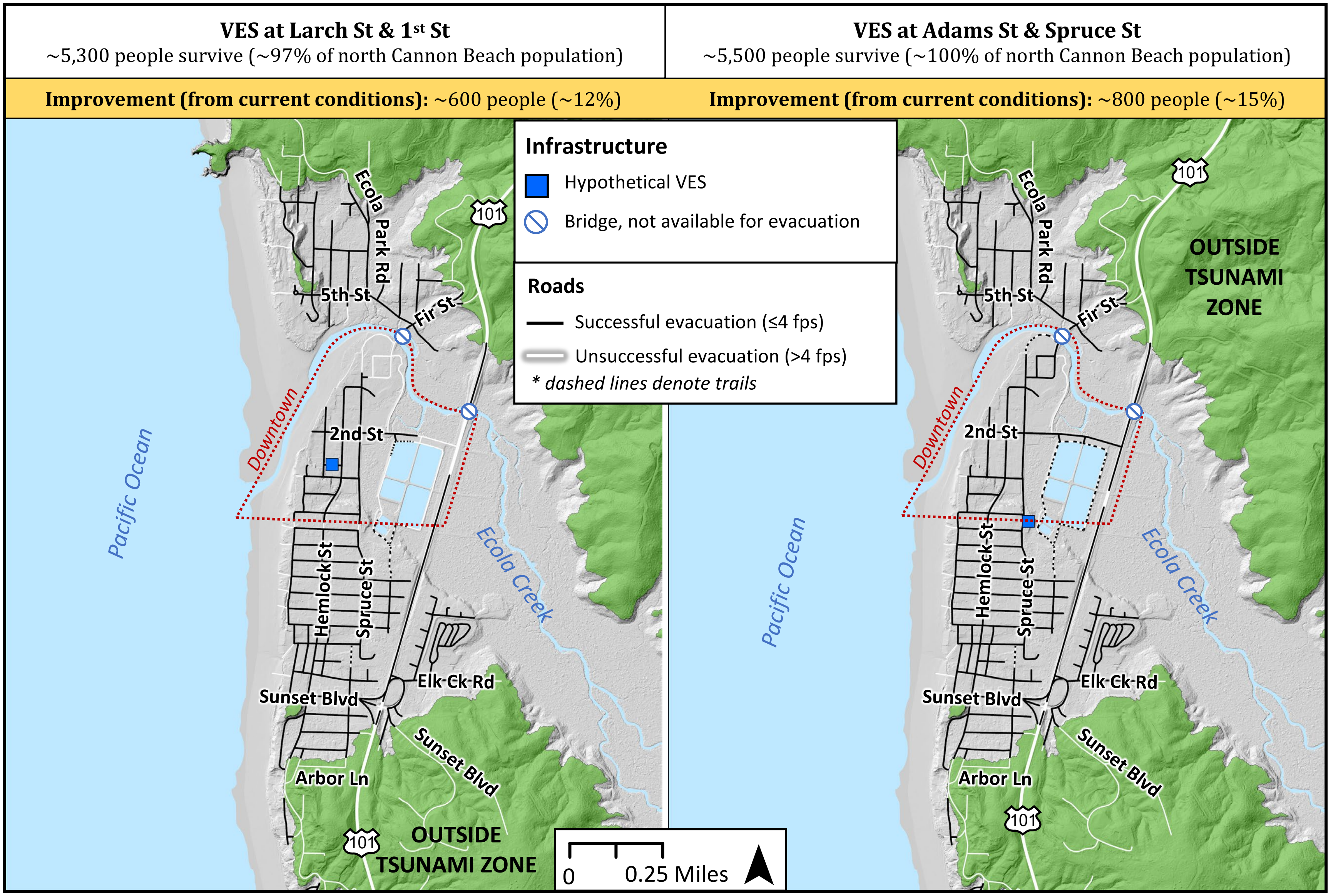


Table 4-4. Number of survivors in north Cannon Beach for all VES scenarios with Current conditions scenario for comparison.

	Survivors				Non-Survivors
Scenario	Permanent residents	Temporary residents*	Total population	Improvement from Current-conditions (Total pop)	Total population
Current-conditions	800	3,900	4,700		800
VES: 2nd & Spruce	900	4,600	5,500	800	0
VES: Larch & 1st	900	4,400	5,300	600	200
VES: Adams & Spruce	900	4,600	5,500	800	0
VES: City Hall	800	3,900	4,700	0	800

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.
** Total population = permanent residents + temporary residents

Figure 4-12. Comparison of survivors for Current conditions and VES scenarios in north Cannon Beach using the total population (permanent plus temporary residents).

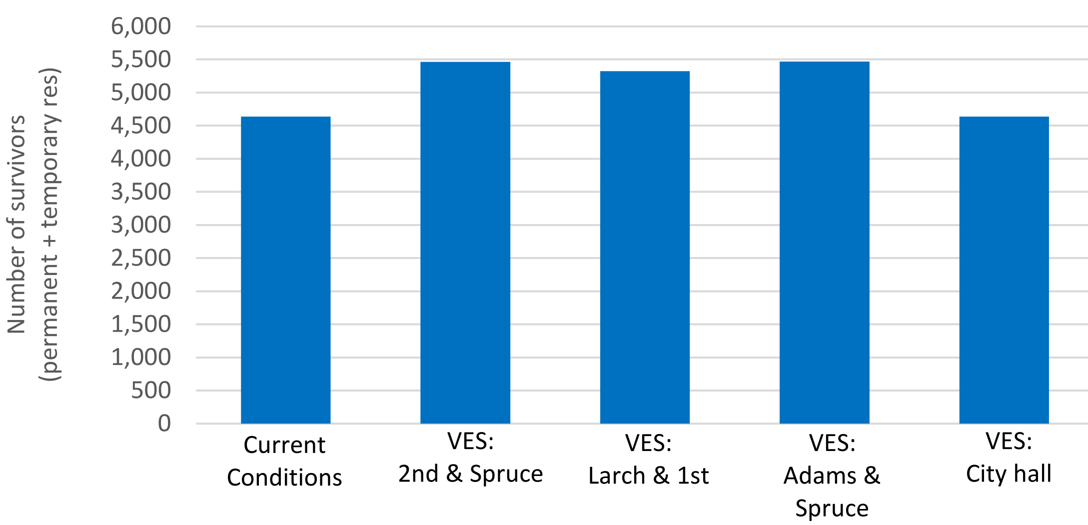


Table 4-5 reports the total number of people that will seek shelter at each hypothetical VES site along with maximum flow depths for three of DOGAMI's deterministic tsunami inundation scenarios (XXL, Extra-Large and Large), which can begin to inform decisionmakers about potential design heights of VES structures at each location. **Table 4-5** includes modeled flow depths for the Extra-Large tsunami inundation scenario because these depths are closest to what would be required under Oregon building codes (OBC). For engineering purposes, VES design must utilize tsunami modeling results and design standards produced by the American Society of Civil Engineers (ASCE, 2017). These design standards account for earthquake shaking, coseismic responses, and hydrodynamic forces of the tsunami on the structure including foundation scour effects, blowout walls and impact forces. For comparison, ASCE 7-16 is more conservative than DOGAMI's Extra-Large tsunami scenario, though the results vary along the coast (Priest and Allan, 2019).

Of the four VES locations, 2nd & Spruce and Larch & 1st are expected to experience the highest maximum flow depths due to being within the Ecola Creek floodplain. The Adams & Spruce VES site is expected to experience the lowest flow depths due to being out of the flood plain, on top of the marine terrace (~42 feet above sea level). This location is also further east, away from the ocean, than the other two downtown locations. City Hall is also on the marine terrace, however it sits about ~10 feet lower due to a localized low spot and has correspondingly larger flow depths.

Table 4-5. Number of survivors that will seek shelter at each hypothetical VES location in Cannon Beach as well as maximum tsunami flow depths (XXL, X-Large, and Large tsunami scenarios).

	Required capacity for residents			Maximum tsunami flow depth (ft)		
VES site	Permanent residents	Temporary residents*	Total population **	XXL tsunami scenario	X-Large tsunami scenario	Large tsunami scenario
2nd & Spruce	100	800	900	52	49	25
Larch & 1st	100	700	800	50	47	22
Adams & Spruce	400	2,100	2,500	23	19	3
City Hall	300	1,700	2,000	32	30	17

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

4.5 Comparison of Mitigation Scenarios

Current conditions results demonstrate that downtown Cannon Beach is the single part of town in which people are unlikely to reach safety in time. Therefore, our comparative analysis will focus on the downtown mitigation options. The number of permanent and temporary residents within downtown Cannon Beach are presented in **Table 4-6**.

Table 4-6. Permanent and temporary resident population in downtown Cannon Beach (a subset of the north Cannon Beach study area).

Permanent Population	Temporary Population*	Total Population**
100	700	800

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

The number of total survivors in downtown Cannon Beach have been tallied for each scenario and presented numerically in **Table 4-7** and graphically in **Figure 4-13**. Gray bars extend to the total population within the tsunami zone and allow the number of survivors for each scenario to be viewed as a proportion of the total population in addition to absolute numbers.

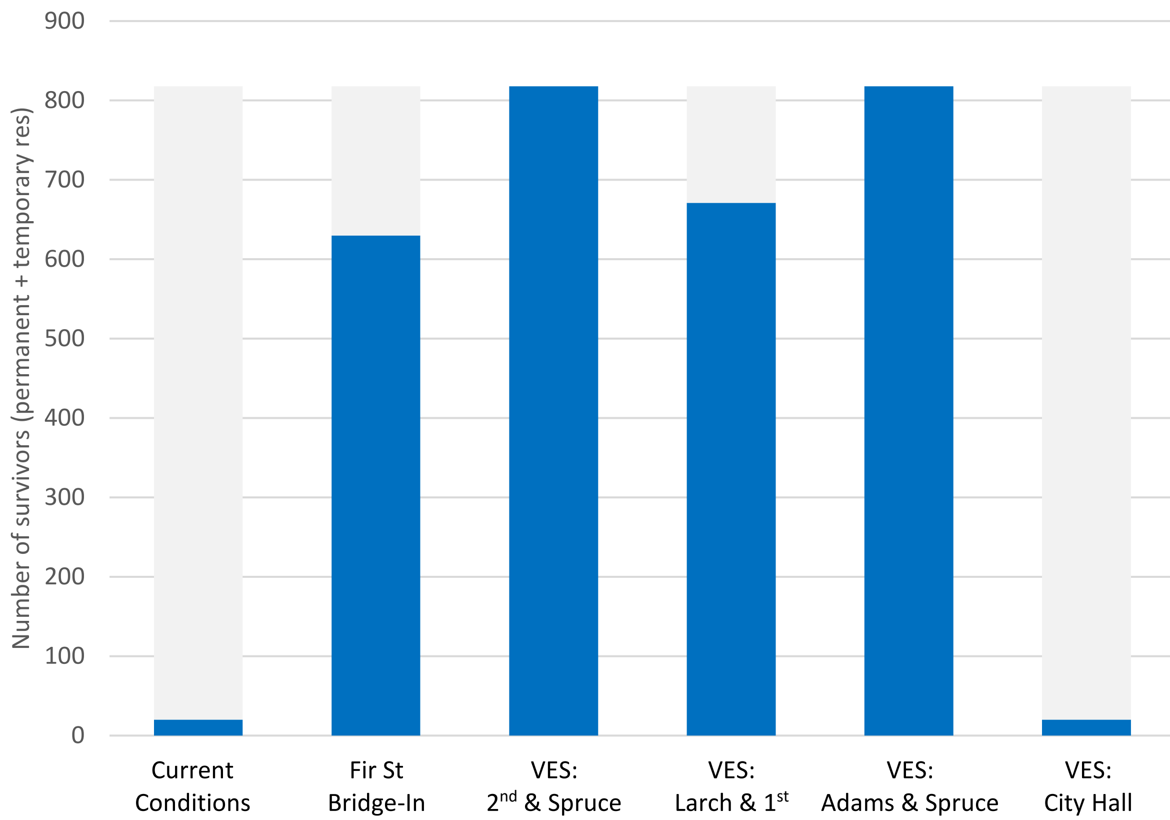
Table 4-7. Number of survivors for all scenarios in downtown Cannon Beach.

	Survivors				Non-Survivors
Scenario	Permanent residents	Temporary residents*	Total population	Improvement from Current-conditions (Total pop)	Total population
Current-conditions	0	0	0		800
Fir St Bridge in	100	500	600	600	200
VES: 2nd & Spruce	100	700	800	800	0
VES: Larch & 1st	100	600	700	700	100
VES: Adams & Spruce	100	700	800	800	0
VES: City Hall	0	0	0	0	800

* Results do not account for day visitors, which can increase the number of visitors in Cannon Beach by ~6,000 people.

** Total population = permanent residents + temporary residents

Figure 4-13. Comparison of survivors for all scenarios in downtown Cannon Beach using the total population (permanent plus temporary residents). Top of gray bar indicates total population inside the tsunami zone for downtown Cannon Beach.



5.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study is to provide an assessment of tsunami evacuation mitigation options in Seaside and Cannon Beach, Clatsop County. We accomplish this by implementing the *Beat the Wave* approach to evacuation analysis developed by Priest and others (2015, 2016), combined with a spatially explicit population model delineating where people are within the tsunami zone. This quantitative approach to community-wide evacuation analyses provides new insight for the area's risk reduction efforts. We note several important findings based on the results of this study:

<u>Seaside</u>

- **Evacuation of much of Seaside in response to a Cascadia Subduction Zone tsunami will be challenging.** Significant portions of the city cannot reach natural high ground before the tsunami arrives due to the long distances that must be traveled. Evacuation routes are as long as ~1.5 mi and require travel speeds of up to 10 fps (6.8 mph or 8.8 minutes/mile), which equates to a run. Further compounding this challenge is the fact that many people will need to cross the Necanicum River and Neawanna Creek, requiring travelling over several bridges. Of the 10 bridges in Seaside, only four were built after 1995 and can be reasonably expected to withstand earthquake shaking (two over the Necanicum River and two over Neawanna Creek); the remaining 6 bridges are expected to fail. We estimate 25% of the total combined population (residents and visitors) inside the tsunami zone are likely to survive given present-day evacuation routes; this equates to ~4,200 people. A scenario in which every Seaside bridge is seismically retrofitted yields a 1% increase in survival (~4,500 survivors). Alternatively, a single VES placed at the downtown parking lot adjacent to the Convention Center results in a 25% increase (~8,500 total survivors). Scenarios incorporating a second, third, and fourth VES further increase life safety to 66%, 74%, and 85% of the total population, respectively. This report presents a stark demonstration of the relative ineffectiveness of seismic bridge retrofits over VES in Seaside, and as a result, the city is reevaluating and adjusting their public safety prioritizations and investments. VES capacity will be a significant challenge due to the large numbers of people that may be in the area at the time of the disaster. We estimate as many as 4,000 people could potentially seek refuge in a VES at the Convention Center location. These numbers exclude the added potential of ~9,000 to 16,000 day visitors that may also be in the area. Additional efforts are needed to resolve the size and number of structures required to meet the needs of downtown Seaside.
- **Bridges remain an important component of resilience in Seaside.** The Venice Park neighborhood (24th Street) has no other choice than to cross Neawanna Creek on the Highway 101 bridge if they hope to reach high ground on Lewis and Clark Road. Our Current conditions scenario presently redirects this neighborhood south to the Broadway Street bridge over Neawanna Creek, resulting in evacuation routes that are considerably longer and require fast evacuation travel speeds in order to survive. A similar situation involves the Avenue S bridge on the south end of Seaside. Ensuring these bridges remain passable will not save every person in Seaside, but it will make a difference.

Cannon Beach

- **Evacuation of downtown Cannon Beach in response to a Cascadia Subduction Zone tsunami will be challenging.** This is primarily due to the expectation that the Fir Street Bridge over Ecola Creek will collapse during the earthquake shaking and hence would be unavailable for evacuation, eliminating access to nearby high ground. Instead, residents and visitors need to evacuate southward, traveling twice as far. Our population model estimates ~800 locals and overnight visitors can be in the downtown district at any given time. We estimate 2% of the downtown population is likely to survive given present-day evacuation routes; this equates to ~20 people. A scenario in which the Fir Street Bridge is seismically retrofitted yields a 75% increase in survival (~610 survivors). We also find that a single VES in downtown Cannon Beach can save 82% to 100% of the downtown population, depending on its location. This report presents a stark demonstration of the effectiveness of a seismic retrofit of the Fir Street Bridge in Cannon Beach and reinforces the city's current efforts in pursuit of this mitigation strategy.
- **Evacuation for the remainder of Cannon Beach should be achievable for much of the population.** This is due to relatively short distances to high ground in south Cannon Beach (Tolovana), the Presidential Streets neighborhood, and Chapman Point (north of Ecola Creek).

Reducing risk

- **Mitigation efforts will reduce loss of life from the tsunami.** Results in Seaside and Cannon Beach demonstrate the value of large-scale mitigation efforts (either VES or bridge retrofits) in potentially saving many thousands of lives. The 'benefits' of each VES scenario may be used to identify and prioritize which projects to pursue. The *value of statistical life*, an economic tool used to assess the value of lives saved resulting from mitigation measures, can be used for further justification. FEMA currently estimates the value of a life at $12.5 million (FEMA, 2023). A mitigation project's cost-benefit analysis can be used to articulate the benefit of a single (or multiple) structure by way of lives saved. For example, a VES at the Convention Center saves an additional ~4,000 people. Therefore, the financial benefit to constructing a structure at this location is:

  4,000 people x $12.5m/person = $50 billion

- **Education and outreach, wayfinding signage, and evacuation drills can still reduce loss of life from the tsunami.** Although evacuation modeling results indicate that many people in Seaside and Cannon Beach are likely to struggle to beat the wave to high ground, many hundreds to thousands of people should be able to successfully evacuate. However, to ensure successful evacuation, communities still need to ensure there are appropriate wayfinding signage along core routes and periodically perform evacuation drills. Educating and preparing at-risk individuals in hazard zones is crucial to lowering loss of life from the tsunami by ensuring that residents and visitors alike know they must evacuate immediately after the earthquake ends. While we recognize there may be unavoidable reasons to delay evacuation following the earthquake, the reality that there is very little time to reach safety cannot be ignored and leaving as soon as possible is key to survival. Evacuation drills provide an opportunity to raise awareness as well as imprint details of key routes into people's minds. Wayfinding signage ensures that everyone, whether they know their route or not, has help getting to high ground as quickly as possible in the heat of the moment.

- **Evacuation challenges not addressed in this study.** Landslides, lateral spreading, and liquefaction are site-specific hazards associated with earthquake shaking that are likely to further impede successful evacuation. Downed power lines and trees may also impede swift travel toward safety. VES can lessen these challenges by reducing how far people must travel to reach safety. We recommend site-specific evaluations along all key evacuation routes to ensure they remain accessible after the earthquake.

There are three broad assumptions to keep in mind when interpreting the results of this tsunami evacuation assessment:

- We measure community-wide survivability using a maximum evacuation speed of 4 fps. In reality, people will be traveling at a wide range of speeds and thus these results are probably conservative.
- Evacuation is restricted to roads and trails rather than permitting travel elsewhere (e.g., across parking lots, backyards, parks, or golf courses). During an actual tsunami evacuation, people should take the fastest and safest route available to them.
- A 10-minute delay between the start of earthquake shaking and evacuation is incorporated into the model to account for the following actions:
    - The time in which earthquake shaking takes place (drop, cover, and hold for 3 minutes–5 minutes)
    - Disorientation, shock, and collecting family members, go bags, etc.
    - The time required to evacuate the building and reach the nearest road (navigating fallen debris inside building, exiting building, crossing fenced yard, etc.)

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

We recommend using these results in conjunction with Allan and others (2020), which evaluates the potential effect of a CSZ earthquake and accompanying tsunami on coastal Clatsop County by providing estimates of potential building losses, generated debris, fatalities, and injuries, as well as numbers of displaced people. The study also provides an assessment of vulnerable population groups, essential facilities, and critical infrastructure that are integral to response and recovery.

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