PEDESTRIAN TRAVEL-TIME MAPS FOR KODIAK, ALASKA: An anisotropic model to support tsunami evacuation planning

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by

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ABSTRACT

Tsunami-induced pedestrian evacuation for the City of Kodiak, U.S. Coast Guard Base and the community of Womens Bay is evaluated using an anisotropic modeling approach developed by the U.S. Geological Survey. The method is based on path-distance algorithms and accounts for variations in land cover and directionality in the slope of terrain. We model evacuation of pedestrians to exit points from the tsunami hazard zone. The pedestrian travel is restricted to the roads only. Results presented here are intended to provide guidance to local emergency management agencies for tsunami inundation assessment, evacuation planning, and public education to mitigate future tsunami hazards.

Photo from Alutiiq Museum and Archaeological Repository

INTRODUCTION

Subduction of the Pacific plate under the North American plate has resulted in numerous great earthquakes and has the highest potential to generate tsunamis in Alaska (Dunbar and Weaver, 2015). The Alaska–Aleutian subduction zone (figure 1), the fault formed by the Pacific–North American plate interface, is the most seismically active tsunamigenic fault zone in the U.S. Refer to Suleimani and others (2017) for an overview of the tsunami hazard in the Kodiak area.

The most recent earthquake that triggered a significant tsunami in Kodiak occurred on March 27, 1964; for this event, tsunami waves were as high as 7.6 m (25 ft) (Lander, 1996). The tsunami caused significant economic damage to the community, including total destruction of cargo dock and heavy damage to roads and bridges. An in-depth analysis of the tsunami hazard in Kodiak and estimation of the tsunami hazard zone in the community is provided by Suleimani and others (2017). According to the tsunami modeling results, individuals and businesses in the low-lying areas along West Rezanof Dr., Shelikof St., Spruce Cape Rd., and at the Kodiak Airport may face challenges to evacuate due to long distances to the assembly areas.

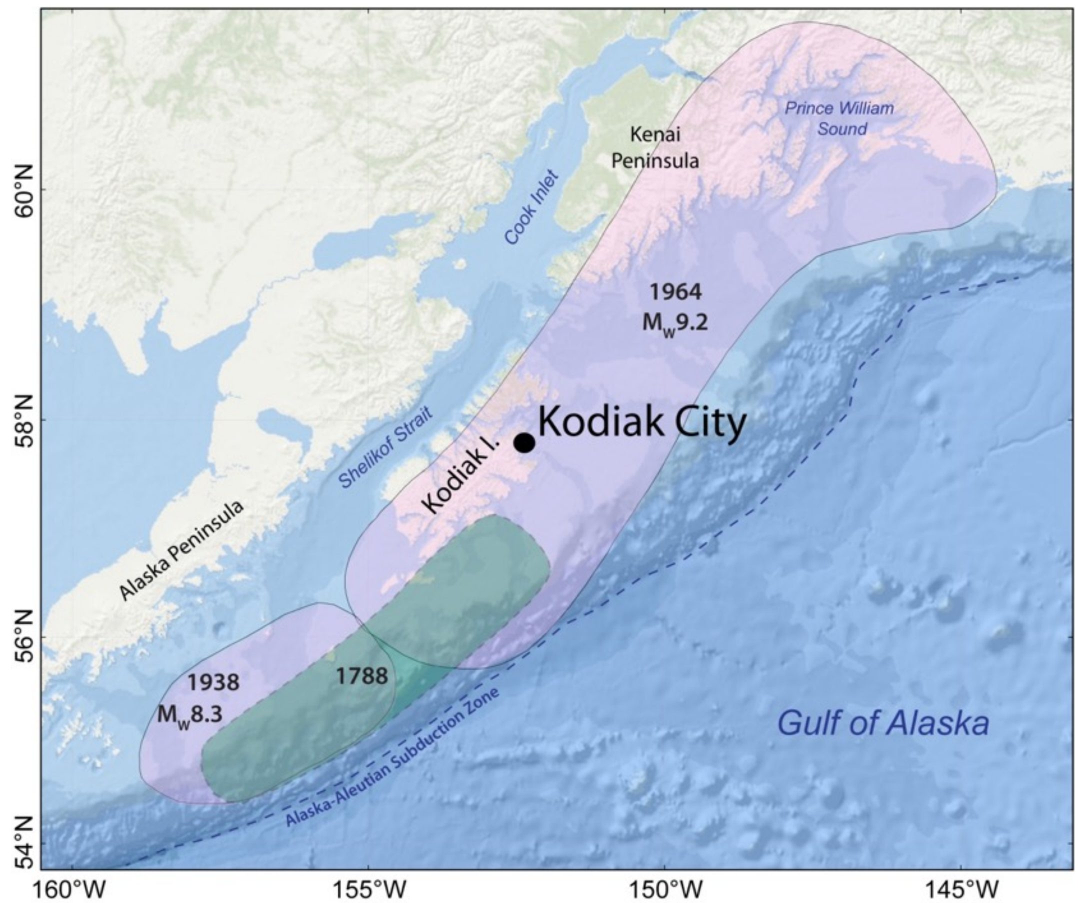

Figure 1: Map of south-central Alaska, showing the location of Kodiak Island and the rupture zones of the 1788, 1938, and 1964 Aleutian subduction zone earthquakes (shaded areas).

In this report, we employ the pedestrian evacuation modeling tools developed by the U.S. Geological Survey (USGS) (Wood and Schmidtlein, 2012, 2013; Jones and others, 2014) to provide guidance to emergency managers and community planners in assessing the amount of time required for people to evacuate out of the tsunami-hazard zone. An overview of the pedestrian evacuation modeling tools, required datasets, and the step-by-step procedure used is provided in Macpherson and others (2017, this series). The maps of pedestrian travel time can help identify areas in Kodiak on which to focus evacuation training and tsunami education.

COMMUNITY PROFILE

The City of Kodiak is near the northwestern tip of Kodiak Island in the Gulf of Alaska at about 57°47'35'' N, 152°23'39'' W, approximately 400 km (250 mi) south of Anchorage and 2,300 km (1,430 mi) northwest of Seattle (figure 1). Kodiak Island is the largest island in Alaska and is the second largest island in the United States. During the Aleutian campaign of World War II, the U.S. Navy and the Army built bases on the island. The U.S. Coast Guard comprises a significant portion of the community, and there is a large seasonal population. Kodiak Station is a U.S. Coast Guard Base, and is south of and adjacent to the city of Kodiak. The community of Womens Bay is 13 km (8 mi) south of Kodiak, at the foot of Old Womens Mountain, along a bay of the same name. Because of Womens Bay's close proximity to Kodiak Station, many of its residents are Coast Guard families.

The 1964 earthquake and subsequent tsunami waves virtually leveled downtown Kodiak. The fishing fleet, processing plant, canneries, and 158 homes were destroyed, resulting in $30 million in damage. The infrastructure was rebuilt and, by 1968, Kodiak had become the largest fishing port in the U.S., in terms of dollar value. The local culture surrounds commercial and subsistence fishing activities. Further information could be obtained from the Alaska Community Database maintained by the State of Alaska Division of Community and Regional Affairs of the Department of Commerce, Community, and Economic Development (DCCED/DCRA, 2015).

TSUNAMI HAZARD

Tsunami hazard assessment for Kodiak was performed by numerically modeling several hypothetical scenarios (Suleimani and others, 2017). The worst-case scenarios for the Kodiak area are thought to be thrust earthquakes in the Gulf of Alaska south of the Kodiak Island with magnitudes from M_w 9.0 to M_w 9.3. The tsunami wave could be 16-18 m (53-60 ft) high and could cause widespread damage and flooding. The numerical simulations estimate that the first wave (tectonic tsunami) may arrive to the community in 20-30 minutes after the earthquake, and that the wave activity could continue for at least 12 hours after the earthquake. Duration of the damaging tsunami currents in the area is estimated in the maritime guidance (AEC, 2016).

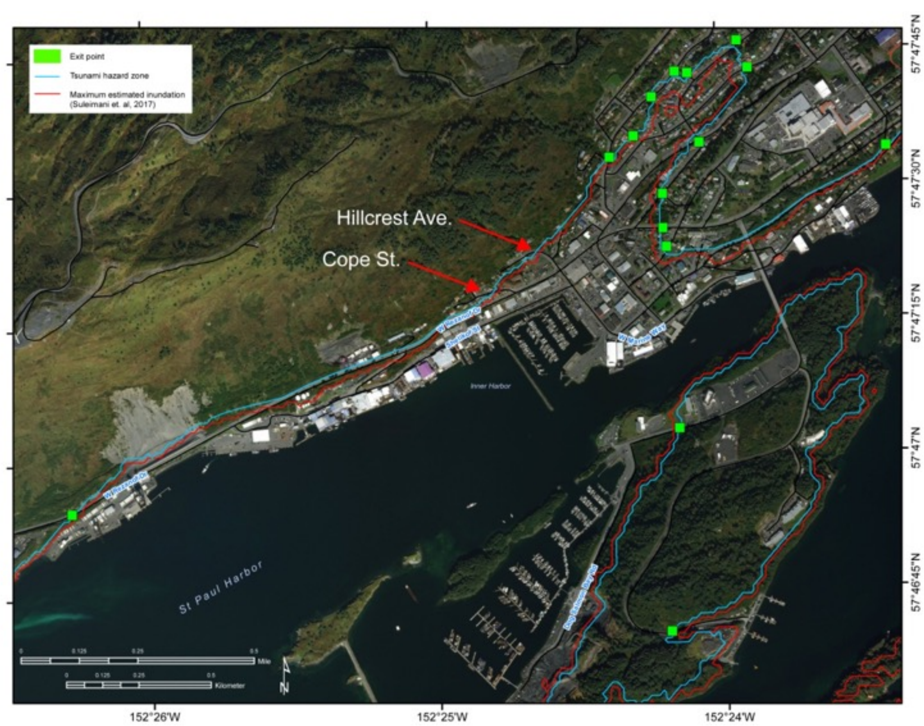

Figure 2: Map of the Kodiak downtown depicting modeled extent of the potential inundation (red line) and the tsunami hazard zone (blue line). Exit points are shown by green squares.

The extent of the potential inundation in the downtown area is shown by the red line in figure 2, also see Map Sheet 1 for a large copy. Much of the economic activity and infrastructure, including harbors, ports, canning facilities, hotels, and restaurants is within the potential inundation zone.

The hydrodynamic model used to calculate propagation and runup of tsunami waves is a nonlinear, flux-formulated, shallow-water model (Nicolsky and others, 2011) that has passed the appropriate validation and verification tests (Synolakis and others, 2007; NTHMP, 2012). We emphasize that although the developed algorithm has met the benchmarking procedures, there is still uncertainty in locating an inundation line. Refer to Suleimani and others (2017) for an in-depth discussion of the uncertainty in the modeled tsunami hazard zone. For example, the accuracy is affected by many factors on which the model is based, including suitability of the earthquake source model, accuracy of the bathymetric and topographic data, and the adequacy of the numerical model in representing the generation, propagation, and runup of tsunamis.

To account for the above-mentioned uncertainties, we enlarge the modeled extent of potential inundation by adding a safety buffer. In particular, areas within 45 m (150 ft) of the inundation line and with the elevations less than 110% of the local runup are thought to be a risk of flooding in the worst-case tsunami event.

The potential inundation extent together with the safety buffer is to be called the tsunami hazard zone, and is used for the evacuation map development. We note that the safety buffer does not extend further than 45 m (150 ft) from the inundation line and can increase the vertical elevation at most by 10%. The safety buffer is smaller in the areas with steeper topography. In rather flat areas, the safety buffer can reach the 45 m (150 ft) in the horizontal direction. Figure 2 shows the tsunami hazard zone in the Kodiak downtown area represented by the blue line, also see Map Sheet 1 for a large copy. Note that the safety buffer is the greatest along Willow St. The City Hall and Kodiak High School are outside the tsunami hazard zone. Extent of the tsunami hazard zones (buffered inundation extent) for other parts of Kodiak and Womens Bay are shown by the blue line in Map Sheets 2-6.

PEDESTRIAN EVACUATION MODELING

Pedestrian evacuation modeling and prediction of population vulnerability to tsunami hazards were successfully applied to coastal communities in Alaska by Wood and Peters (2015). Also refer to Wood and Schmidtlein (2012, 2013) for an overview and limitations of the anisotropic, least-cost distance (LCD) approach to modeling pedestrian evacuation. We stress that the LCD focuses on the evacuation landscape, using characteristics such as elevation, slope, and land cover to calculate the most efficient path to safety. Therefore, computed travel times are based on optimal routes, and actual travel times may be greater depending on individual route choice and environmental conditions during an evacuation.

Recently, Jones and others (2014) developed the Pedestrian Evacuation Analyst Extension (PEAE) for ArcGIS, which facilitates development of pedestrian travel-time maps. A brief overview of the PEAE and a step-by-step procedure to compute the pedestrian travel-time maps for Alaska coastal communities are provided in Macpherson and others (2017, this series). Note that the data required for the PEAE include: either the tsunami hazard zone or exit points, digital elevation model (DEM) of the community, and land-cover datasets. In the following sections we describe datasets required to compute the travel-time maps, considered scenarios, and modeling results.

DATA COMPILATION AND SOURCES

The following section details the datasets that were obtained and/or created for the community to be used as input for the PEAE. In all cases we used the maximum composite tsunami hazard zone instead of a specific tectonic scenario. All datasets and layers were projected to NAD83 Alaska State Plane Zone 5 m to allow us to compute the final evacuation times in minutes. The original sources of data are summarized in Table 1.

- **Exit points:** Exit points are located on the roads leading from the tsunami hazard zone to the assembly areas and shelters (e.g. the Kodiak High School). Locations of the exit points were determined together with the community members during on-site visits to Kodiak in 2018. Green rectangles in figure 2 (or Map Sheet 1) mark locations of the exit points in the downtown area. Exit points in other parts of Kodiak are shown by green rectangles in Map Sheets 2-6.
- **Digital Elevation Model:** The DEM employed in this study is consistent with the tsunami DEM used by Suleimani and others (2017) to compute the tsunami inundation. The original source for topographic elevations is the National Geophysical Data Center (NOAA), with a spatial resolution of about 12 × 12 m (40 x 40 ft). Note that the tsunami DEM was re-sampled using the PEAE tool to set the analysis cell size at 3 m (10 ft) resolution to improve the accuracy of the travel-time maps.
- **Land Cover:** The land-cover layer by Wood and Peters (2015) was expanded using the high-resolution imagery from Digital Globe world imagery (ESRI). The road network was added from the Kodiak Borough GIS Database. Only the constructed and well-maintained roads are used in the computations.

Table 1. Data sources of the input layers required for the Pedestrian Evacuation Analyst Extension.

Layer in PEAE	Data Sources
Tsunami Inundation Extent	Suleimani and others (2017)
Exit points	Located on the roads leading from the buffered inundation extent. Locations of the exit points are chosen together with the community members
DEM	Carignan and others (2013)
Land Cover	Wood and Peters (2015), expanded using Digital Globe imagery
Roads	Kodiak Borough GIS database, constructed roads only
Water	Wood and Peters (2015), expanded using Digital Globe imagery
Imagery	Digital Globe imagery

EVACUATION SCENARIOS

We model the pedestrian evacuation time for two scenarios. We emphasize that the assumed base speed of the evacuee is set according to the "slow walk" option (0.91 m/s, 3 ft/s, or 2 mph) in the PEAE settings. Note that this is a conservative speed and many residents would be able to evacuate faster (1.52m/s "fast walk", if not 1.79m/s "slow run") as the modeled rate. However, soil liquefaction, darkness, freezing rain, ice and/or snow on the road can also significantly impact the walking pace of evacuees. Additionally, in the case of severe weather conditions or a thick snow cover, the evacuation might be confined to well-traveled roads and paths. We therefore assume that pedestrians will travel to the closest road and then stay on roads to leave the tsunami hazard zone. We also assume that individuals travel to the nearest exit point in the most optimal way. The latter requires tsunami evacuation signage along the roads.

In this study we consider two scenarios:

Scenario 1. Evacuation to the nearest exit point by roads only

We also consider another evacuation scenario where two more exit points at Cope St. and Hillcrest Ave. are added, see figure 2.

Scenario 2. **Evacuation to the nearest exit point assuming two additional exit points at Cope St. and Hillcrest Ave. are present.**

Individuals traveling to Cope St. and Hillcrest Ave. need to be advised that no emergency services are to be provided at these locations.

MODELING RESULTS

We apply the methodology outlined in Macpherson and others (2017, this series) to compute the travel times according to the considered scenarios. The pedestrian travel-time maps for the downtown area corresponding to Scenarios 1 and 2 are shown in figure 3. Modeling results for other Kodiak areas, including the community of Womens Bay and the U.S. Coast Guard Base, are shown on Map Sheets 7–12.

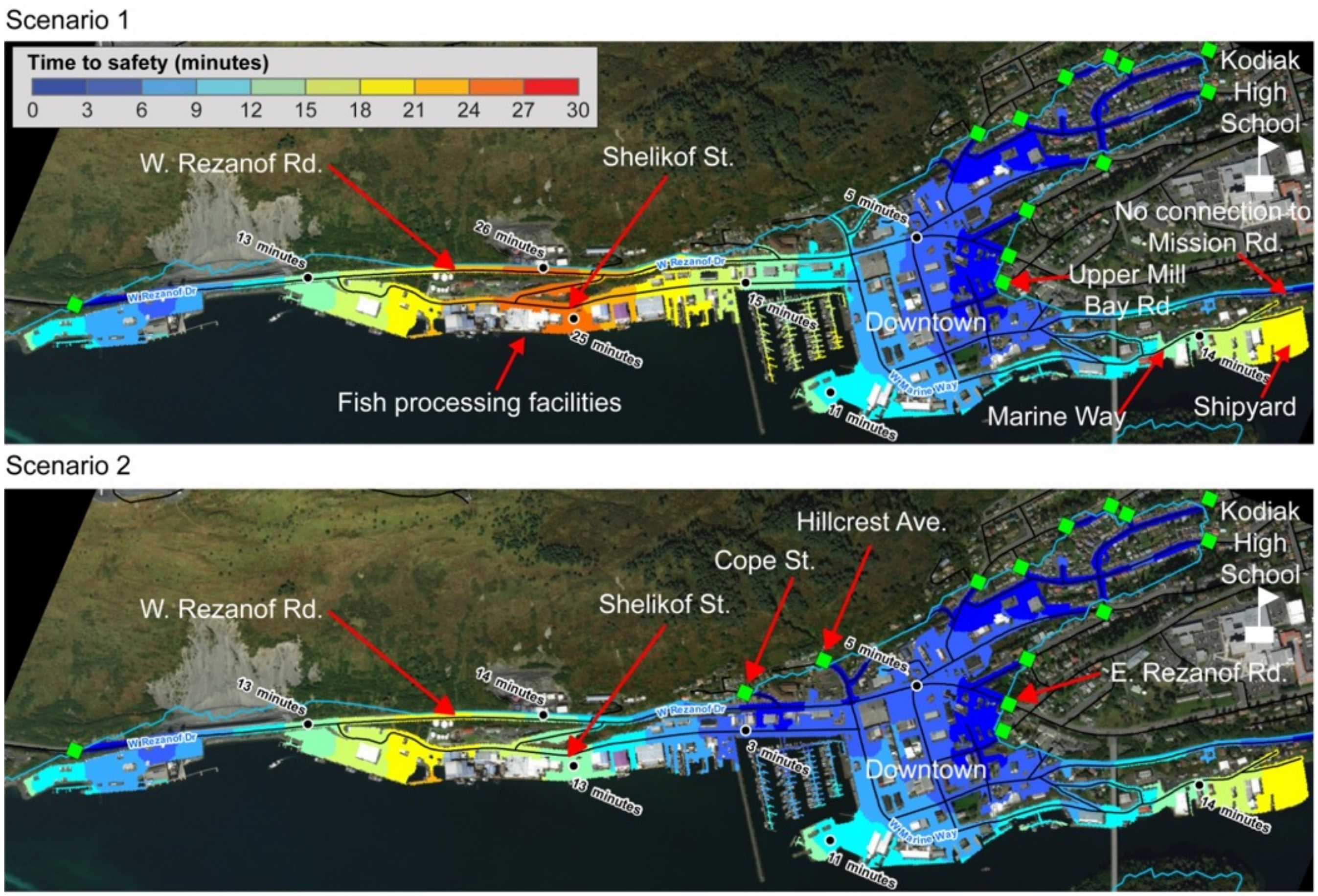

Figure 3: Travel time maps for the pedestrian evacuation from the Kodiak downtown area according to Scenario 1 and 2 (top and bottom panels, respectively). Exit points are marked by the green rectangles, the tsunami hazard zone is shown by the blue line. Color gradation indicates how many minutes it would take for an evacuee to walk to the nearest exit point. The walking speed is assumed to be 3 ft/s or 2 mph.

Scenario 1, see the top plot in figure 3, predicts that pedestrian evacuation to exit points in the downtown area could be achieved in 12 minutes, except for the fish processing facilities on Shelikof St. and a shipyard at the eastern end of East Marine Way. Since there is no constructed road connecting E. Marine Way with Mission Rd., evacuees from the shipyard would need to travel all the way along E. Marine Way or Sargent Dr. and then walk uphill to the exit point on Upper Mill Bay Rd. At the same time, evacuees in the middle of Shelikof St. would need to travel either west to the nearest exit point on W. Rezanof Rd. or east through the downtown and then walk uphill along E. Rezanof St. However, if two additional exit points at Cope St. and Hillcrest Ave. are added as in Scenario 2, see the bottom plot in figure 3, then the pedestrian travel time from the middle of Shelikof St. is reduced by half. Discussions with the city officials revealed that it would be a challenge to provide emergency services to the evacuees at Cope St. and Hillcrest Ave., since the low-lying roads might be impassable after the tsunami impact. Therefore, it was suggested that people along Shelikof St. evacuate to the higher ground along the Upper Mill Bay Rd. and Rezanof St. and then further to the Kodiak High School area.

Another conclusion from the modeling study is that educational efforts could be more extensively focused on facilities along Shelikof St. in order to minimize the milling time and to prompt an evacuation at the first sign of the tsunami danger.

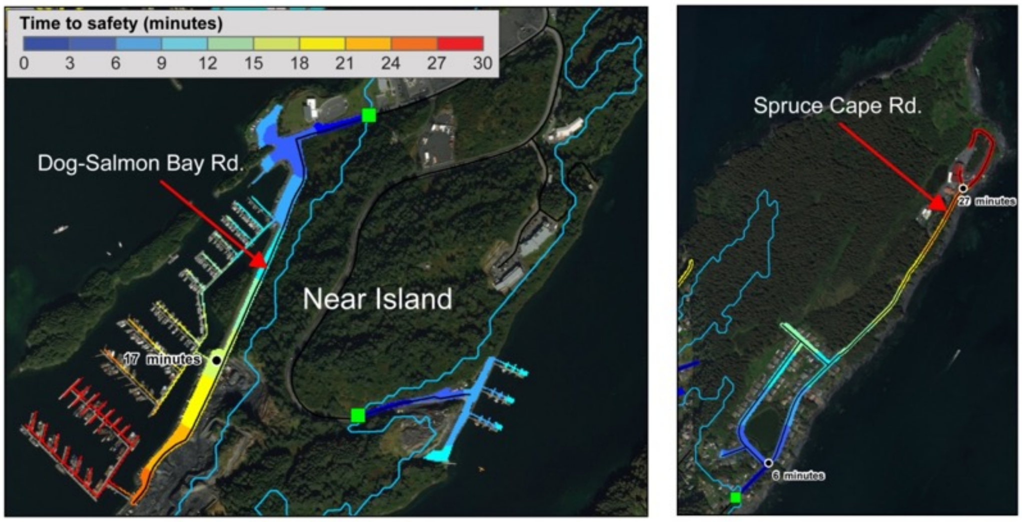

Figure 4: Travel time maps for the pedestrian evacuation in the Near Island (left) and Spruce Cape area (right) according to Scenario 1. Exit points are marked by the green rectangles, the tsunami hazard zone is shown by the blue line. Color gradation indicates how many minutes it would take for an evacuee to walk to the nearest exit point. The walking speed is assumed to be 3 ft/s or 2 mph.

The modeling results in other areas of Kodiak according to Scenario 1 show that significant travel time to exit points is present along the Dog-Salmon Bay Rd. on the Near Island (Figure 4, left plot or Map Sheet 6), Spruce Cape Rd. (Figure 4, right plot or Map Sheet 9), W. Rezanof Rd along the head of Womens Bay (Map Sheet 11) and the airport runways (Map Sheet 12). Clear tsunami evacuation signs and direction could be used to guide the public out of the hazard zone.

SOURCES OF ERRORS AND UNCERTAINTIES

The modeling approach described in this report will not exactly represent an actual evacuation; like all evacuation models, the LCD approach cannot fully capture all aspects of individual behavior and mobility (Wood and Schmidtlein, 2012). The weather conditions, severe shaking, soil liquefaction, infrastructure collapse, downed electrical wires, and the interaction of individuals during the evacuation will all influence evacuee movement. Refer to Wood and Schmidtlein (2012, 2013), Jones and others (2014), and Macpherson and others (2017, this series) for an in-depth discussion of the limitations of the LCD approach in estimating the travel times to safety.

SUMMARY

Kodiak like many other Alaska coastal communities is built between the mountains and ocean. Hence, there are long stretches of roads in the tsunami hazard zone, the evacuation from which may be challenging since it would take a considerable amount of time for evacuees to reach a nearest exit point out of the tsunami hazard zone. Evacuation up the mountain slope is not considered, because of the steep terrain and absence of emergency services. Potential rock falls and snow avalanches could be triggered by aftershocks leading to secondary causalities. At the same time, stockpiling supplies at the Cope St. and Hillcrest Ave. exit points could potentially help evacuees stranded at these locations. Individuals along some parts of W. Rezanof Rd. and Chiniak Hwy. need to walk faster than 2mph or seek alternative evacuation routes (e.g. trails) in order to reach safety before the first wave arrives.

Maps accompanying this report have been completed using the best information available and are believed to be accurate; however, the report's preparation required many assumptions. In most cases the actual walking speeds proved faster than those modeled. The information presented on these maps is intended to assist state and local agencies in planning emergency evacuation and tsunami response actions. These results are not intended for land-use regulation or building-code development.

ACKNOWLEDGMENTS

Local knowledge was invaluable to this project and the members of the community were eager to discuss their plans and thoughts. This project received support from the National Oceanic and Atmospheric Administration (NOAA) Award NA17NWS4670006.

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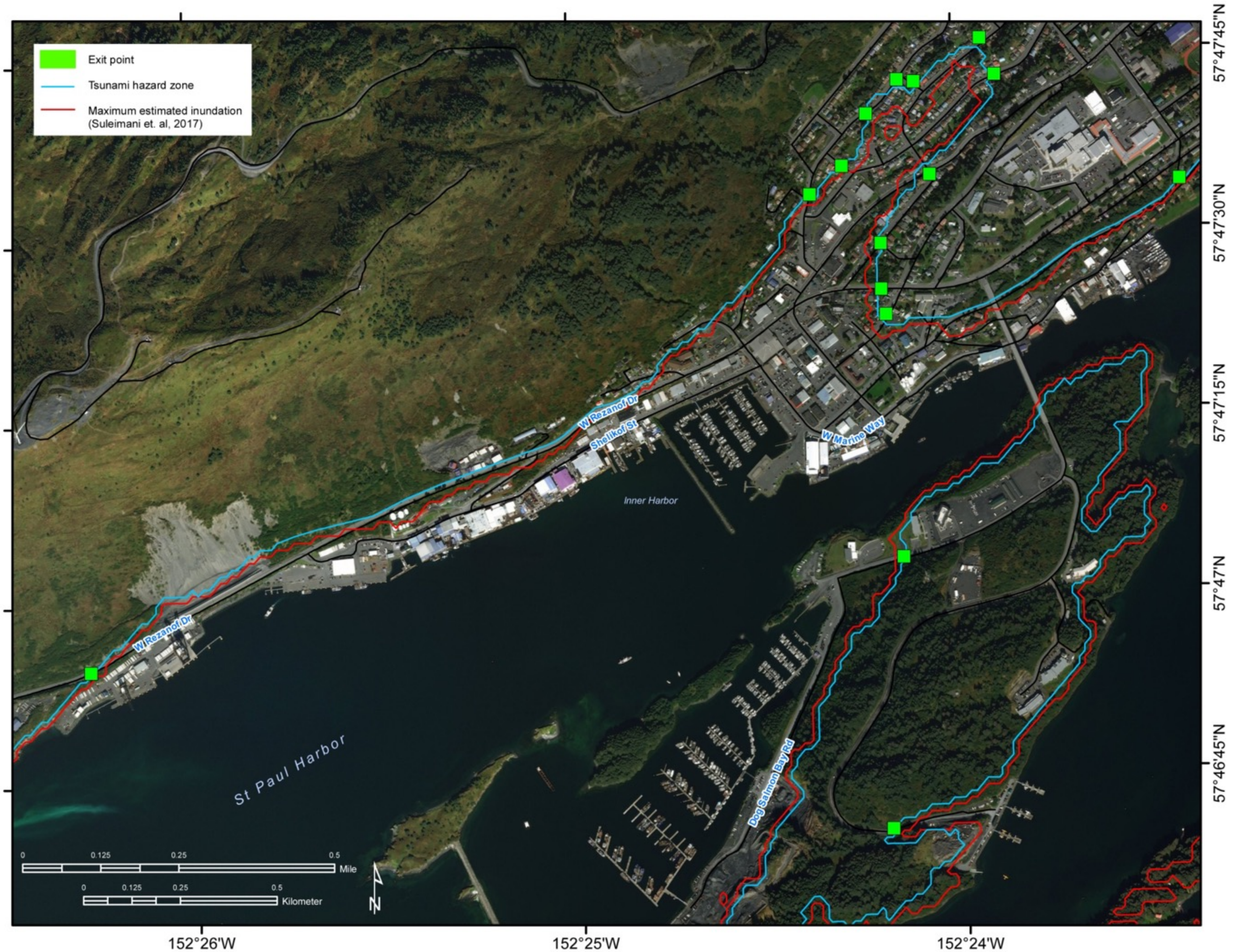
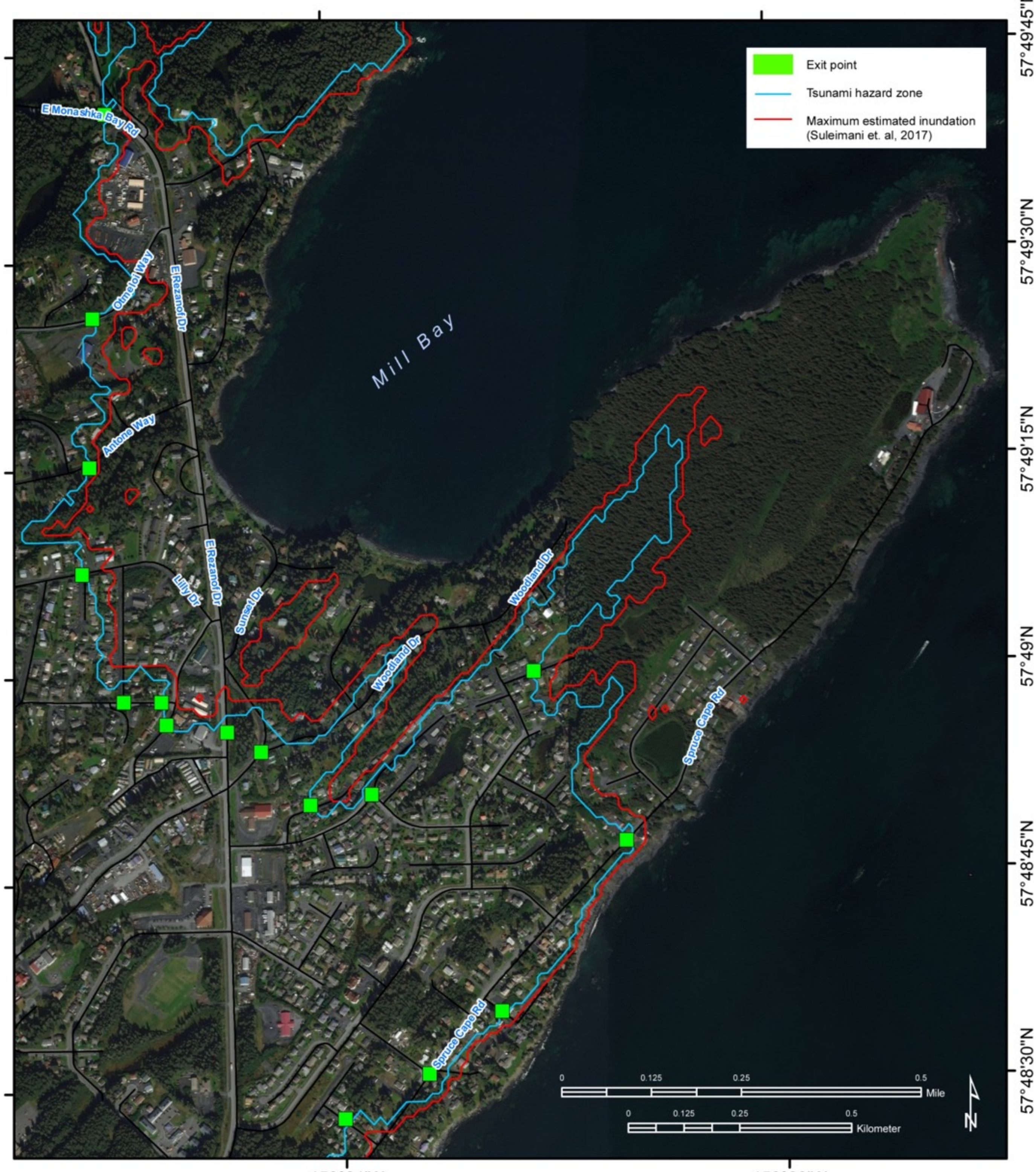


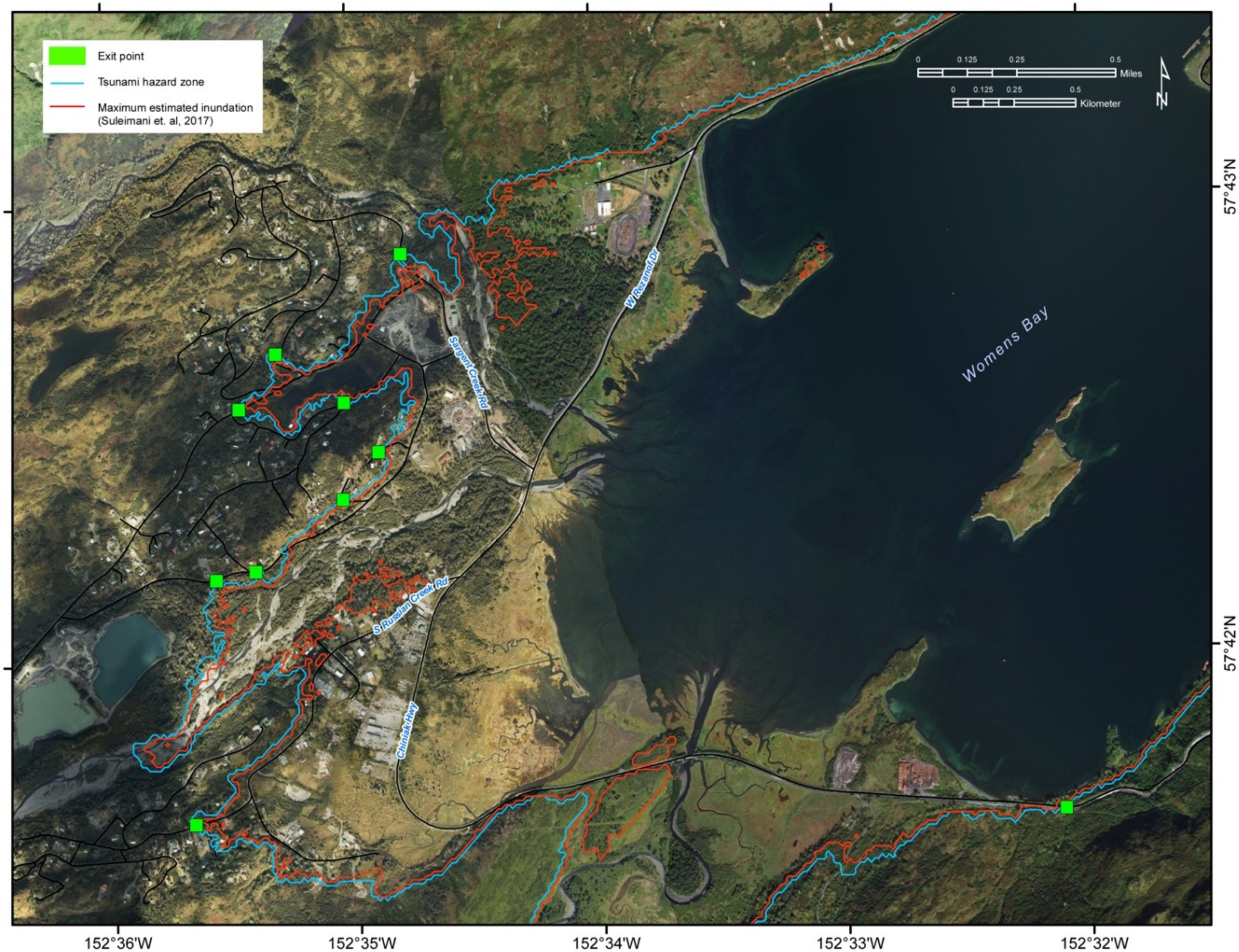
MAP SHEET 1: Modeled extent of the potential inundation and estimated tsunami hazard zone.

MAP SHEET 2: Modeled extent of the potential inundation and estimated tsunami hazard zone (continued).

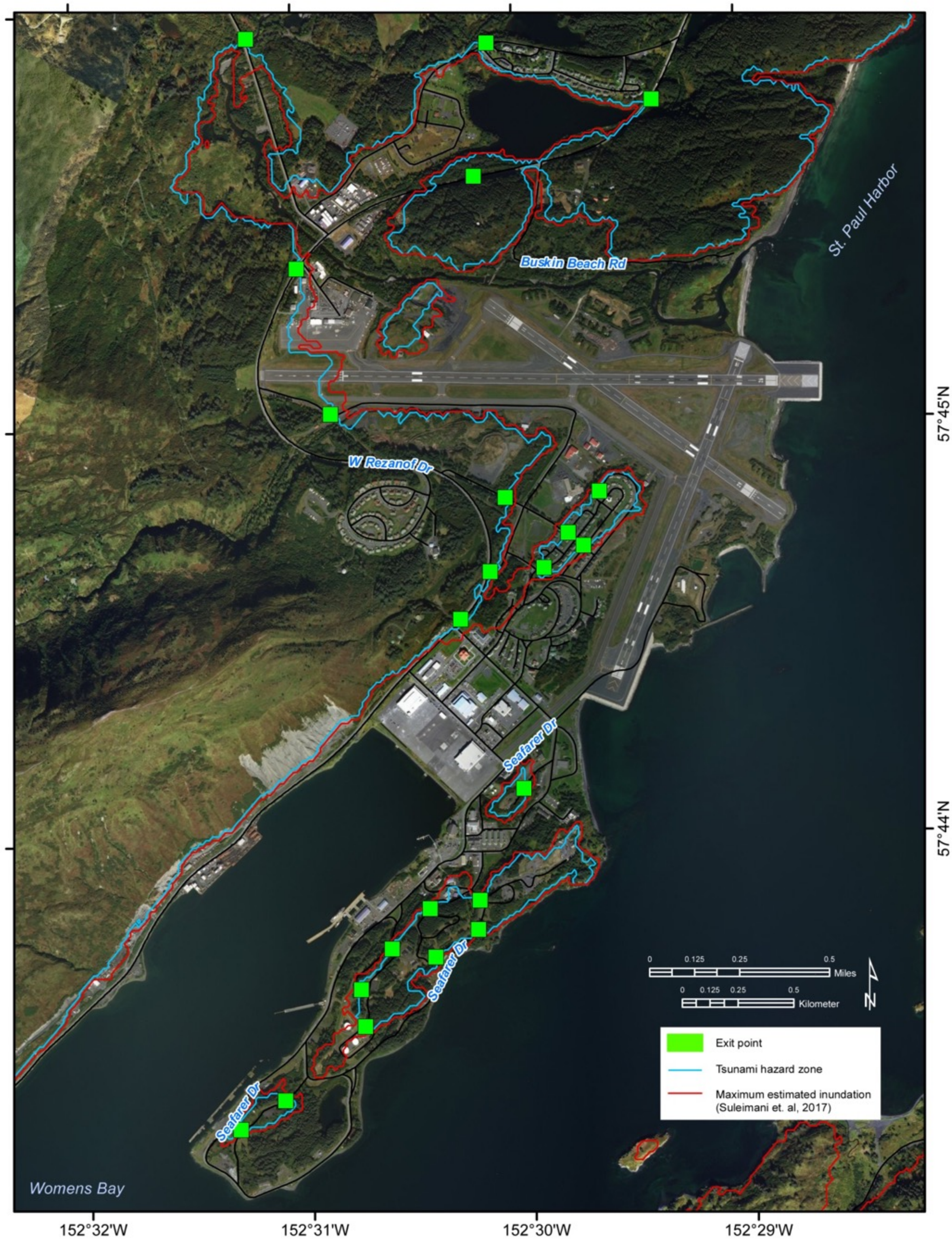


MAP SHEET 3: Modeled extent of the potential inundation and estimated tsunami hazard zone (continued).

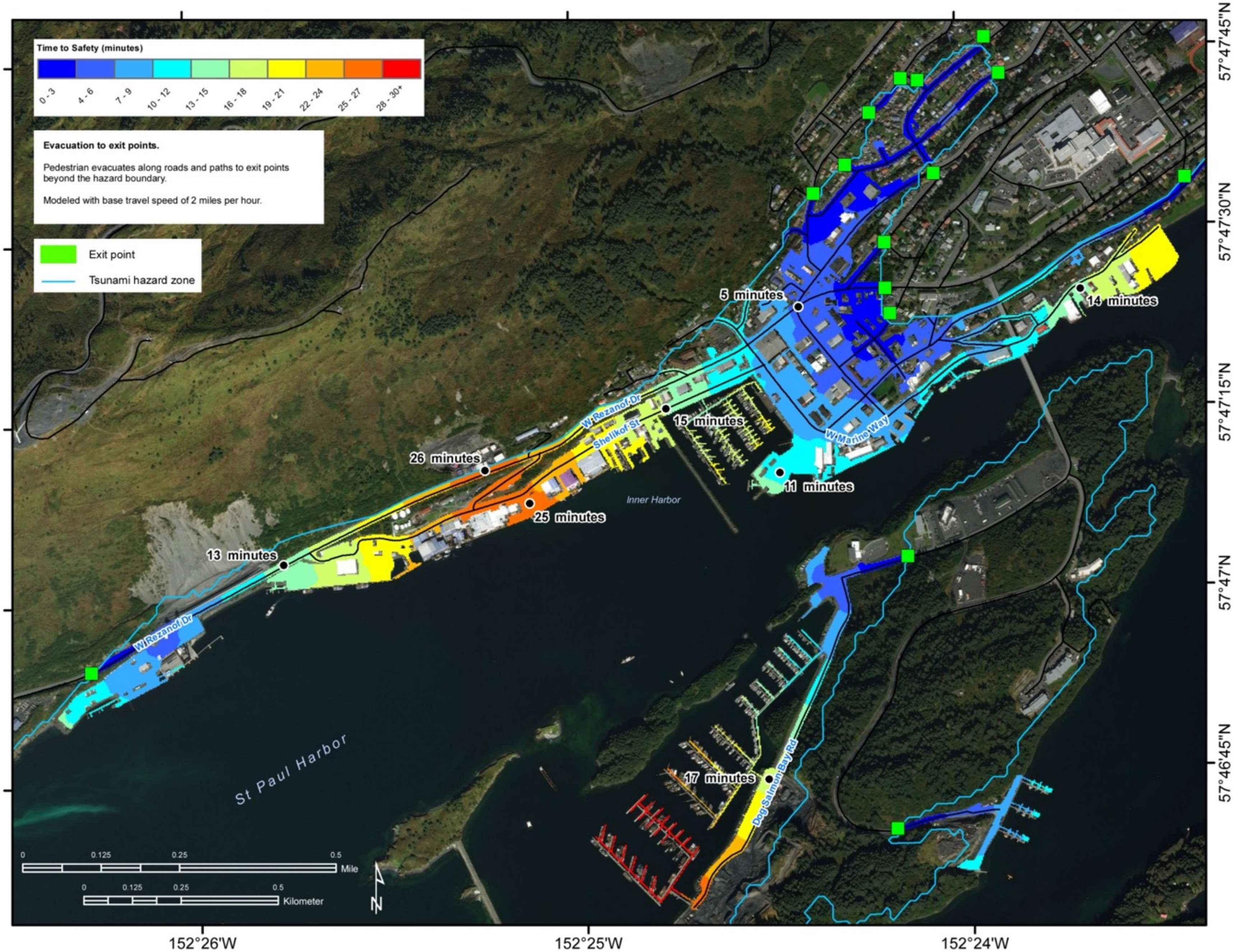
MAP SHEET 4: Modeled extent of the potential inundation and estimated tsunami hazard zone (continued).



MAP SHEET 5: Modeled extent of the potential inundation and estimated tsunami hazard zone (continued).

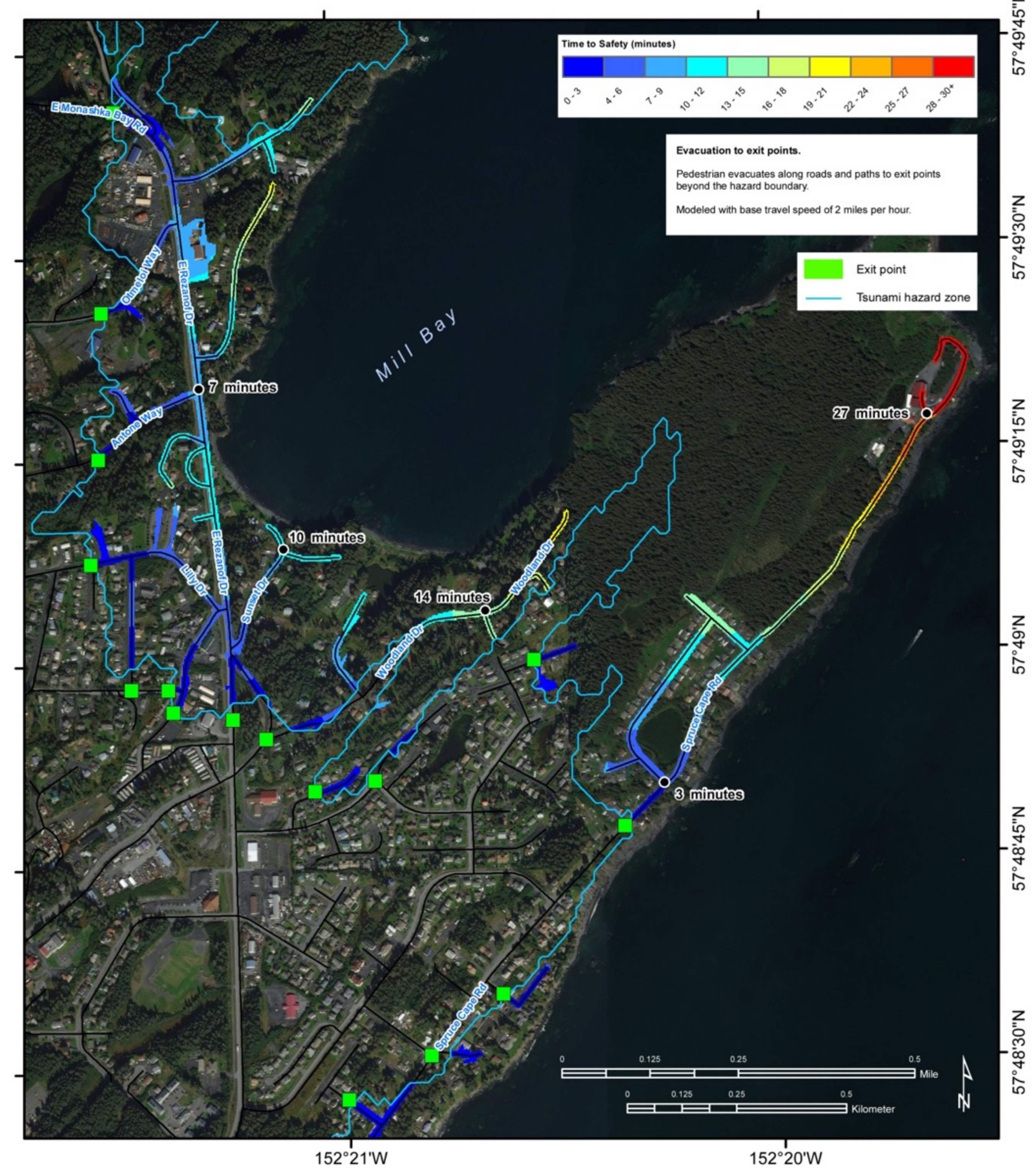


MAP SHEET 6: Modeled extent of the potential inundation and estimated tsunami hazard zone (continued).

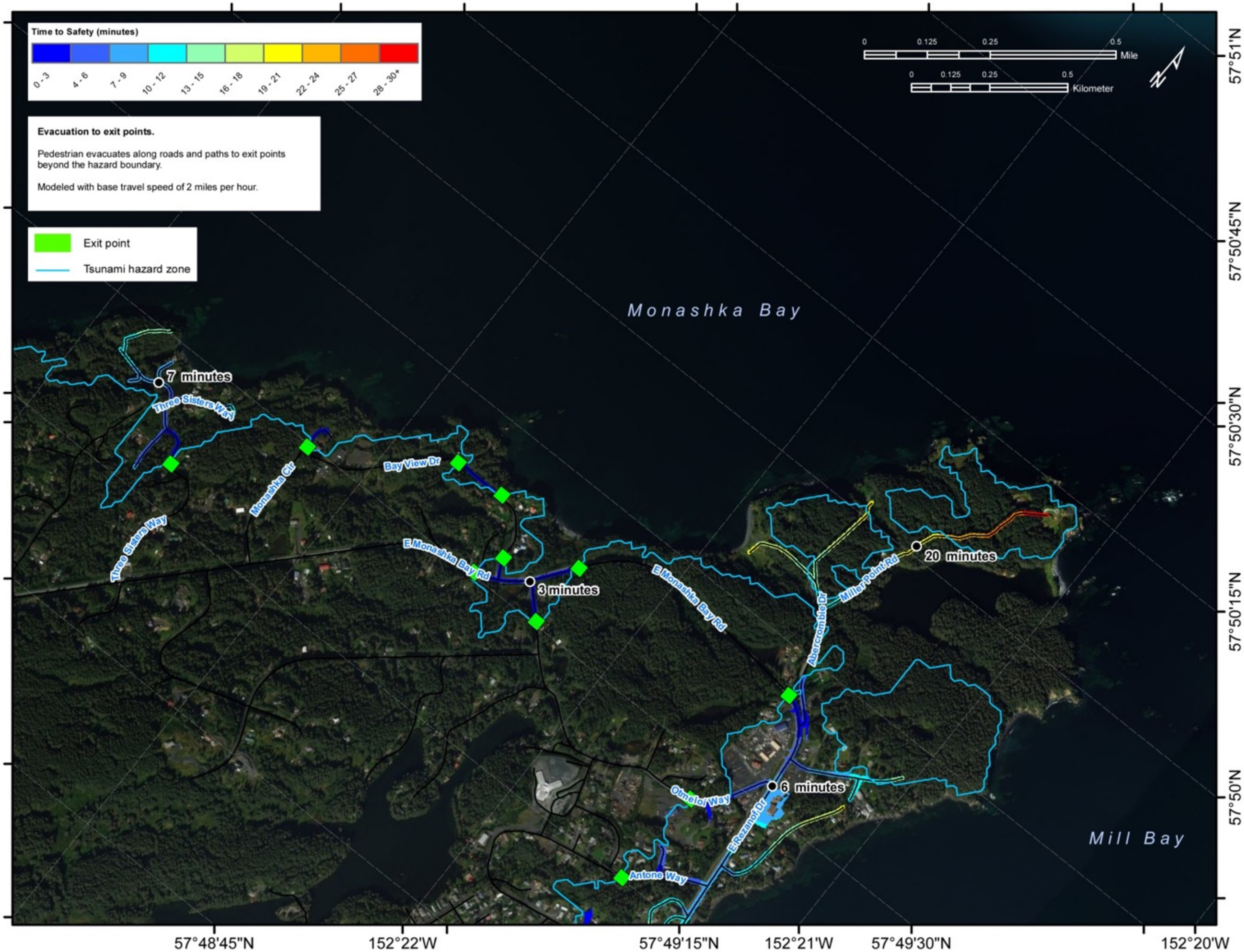


MAP SHEET 7: Travel-time map of pedestrian evacuation in the Kodiak downtown area according to Scenario 1.

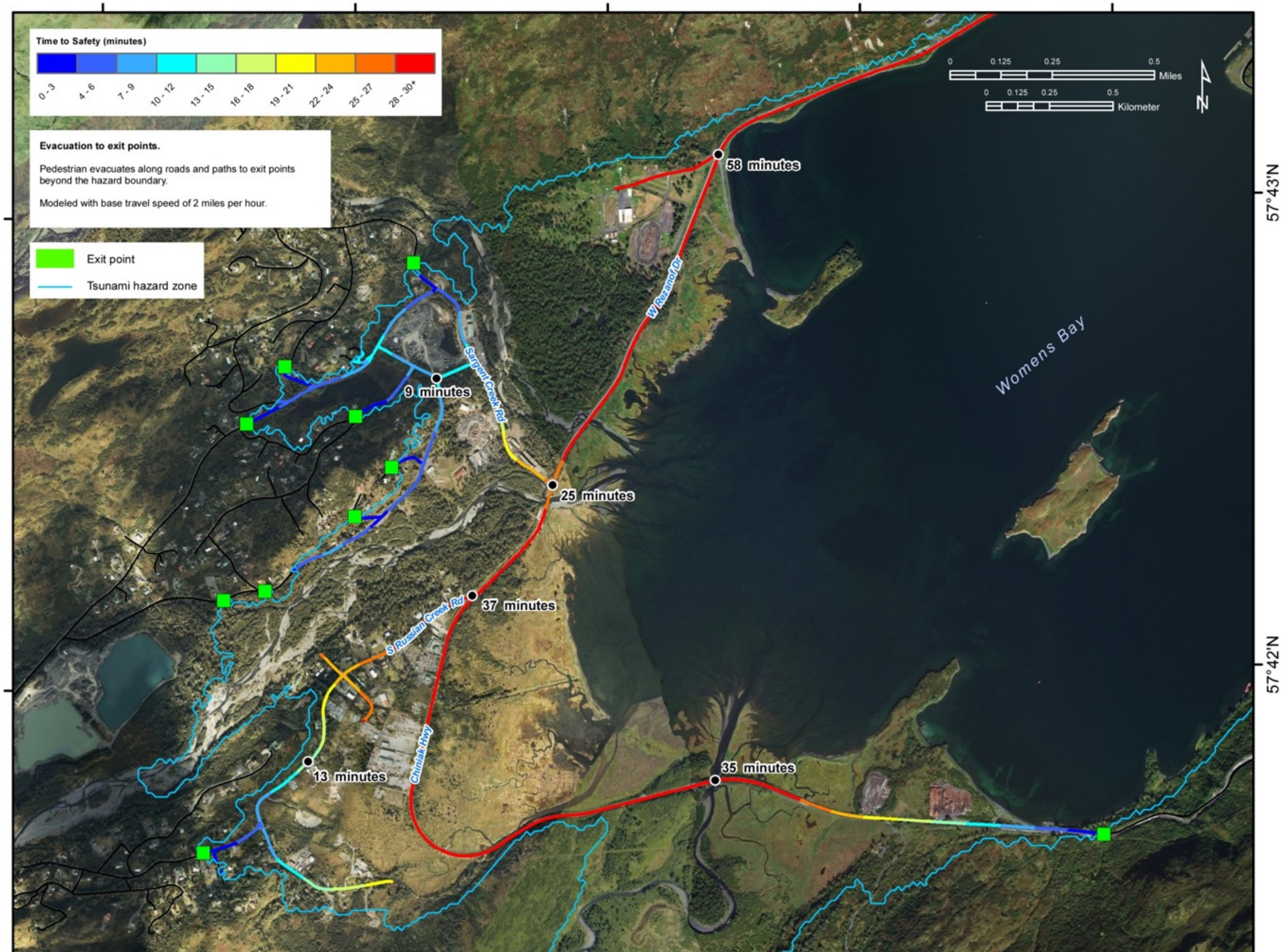
MAP SHEET 8: Travel-time map of pedestrian evacuation from the coast of Woody Island Channel according to Scenario 1.



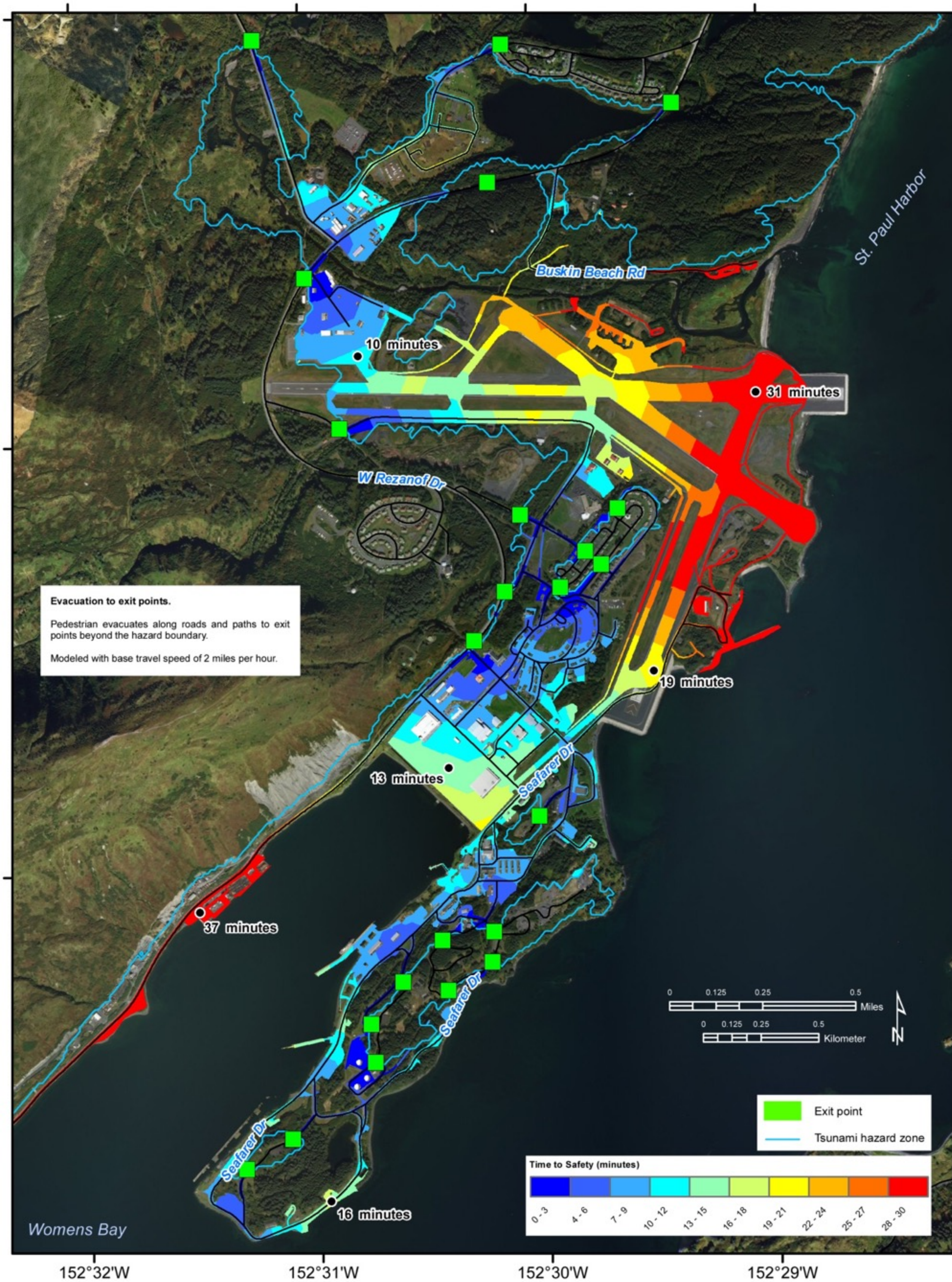
MAP SHEET 9: Travel-time map of pedestrian evacuation from the coast of Mill Bay according to Scenario 1.



MAP SHEET 10: Travel-time map of pedestrian evacuation from the coast of Monashka Bay according to Scenario 1.



MAP SHEET 11: Travel-time map of pedestrian evacuation from the coast of Womens Bay according to Scenario 1.



MAP SHEET 12: Travel-time map of pedestrian evacuation at the U.S. Coast Guard Base according to Scenario 1.