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

by

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ABSTRACT

Tsunami-induced pedestrian evacuation for the community of King Cove is evaluated using an anisotropic modeling approach developed by the U.S. Geological Survey. The applied 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 the tsunami hazard zone boundary and to predetermined assembly areas. The pedestrian travel-time maps are computed for two cases: for travel across all viable terrain or by 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.

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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, 2008). 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 (2016) for an overview of the tsunami hazard in King Cove.

On April 1, 1946, the eastern Aleutian Islands were struck by a M_w 8.6 megathrust earthquake near Unimak Island (figure 1). This earthquake generated a major destructive tsunami that resulted in an extremely high runup of 42 m (138 ft) at Unimak Island (Okal and others, 2002). The city of King Cove was also affected by this tsunami, with local waves reaching 1.5 m (4.92 ft) (Lander, 1996). An in-depth analysis of the tsunami hazard in King Cove and estimation of the tsunami hazard zone in the community is detailed in Suleimani and others (2016). According to the tsunami modeling results, fish processing facilities and the city harbor may face a challenge in evacuating due to long walking distances to safety.

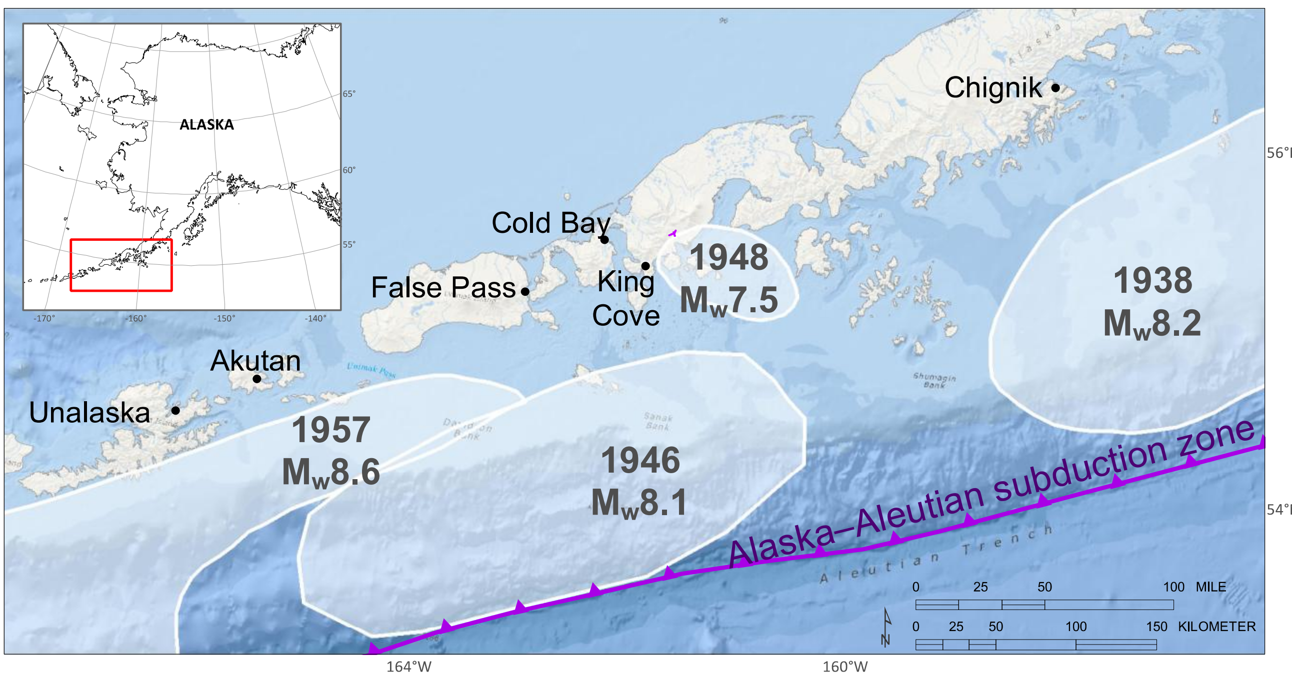


Figure 1. Map of the eastern Aleutian Islands and the southern tip of the Alaska Peninsula, identifying major active faults (dark purple lines) and the rupture zones of the 1938, 1946, 1948, and 1957 earthquakes (light shaded areas).

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).

The maps of pedestrian travel time can help identify areas in King Cove on which to focus evacuation training and tsunami education. The resulting travel-time maps can also be used to examine the potential benefits of vertical evacuation structures, which are buildings or berms designed to provide a local high ground in low-lying areas of the hazard zone.

COMMUNITY PROFILE

The community of King Cove (figure 2) (55.04'20"N 162.19'05"W), population 905 (certified in 2014 by the Commissioner of DCCED), is on the Pacific (south) side of the Alaska Peninsula on a sand spit fronting Deer Passage and Deer Island (DCCED/DCRA, 2015). It is 29 km (18 mi) southeast of Cold Bay and 1,006 km (625 mi) southwest of Anchorage. Today, the town is home to Peter Pan Seafoods' largest processing facility, boasting the largest salmon canning capacity of any plant in Alaska. King Crab, pollock, salmon, halibut and black cod are processed here throughout the year. At peak seasons, in both winter and summer, nearly 500 employees staff the plant. The economy of King Cove depends almost completely on year-round commercial fishing and processing. King Cove has no road access and is accessible by air and sea only. A state-owned gravel runway exists but gale-force crosswinds are common, as the airport lies in a valley between two volcanic peaks. A state ferry (Alaska Marine Highway System) provides regular service to King Cove between May and October. A new harbor provides moorage for large vessels 60–150 feet in length.

Figure 2. A view over King Cove Harbor, Alaska, looking northwest toward the Peter Pan Seafoods facility.

TSUNAMI HAZARD

Tsunami hazard assessment for King Cove was performed by numerically modeling several hypothetical scenarios (Suleimani and others, 2016). Worst-case hypothetical scenarios were defined by analyzing the tsunami dynamics related to various slip distributions along the Alaska–Aleutian subduction zone. The worst-case scenarios for King Cove are thought to be thrust earthquakes in the region of the western Alaska Peninsula, with magnitudes ranging from M_w 8.9 to M_w 9.25, which have their greatest slip at 10–20 km (6–12 mi) depth. The maximum predicted wave in King Cove's small boat harbor might reach 15 m (49 ft) and could cause widespread damage and flooding. The numerical simulations estimate that the first wave could arrive as quickly as 30 minutes after the earthquake, whereas the highest wave might arrive 60 minutes after the earthquake. Significant wave activity could continue for at least 12 hours after the earthquake.

The estimated extent of inundation in King Cove is shown in figure 3. Much of the economic activity, infrastructure, city offices, and residential houses are within the hazard zone; harbors, ports, and canning facilities are all situated inside the zone. The new school, community center, and some newer residential housing have been built on the higher ground of the southeast coast of the cove.

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 (2016) for an in-depth discussion of the uncertainty in the modeled tsunami hazard zone. For example, the accuracy of modeling results 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.

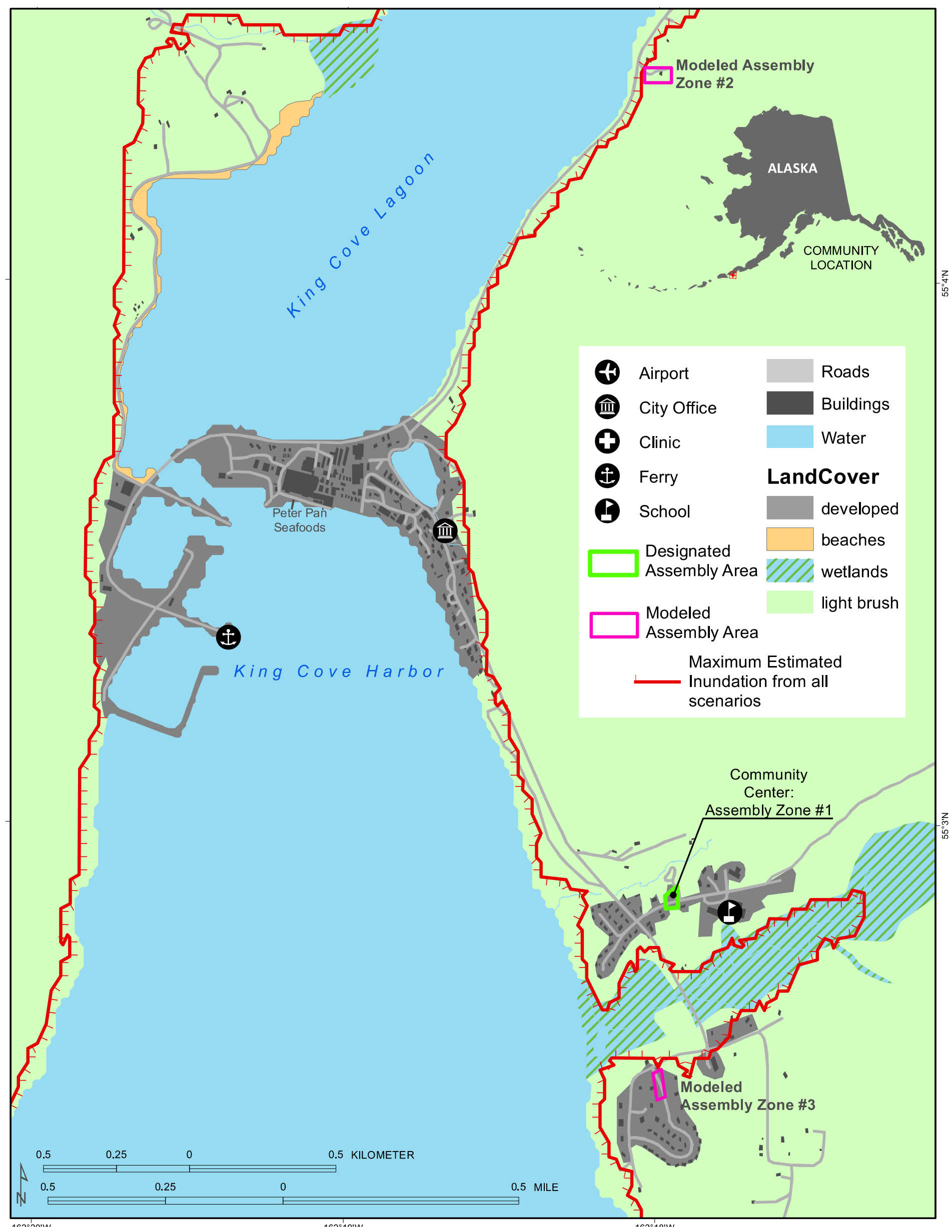


Figure 3. Map of King Cove, depicting key facilities, land cover, and the tsunami hazard zone (red line with hatch marks toward the potential inundation zone).

PEDESTRIAN EVACUATION MODELING

Pedestrian evacuation modeling and population vulnerability to tsunami hazards was 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 the Alaska coastal communities are provided in Macpherson and others (2017). Note that the data required for the PEAE include: the tsunami hazard zone, assembly areas, digital elevation model (DEM) of the community, and land-cover datasets. In the following subsections we describe the compilation of the datasets required to compute the travel-time maps, the scenarios considered, and the modeling results for King Cove.

We visited King Cove at the end of 2014 to gain knowledge of the physical setting, collect land-cover data, and collect data necessary to validate the travel-time maps. We investigated several routes and recorded the time required to walk them. Details of walked routes and further information gathered on the site visit can be found in Appendix A.

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 7 m to allow us to compute the final evacuation times in meters per second. The original sources of data are summarized in Table 1.

- **Tsunami Hazard Zone:** A hazard-zone polygon for PEAE was created by using the modeled maximum estimated inundation line for King Cove (Suleimani and others, 2016) as a boundary.
- **Assembly Areas:** The assembly areas were determined in discussions with community members as well as by selecting some open areas near public buildings as potential evacuation points. We note that safety zones may be important buildings, places that have been agreed upon by the community as gathering places in times of emergency, or just relatively flat land that is out of the hazard zone.
- **Digital Elevation Model:** The DEM employed in this study is consistent with the tsunami DEM used by Suleimani and others (2016) to compute the tsunami inundation. The original source for topographic elevations is the 2013 King Cove DEM (Carignan and others, 2013) with a spatial resolution of about 16 × 16 m (52.5 × 52.5 ft). Note that the tsunami DEM was resampled using the PEAE tool to set the analysis cell size at 5 m (16.4 ft) resolution to improve the accuracy of the travel-time maps.
- **Land Cover:** A land-cover layer was created by sampling the 2011 National Land Cover Database (NLCD) for Alaska (Jin and others, 2013). Using the high-resolution imagery from BING maps and DCCED/DCRA as source imagery, the land-cover layer was further modified by adding building footprints, eliminating some artifacts, and digitizing paths. Roads were added using data extracted from the OpenStreetMap API (OSM, 2015) and edited using BING and DCCED/DCRA imagery.

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

Layer in PEAE	Data Sources
Tsunami Hazard Zone	Suleimani and others (2016)
Assembly Areas	1. Open areas digitized from DCCED/DCRA imagery 2. King Cove Community Center
DEM	Carignan and others (2013)
Land Cover	NLCD 2011 edited
Buildings	Digitized from BING imagery
Roads	Modified from OpenStreetMap
Water	Digitized from BING imagery
Imagery	BING WMS

EVACUATION SCENARIOS

We model the pedestrian evacuation time for four scenarios (Macpherson and others, 2017). We emphasize that the assumed base speed of the evacuee is set according to the "slow walk" option (0.91 m/s or 3 ft/s) in the PEAE settings. Note that this is a very conservative speed and many residents should be able to evacuate twice as fast (1.52 m/s [5 ft/s] "fast walk", if not 1.79 m/s [5.9 ft/s] "slow run") as the modeled rate.

Scenario 1. Evacuation to the hazard zone boundary across all terrain

Pedestrian evacuation from the tsunami hazard zone **over all viable surfaces** to the outer boundary of the hazard zone.

In the case of severe weather conditions or a thick snow cover, the evacuation might be confined to well-traveled roads and paths, therefore we assume that pedestrians will travel to the closest road and then stay on roads to leave the hazard zone.

Scenario 2. Evacuation to the hazard zone boundary by roads only

Pedestrian evacuation from roads and paths in the tsunami hazard zone **along the roads and paths** to the outer boundary of the hazard zone.

In addition to examining pedestrian evacuation to the boundary of the tsunami hazard zone, we consider the following two evacuation scenarios, where each scenario consists of two subscenarios. In each subscenario, we assume that individuals travel to one or multiple assembly points. The assembly points (figure 3) are chosen on (or immediately outside of) the boundary of the tsunami hazard zone on a likely evacuation route.

Scenario 3.1. Evacuation to the assembly area at the King Cove Community Center across all terrain

Pedestrian evacuation from the tsunami hazard zone **over all viable surfaces** to the assembly area at the King Cove Community Center.

Scenario 3.2. Evacuation to the nearest assembly area across all terrain

Pedestrian evacuation from the tsunami hazard zone **over all viable surfaces** to the nearest assembly area. We assume six assembly areas (the King Cove Community Center; in the north along the main road to the airport; and over the bridge to the south of the Community Center; at the head of King Cove Lagoon; uphill of the lake; and on the western side of the King Cove Lagoon) around the boundary of the tsunami hazard zone.

Scenario 4.1. Evacuation to the assembly area at the King Cove Community Center by roads/paths only

Pedestrian evacuation from roads and paths in the tsunami hazard zone **along the roads and paths** to the assembly area at the King Cove Community Center.

Scenario 4.2. Evacuation to the nearest assembly area by roads/paths only

Pedestrian evacuation from roads and paths in the tsunami hazard zone **along the roads and paths** to the nearest assembly area. We assume the above-mentioned assembly areas around the boundary of the tsunami hazard zone.

MODELING RESULTS

We apply the methodology outlined in Macpherson and others (2017) to compute the travel times produced by the four scenarios. The pedestrian travel-time maps are shown in Sheets 1–4, corresponding to Scenarios 1–4.

Scenario 1 predicts that evacuation to the boundary of the hazard zone could be achieved in less than 20 minutes. The longest walking time to safety is from the state ferry dock and from the areas around the Peter Pan Seafoods facilities. We note that the boundary of the tsunami hazard zone—a line to which people evacuate in this scenario—lies on mountain slopes. Therefore, despite fast evacuation times out of the tsunami hazard zone, some evacuees might be vulnerable to severe weather conditions, mountain slope failures, snow avalanches, etc.

In the event of a large snowfall, evacuation might be restricted to only the road network. Scenario 2 shows that in the case of evacuation by major roads only the travel time to safety is significantly increased. In this scenario as in Scenario 1, the longest walking time to safety is from the harbor area and from the Peter Pan Seafoods facilities. The walking time from the state ferry dock to the boundary of the hazard zone is about 50 minutes.

The King Cove Community Center functions as a present-day assembly point for the community. The computations for Scenario 3.1 estimate that walking times to the assembly area at the Community Center are greater than 65 minutes from the west side of the bridge, and up to 90 minutes from the west side of the lagoon. Difficult terrain with steep slopes and marshy areas to the west and north of the harbor could make this evacuation likely unfeasible for the west side of the lagoon. The computational results according to Scenario 3.2 illustrate that the community could be well served by designating additional evacuation sites nearer to the harbor facilities.

As mentioned earlier, under certain weather conditions the evacuation might be confined to the roads and major paths. Numerical results for Scenarios 4.1 and 4.2 show the travel-time maps to a single assembly point near the Community Center and to all assembly points, respectively. As with the earlier results, the evacuation travel times are increased if the evacuation is confined to roads only.

MODEL VALIDATION

Validation of the results is an important component of each modeling study. We note that Wood and Schmidtlein (2012, 2013) and Jones and others (2014) indicate that the modeling results might be sensitive to the spatial resolution of the DEM. Therefore to ensure that our computations are accurate, we compare numerical calculations for Scenario 4.1 with site visit data (walking and timing the various routes confined to roads). While it is not feasible to walk every potential route to safety it is a good test to ensure that the model is producing reasonable times for pedestrian evacuation over the most likely paths to safety.

In this report, we investigate an evacuation route comprising two tracks, from the boat harbor and along Boat Harbor Service Road (Track 1), and then up the hill (Track 2) along Ram's Creek Road to the King Cove Community Center (figure 4) to estimate the most likely pedestrian evacuation route from Peter Pan Seafoods to the Community Center. Actual walking times and distances covered were recorded for each route and are listed in Table 2.

To compare the *in situ* measured walking times to the modeled results, the measured walking times must be adjusted to account for the differences between the *in situ* walking speed and the modeled walking speed of 0.91 m/s (3 ft/s). It took about 32.25 minutes to walk 2,140 m (7,021 ft) along Track 1. Thus, an average

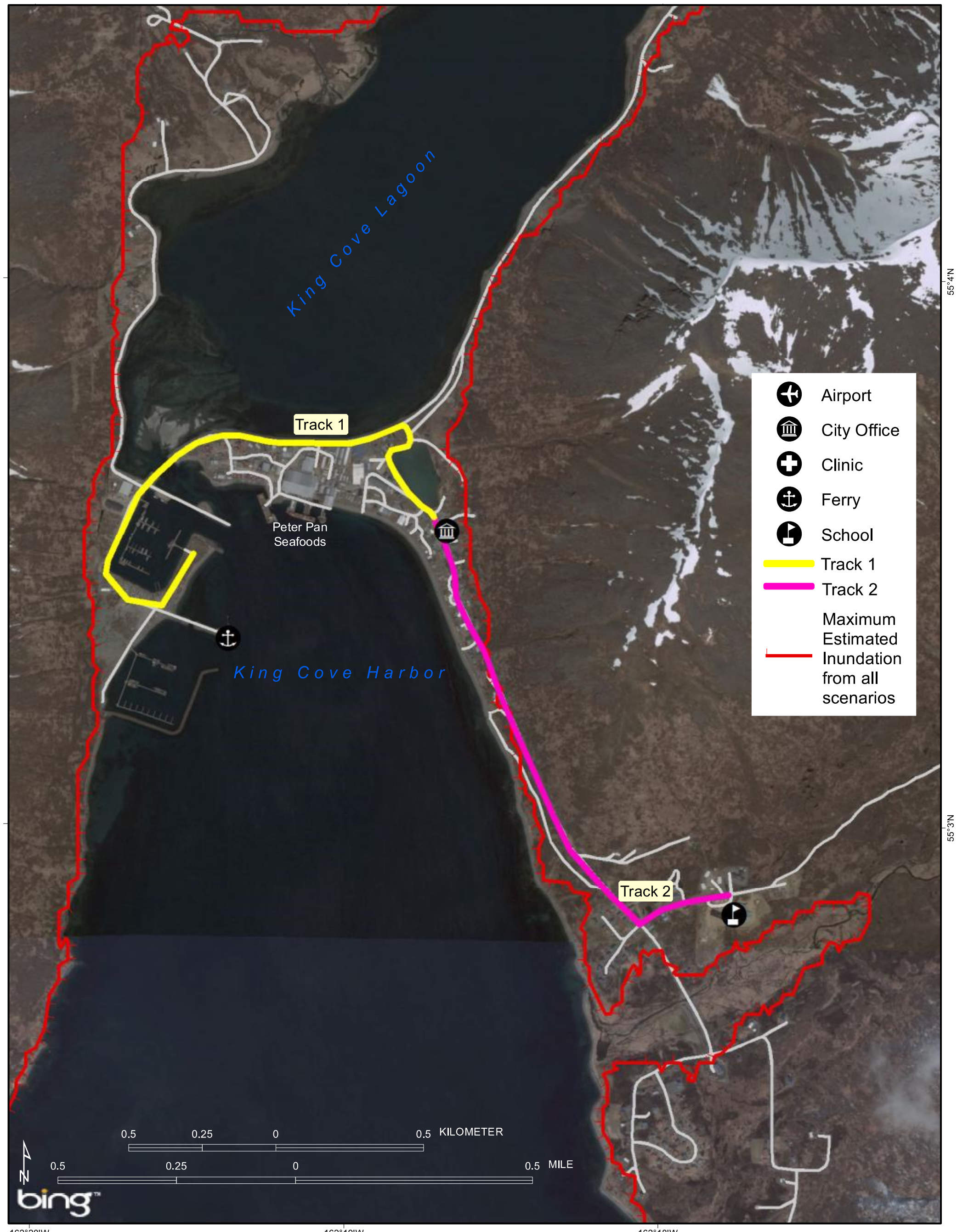


Figure 4. Tracks from site visit used to validate evacuation model times.

in situ walking speed along Track 1 is about 1.10 m/s (3.61 ft/s). If the same route had been traveled at a slower speed of 0.91 m/s (3 ft/s), then the travel time would be $32.25 \times 1.10 \div 0.91 \approx 39$ minutes. The *in situ* measured walking time, average speed, and adjusted travel times are listed in Table 2. The modeling results according to Scenario 4.1 (evacuation by roads to the Community Center) indicate that it takes about 45 minutes to cover the same route. Similar calculations are performed to compare the measured and modeled travel times along the second route. In both cases, the models show reasonably good agreement with the field observations, although along Track 2 there is a larger difference between the modeled and actual walking times. This could be due to inaccuracy of the DEM (possibly overestimating the relief in this area) as well as the inability to perfectly match the modeled route to the walked route.

Table 2. Measured and modeled travel time along two routes in the tsunami hazard zone.

Track	*In situ* measured walking time (minutes)	Walked distance (meters)	Average walking speed (m/s)	Modeled time (minutes)	Recalculated *in situ* walking time (minutes)
1	32.25	2,140	1.106	45	39
2	28.75	1,883	0.916	42	29

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. We employ a "slow walk" travel speed of 0.91 m/s (3 ft/s). Refer to Wood and Schmidtlein (2012, 2013), Jones and others (2014) and Macpherson and others (2017) for an in-depth discussion of the limitations of the LCD approach to estimate the travel times to safety.

SUMMARY

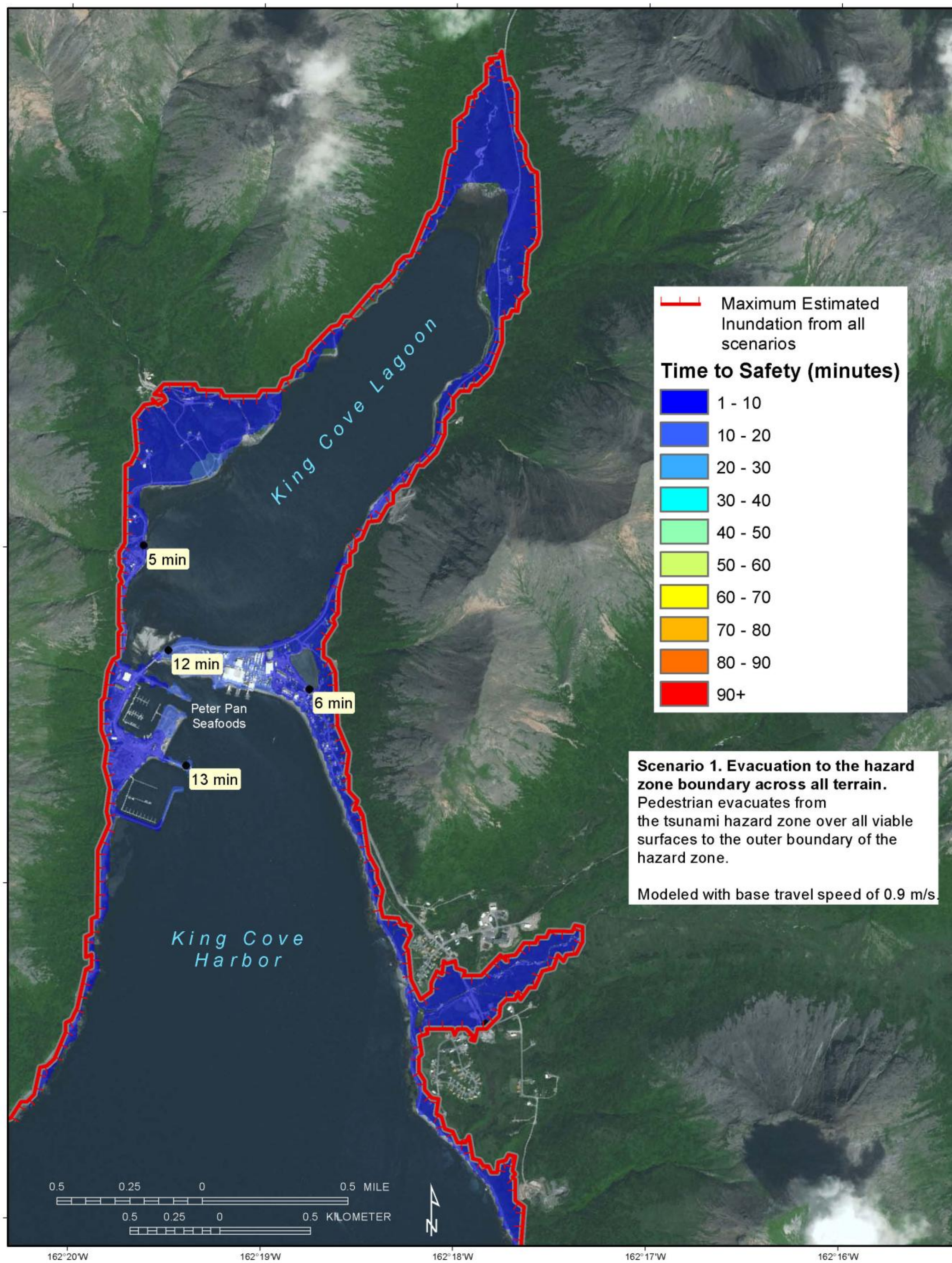
Maps accompanying this report have been completed using the best information available and are believed to be accurate; however, the report's preparation required many assumptions. Overall, times generated by the model seem reasonable when compared to actual walking times and routes. Designation of places of refuge near the harbor facilities can drastically decrease pedestrian travel time to safety. The pedestrian travel times should be used only as a guideline for emergency planning and response action. Some individuals less familiar with the area might take a less optimal route and will require a longer time to reach safety. Moreover, in case of emergency, some individuals might require some time to recognize an imminent tsunami danger, delaying their evacuation. The information on this map 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

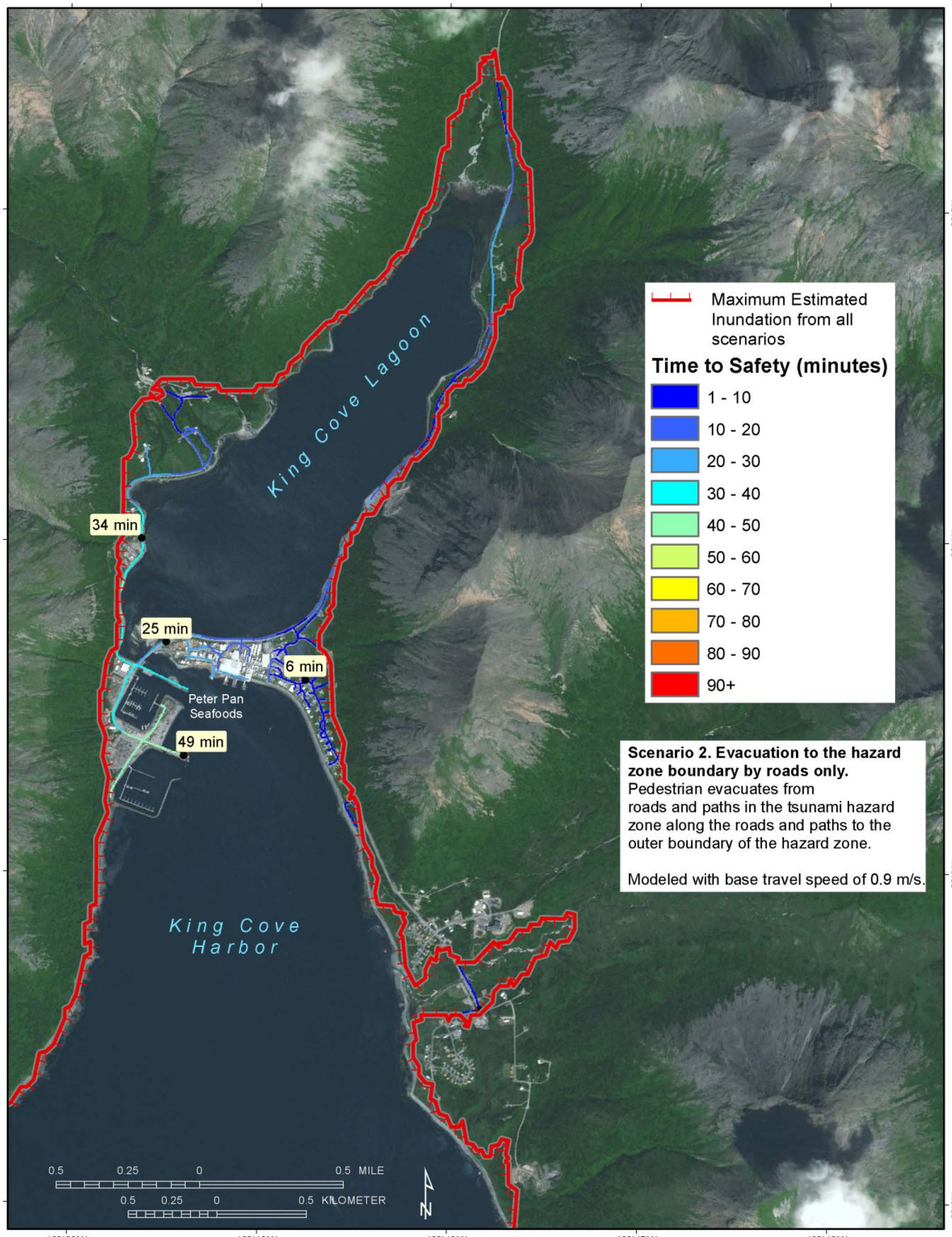
Local knowledge was invaluable to this project and the members of the community were eager to discuss their plans and thoughts. This project received support from the National Oceanic and Atmospheric Administration (NOAA) under Reimbursable Service Agreement ADN 952011 with the State of Alaska's Division of Homeland Security and Emergency Management (a division of the Department of Military and Veterans Affairs). A thoughtful review by Nathan Wood (USGS)improved the report and maps.

APPENDICES

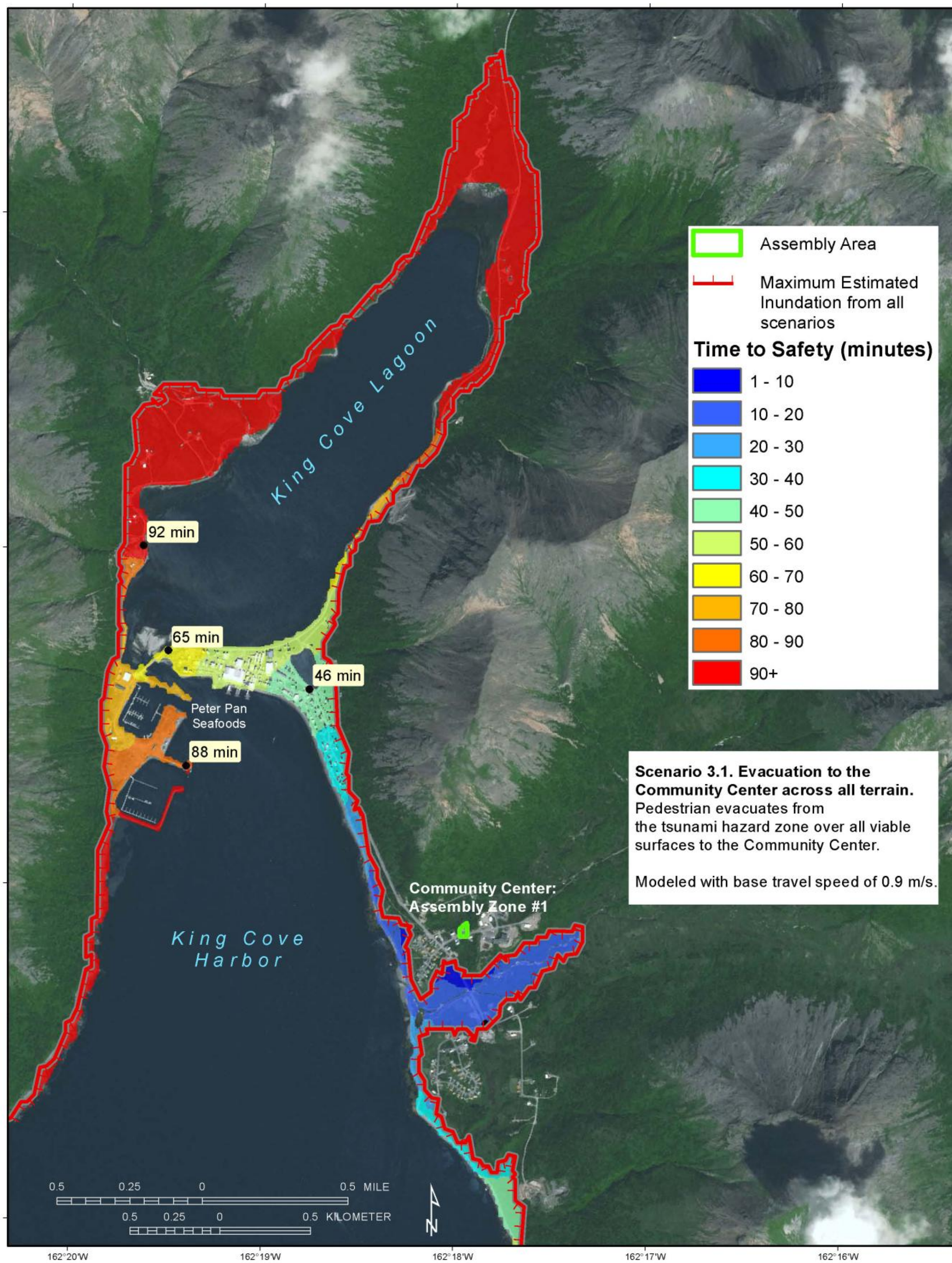
APPENDIX A: Site Visit Report for King Cove, Alaska



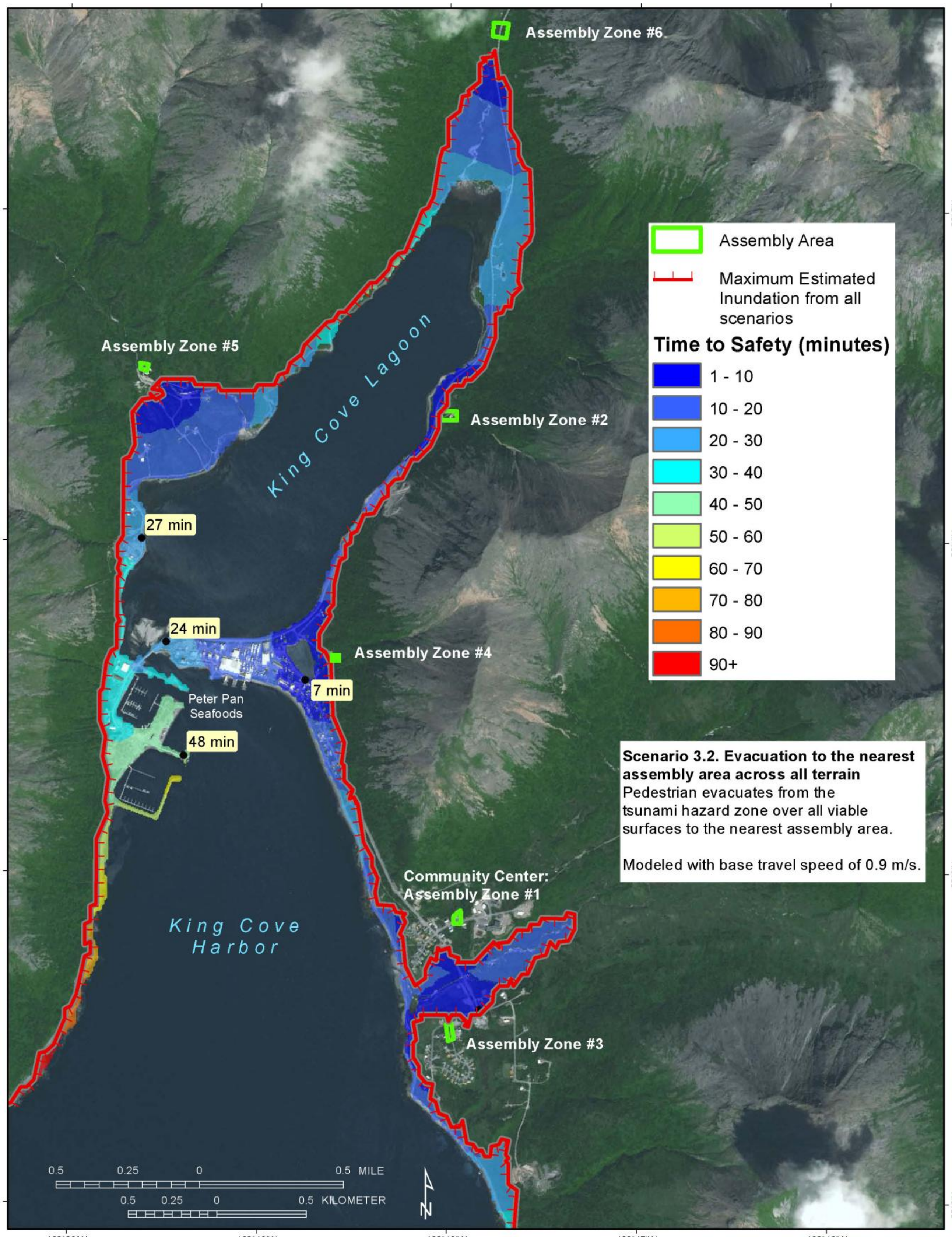
MAP SHEET 1: Travel-time map of pedestrian evacuation to the hazard zone boundary across all terrain



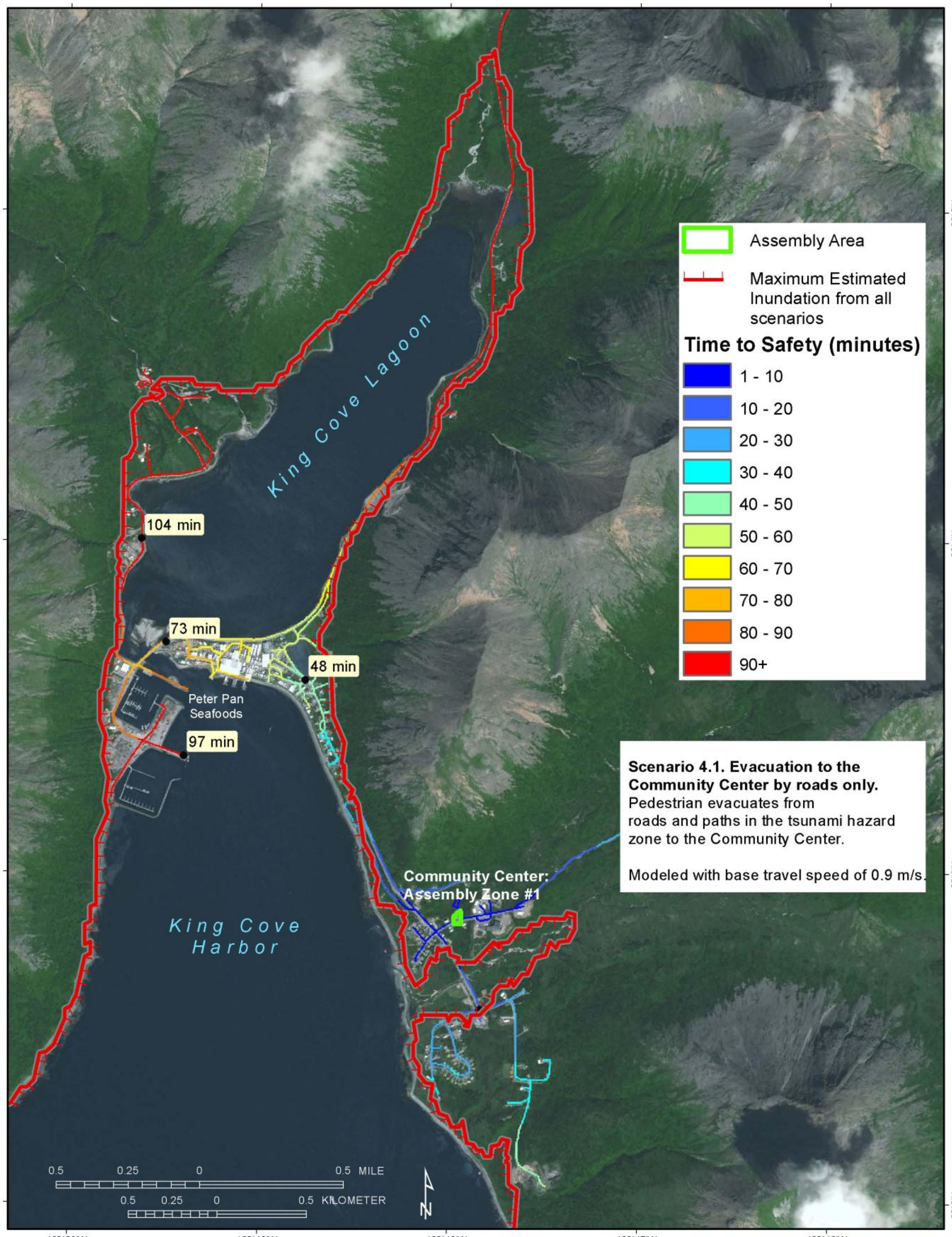
MAP SHEET 2: Travel-time map of pedestrian evacuation to the hazard zone boundary by roads only



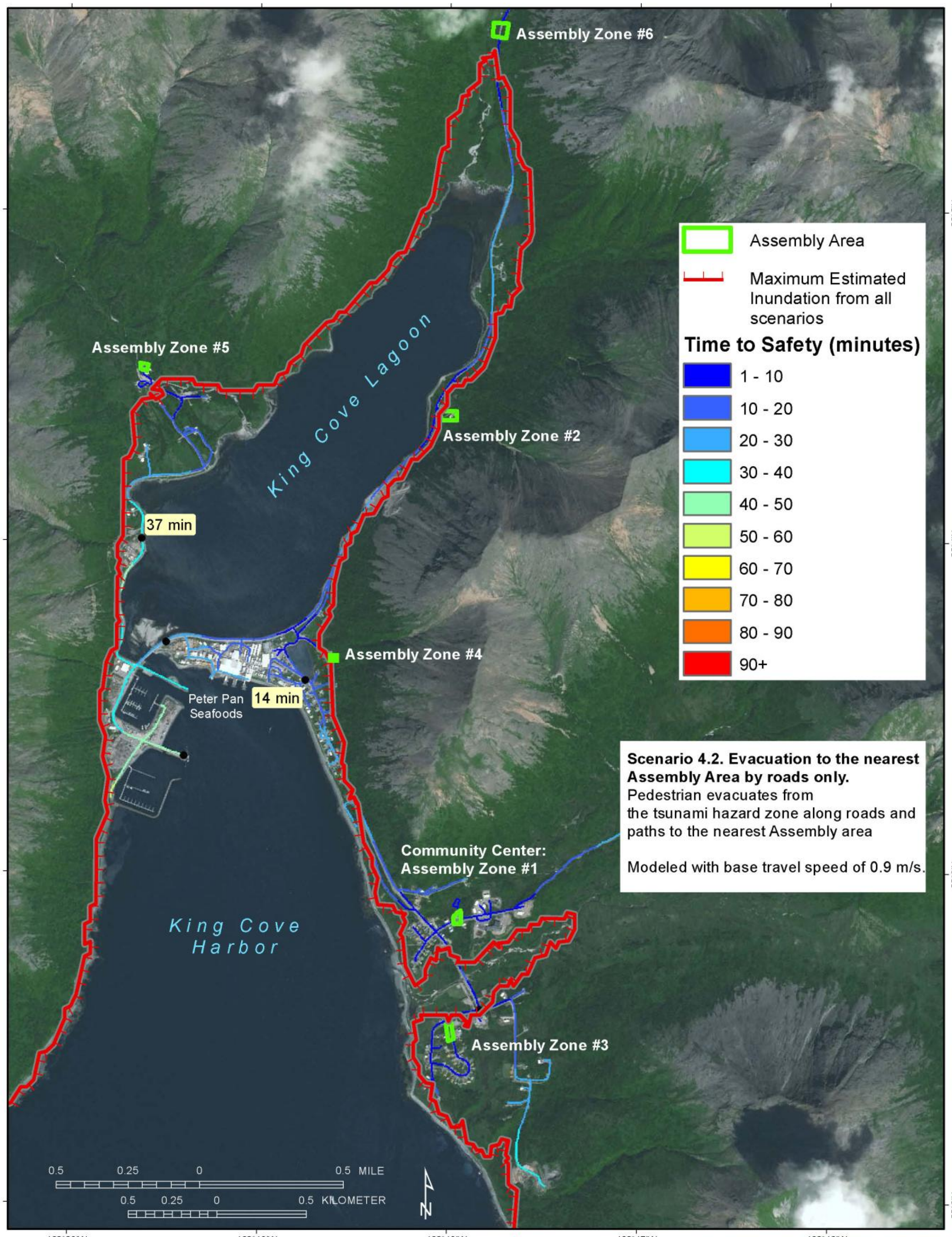
MAP SHEET 3.1: Travel-time map of pedestrian evacuation to the assembly area at the King Cove Community Center across all terrain



MAP SHEET 3.2: Travel-time map of pedestrian evacuation to assembly areas across all terrain



MAP SHEET 4.1: Travel-time map of pedestrian evacuation to the assembly area at the Community Center by roads only



MAP SHEET 4.2: Travel-time map of pedestrian evacuation to assembly areas by roads only

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