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

by

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ABSTRACT

Tsunami-induced pedestrian evacuation for the community of Chignik 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 the tsunami hazard zone boundary and to predetermined assembly areas. 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 Nicolsky and others (2016) for an overview of the tsunami hazard in the Chignik area.

The most recent earthquakes that triggered great tsunamis in Chignik occurred on April 1, 1946, and March 27, 1964; for these events, tsunami waves were as high as 1.5 m (5 ft) and 3.0 m (10 ft), respectively (Lander, 1996). An in-depth analysis of the tsunami hazard in Chignik and estimation of the tsunami hazard zone in the community is provided by Nicolsky and others (2016). According to the tsunami modeling results, individuals in many residential buildings, fish-processing facilities, around the city harbor, and airport may face a challenge to evacuate due to long walking distances to designated assembly areas.

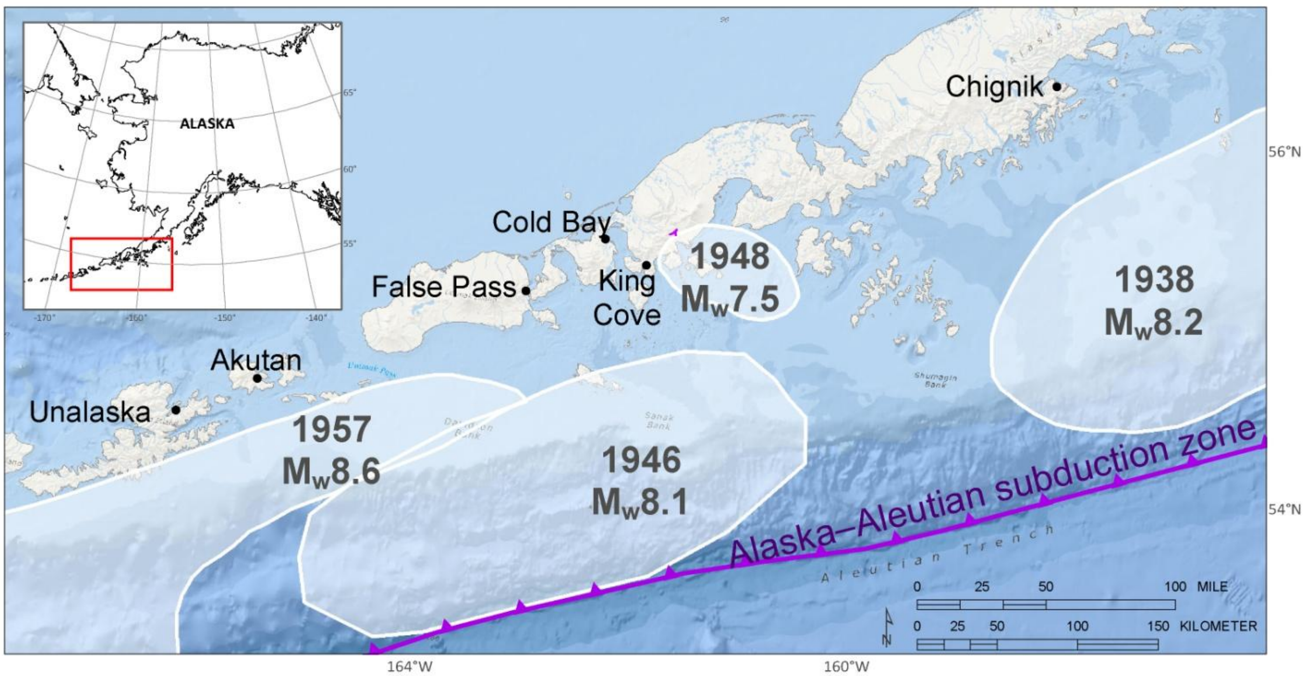


Figure 1: Map of the eastern Aleutian Islands and the southern tip of the Alaska Peninsula, identifying major active faults (dark purple lines) and the rupture zones of the 1938, 1946, 1948, and 1957 earthquakes (light shaded areas).

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, this series).

The maps of pedestrian travel time can help identify areas in Chignik 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 city of Chignik (figure 2) is at the head of Anchorage Bay at 56°18'N, 158°24'W, or about 750 km (466 mi) west of Anchorage, 168 km (104 mi) northeast of Sand Point, and about 420 km (260 mi) southwest of Kodiak. As of the U.S. Census of 2010, there were 91 people, 41 households, and 26 families residing in the city (DCCED/DCRA).

Figure 2: Looking to the southeast down toward the city of Chignik.

Chignik is accessible by air with regular flights from King Salmon. Flights directly from Anchorage can be scheduled on an as-needed basis. There is a state-owned ~800 m (2,600 ft) gravel runway in the community. The Alaska Marine Highway System provides regular service from Kodiak and Sand Point between May and October. Additionally, barge services arrive weekly from late spring through early fall, and monthly during the remainder of the year. A 110-slip small-boat harbor, public docks, and boat haul-out are available. Four-wheel drive vehicles are the primary means of local transportation, all-terrain vehicles (ATVs) are a secondary means, and skiffs are used to travel to surrounding communities. As in many other coastal communities, much of the economic activity and infrastructure is on or near the coast—a potential tsunami inundation area. Refer to Community Development Plans (DCCED/DCRA) for a review of the history, economy, and infrastructure of Chignik.

TSUNAMI HAZARD

Tsunami hazard assessment for Chignik was performed by numerically modeling several hypothetical scenarios (Nicolsky and others, 2016). Worst-case hypothetical scenarios were defined by analyzing results of a sensitivity study of the tsunami dynamics related to various slip distributions along the Alaska–Aleutian subduction zone. The worst-case scenarios for the Chignik area are thought to be thrust earthquakes along the Alaska Peninsula with magnitudes ranging from M_w 9.0 to M_w 9.3 that have their greatest slip at 5–35 km (3.1–21.7 mi) depth. The maximum predicted wave in Anchorage Bay, near the small skiff landing area, can reach 32 m (105 ft) and could cause widespread damage and flooding. The numerical simulations estimate that the first devastating wave might arrive at the community within 45 to 60 minutes, whereas the highest wave might arrive shortly more an hour after the earthquake. Significant wave activity could continue for at least 12 hours after the earthquake.

The estimated extent of inundation in Chignik is shown by the hatched red line in figure 3. Much of the economic activity and infrastructure for the area, along with harbors, ports, canning facilities, the airport, schools, and even City Hall and the Office of Public Safety are within the tsunami hazard 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 Nicolsky and others (2016) 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.

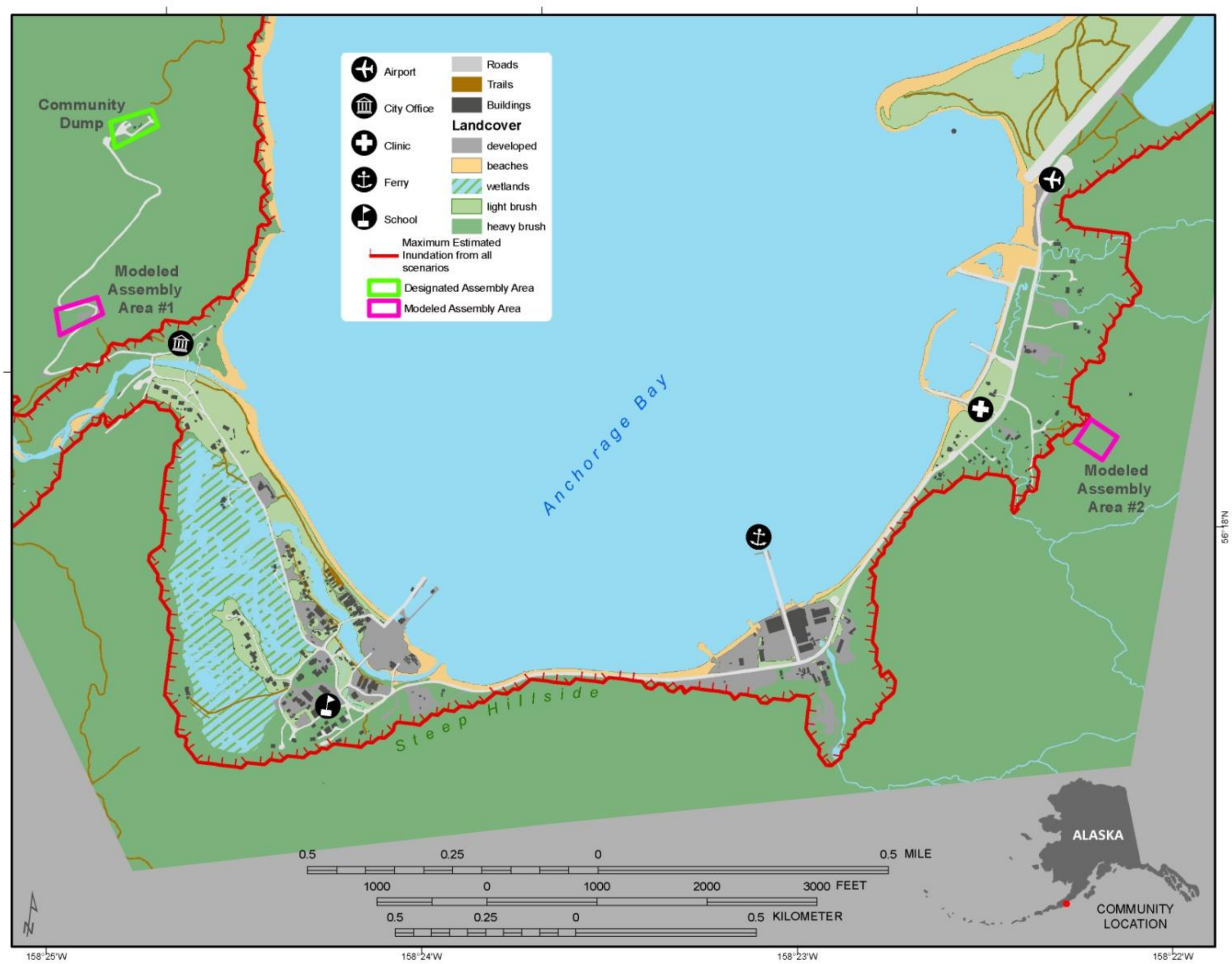


Figure 3: Map of Chignik, depicting key facilities, land cover, and the tsunami hazard zone (red line with hatch marks toward the potential inundation zone).

PEDESTRIAN EVACUATION MODELING

Pedestrian evacuation modeling and 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: 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 we considered, and the modeling results for Chignik.

We visited Chignik at the end of 2014 to gain knowledge of the physical setting, collect land-cover data, and collect other 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

All original datasets were projected to NAD83 Alaska State Plane Zone 6 m to allow us to compute the final evacuation times in meters per second. Original data sources are summarized in Table 1.

- **Tsunami Hazard Zone:** A hazard-zone polygon for PEAE was created using the modeled maximum estimated inundation line from all scenarios for Chignik (Nicolsky and others, 2016) as a boundary.
- **Assembly areas:** An assembly area may be an important building, or a place that has been agreed upon by the community as a gathering place in times of emergency, or could be just flat land that is out of the hazard zone. We chose two assembly areas: the first area is near the community dump site—where people usually go in case of the imminent tsunami hazard; the second area is near the harbor. All assembly areas are marked by green rectangles in figure 2.
- **Digital Elevation Model:** The DEM used in this study is consistent with the Chignik Tsunami DEM (Carignan and others, 2014) used by Nicolsky and others (2016) to compute the tsunami inundation. The spatial resolution of the Chignik DEM is about 15 × 16 m (49.2 × 52.5 ft). Note that the tsunami DEM was resampled 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:** A land-cover layer was created by sampling the 2011 National Land Cover Database (NLCD) for Alaska (Jin and others, 2013). We created the buildings, roads, and water portions of the land-cover dataset by extracting individual drawing layers such as roads, streams, and building footprints from a CAD dataset provided by the Alaska Division of Community and Regional Affairs. In particular, we added footprints for large tanks, eliminated some data artifacts, and removed digitizing paths through some parking lots. The heavy brush CAD layer was used to update the land cover dataset as well. We note that the CAD data are based on photography acquired during 2002 at a nominal scale of 1 m = 800 ft and referenced vertically to mean high water (MHW) and horizontally to the NAD83 datum.

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

Layer in PEAE	Data Sources
Tsunami Hazard Zone	Nicolsky and others (2016)
Assembly areas	1. Near community dump site; 2. Near old water tank
DEM	Carignan and others (2014)
Land Cover	NLCD 2011 edited
Buildings	DCRA CAD data, edited
Roads	DCRA CAD data, edited
Water	DCRA CAD data, edited
Imagery	DCRA

EVACUATION SCENARIOS

We model the pedestrian evacuation time for four scenarios. The last two scenarios have two subscenarios. 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 (1.52m/s "fast walk", if not 1.79m/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/paths 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 community dump across all terrain**

Pedestrian evacuation from the tsunami hazard zone **over all viable surfaces** to the assembly area near the community dump.

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 two assembly areas (at the community dump and near the water tank) around the boundary of the tsunami hazard zone.

Scenario 4.1. **Evacuation to the assembly area at the community dump by roads/paths only**

Pedestrian evacuation from the tsunami hazard zone **using the roads and paths** to the assembly area near the community dump.

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

Pedestrian evacuation from the tsunami hazard zone **using the roads and paths** to the nearest assembly area. We assume two assembly areas (at the community dump and near the water tank) around the boundary of the tsunami hazard zone.

MODELING RESULTS

We apply the methodology outlined in Macpherson and others (2017, this series) to compute the travel times produced by the four scenarios. The pedestrian travel-time maps are shown on 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 15 minutes. Walking times from the airport are roughly 10 minutes. The longest walking time to safety is from the dock. We note that the boundary of the tsunami hazard zone—a line to which people evacuate in this scenario—lies on steep slopes. Therefore, despite fast evacuation times out of the tsunami hazard zone some evacuees might be vulnerable to severe weather conditions, 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 roads only, the travel time to safety is significantly increased. In this scenario the longest walking time to safety is from the state ferry dock. The walking time from the state ferry dock to the boundary of the hazard zone is about 43 minutes and walking time from the airport increases to 32 minutes when only roads are used.

The community dump site functions as a present-day assembly point for the community. The computations for Scenario 3.1 reveal that walking times to the dump site are substantially higher than those from Scenarios 1 and 2, where evacuees are only making their way to the nearest hazard zone boundary. Walking time from the state ferry dock to the boundary of the hazard zone nearest the community dump is about 81 minutes and walking times from the airport, 122 minutes. The computational results according to Scenario 3.2 illustrates that the community could be well served by additional evacuation sites nearer to the harbor. We propose using the old water tank site, which has an overgrown trail leading to it, as a secondary site. In this scenario, walking times from the state ferry dock decrease to 38 minutes and from the airport, 31 minutes.

Last, we model walking times to the assembly areas via roads only. We do this in two scenarios again to show the benefit of the second assembly area in the east. Scenario 4.1 shows that walking times to the assembly area at the community dump from the airport to be 135 minutes and from the state ferry dock 96 minutes. Scenario 4.2 shows reduced walking times, to 35 minutes from the airport and 46 minutes from the state ferry dock.

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 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 2 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 a possible evacuation route comprising two tracks, from the airport entrance to the bridge near the City of Chignik office (track 1) and one route traveling up the hillside on the road to the community dump (track 2) (figure 4). Actual walking times and distances covered were recorded for each track and 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 51.27 minutes to walk 3,986 m (13,077 ft) along Track 1. Thus, an average *in situ* walking speed along Track 1 is about 1.296 m/s (4.25 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 $51.27 \times 1.296 \div 0.91 \approx 73$

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 dump) indicate that it takes about 101 minutes to cover the same route. Similar calculations are performed to compare the measured and modeled travel times along the second route, with the result being a modeled time of 17 minutes and a recalculated in situ walking time of 11.2 minutes. The model shows reasonably good agreement with the field observations along Track 2, but there is a larger difference between the modeled and actual walking times along Track 1. This could be due to accuracy 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. With a longer walk it can be assumed that the pace varies considerably as one speeds up or slows down to avoid traffic obstacles, walking faster downhill, etc., and it should be noted that this is an average pace for the length of the route. Both calculations potentially suffer from a very poor GPS signal because of the extremely poor weather, consisting of sheeting rain and dense clouds, combined with the rugged surrounding terrain.

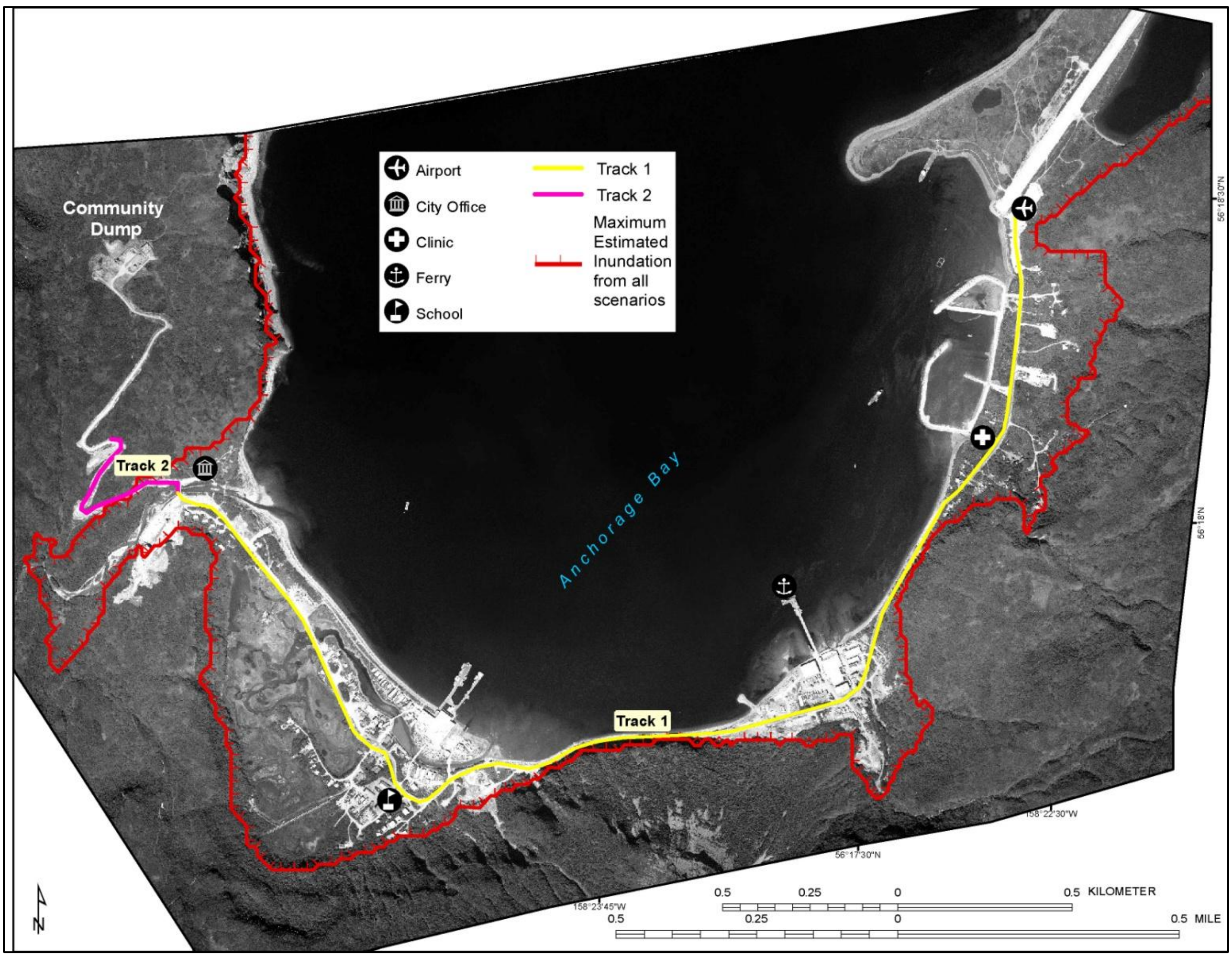


Figure 4: Tracks from site visit used to validate evacuation model times.

Table 2. Comparison of modeled times to actual walking times for Chignik.

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	51.27	3,986	1.296	101	73
2	10.05	595	1.014	17	11.2

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

Chignik poses a unique situation, as it is a small but elongated community, stretching for several miles along the low coastline. The main finding from the scenario time maps is that, because of the layout of the community, those on the far eastern side of town (near the airport) would face very long walking travel times to reach the designated evacuation gathering point at the community dump. Adding a second evacuation assembly area at the east side of the community shortens those modeled walking times considerably.

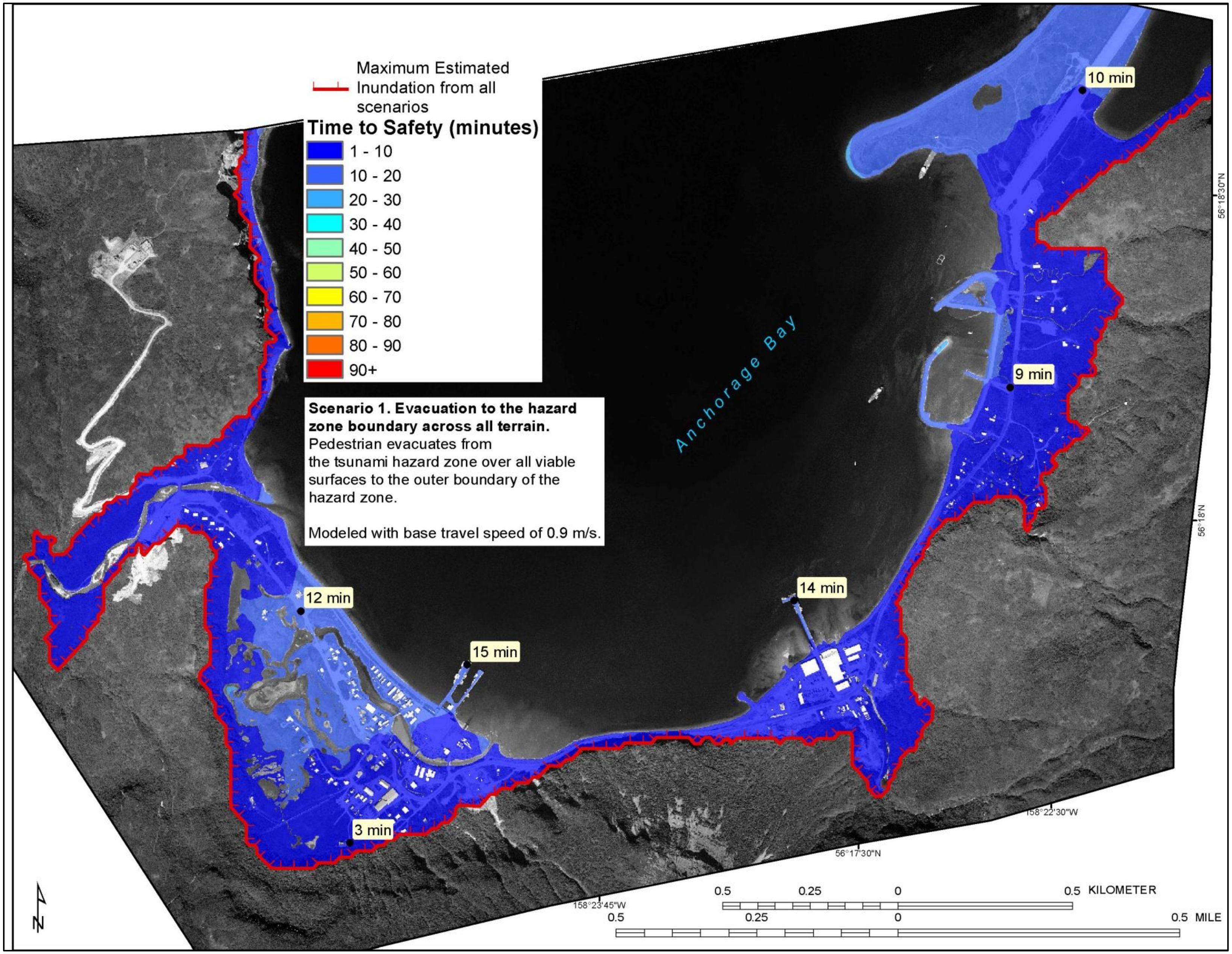
Maps accompanying this report have been completed using the best information available and are believed to be accurate; however, the report's preparation required many assumptions. In most cases the actual walking speeds proved faster than those modeled. This is preferable to the alternative, with the goal being a conservative estimate for evacuation times. The comparison for the community of Chignik is unique, in that the actual walking times vary considerably (roughly 30 minutes difference) from the modeled times. Unfortunately, poor weather conditions made it difficult to collect GPS data in this area. Further investigation into this area might be conducted if and when the digital elevation map (DEM) is updated or more data can be gathered in the field under better conditions. 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

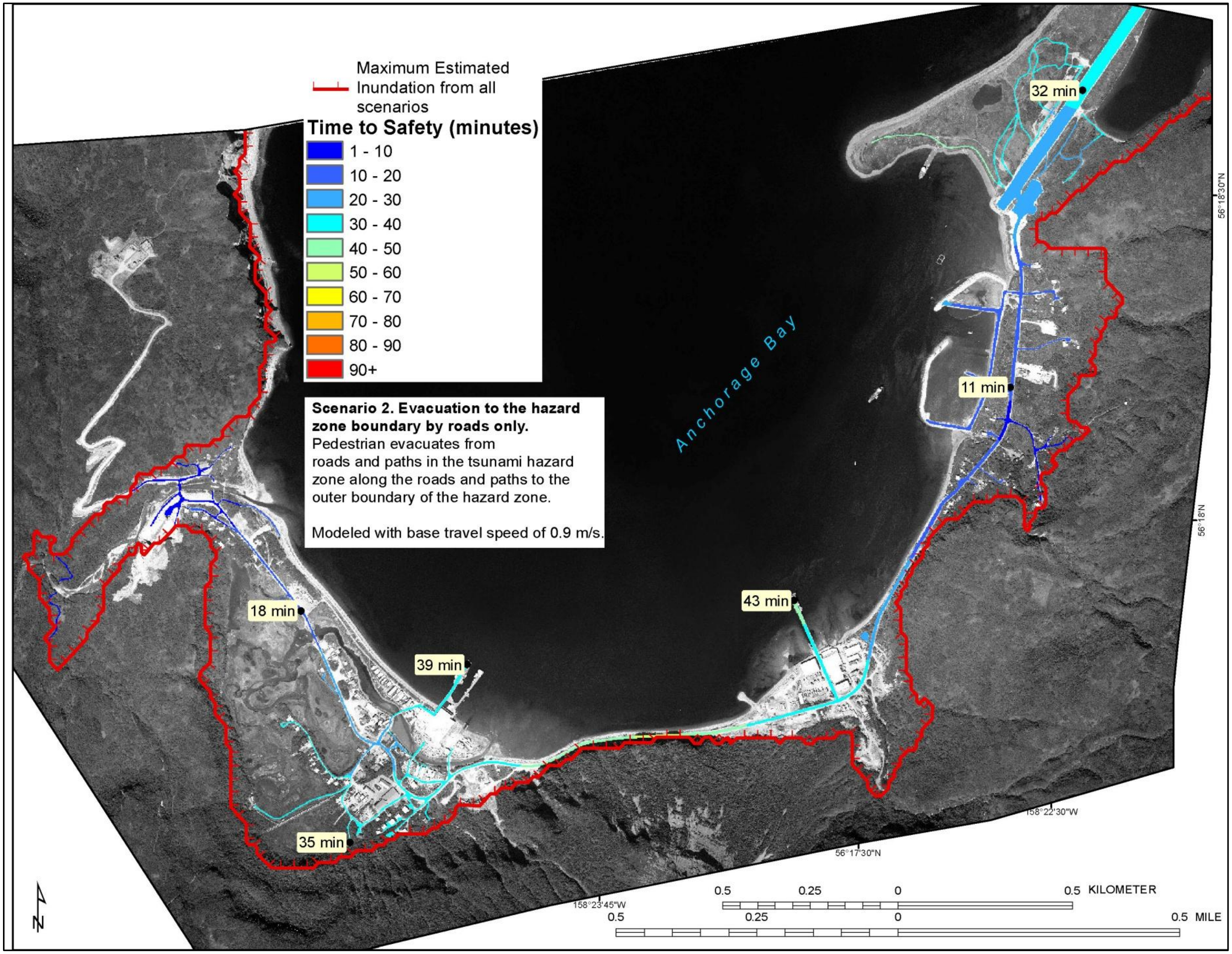
Local knowledge was invaluable to this project and the members of the community were eager to discuss their plans and thoughts. This project received support from the National Oceanic and Atmospheric Administration (NOAA) under Reimbursable Service Agreements ADN 952011 with the State of Alaska's Division 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

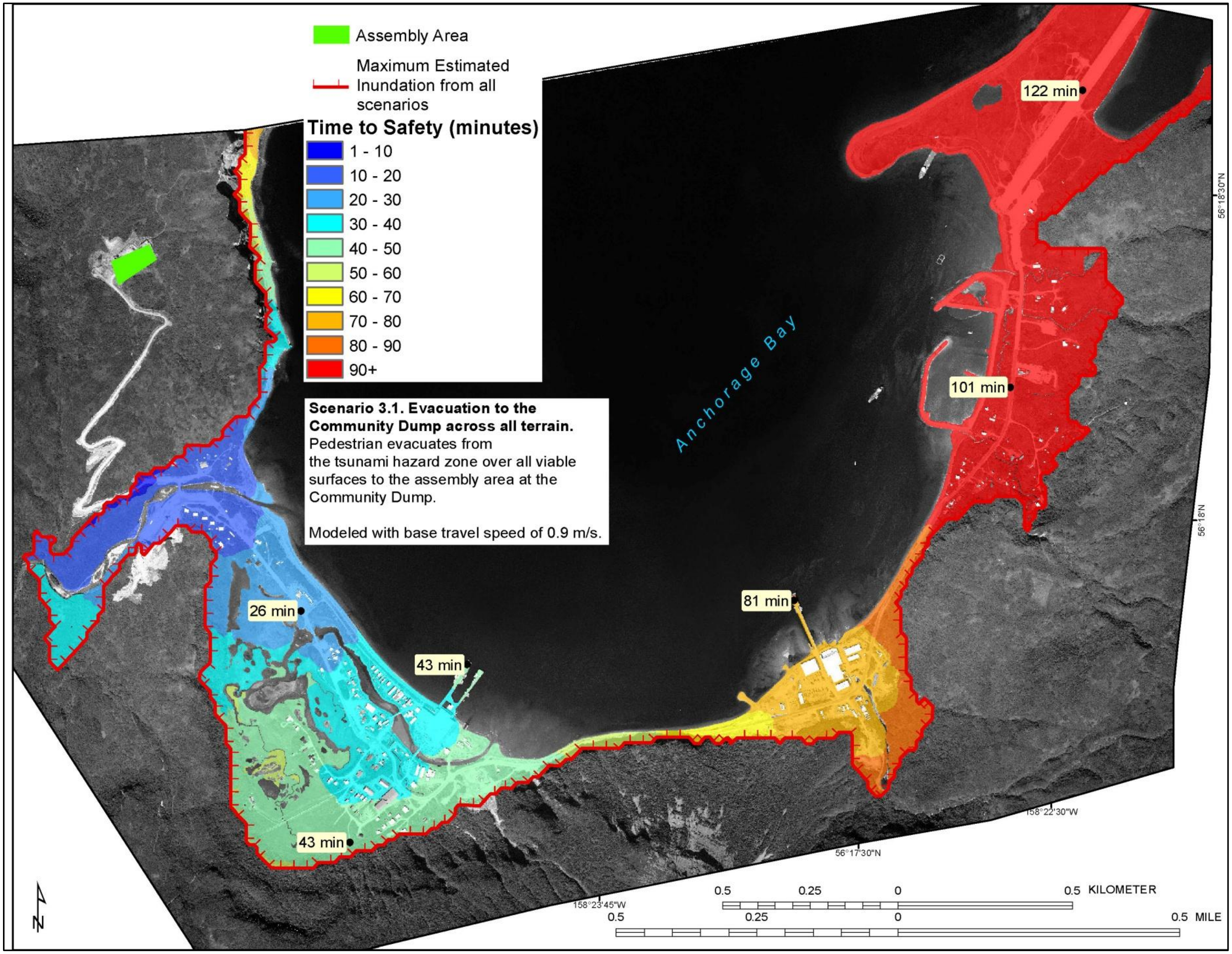
APPENDIX A: Site Visit Report for Chignik, Alaska



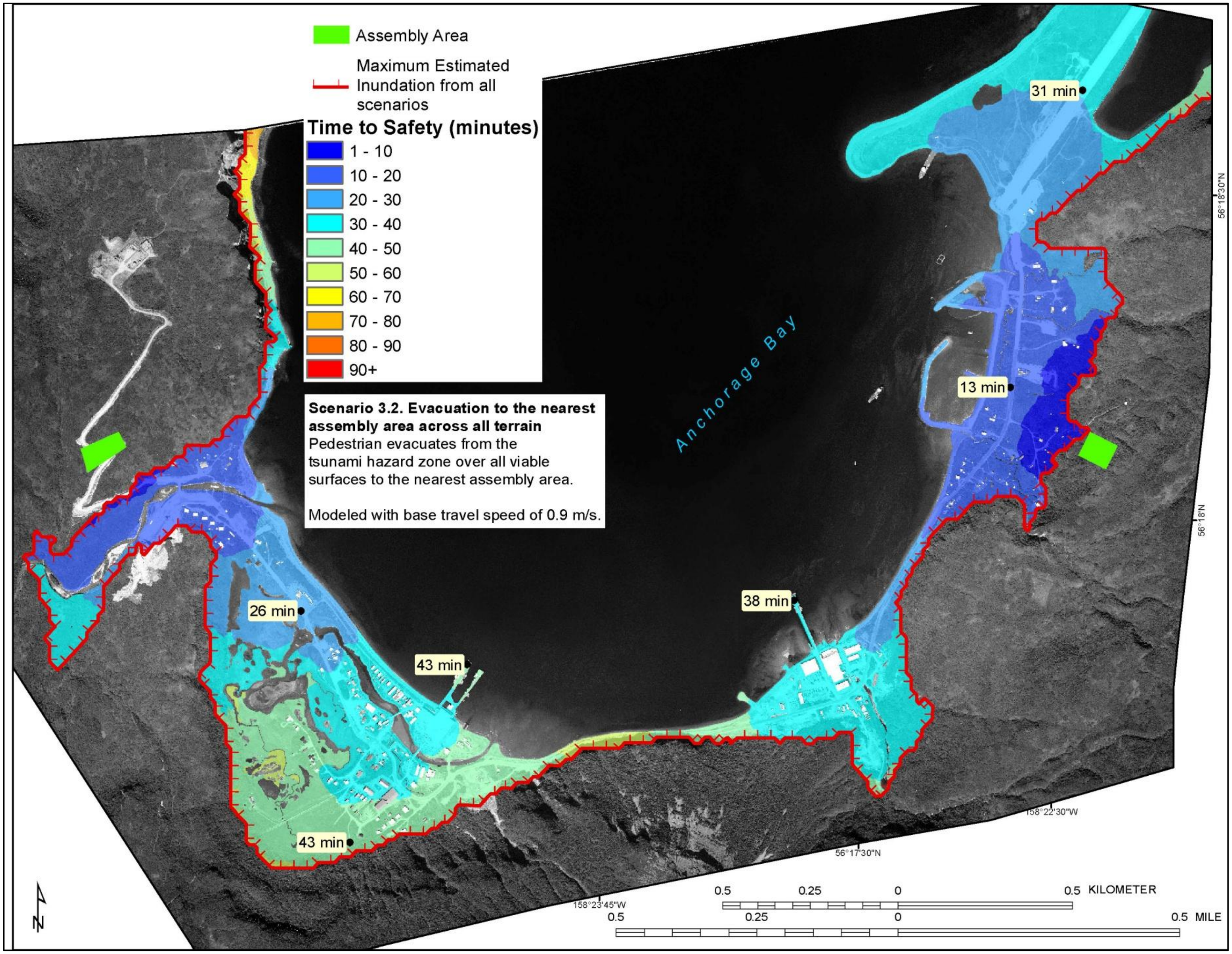
MAP SHEET 1: Travel-time map of pedestrian evacuation to the hazard zone boundary across all terrain



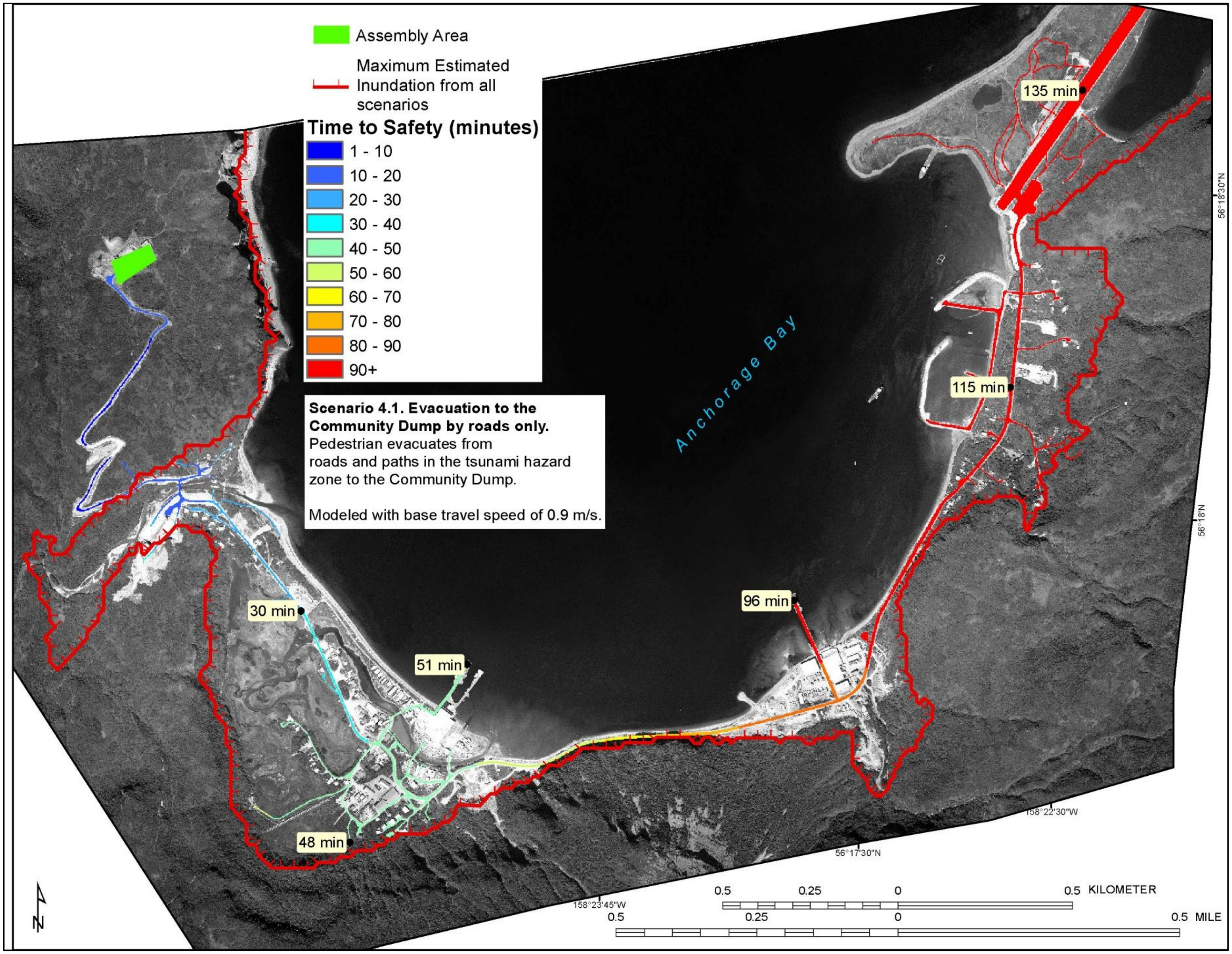
MAP SHEET 2: Travel-time map of pedestrian evacuation to the hazard zone boundary using roads only



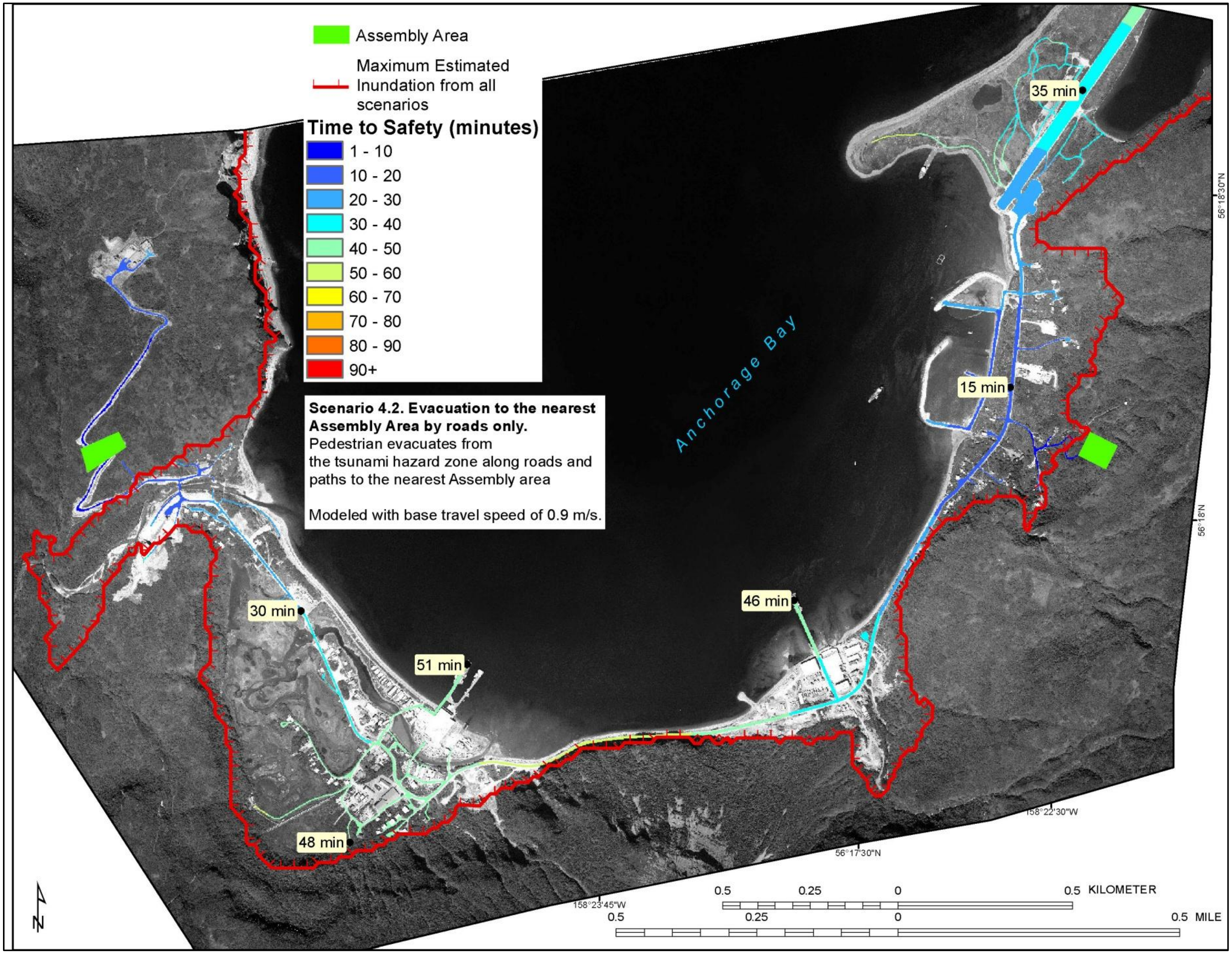
MAP SHEET 3.1: Travel-time map of pedestrian evacuation to the assembly area at the community dump across all terrain



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 dump by roads only



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

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