Technical Memorandum

Wave Numerical Modeling

Monroe County Roadway Vulnerability Analysis and Capital Plan
Monroe County, Florida

August 26, 2020

Prepared for Monroe County

FDR

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1 Introduction

As the governing body of the Florida Keys, Monroe County is conducting a vulnerability study of the region's roadways to sea level rise (SLR), king tides, and waves. HDR performed a wave vulnerability study using MIKE21 Spectral Wave (MIKE21 SW) numerical modeling software to provide projections of potential roadway vulnerability to wave impacts during seasonal storms, which are magnified by SLR and exceptionally high tides, sometimes referred to as king tides. According to Church et al. (2013), "the east coast of North America has a chance of experiencing higher Sea Level Rise relative to the global mean, with southern Florida projected to experience a 10-20% higher rise in sea level." This rise in sea level increases the impact of king tide events while allowing extreme and seasonal storm events to penetrate deeper inland. This technical memorandum provides a brief description of the planning and execution of the Monroe County Roadway Vulnerability Study wave numerical modeling effort. It consists of a description of the project location, the purpose of the study, a description of the data, model setup, and results.

1.1 Location

The Florida Keys are a chain of low-lying islands located south of mainland Florida between the Straits of Florida to the east, and the Gulf of Mexico to the west. The location and low elevation of the Florida Keys have made them susceptible to extreme weather, high water level events, and wave impacts during those events. The roadway vulnerability study focused on County roadways in three regions within the Keys: Upper Keys (Key Largo), Duck Key, and Lower Keys (Key West) shown in Figure 1. Roadways assessed in the study were selected by Monroe County.
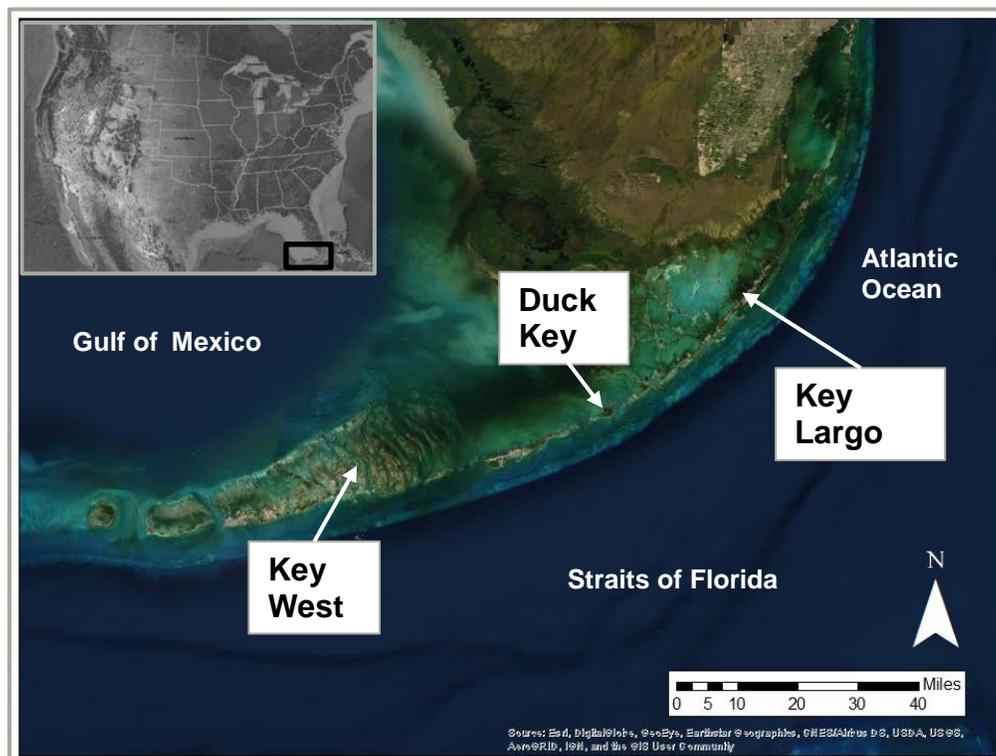

Figure 1: Location map showing regions of interest in the project study

1.2 Approach

The vulnerability study assessed the potential for wave induced impacts to county roadways within Monroe County at increasing levels of SLR and during king tide conditions. The wave conditions used for the study are seasonal wave events generated by inclement wind conditions. Hurricanes and more severe storms with recurrence intervals greater than 1 year were considered but were ultimately not modeled. During these more severe events, the roadways are expected to be completely inundated and much of the wave energy will pass over the roads. The intent of this study was to focus on events that would impact the daily lives of residents and visitors. In addition, understanding impacts from seasonal events will provide decision makers with additional information on areas that may need erosion protection, raised roads, or future increased maintenance. Ultimately, wave vulnerability was assessed for seven SLR scenarios that were developed under a separate phase of this study conducted by Wood (2019). These include anticipated SLR values for the years 2025, 2030, 2035, 2040, 2045, 2060, and 2100. Numerical wave modeling was performed to develop wave conditions for each scenario.

The numerical wave modeling was performed using the MIKE21 SW software. MIKE21 SW, developed by the Danish Hydraulic Institute (DHI), is a software package for creating spectral wind-wave models based on a flexible (unstructured) mesh. The model simulates growth, decay, and transformation of wind-generated waves and swell in offshore and coastal areas (DHI, 2017).

Modeling simulations were forced by wind and wave climates extracted from the United States Army Corps of Engineers (USACE) Wave Information Studies (WIS) hindcast stations. These wave climates were applied as a constant wave height, wave period, and wind speed across the offshore model boundary. Typically, when using MIKE21 SW a model can be refined around the project site, but the size of the study area meant that refinement of a single model domain would significantly increase the model run time and reduce efficiency. Therefore, a larger regional domain with a smaller nested domain approach was adopted. This methodology uses the results of regional models to develop a wave climate at the boundaries of nested domains located within the regional model. The smaller, more refined nested domains then transformed the waves to the areas of interest. This approach reduces overall model run time and generates more accurate results at the project sites.

2 Forcing Data

The model inputs consisted of wave, wind, and water level data. Details of the specific inputs applied to the model are included in this section.

2.1 Water Level

2.1.1 Sea Level Rise

The water level data used SLR projections provided by Wood (2019) coupled with king tide events. Wood (2019) conducted an assessment of available SLR projections provided by the Intergovernmental Panel on Climate Change (IPCC), USACE, and the National Oceanic and Atmospheric Administration (NOAA). Wood (2019) suggests basing SLR projections on the intermediate-high scenario calculated by NOAA (2017). A summary of the recommendations is shown in Table 1 below with elevations relative to Mean Sea Level (MSL).

Table 1: Projected SLR values from NOAA 2017 study (Wood 2019)							
Time Period	2025 (in, MSL)	2030 (in, MSL)	2035 (in, MSL)	2040 (in, MSL)	2045 (in, MSL)	2060 (in, MSL)	2100 (in, MSL)
Intermediate-Low	5	6	7	8	10	13	21
Intermediate	7	9	11	12	14	21	46
Intermediate-High	9	12	14	17	20	31	74
High	11	14	18	21	25	41	103

2.1.2 King Tides

Using the NOAA Tides and Currents database, Wood (2019) extracted water level data for 22 years (1996 to 2018) at three tide stations. Locations of the tide stations are provided in Figure 2. The tide stations provided water elevation data, which included normal tide conditions and other meteorological effects. The data was processed to remove the normal tidal signal providing isolated king tide events and wind setup over the data record. The resulting peak king tides are shown in Table 2. Wood (2019) recommends using king tide water levels calculated at the Naples tide station for the modeling run because it contained the largest projected water levels.
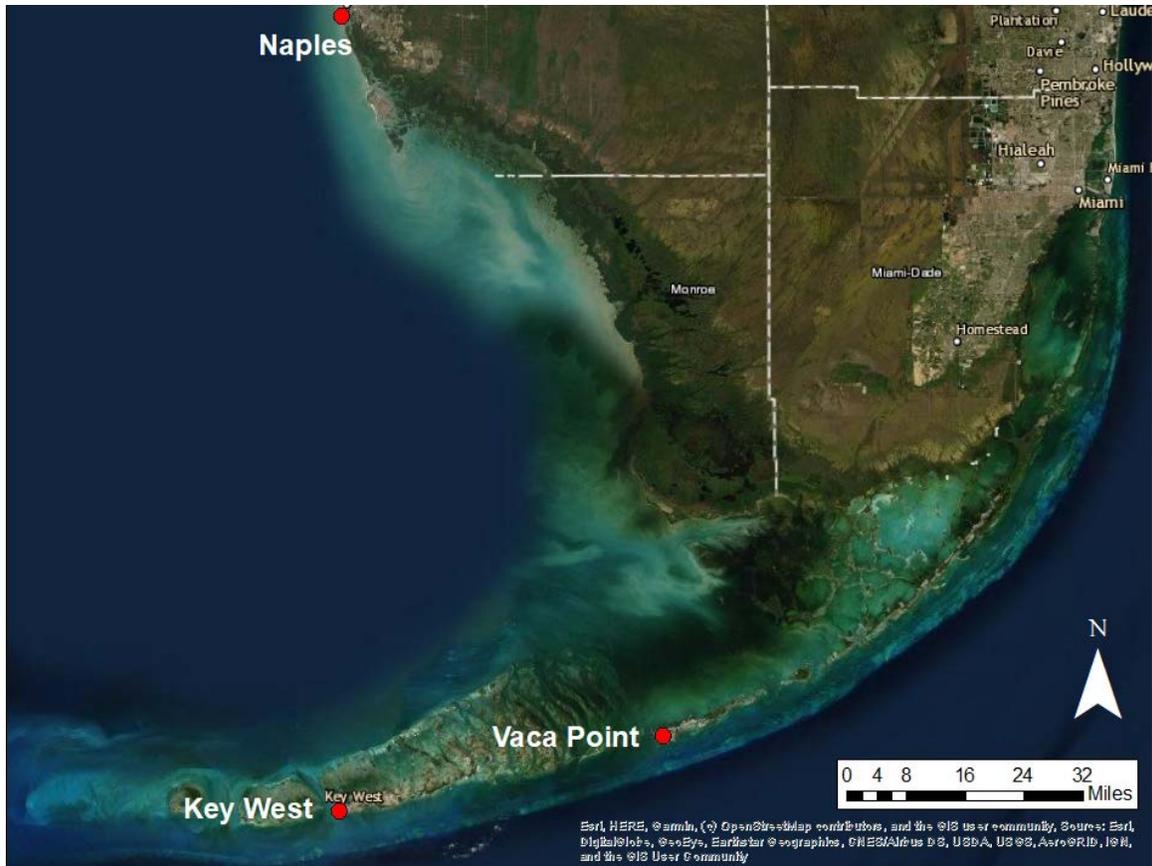
Figure 2: Location of NOAA tide stations used in Wood (2019)

Table 2: Peak water levels observed at different locations during king tide events		
Location	**King Tides Water Level (in, MSL)**	**Wind Setup (Mean) Water Level (in, MSL)**
Key West	20.9	2.4
Vaca Key	13.8	2.4
Naples	25.6	2.8

2.1.3   Modeled Water Level

Water levels used in the wave modeling added the intermediate-high SLR values, as shown in Table 1, to the peak king tide water level. A summary of the combined water levels is shown in Table 3. Numerical modeling simulations were conducted in meters with elevations relative to the North American Vertical Datum of 1988 (NAVD).

Table 3: Modeled Water Elevations				
Year	Water Level (in, MSL)	Water Level (ft, MSL)	Water Level (m, MSL)	Water Level (m, NAVD)
2025	37.5	3.13	0.95	0.76
2030	40.1	3.34	1.02	0.83
2035	42.5	3.54	1.08	0.89
2040	44.9	3.74	1.14	0.95
2045	48.2	4.02	1.22	1.03
2060	59	4.92	1.50	1.31
2100	102	8.50	2.59	2.40

2.2 Wave and Wind Data

Representative seasonal wind conditions that can occur during the king tide events were used to force the regional wave models. The intent was to simulate wind conditions not associated with tropical cyclones, but that occur within the same season as king tide events. The following provides an outline of the analysis that was used to determine the input conditions for winds and waves.

1. Wind and wave data was downloaded from USACE Wave Information Studies Stations 63495, 63487, and 63477 for the period from 1980 to 2014.
2. The months during which king tides occur, October and September, were isolated in the data set with data from all other months removed.
3. Tropical cyclone events were identified and removed from the data set. These events were determined by identifying wind speeds greater than 38 mph (minimum wind speed associated with tropical depressions). The remaining periods were then cross-referenced with a list of historical tropical cyclones to confirm that they were not associated with categorized storms.
4. Wind and waves approaching from directions that were determined to not significantly impact the areas of interest were removed. The remaining wind and wave directions that were used are summarized in Table 4.
5. The largest spectral mean wave height (H_{mo}) and associated peak period (T_p) and wind speed were then determined using the remaining filtered data and are summarized in Table 4.

Table 4. Modeled wave conditions						
WIS Station	Max H_{mo} (ft)	Max Hmo (m)	Tp (s)	Max Wind Speed (mph)	Max. Wind Speed (m/s)	Direction Range (Degrees)
Lower Keys (Key West)						
ST63495	8.7	2.65	7.3	34.4	15.4	100 - 120
Duck Key						
ST63487	7.3	2.23	6.7	27.3	12.3	100 - 135
Upper Keys (Key Largo)						
ST63477	7.1	2.16	6.2	27.5	12.4	90 - 135

3 Model Mesh

3.1 Model Domain

Given the large spatial area of the study, three regional model domains were developed for each project study area. Splitting the overall area of interest allowed for finer resolution in the model mesh. The three regional domains focused on the southern section of the Upper Keys (including Key Largo), Duck Key, and the Lower Keys (including Key West). Each regional domain was used to simulate offshore wave conditions and therefore extended 10 miles offshore to an approximate depth of 700 feet to align with the WIS station locations. The model domains are shown in Figure 3.
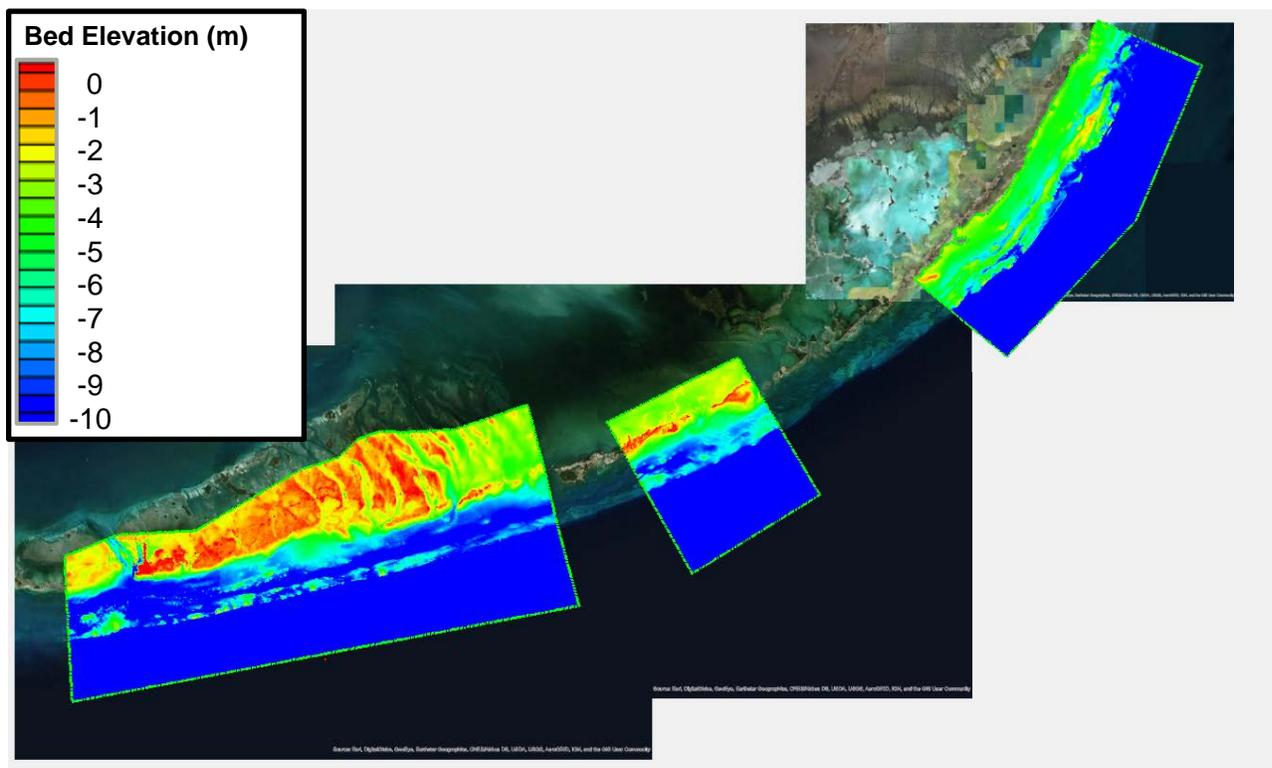
Figure 3. Location of regional domains

Eight nested domains were developed to increase model resolution and add precision to the model bathymetry and simulation of wave conditions. Five domains are within the Lower Keys regional domain (Key West, Naval Air Station, Pine Key, Sugarloaf Key, and Summerland Key), one is in the Duck Key regional domain, and two are in the Upper Keys regional domain (Key Largo and Tavernier). Figure 4 shows the location of the nested domains.
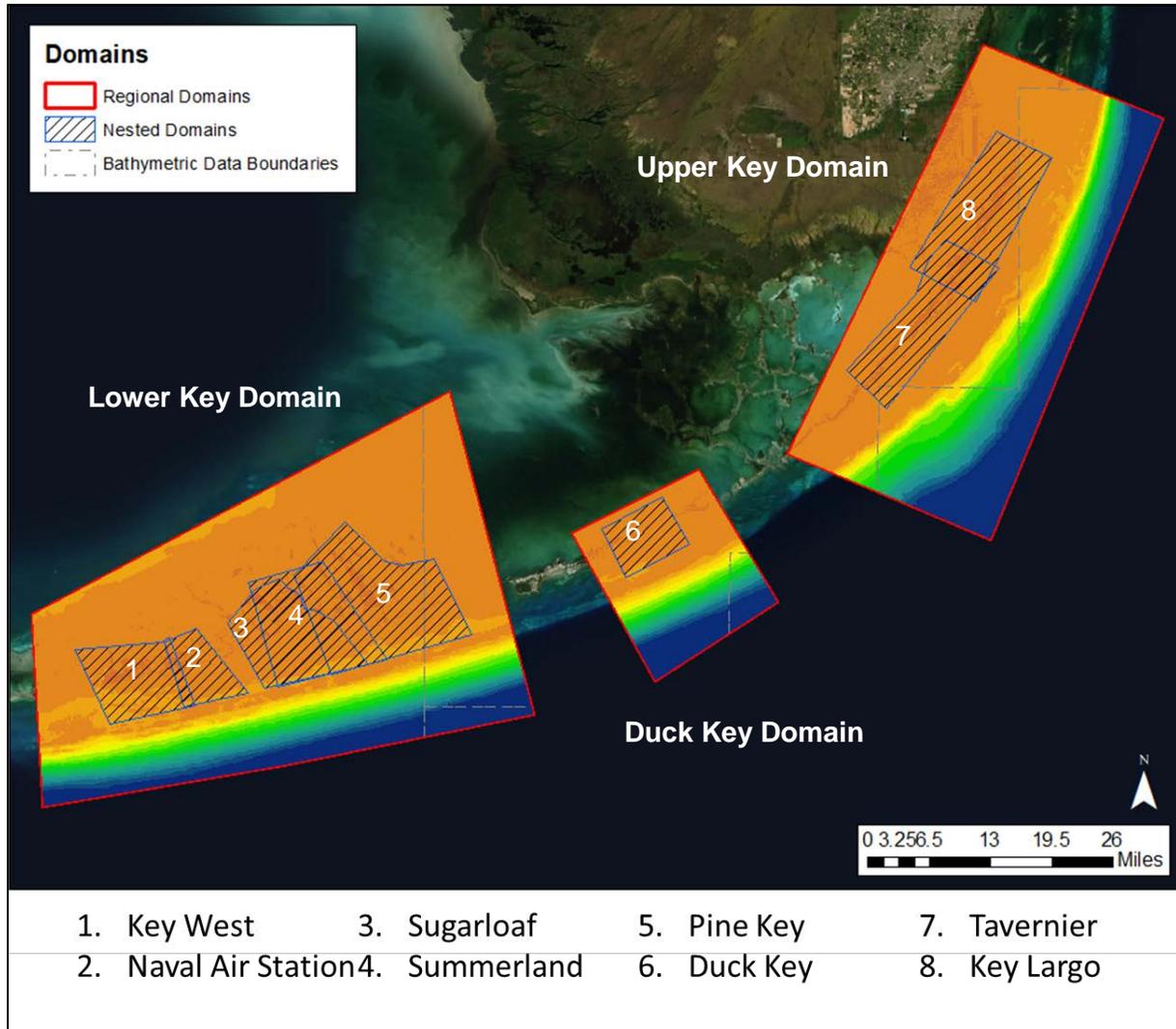
Figure 4. Location of nested and regional model domains

The elements in the modeling domains were largest offshore and decreased in size towards shallower water, which increases the resolution near the project sites. The meshes targeted higher resolution in areas of expected wave transformation such as steep slopes, channels, and other bathymetric or topographic features. The highest element resolution occurred at roadways of interest. The size of the fine elements varied from 50 m^2 and 5,000 m^2. The size of the coarse elements offshore or in areas far from the project location varied from 5,000 m^2 to 45,000 m^2.

3.2 Bathymetric and Topographic Data

Bathymetric and topographic data were gathered from NOAA bathymetric data sets and Monroe County topographic data. The NOAA bathymetric data include the following datasets:

- Continuously Updated Digital Elevation Model (CUDEM)
- Florida Keys Digital Elevation Model (DEM)
- U.S. Coastal Relief Model (CRM)

The CUDEM dataset was used for the Upper Keys and Duck Key regional and nested domains. The dataset has a 1/9th arc second (10 ft) resolution. The CRM dataset was also used for the offshore conditions in the Upper Keys regional and the Duck Key regional domains, but the resolution was too coarse for use in the nested domains. The Florida Keys DEM dataset was used on the Lower Keys regional and nested domains. This dataset has a 1/3rd arc (33 ft) resolution. Figure 5 shows the limits of the data sets used.

Monroe County provided a 0.8 m (2.75 ft) resolution road survey and a 3 m (10 ft) resolution topographic dataset, which were used to model the roadways and other upland topographic features.
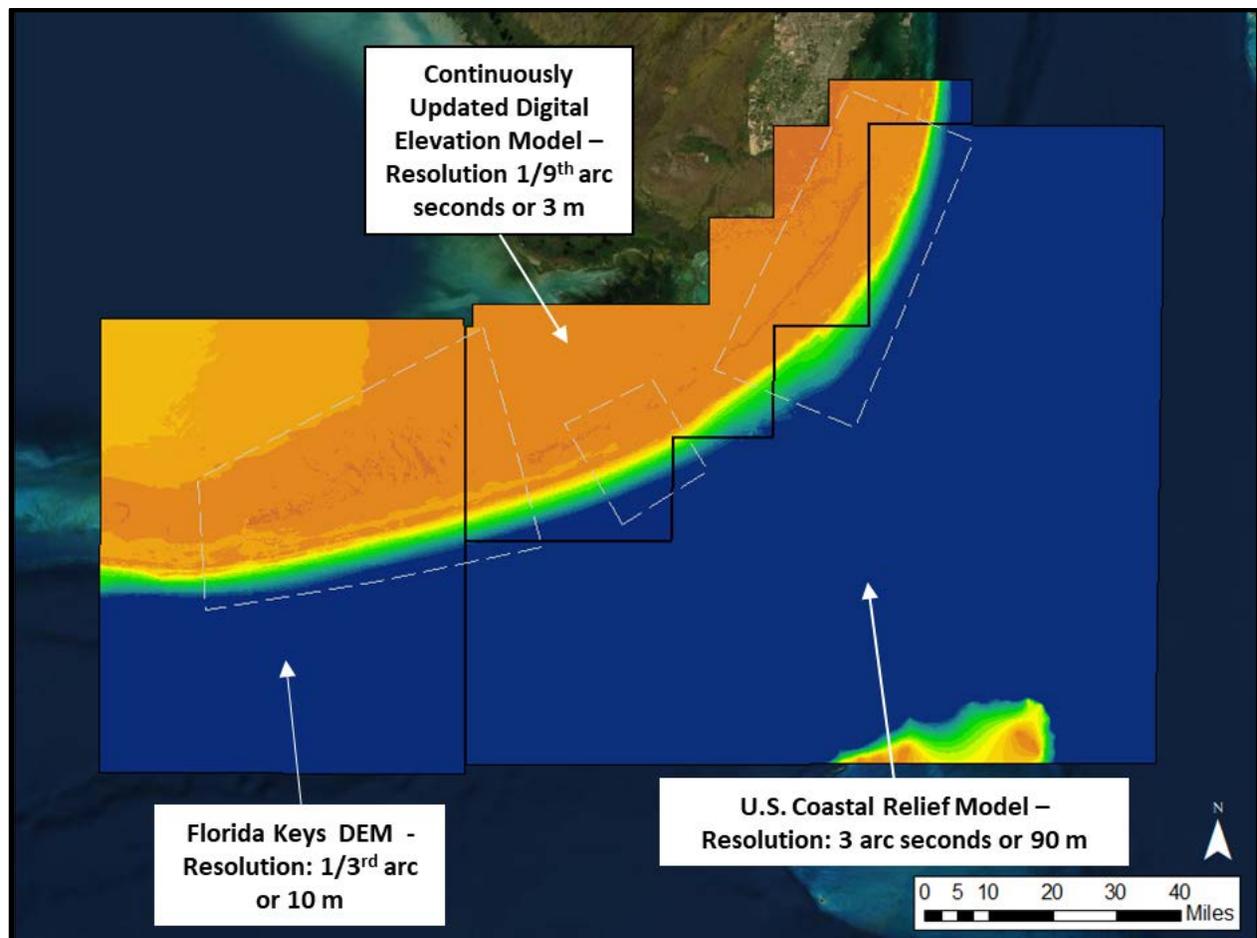

Figure 5: Location of bathymetric/ topographic datasets used to develop model domains

4 Model Setup

4.1 Boundary Conditions

The models consisted of three boundary types; closed boundaries, lateral boundaries, and forced boundaries. Closed boundaries absorb wave energy and do not reflect or generate it. These boundaries were placed on land or at areas where waves would typically exit to prevent unrealistic wave reflection back into the domain. Lateral boundaries provide an interpolated wave height along the boundary by solving a "one dimensional calculation and basic equation along the boundary line" (DHI, 2017). These boundaries were placed perpendicular to the coast and help reduce potential unrealistic shadow zones. The forced boundaries apply a wave height, direction, and period along the boundary. The regional domains used a constant wave condition. Wave results from the regional wave models were then applied as the input wave conditions along the offshore boundary of the nested models. Figure 6 and Figure 7 below show the locations of these boundaries for an example regional domain and nested domain.
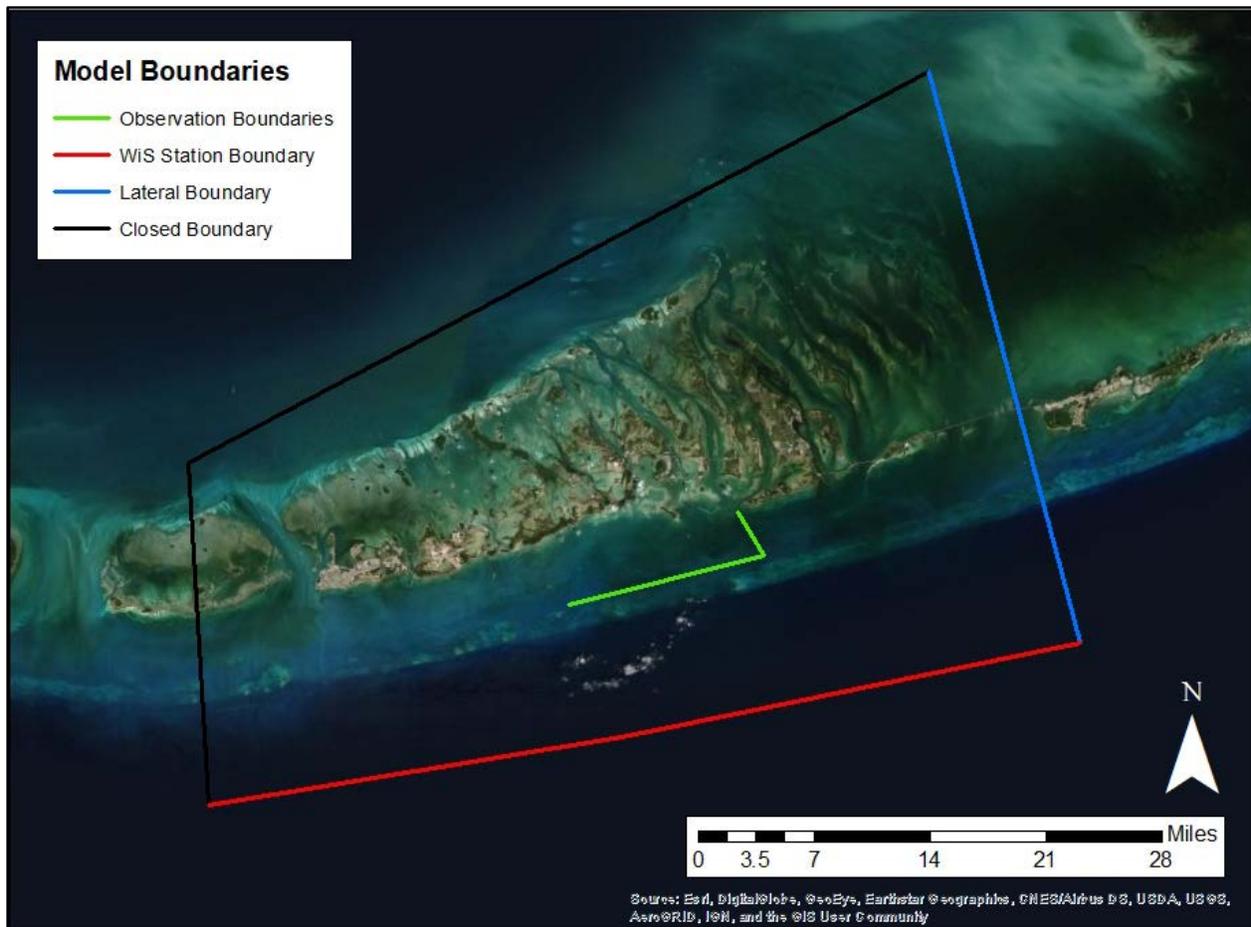
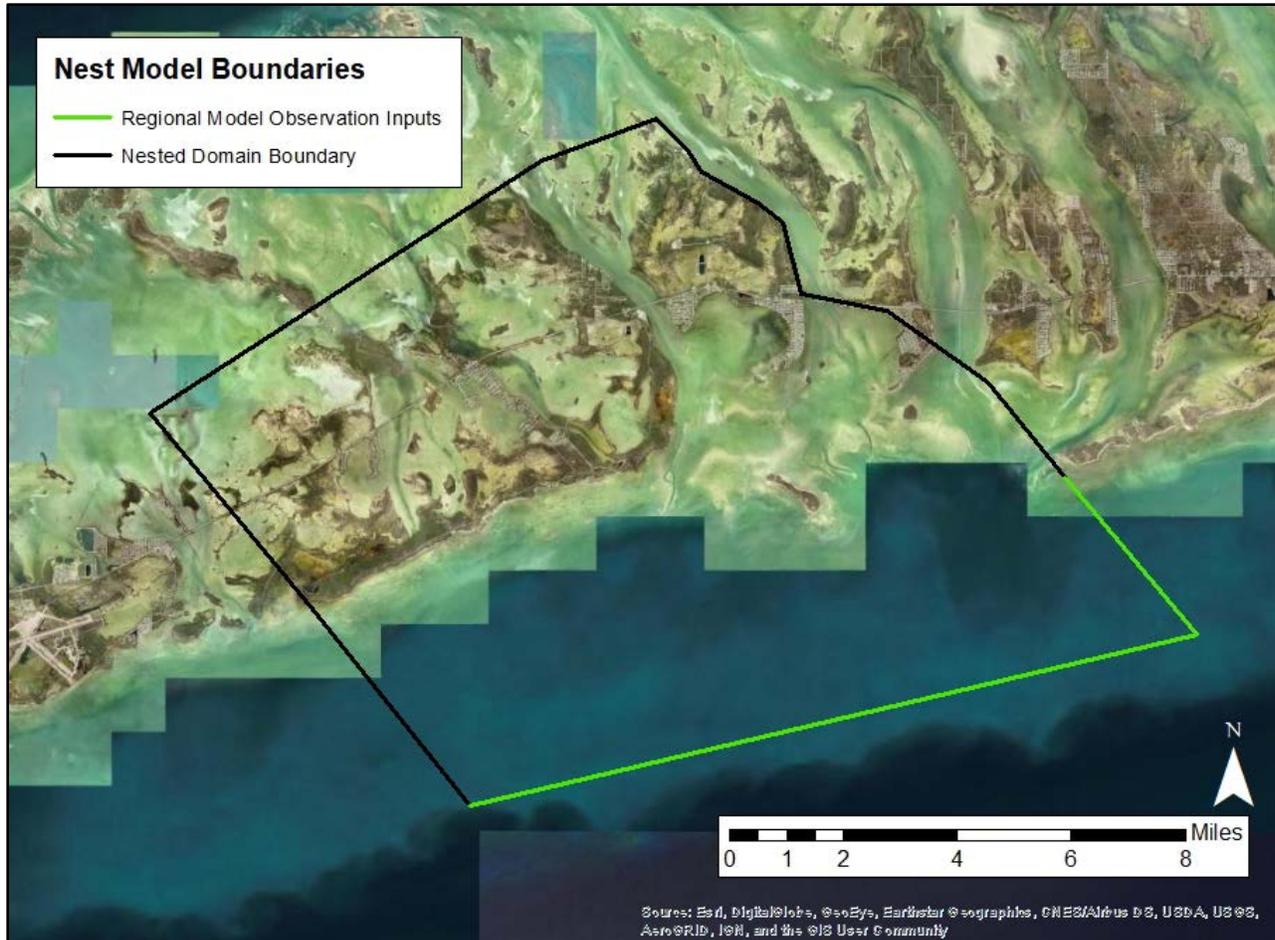**Figure 6: Example of regional domain model boundary conditions location**

Figure 7: Example of nested domain model boundary conditions location

4.2 Model Parameters

The wave model used a fully spectral, quasi stationary formulation. The quasi stationary formulation allows each time step to consist of an independent forcing criteria, allowing a single model to run multiple cases. Other parameters were selected following MIKE21 SW guidance and past experience.

5 Results

5.1 Limitations

Limitations concerning developed areas and heavy vegetation must be considered when reviewing the model results.

Developed areas: The three-dimensional and complex effects of individual homes and buildings in developed areas cannot be represented with high accuracy using the MIKE21 SW model. Therefore results within and on the leeward side of developed areas are expected to have less accuracy. Because developed areas (houses, buildings, etc.) are expected to reduce the approaching wave energy, roadways within these areas are not expected to be at risk from damaging waves.

Heavy Vegetation: The Florida Keys have various forms of vegetation in the region that are dense in coverage and which may aid in reducing wave energy as waves pass through the area. Because model bathymetry is not able to distinguish between differing types of vegetation, modeled waves traveling through areas where known dense vegetation occurs are anticipated to be conservative.

To provide a more complete assessment of wave impacts when considering developed areas and dense vegetation, model results were qualitatively analyzed to identify roadways where vulnerability may be impacted by vegetation or development as described in Section 5.2.

5.2 Post Processing Approach

The model results provide the significant wave height across the full domain for all of the wind conditions modeled. These results were processed to provide a dataset showing the maximum significant wave height at each point throughout the model domain considering all wind directions. These results were then interpolated along the county roadways to determine significant wave heights continuously for all roadways of interest. Because all of the wind directions are considered, wave results applied to the roadways should be considered conservative in this analysis. Two adjacent roadways may have the same level of wave vulnerability but are based on different wind and wave directions. These results are intended to provide a qualitative assessment of potential vulnerability.

5.2.1 Developed Areas

As described in Section 5.1, roadways that are located within developed areas or significantly sheltered by land and other upland features were not included within the analysis. Because of their location, waves during typical seasonal events are not expected to occur. These areas are labeled as "Development" within the results figures in the following sections.

5.2.2 Vegetation Protected Roadways

Vegetation has the potential to reduce incoming wave heights (wave dissipation) due to drag force. This is particularly true for emergent vegetation such as mangroves found throughout the Florida Keys, which have shown to be particularly effective at wave dissipation (McIvor, 2012).

The complexity of the dissipation process makes it difficult to effectively recreate it in the model. Typically, vegetation is represented in models using Manning maps, which are layers that identify the location of vegetation and apply a roughness value to represent the dissipation that occurs over the vegetation. However, this approach ignores complex dissipation processes that can result in significant underestimation of wave dissipation (drag forces, turbulent flow etc.). Since wave heights are very sensitive to these calibration parameters, the use of these methods was determined to not be appropriate for this study. Instead, the vegetation was qualitatively analyzed using a combination of US Geological Survey (USGS) land cover data and aerial photographs. The land cover data provides information on the type of vegetation while the aerial photographs were used to verify the data. Roadways with over 300 ft of vegetation between the roadway and the land-water boundary to obstruct incoming waves were identified as low vulnerability roads (McIvor, 2012). Figure 8 shows an example of the land cover data and roadways considered potentially protected by the vegetation.

5.3 Roadway Vulnerability Designations

According to the Federal Highway Administration (FHWA) Hydraulic Engineering Circular (HEC) HEC-25 Section 8.2, wave attack is a failure mechanism of coastal roadways that can either directly erode the seaward shoulder of a roadway or "exacerbate the weir-flow damage mechanism". Sediment erosion typically occurs when hydrodynamic forces are large enough to suspend sediment in the water column. Once the sediment is suspended, current transports it downstream. The oscillatory motion and the wave impact caused by propagating and breaking waves are effective at suspending and transporting sediment. When this process occurs near roadways it can undermine existing roadways making them less structurally stable and more likely to fail.

Beside structural failure of roadways, failure can also occur when traversing a roadway becomes too hazardous for vehicles and pedestrians. The combination of high water levels, currents, and waves can make using roadways potentially hazardous.

HEC-25 Section 3.3.1 suggest that wave heights that reach 0.5 ft or higher can begin to cause damage to roadways. The roadways in the study were separated into areas exposed to no waves, wave heights between 0 ft – 0.5 ft, wave heights between 0.5 ft – 1 ft and wave heights larger than 1 ft. The vulnerability categories used to classify the roadways are shown in Table 5 below.

Figure 8. Roadways potentially protected by vegetation

Table 5. Vulnerability categories, wave heights, hazard levels, potential failure, and course of action				
VULNERABILITY CATEGORIES	**ASSOCIATED WAVE HEIGHT**	**WAVE HAZARD LEVEL[1]**	**POTENTIAL FAILURE**	**POSSIBLE COURSE OF ACTION**
Vegetation	Waves obstructed by vegetation	Low[2,5]	No Wave damage[5]	--
Development	Waves obstructed by infrastructure	Low[2,5]	No Wave damage[5]	--
No Vulnerability	0 ft	Low[2,5]	No Wave damage[5]	--
Low Vulnerability	0 ft - 0.5 ft	Moderate[3]	Minor erosion	Monitoring
Moderated Vulnerability	0.5 ft - 1 ft	High[4]	Possible Erosion/ Undermining	Monitoring / Maintenance
High Vulnerability	Above 1 ft	High[4]	Significant Erosion/ Structural Damage	Monitoring/ Revetments/ Seawalls/ Breakwaters/

Notes:
1. Hazards represent dangers to pedestrians and vehicles
2. Low Hazards indicate a climate where wave action should not pose a danger to pedestrians or vehicles.
3. Moderate Hazard indicates potential danger to pedestrians or vehicles
4. High Hazard indicates dangerous wave conditions for pedestrians or vehicles
5. No wave damage or low wave hazard does not mean that these areas are not vulnerable to damage associated with general flooding.
6. SLR can impact vegetation growth, causing loss in some cases that could alter the classification of the regions based on their exposure. It is therefore recommended to monitor vegetation development trends to identify roadways that may be at risk in the future.

5.4 Roadway Vulnerability Results

The following sections provide observations of roadway vulnerability results for the various study locations for the years 2025, 2030, 2035, 2040, 2045, 2060, and 2100. Detailed results for each year and location can be found in the appendices. In addition, the roadway vulnerability can be viewed in more detail using the Monroe County Roadway Vulnerability Study online GIS viewer.

5.4.1   2025 Roadway Vulnerability Results

5.4.1.1   UPPER KEYS 2025 VULNERABILITY RESULTS OBSERVATIONS

The Upper Keys region contained a significant amount of vegetation that reduced vulnerability. The ground elevations of the Upper Keys were generally higher than the Lower Keys, resulting in overall lower vulnerability. From the 2025 vulnerability results, the majority of the Upper Keys domain show low to no vulnerability to incoming waves. Figure 9 provides the 2025 vulnerability results for the Upper Keys.

5.4.1.2   DUCK KEY 2025 VULNERABILITY RESULTS OBSERVATIONS

Duck Key was the least vulnerable of the 3 regions assessed which is primarily attributed to the breakwater surrounding the site. A significant portion of Duck Key was also designated as no

vulnerability due to the majority of the roadways being located in the interior of the neighborhood. Conch Key to the northeast, however, was found to have moderate vulnerability in 2025. Figure 10 provides the 2025 vulnerability results for Duck Key.

5.4.1.3   LOWER KEYS 2025 VULNERABILITY RESULTS OBSERVATIONS

A majority of the Lower Keys domain experienced no to low wave vulnerability. However, spots of moderate to high vulnerability can be found in the Pine Key domain found in Figure 12. Areas of moderate to high roadway vulnerability were also present in the Key West and Naval Air Station domains shown in Figure 11.
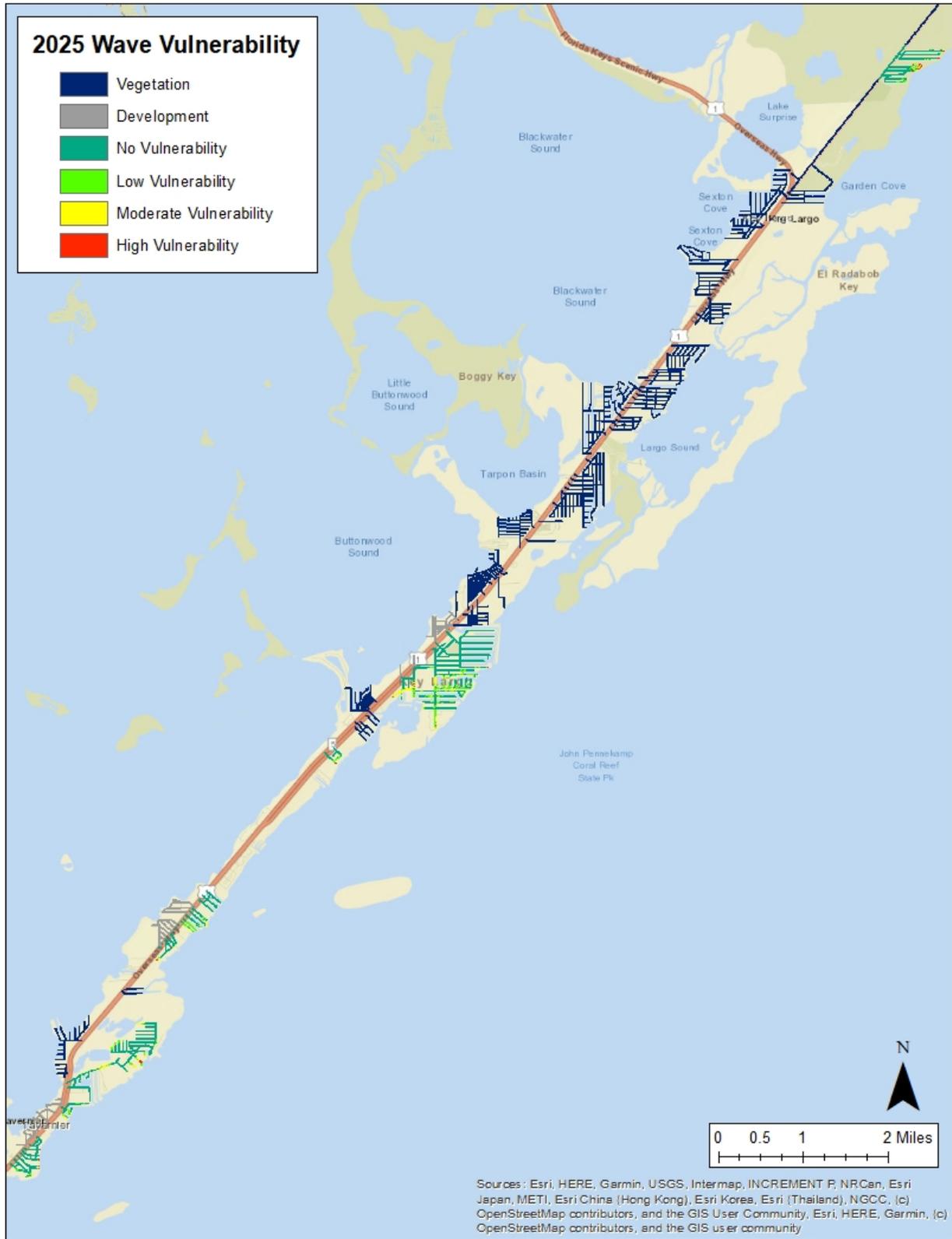
Figure 9: 2025 Upper Key vulnerability results

Figure 10: 2025 Duck Key vulnerability results
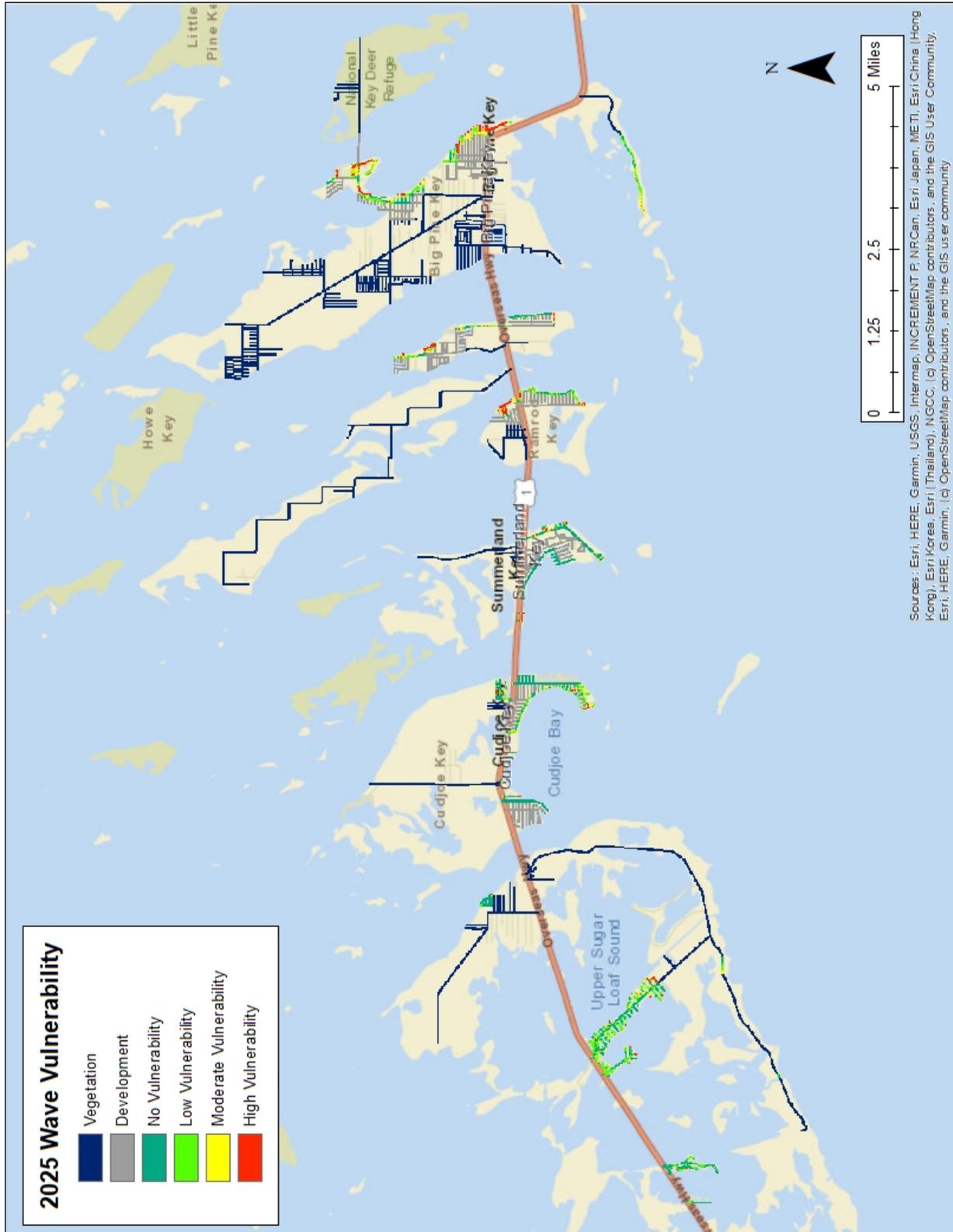
Figure 11: 2025 Sugarloaf, Summerland and Pine Key vulnerability results

2025 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability
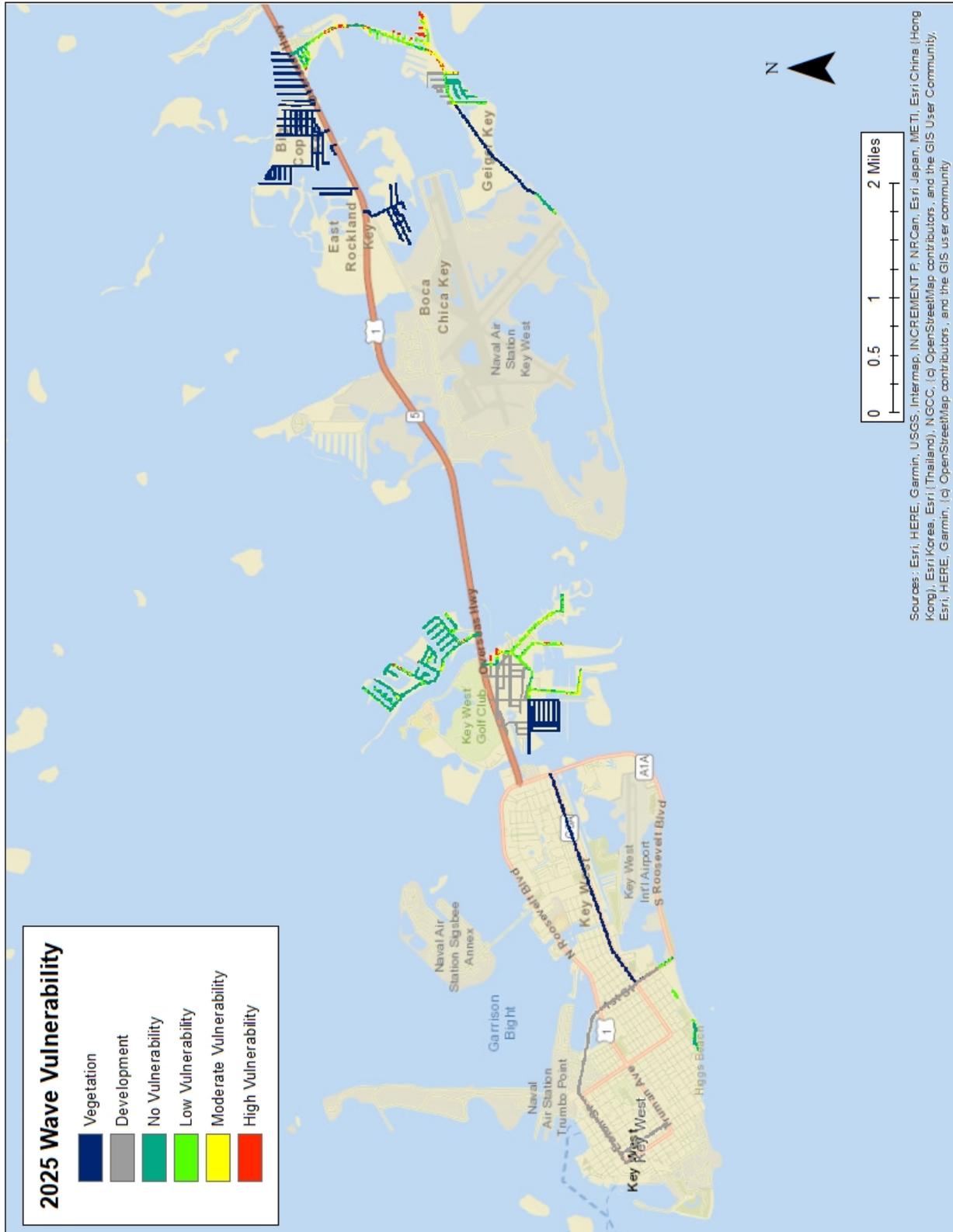
Figure 12: 2025 Key West and Naval Air Station roadway vulnerability results

5.4.2   2030 Roadway Vulnerability Results

Results show that the roadway vulnerabilities across all domains for 2030 does not differ significantly from the 2025 roadway vulnerabilities, except for several areas in the Lower Keys region.

5.4.2.1   UPPER KEYS 2030 VULNERABILITY RESULTS OBSERVATIONS

Vulnerability at Key Largo was observed to have minimal changes from 2025 to 2030 with mostly low to no vulnerability. However, there was an increase in low vulnerability region observed.

5.4.2.2   DUCK KEY 2030 VULNERABILITY RESULTS OBSERVATIONS

Vulnerability at Duck Key was observed to have minimal changes from 2025 to 2030 with only low to no vulnerability assessed.

5.4.2.3   LOWER KEYS 2030 VULNERABILITY RESULTS OBSERVATIONS

The 2030 Lower Keys vulnerability results showed an increase in moderate vulnerability in the Big Pine Key domain from 2025 to 2030 as shown in Figure 13. The eastern portion of the Key West and the Naval Air Station domains results are shown in Figure 14.
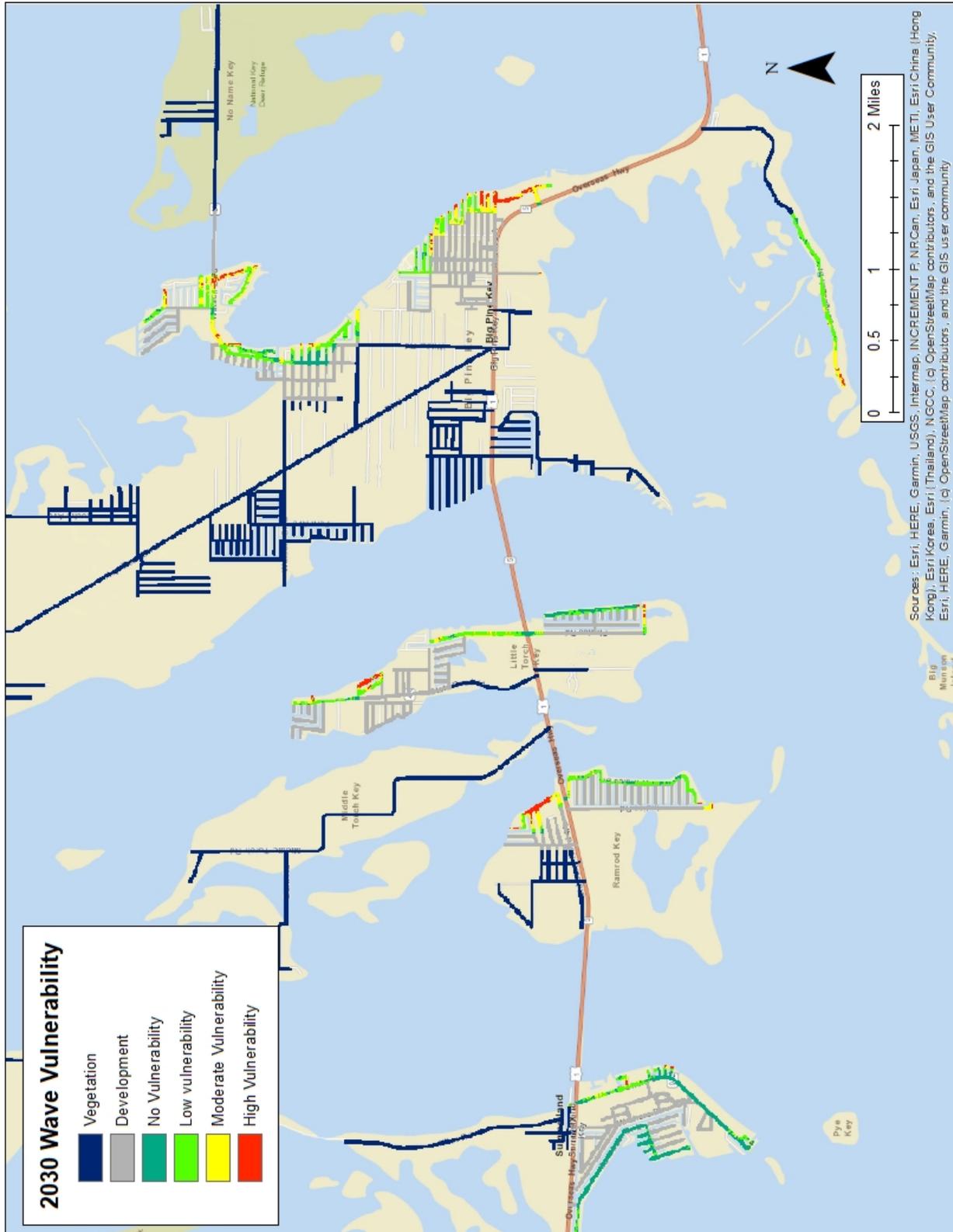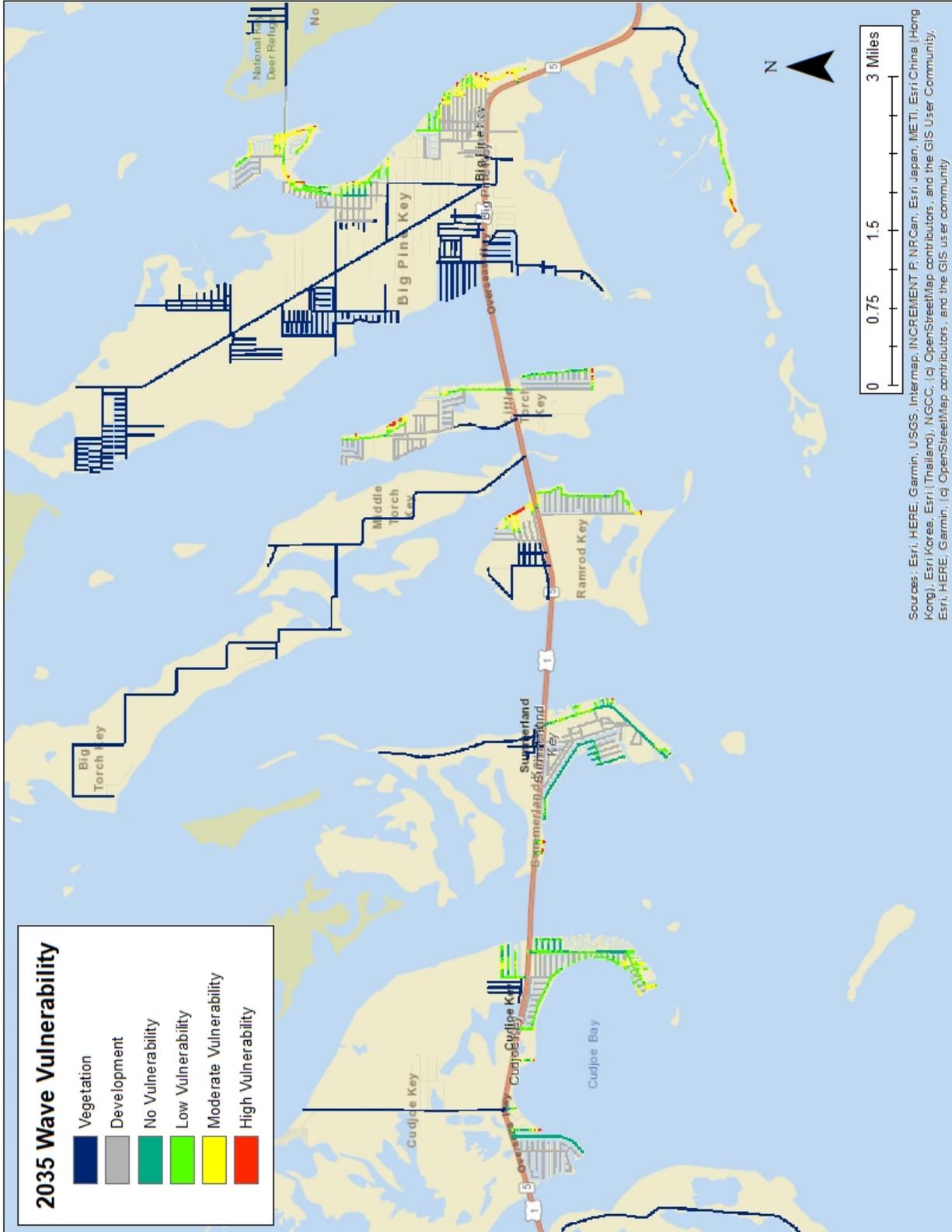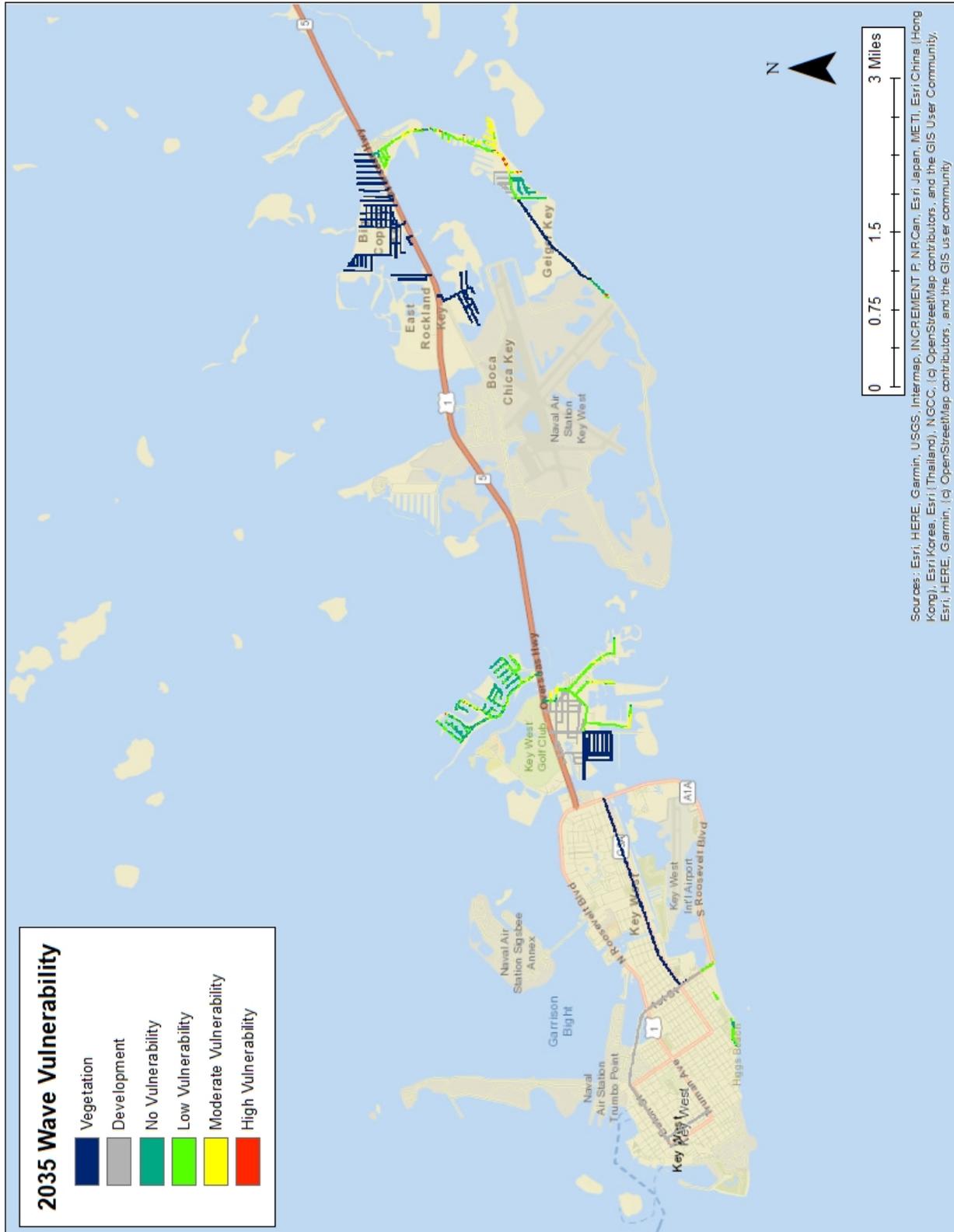
Figure 13. 2030 Big Pine Key vulnerability results
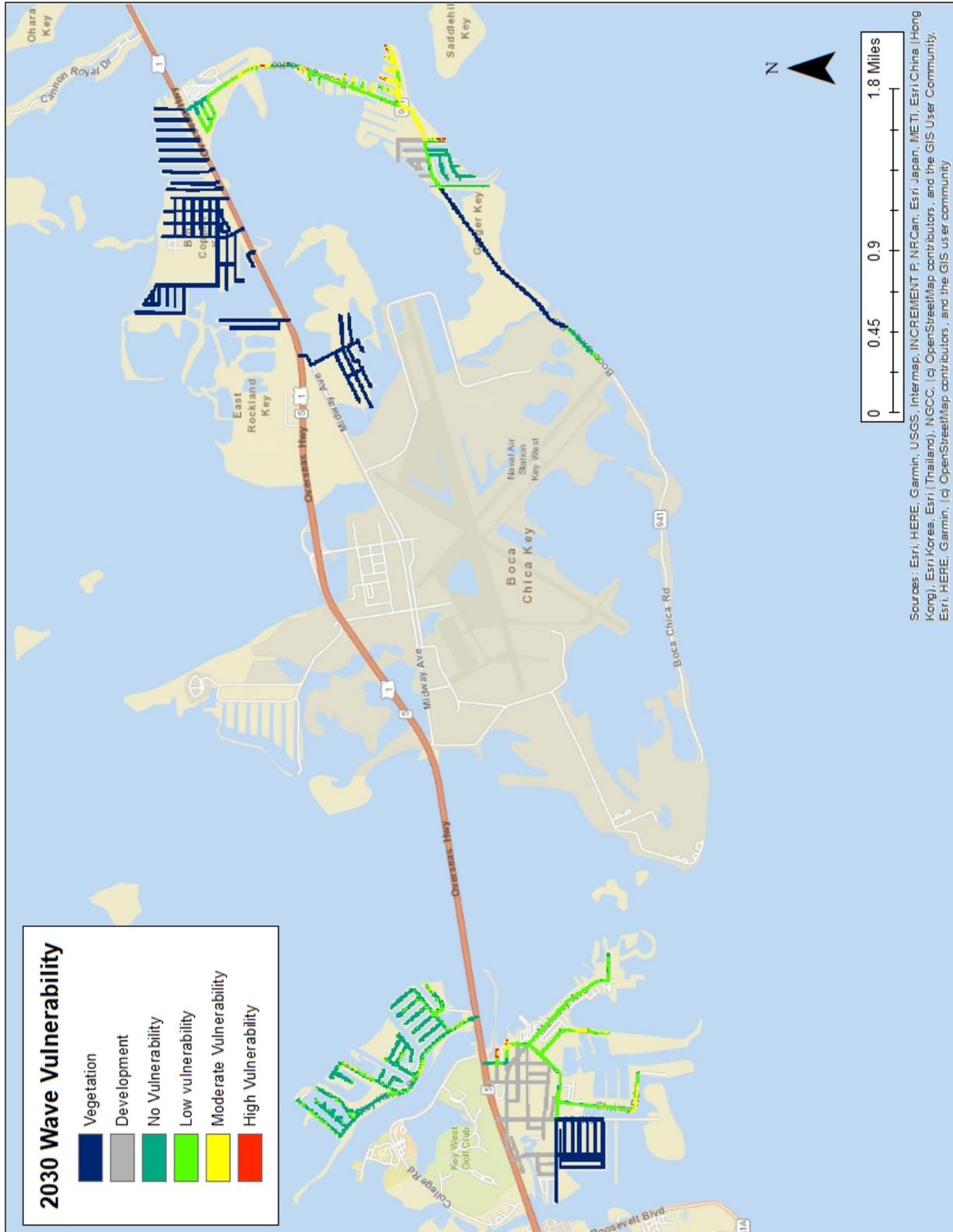
Figure 14. 2030 Key West and Naval Air Station vulnerability results

5.4.3   2035 Roadway Vulnerability Results

2035 vulnerability experience a continued increase in moderate vulnerability in both the Upper Keys and Lower Keys regions.

5.4.3.1   UPPER KEYS 2035 VULNERABILITY RESULTS OBSERVATIONS

The 2035 Key Largo vulnerability began to experience moderate to high vulnerability while increasing the amount of low vulnerability regions and decreasing the amount of no vulnerability regions. The 2035 Key Largo vulnerability results are shown in Figure 15.

5.4.3.2   DUCK KEY 2035 VULNERABILITY RESULTS OBSERVATIONS

The 2035 Duck Key vulnerability is similar to the 2030 vulnerability with the entire domain experiencing low to no vulnerability.

5.4.3.3   LOWER KEYS 2035 VULNERABILITY RESULTS OBSERVATIONS

Similar to the 2030 vulnerability results, the Lower Keys experienced an increase in moderate vulnerability and a decrease in low to no vulnerability regions in 2035 vulnerability results. The 2035 vulnerability results for the Summerland/Big Pine Key area and the Key West are shown in Figure 16 and Figure 17 respectively.
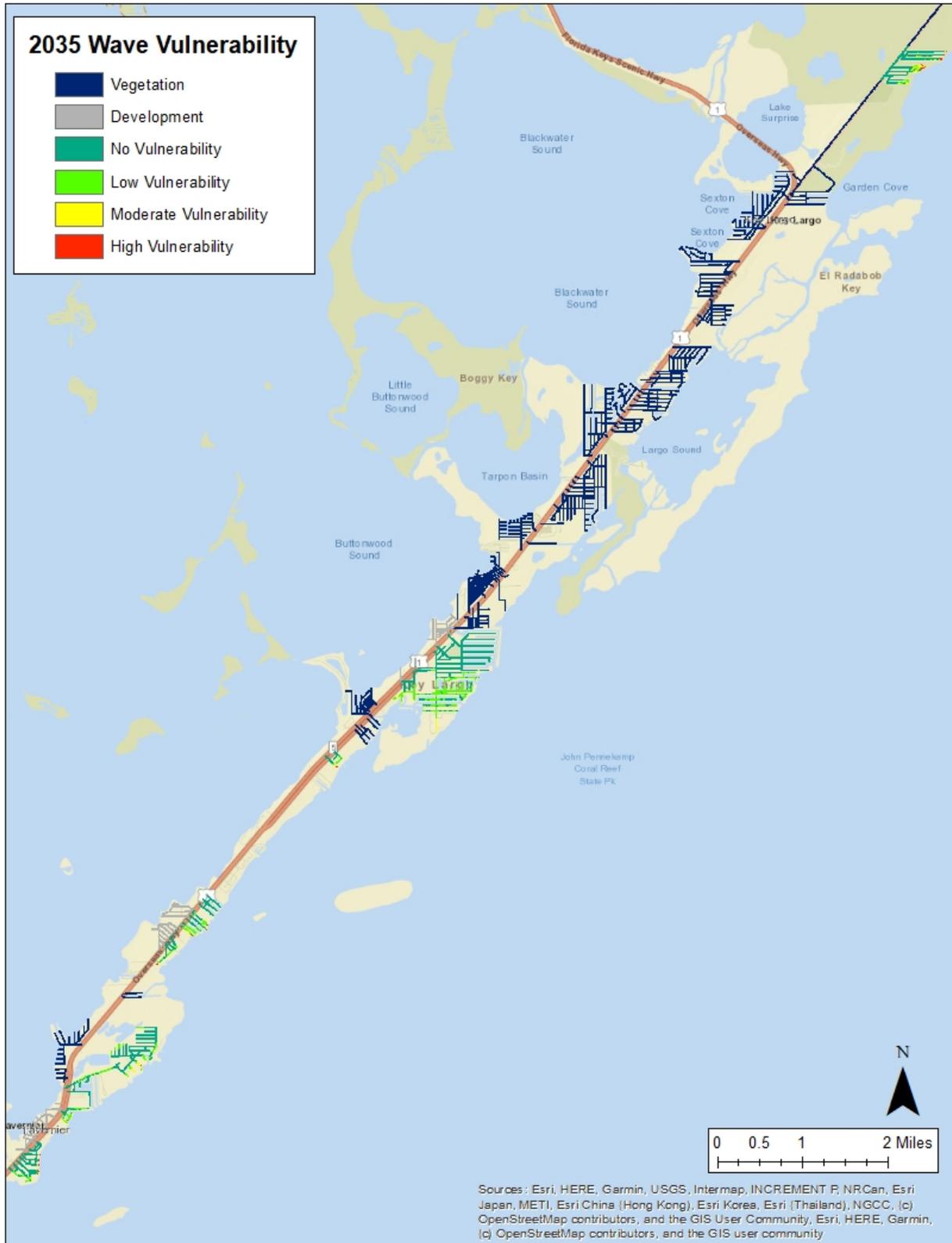
Figure 15: 2035 Upper Keys vulnerability results
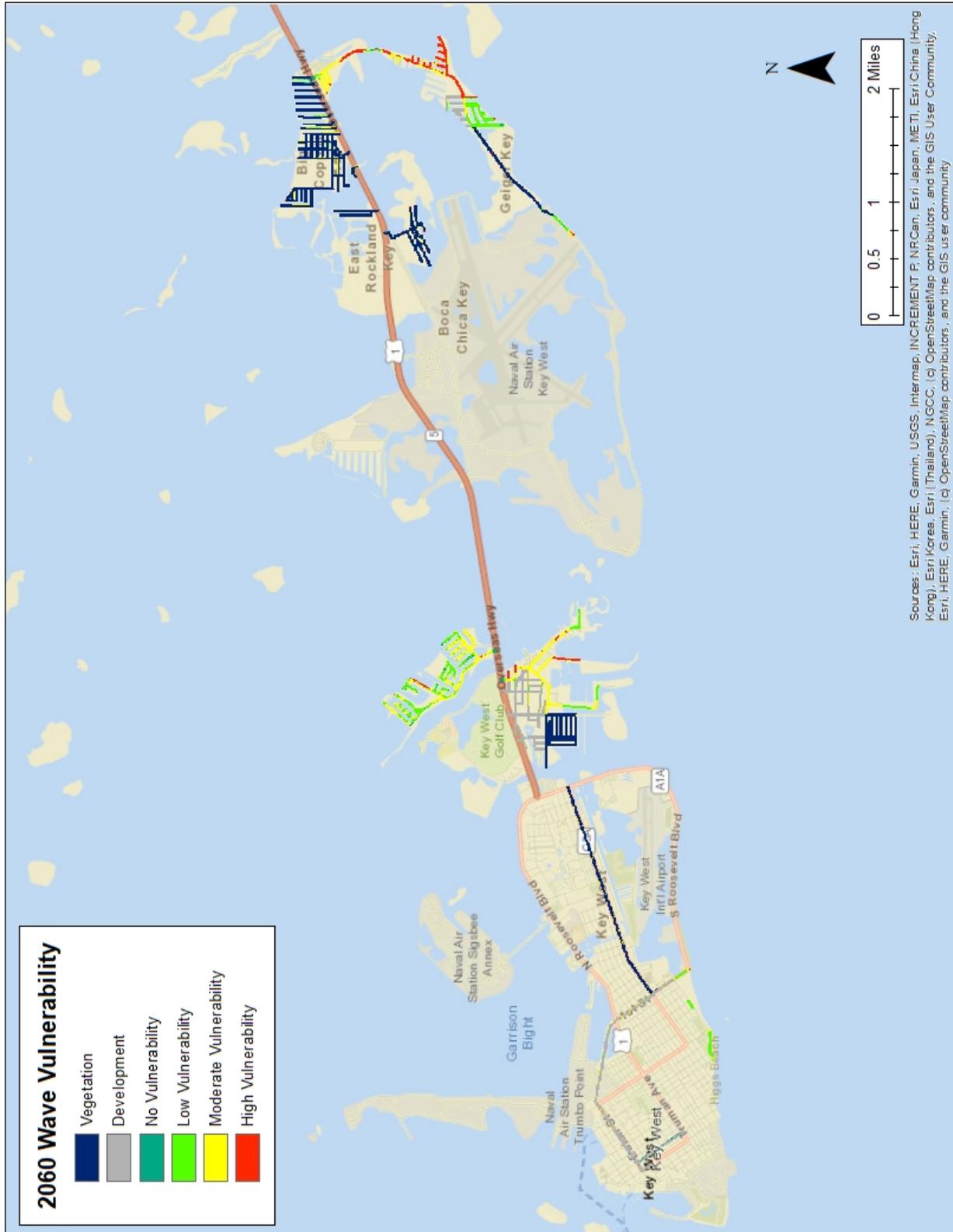
Figure 16: 2035 Summerland and Big Pine Key vulnerability results

Figure 17: 2035 Key West and Naval Air Station vulnerability results

5.4.4   2040 Roadway Vulnerability Results

The vulnerability for each region followed the same trend observed for the year 2035 vulnerability results. The Lower Keys domain continued to experience an increase in moderate vulnerability, specifically around the Big Pine Key and Summerland regions. The Duck Key domain continued to experience an increase in low vulnerability and decrease in no vulnerability regions. The Upper Keys domain continued to experience an increase of moderate to high vulnerability in the Tavernier/Key Largo regions.

5.4.5   2045 Roadway Vulnerability Results

The three regions continued to follow the same trends in the 2045 vulnerability results as was observed for the year 2040.

5.4.6   2060 Roadway Vulnerability Results

The 2060 scenario was when the first significant increase in high vulnerability roadways occurred. This increase is observed primarily in the Lower and Upper Key Largo regions. The Duck key region continued to experience an increase in low vulnerability areas.

5.4.6.1   UPPER KEYS 2060 VULNERABILITY RESULTS OBSERVATIONS

The 2060 Upper Keys domain vulnerability increased from low vulnerability to moderate vulnerability and from moderate vulnerability to higher vulnerability in the Key Largo and Tavernier region. Figure 18 shows the 2060 Upper Keys vulnerability results.

5.4.6.2   DUCK KEY 2060 VULNERABILITY RESULTS OBSERVATIONS

Duck Key experienced mostly low vulnerability conditions as observed in the 2060 vulnerability results. Conch Key, however, experienced high vulnerability conditions. Figure 19 shows the 2060 vulnerability of Duck Key.

5.4.6.3   LOWER KEYS 2060 VULNERABILITY RESULTS OBSERVATIONS

The Lower Key domain's low vulnerability roadways transitioned to moderate and high vulnerability roadways across the entire region. Sugar Loaf, Summerland, and Big Pine key were observed to have the most vulnerable regions during 2060 as shown in Figure 20. Figure 21 provides the 2060 vulnerability results for Key West.
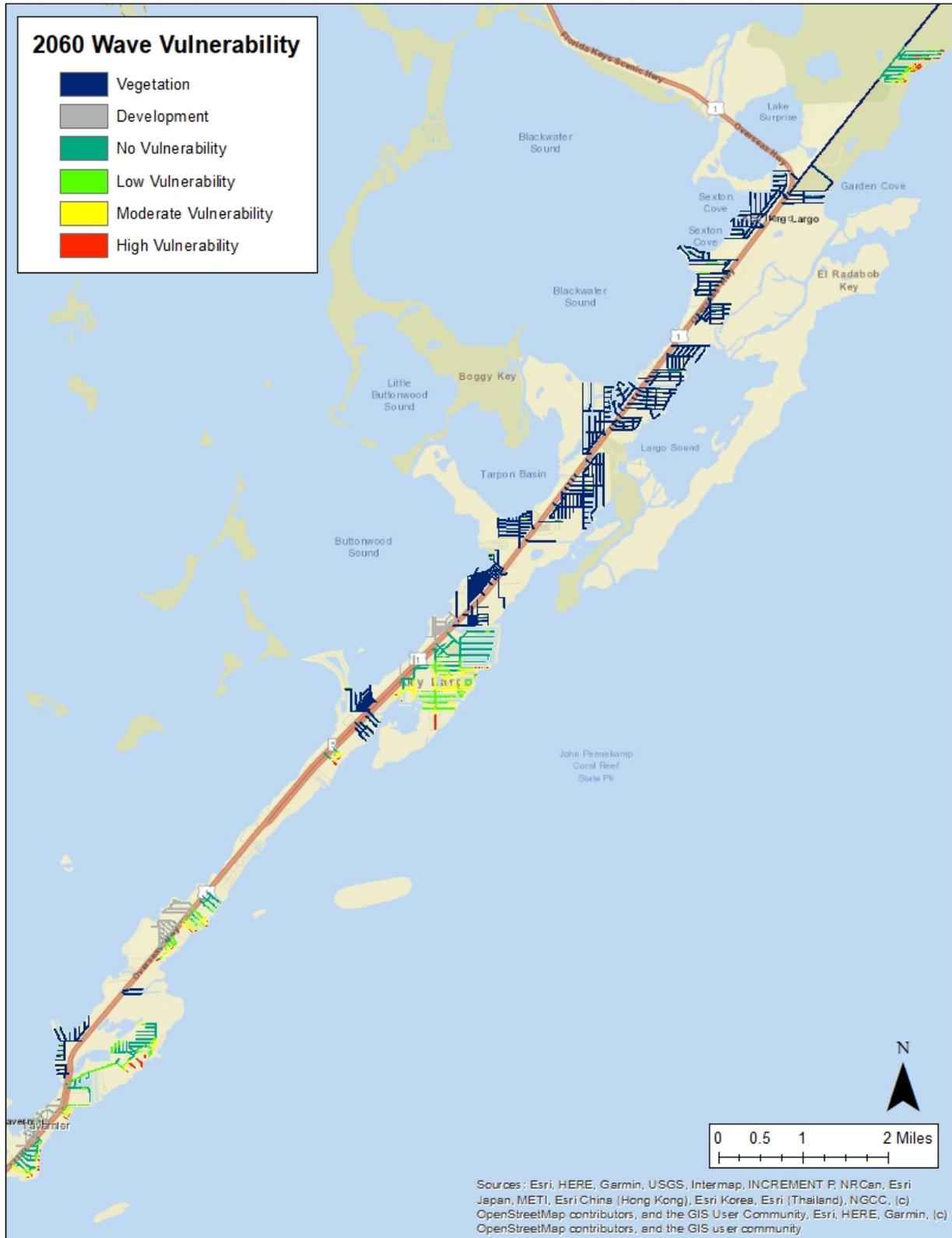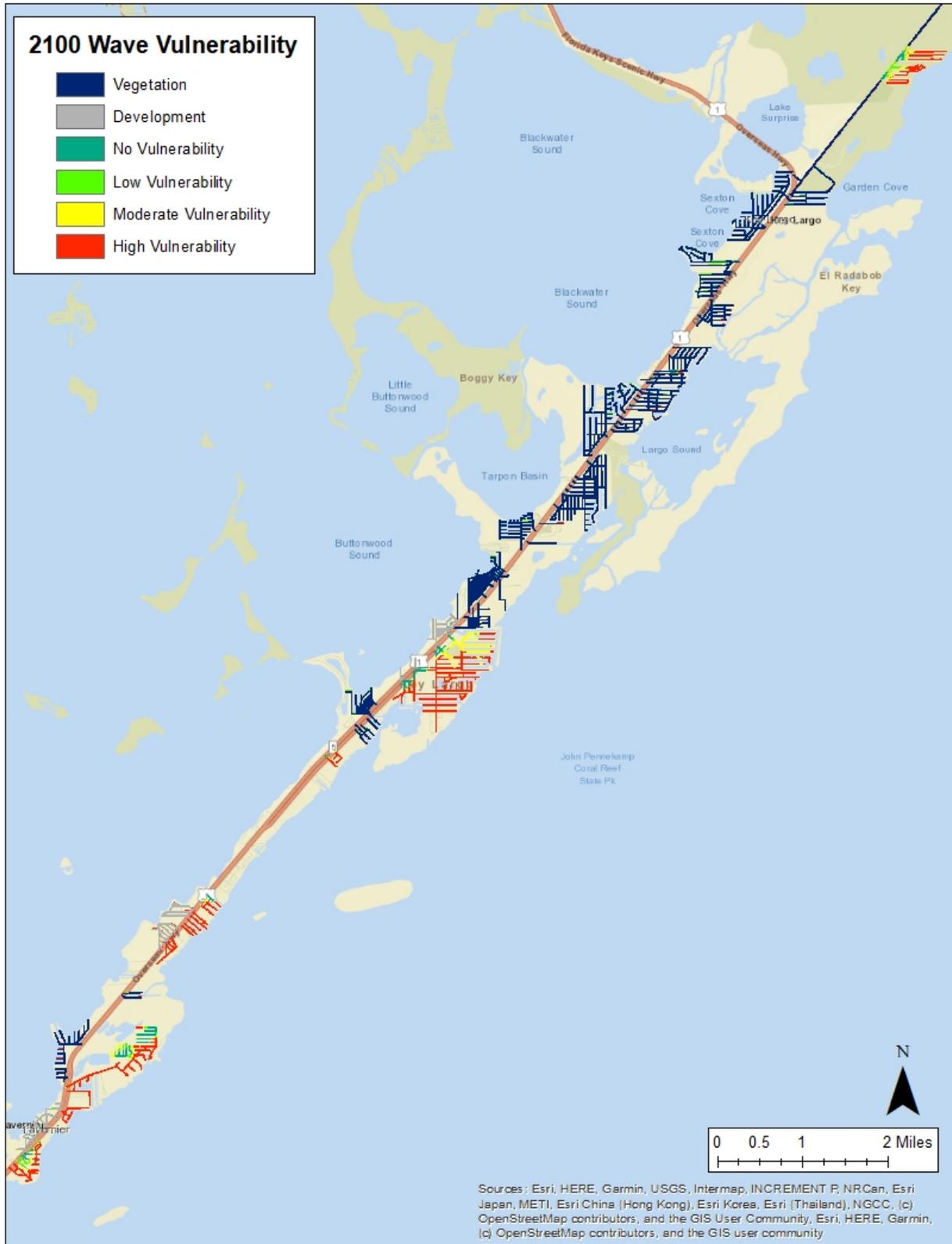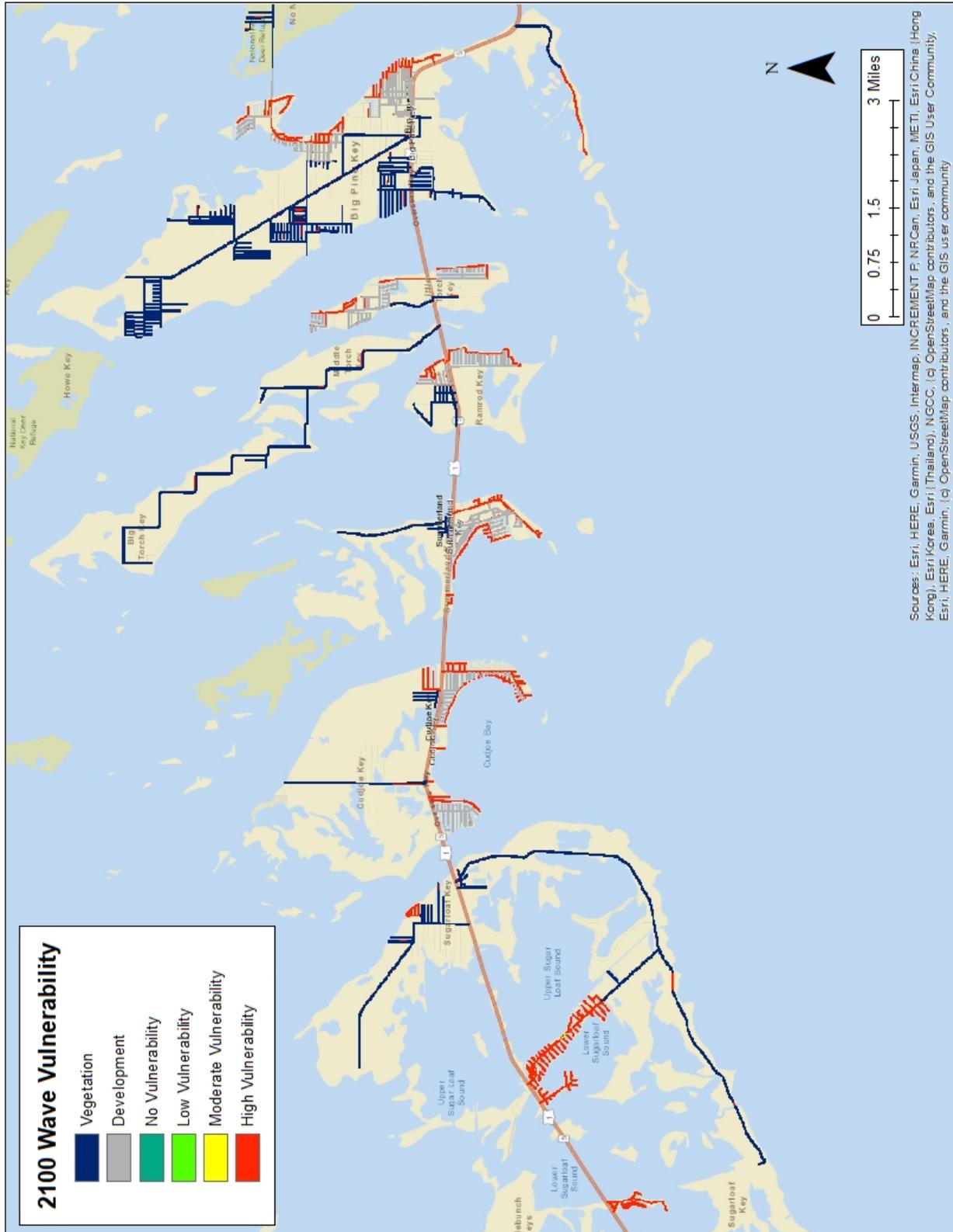
Figure 18: 2060 Upper Keys vulnerability results

Figure 19: 2060 Duck Key vulnerability results

**Figure 20: 2060 Summerland, Sugarloaf and Pine Key vulnerability results**

2060 Wave Vulnerability

Vegetation
Development
No Vulnerability
Low Vulnerability
Moderate Vulnerability
High Vulnerability

Figure 21: 2060 Key West and Naval Air Station vulnerability results

5.4.7   2100 Roadway Vulnerability Results

5.4.7.1   UPPER KEY VULNERABILITY RESULTS OBSERVATIONS

Similar to the other two domains, the Upper Keys domain also experienced a significant increase in the amount of high vulnerability roadways in the region. However, the Key Largo region was observed to be the most resilient to the 2100 water level based on the model results. Figure 22 shows the Key Largo 2100 vulnerability.

5.4.7.2   DUCK KEY VULNERABILITY RESULTS OBSERVATIONS

The breakwater's effectiveness at reducing the incoming waves is significantly reduced because of the high water levels anticipated in 2100. This results in a significant increase in vulnerability from low vulnerability to high vulnerability. Figure 23 shows the 2100 Duck Key vulnerability.

5.4.7.3   LOWER KEYS VULNERABILITY RESULTS OBSERVATIONS

A majority of the Lower Keys domain experienced high vulnerability due to the high water levels modeled in 2100. The presence of vegetation in some areas, however, reduced wave impacts. Figure 24 and Figure 25 shows the 2100 Lower Keys vulnerability results.

Figure 22: 2100 Upper Keys vulnerability results

Figure 23: 2100 Duck Key vulnerability results

Figure 24: 2100 Summerland, Sugar Loaf and Pine Key vulnerability results
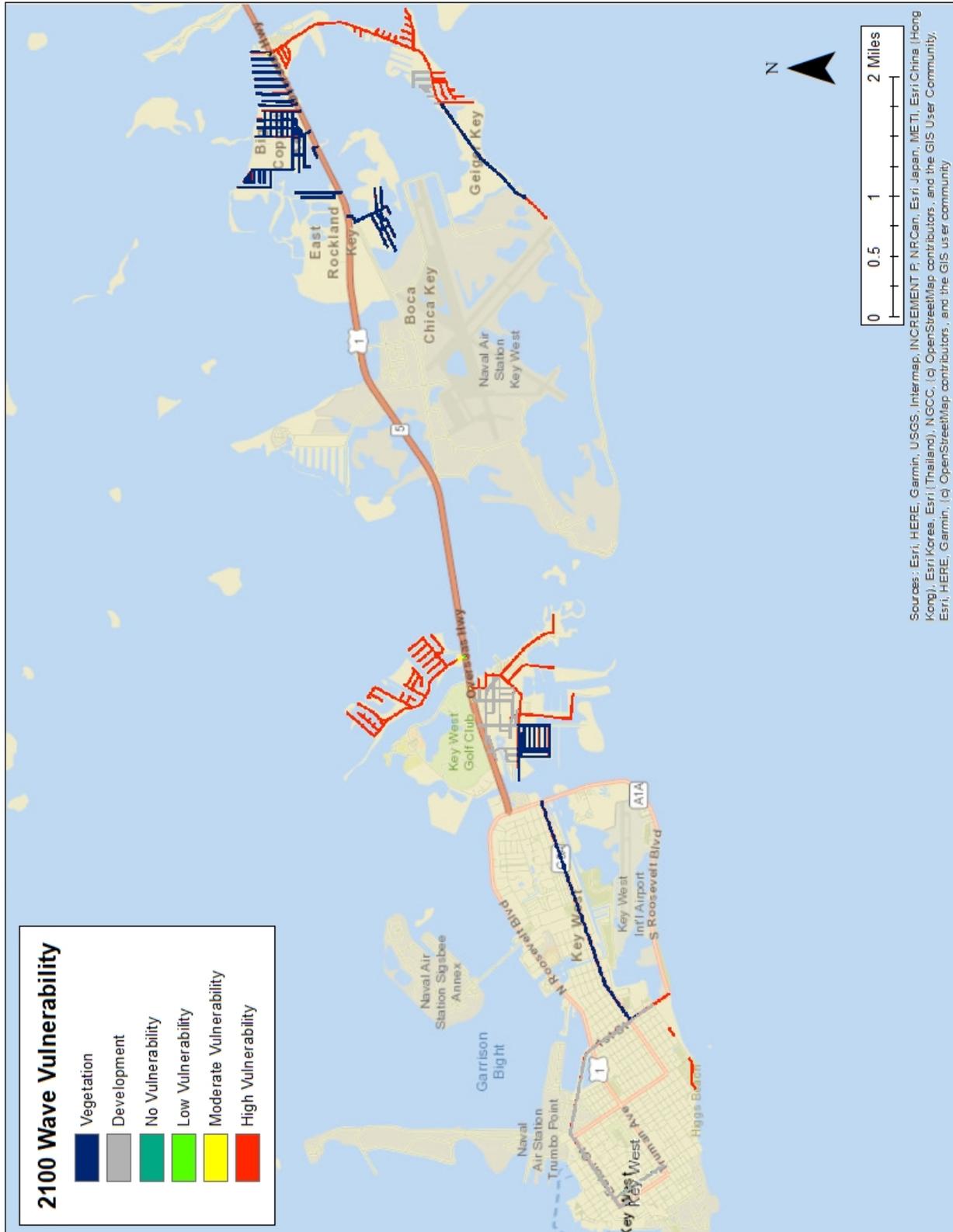
Figure 25: 2100 Key West and Naval Air Station vulnerability results

6 Conclusion

Based on the wave modeling effort performed for the Monroe County Roadway Vulnerability Study, wave vulnerability increases with an increase in water level associated with SLR. High vulnerability regions began to expand from 2045 to 2100 for the Upper and Lower Keys regions. By 2100 the majority of the Florida Keys region was highly vulnerable to damaging wave action that may not only require the increase in roadway elevation but also the construction of coastal protections such as revetments, seawalls, or breakwaters.

The area from Big Pine Key to Key West was particularly vulnerable because of its low elevation and exposure to offshore wave climates. By 2035 a majority of the exposed roadways were becoming moderately vulnerable to wave attack, while small spots of high vulnerability were appearing.

While a majority of these roadways will likely need an increase in elevation due to increasing water levels, roadways of moderate vulnerability should be monitored and maintained while roadways of high vulnerability may need to be protected.

It is also important to note that large amounts of coastal vegetation play a significant role in reducing vulnerability. The reduction in vulnerability can be significant, in some case converting high vulnerability areas into no vulnerability regions. This decreases the work and associated cost necessary to improve resiliency. However, the range and transformation of vegetated habitats is likely to change over the years as water levels rise, so an update in protection and vulnerability analysis is recommended for future assessments.

7 References

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Appendix A: Upper Keys Vulnerability Results

Figure A.1 - Wave vulnerability for the Upper Keys domain for 2025

Figure A.2 - Wave vulnerability for the Upper Keys domain for 2030

2035 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability

Figure A.3 - Wave vulnerability for the Upper Keys domain for 2035

2040 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability

Figure A.4 - Wave vulnerability for the Upper Keys domain for 2040

Figure A.5 - Wave vulnerability for the Upper Keys domain for 2045

Figure A.6 - Wave vulnerability for the Upper Keys domain for 2060

Figure A.7 - Wave vulnerability for the Upper Keys domain for 2100

Appendix B: Duck Key Vulnerability Results

Figure B.1 - Wave vulnerability for the Duck Key domain for 2025

2030 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low vulnerability
- Moderate Vulnerability
- High Vulnerability

Figure B.2 - Wave vulnerability for the Duck Key domain for 2030

Figure B.3 - Wave vulnerability for the Duck Key domain for 2035

Figure B.4 - Wave vulnerability for the Duck Key domain for 2040

Figure B.5 - Wave vulnerability for the Duck Key domain for 2045

Figure B.6 - Wave vulnerability for the Duck Key domain for 2060

Figure B.7 - Wave vulnerability for the Duck Key domain for 2100
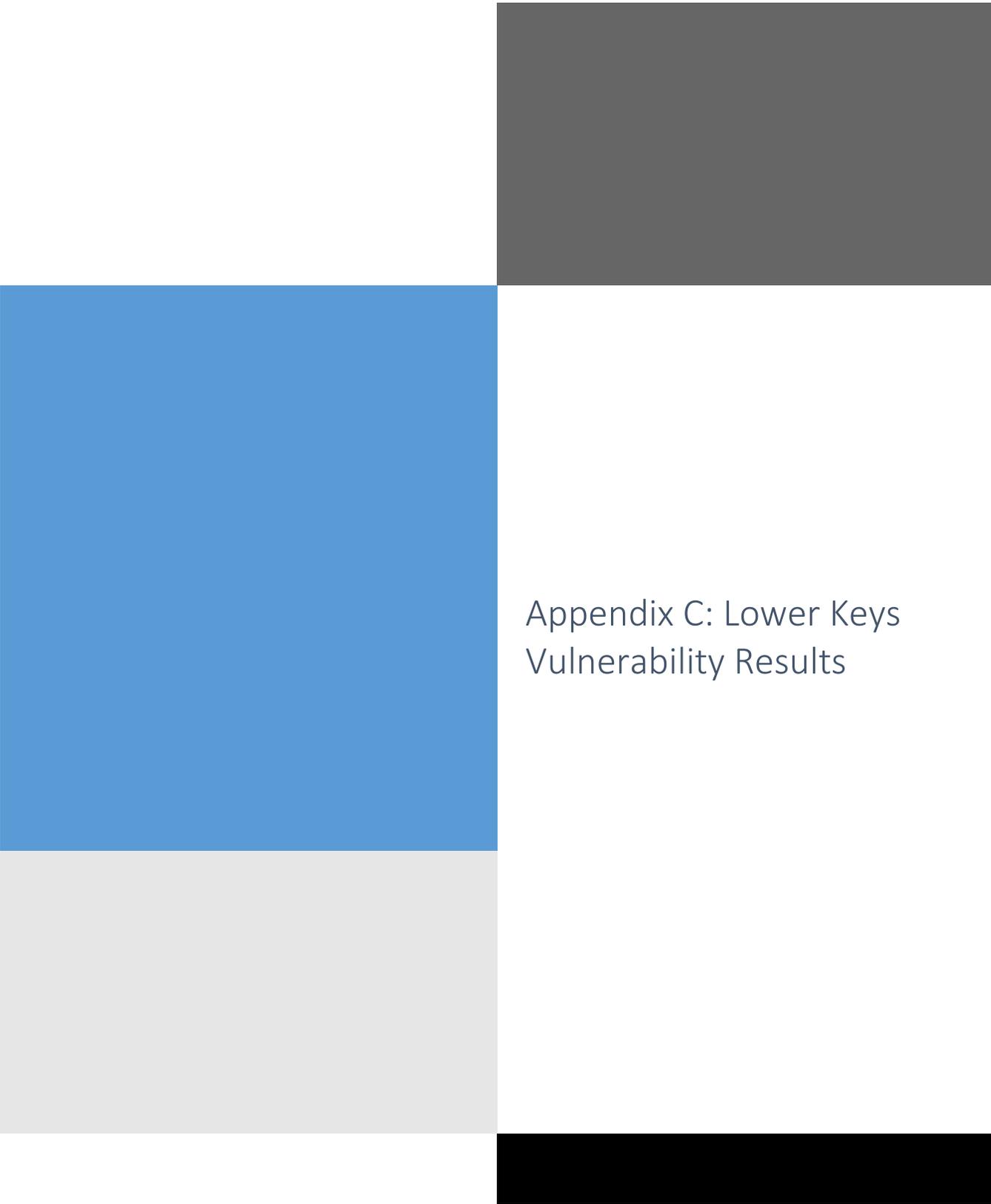
Appendix C: Lower Keys Vulnerability Results
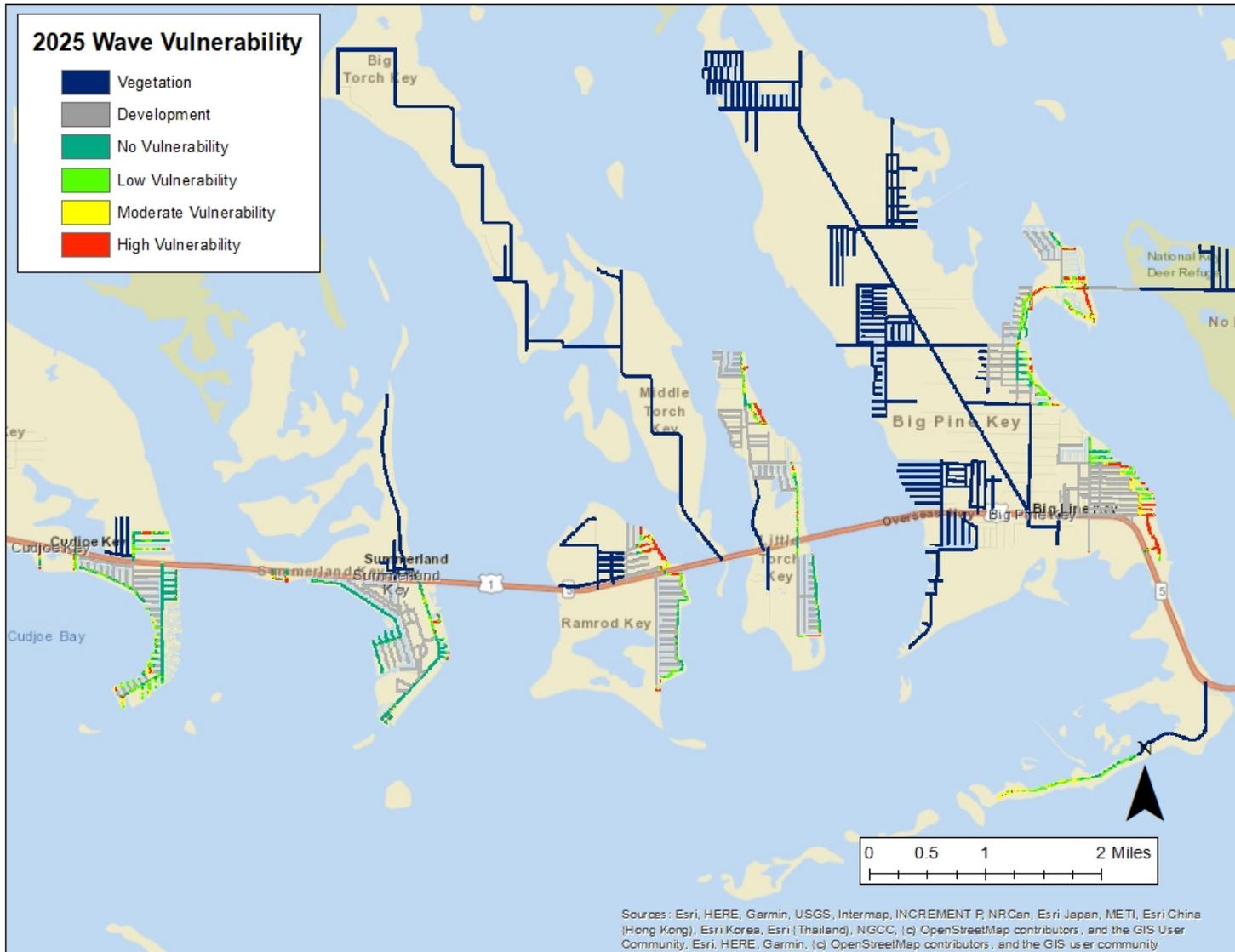
**Figure C.1 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2025**

Figure C.2 - Wave vulnerability of the Sugarloaf nested domains for 2025
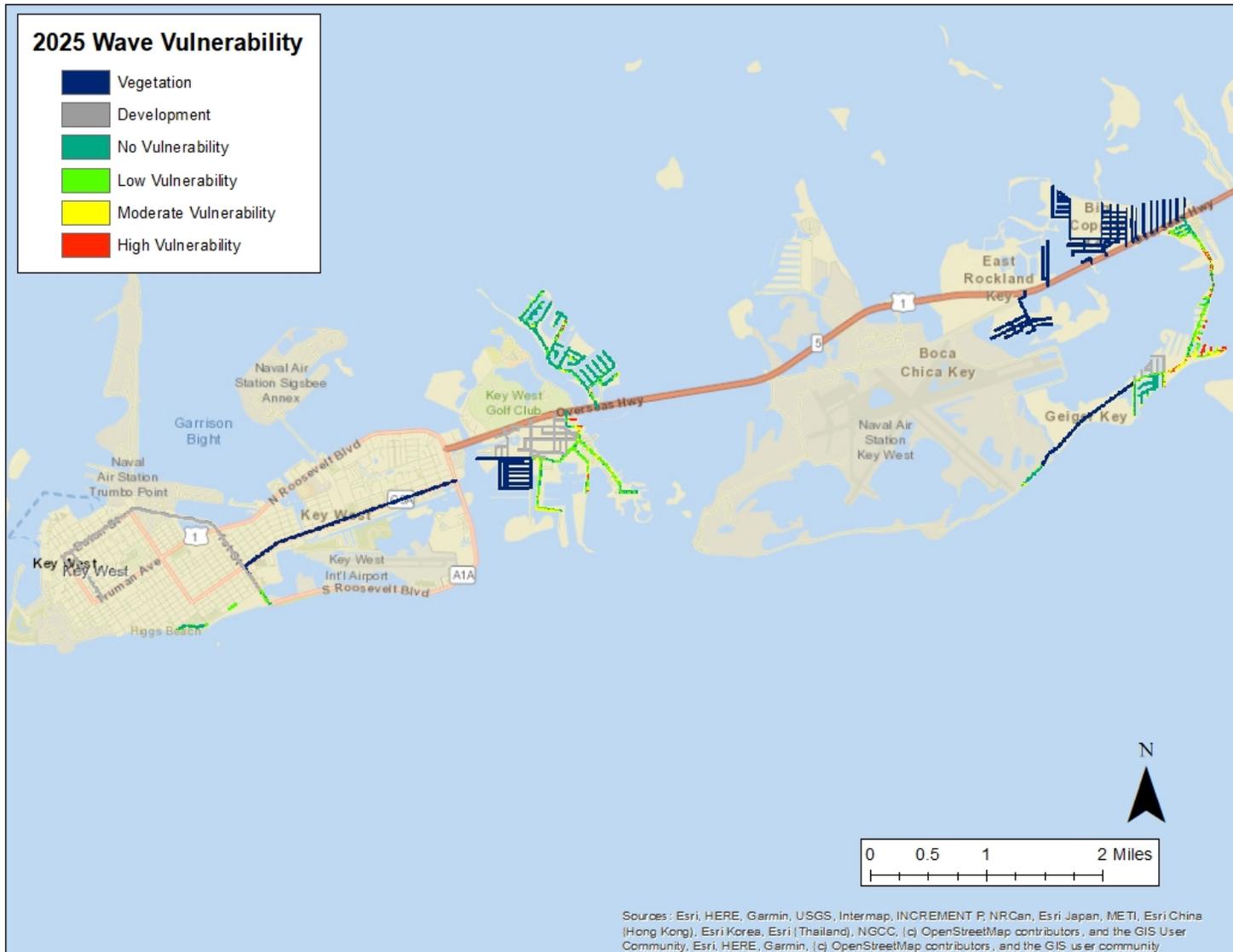
Figure C.3 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2025

2030 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low vulnerability
- Moderate Vulnerability
- High Vulnerability
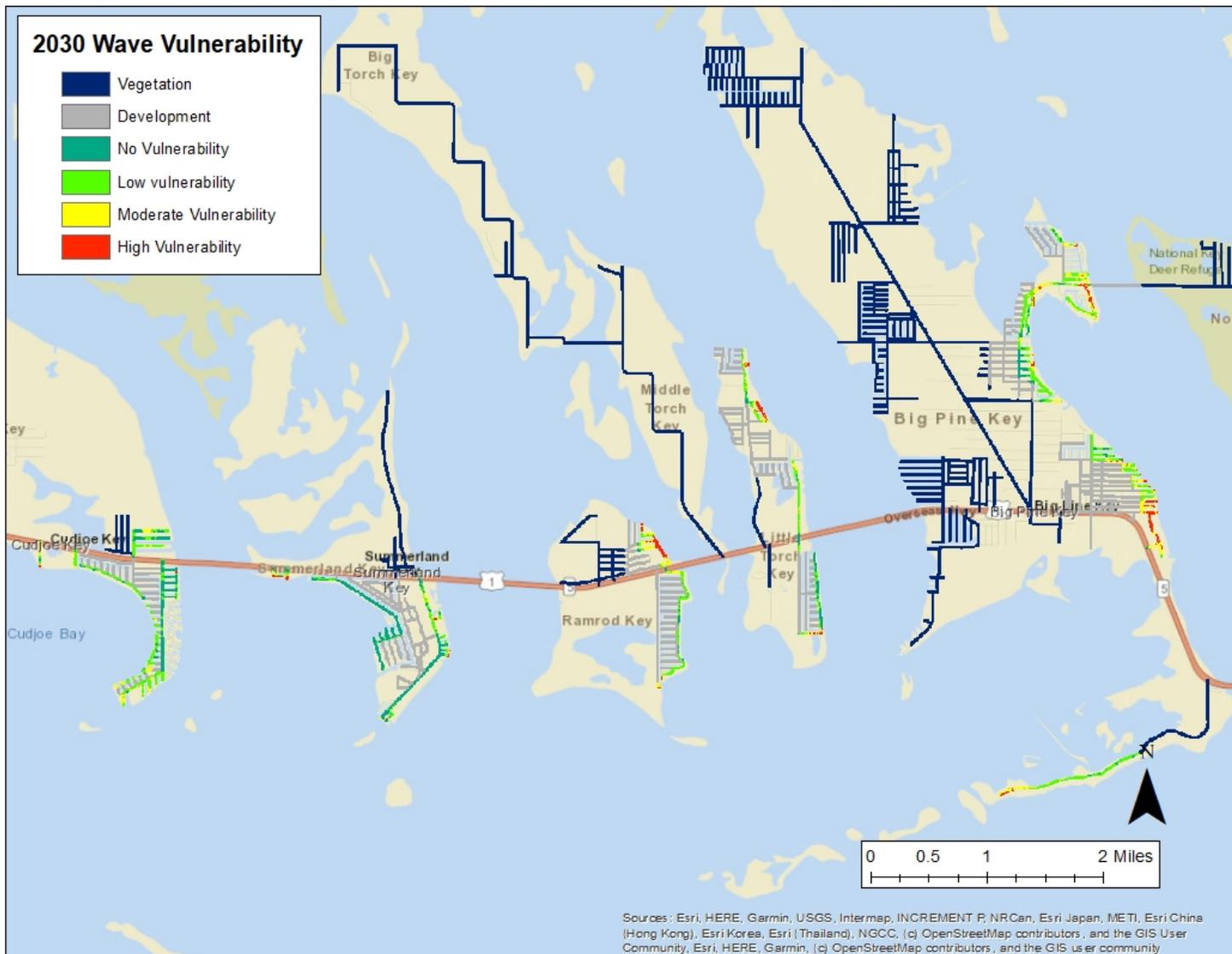
Figure C.4 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2030

Figure C.5 - Wave vulnerability of the Sugarloaf nested domains for 2030

Figure C.6 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2030
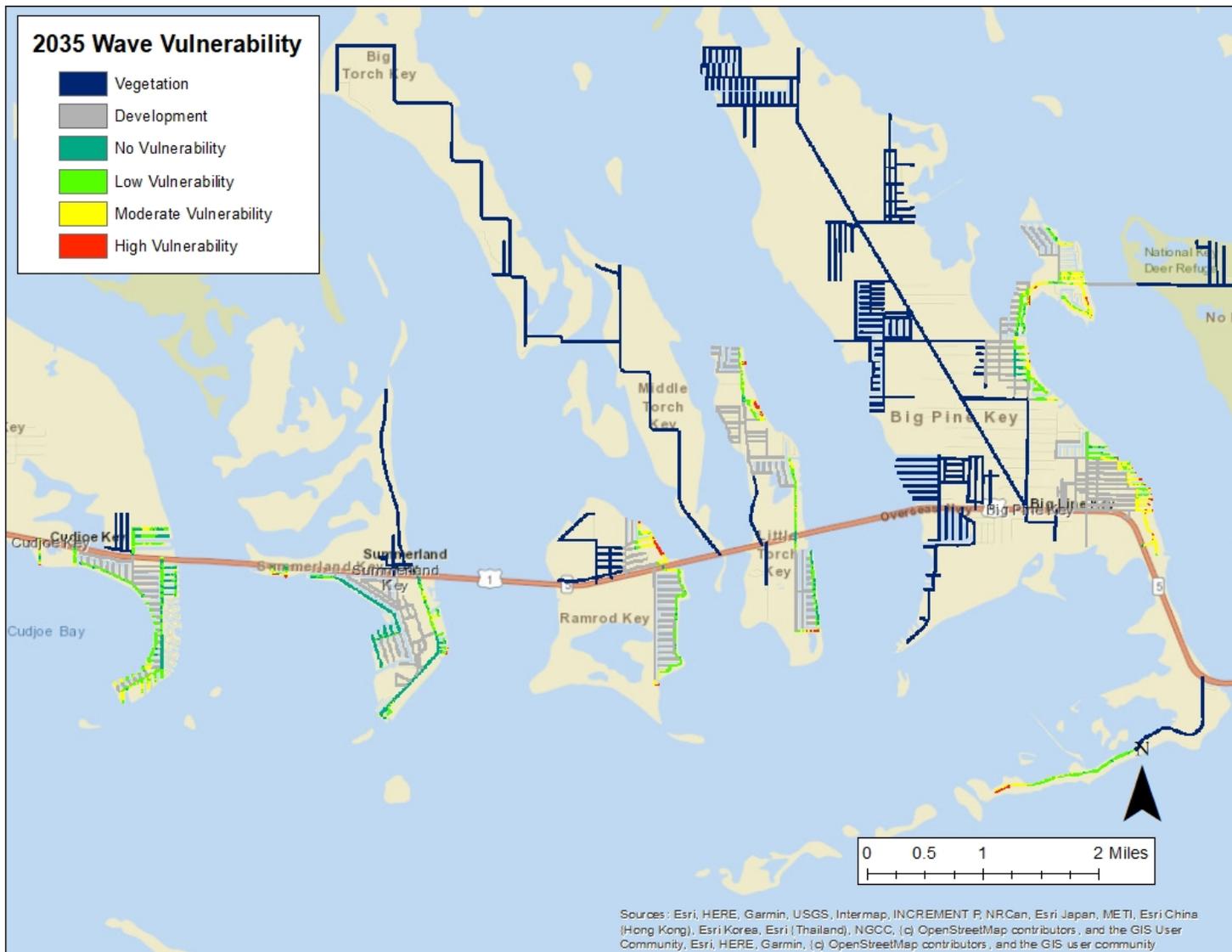
Figure C.7 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2035
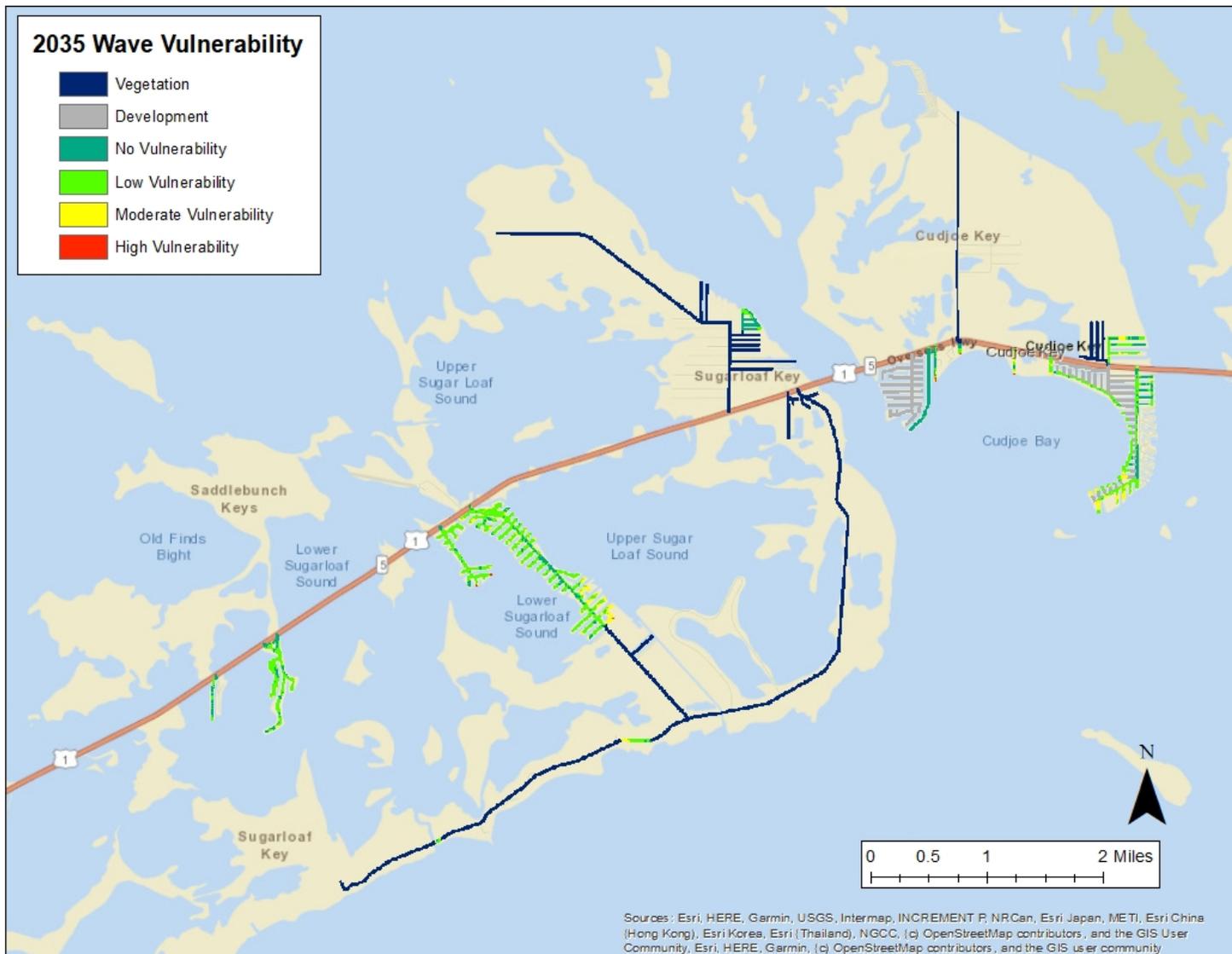
Figure C.8 - Wave vulnerability of the Sugarloaf nested domains for 2035

Figure C.9 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2035
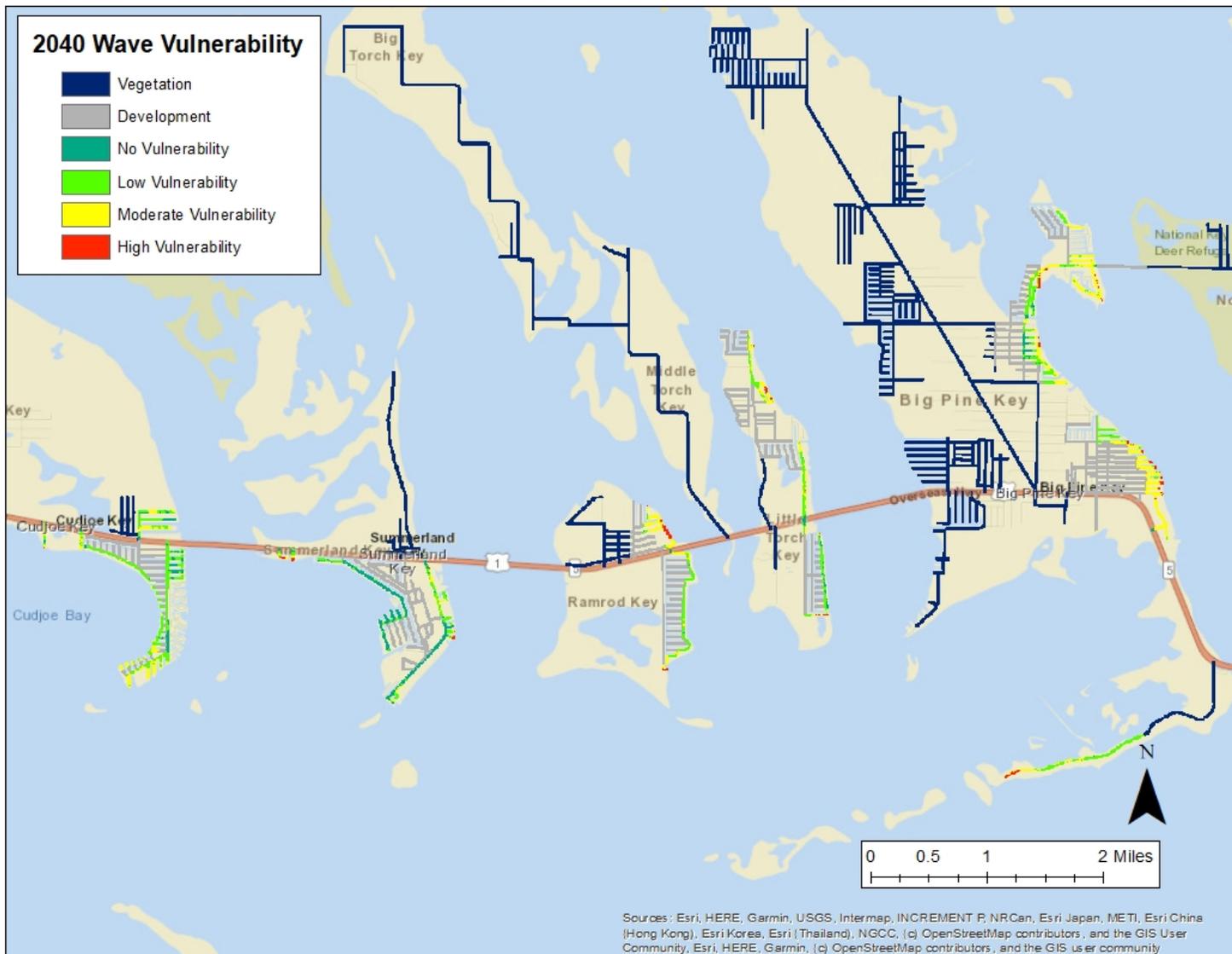
Figure C.10 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2040

Figure C.11 - Wave vulnerability of the Sugarloaf nested domains for 2040

2040 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability
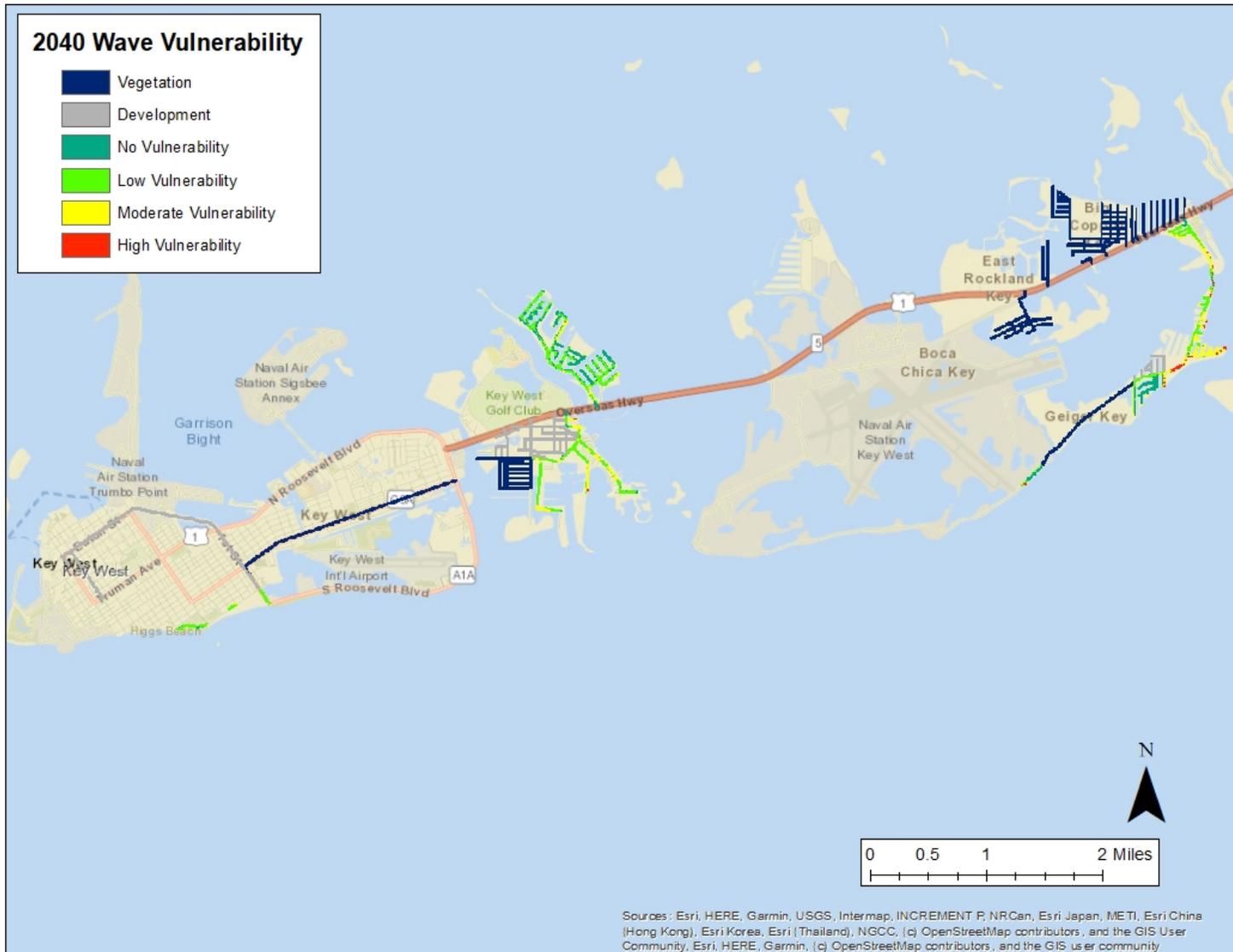
Figure C.12 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2040

2045 Wave Vulnerability

- Vegetation
- Development
- No Vulnerability
- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability

Figure C.13 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2045
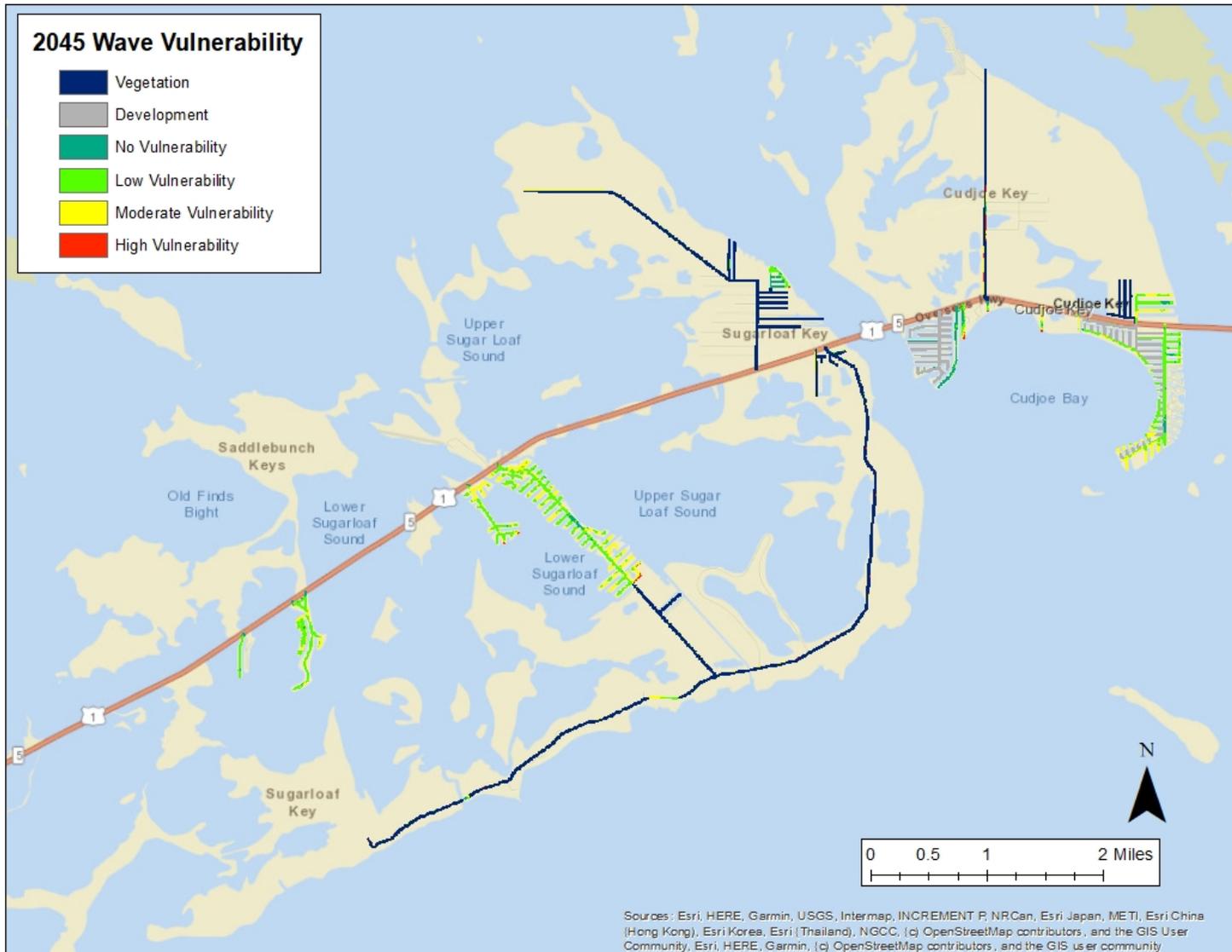
Figure C.14 - Wave vulnerability of the Sugarloaf nested domains for 2045
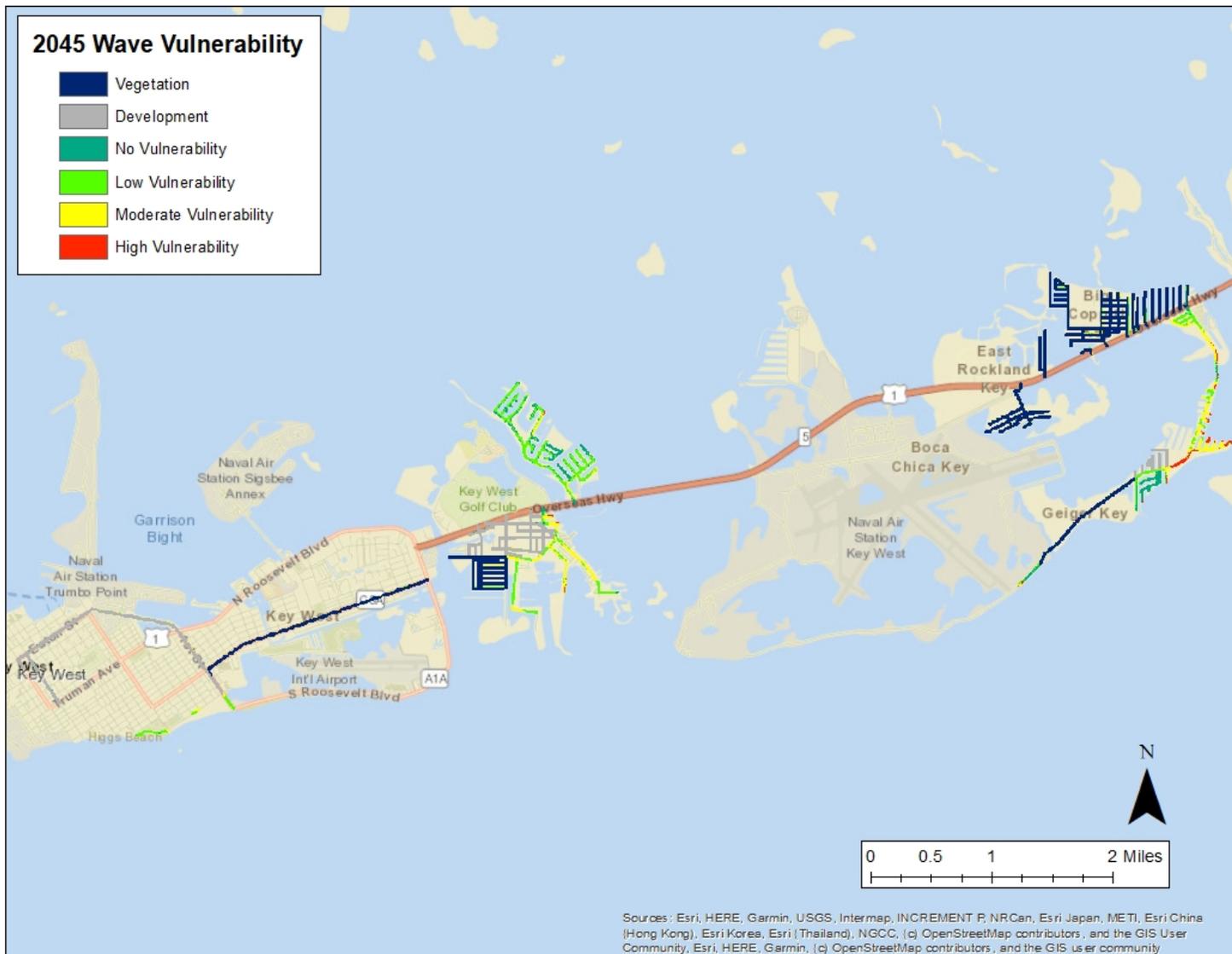
Figure C.15 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2045
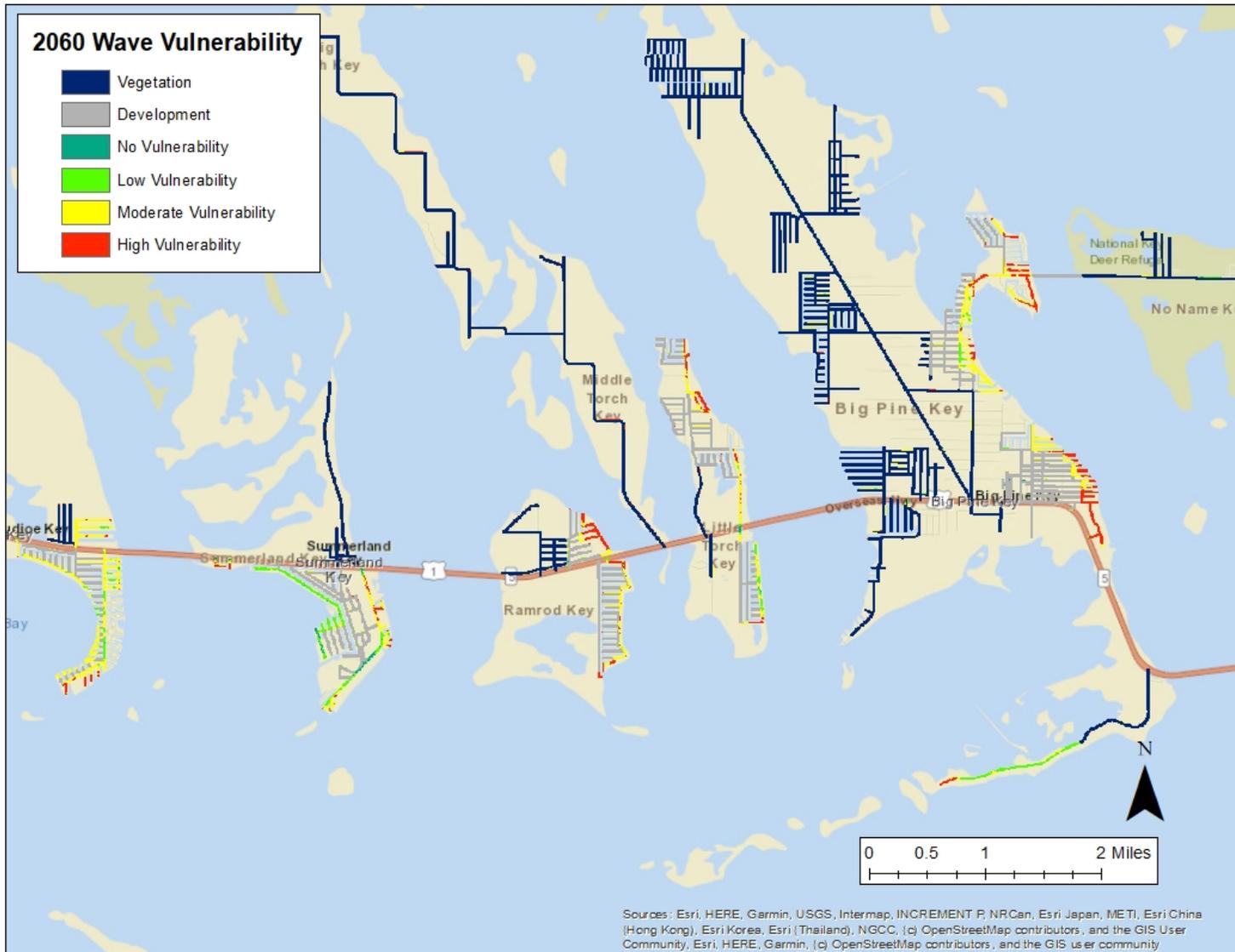
Figure C.16 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2060
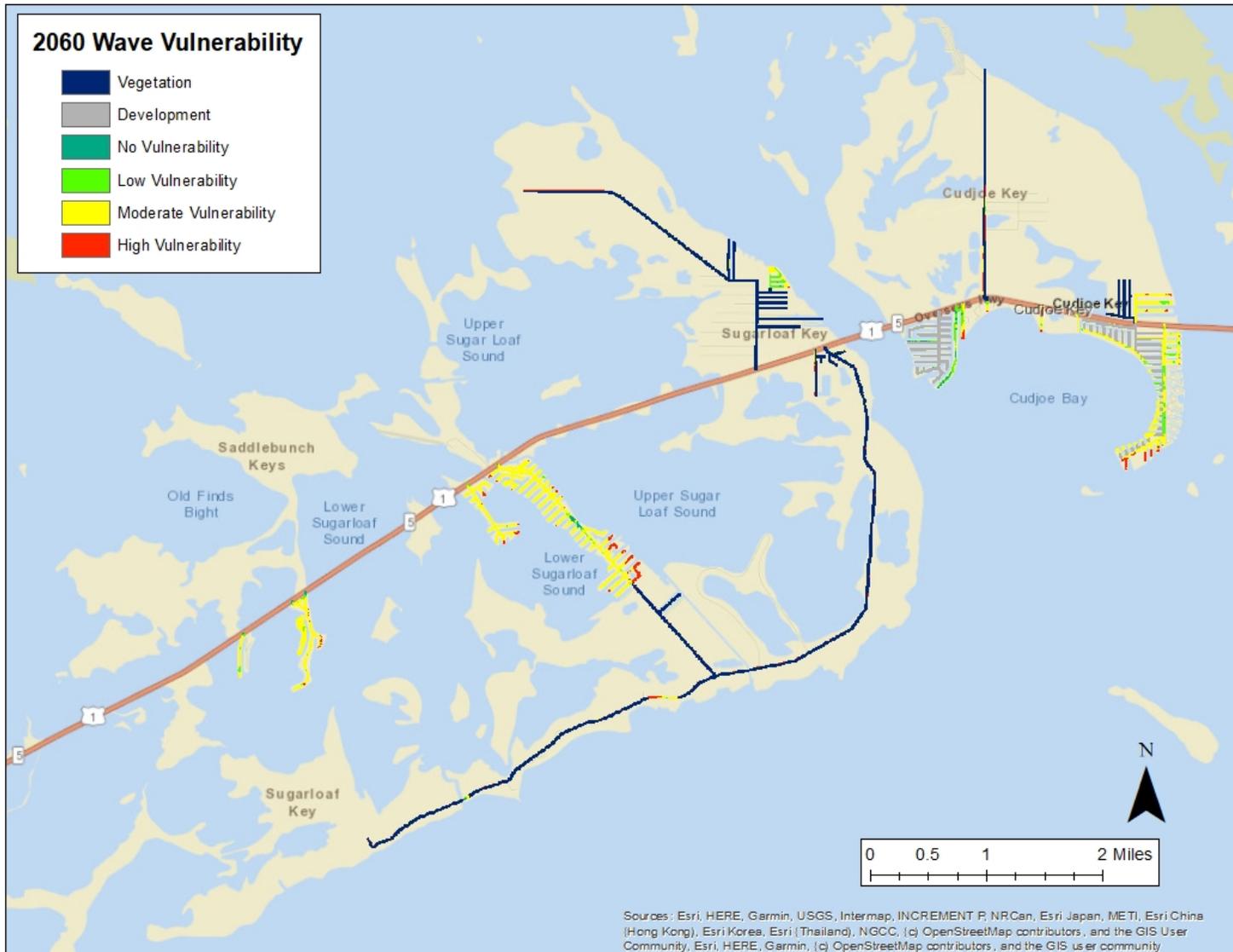
Figure C.17 - Wave vulnerability of the Sugarloaf nested domains for 2060

Figure C.18 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2060
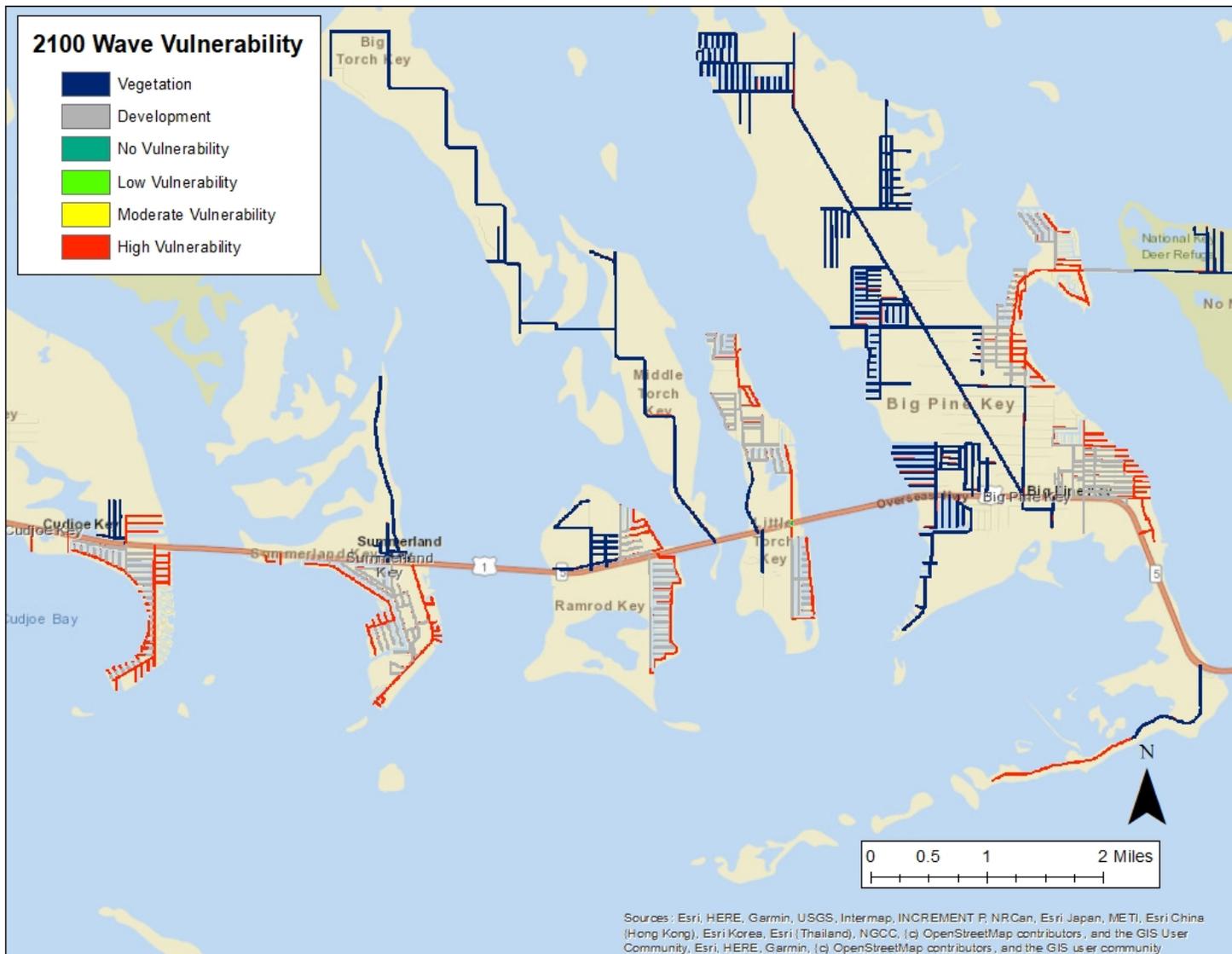
Figure C.19 - Wave vulnerability for the Summerland and Big Pine Key nested domains for 2100
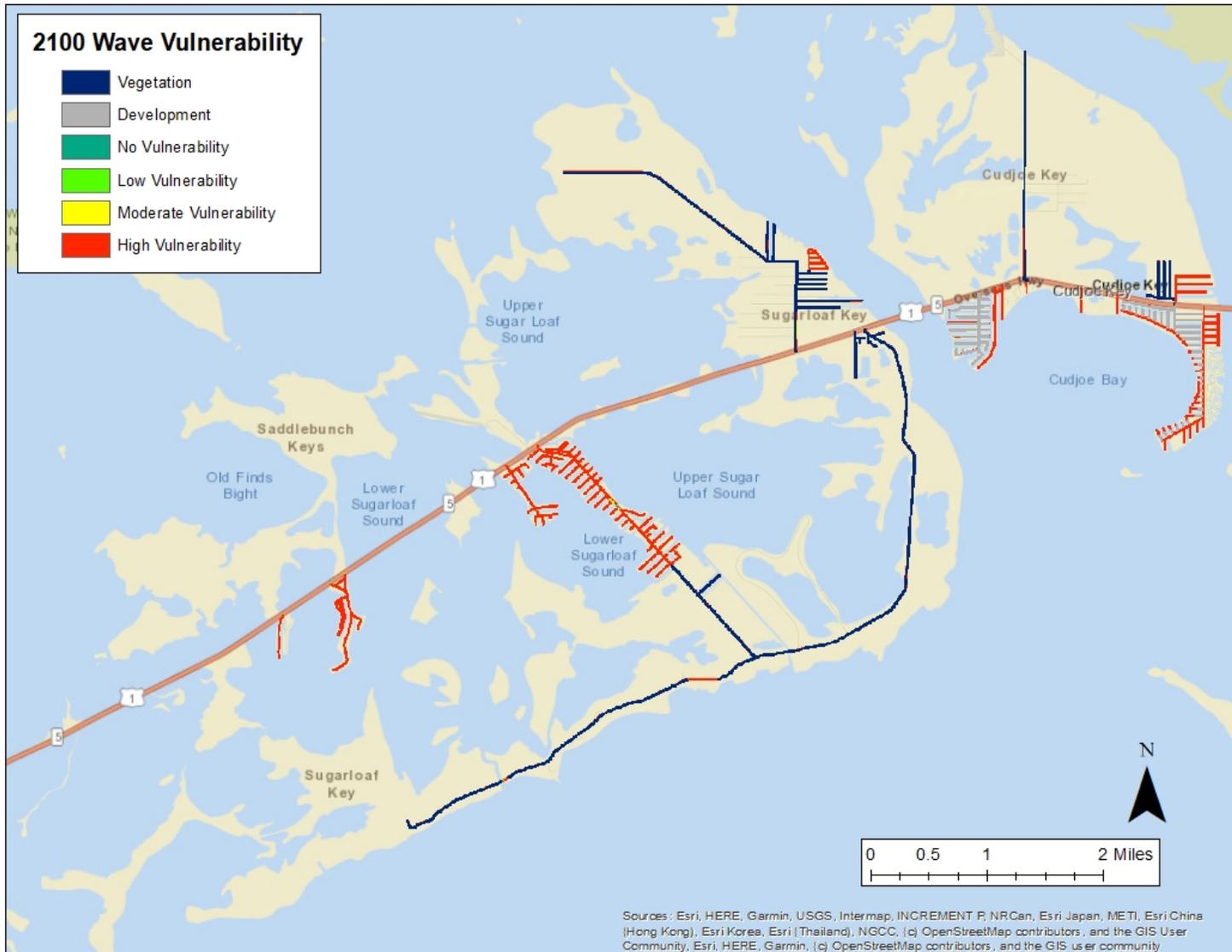
Figure C.20 - Wave vulnerability of the Sugarloaf nested domains for 2100
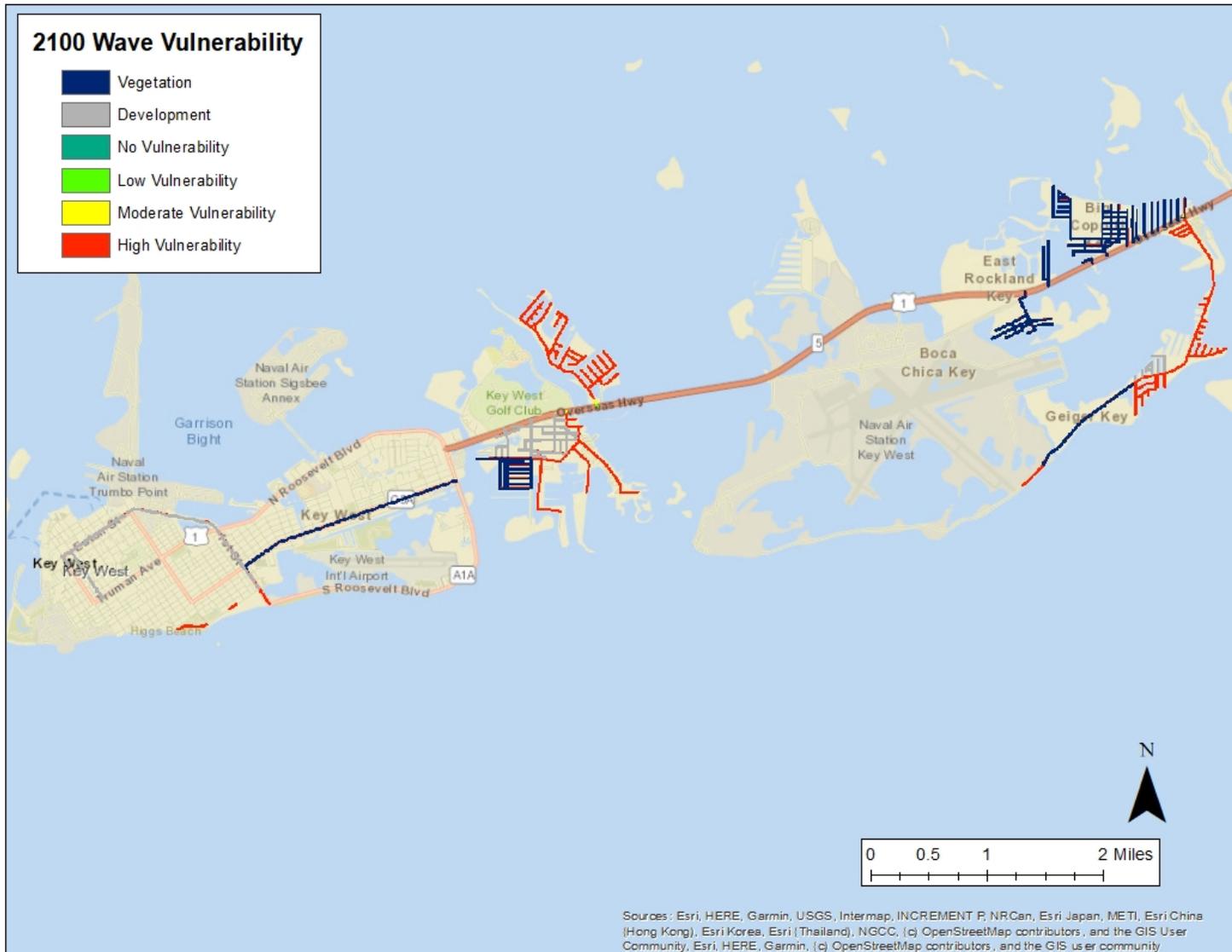
Figure C.21 - Wave vulnerability for the Key West and Naval Air Station nested domains for 2100
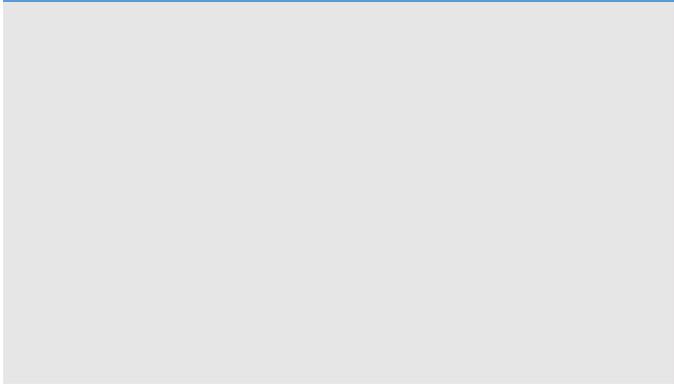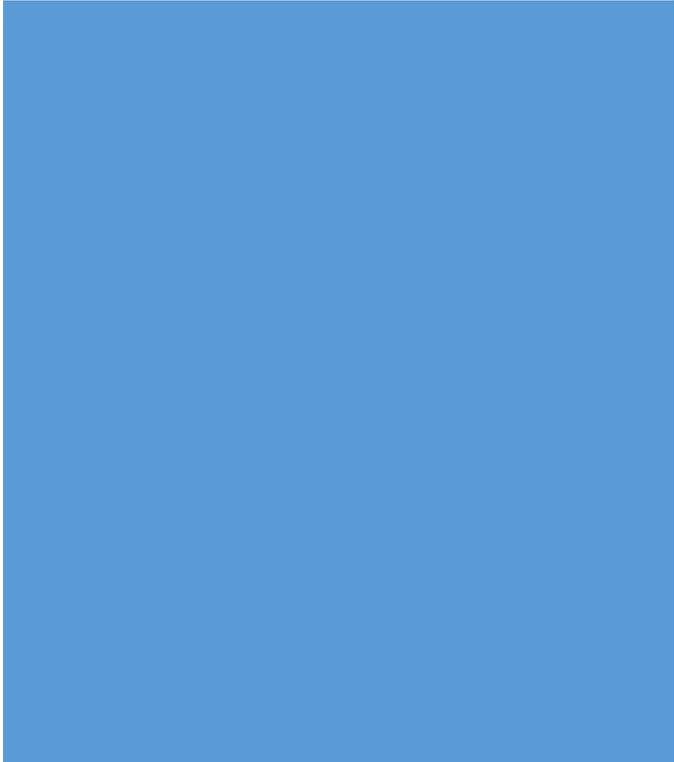
Appendix D: Maximum Wave Height Results
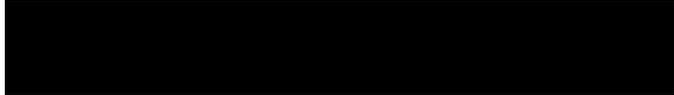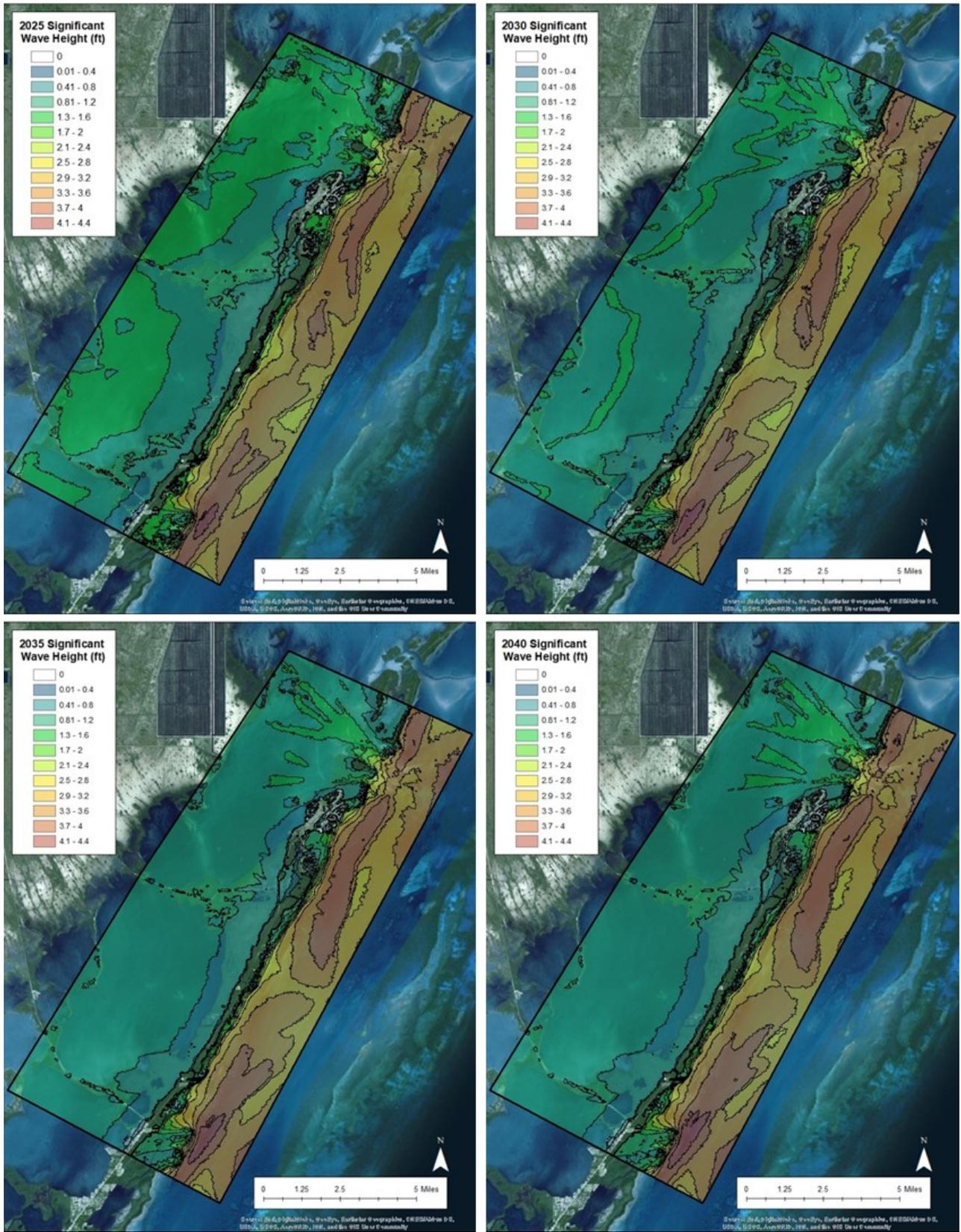
Figure D.1 - Significant wave heights for the North Key largo nested domain for 2025 to 2040
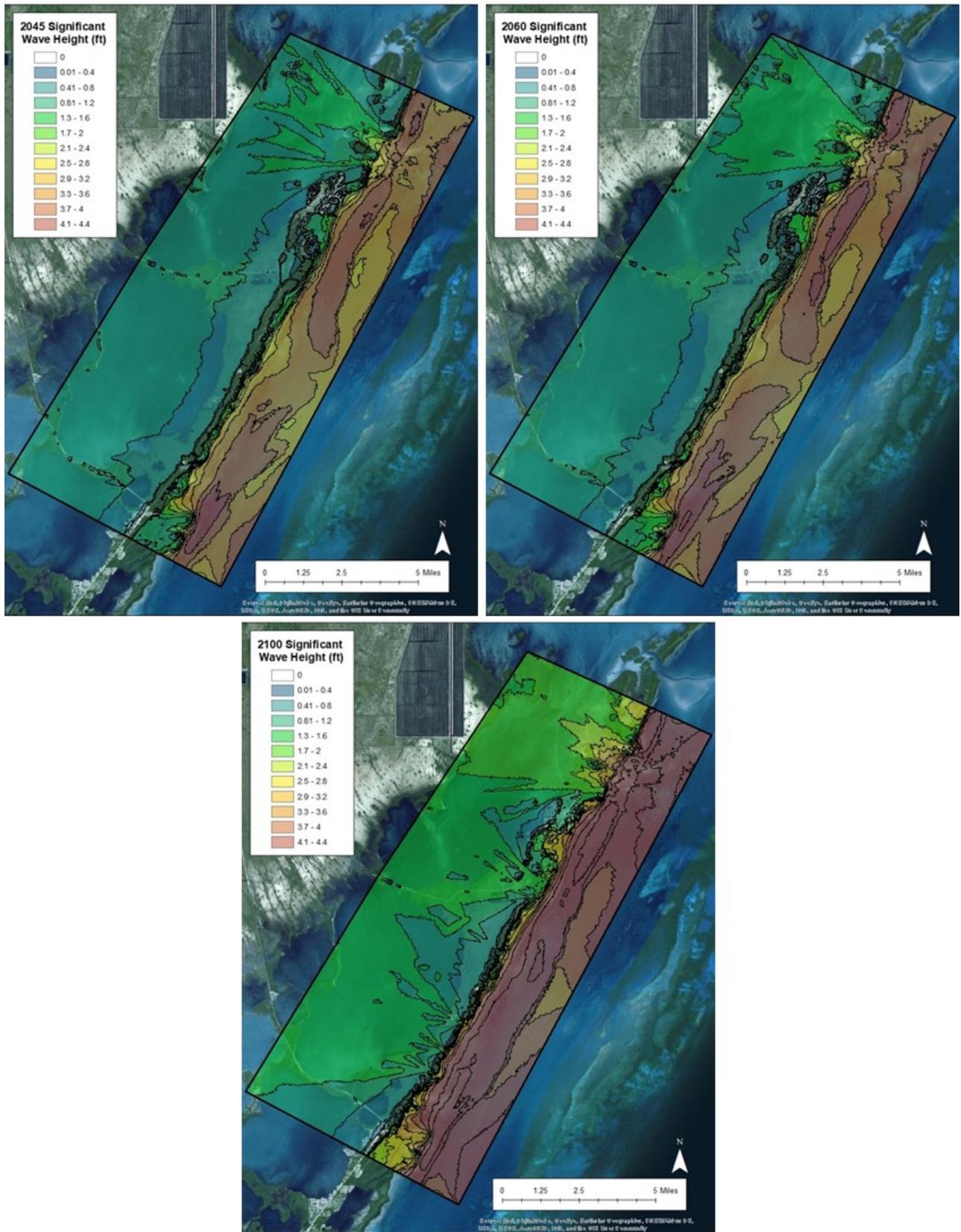
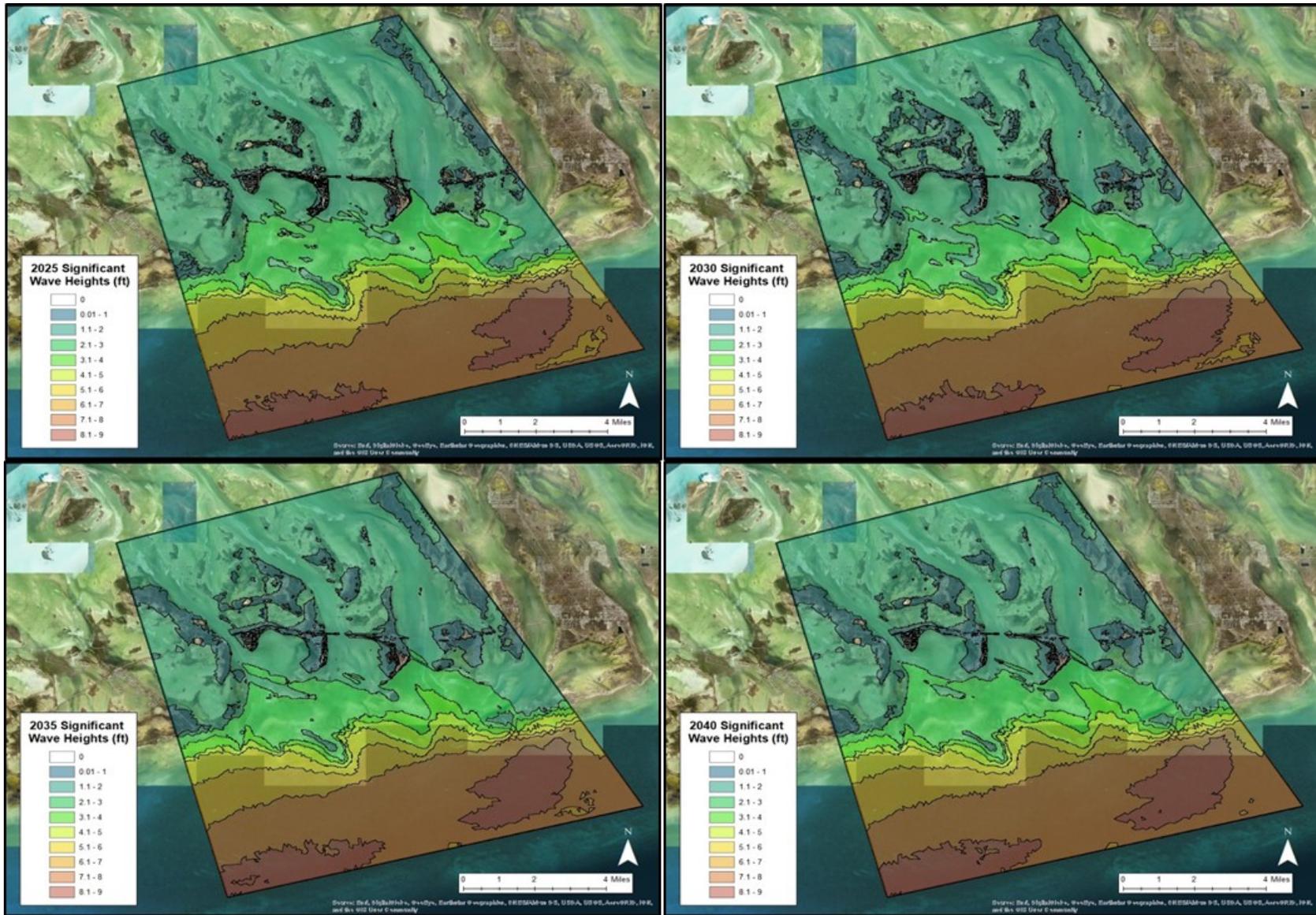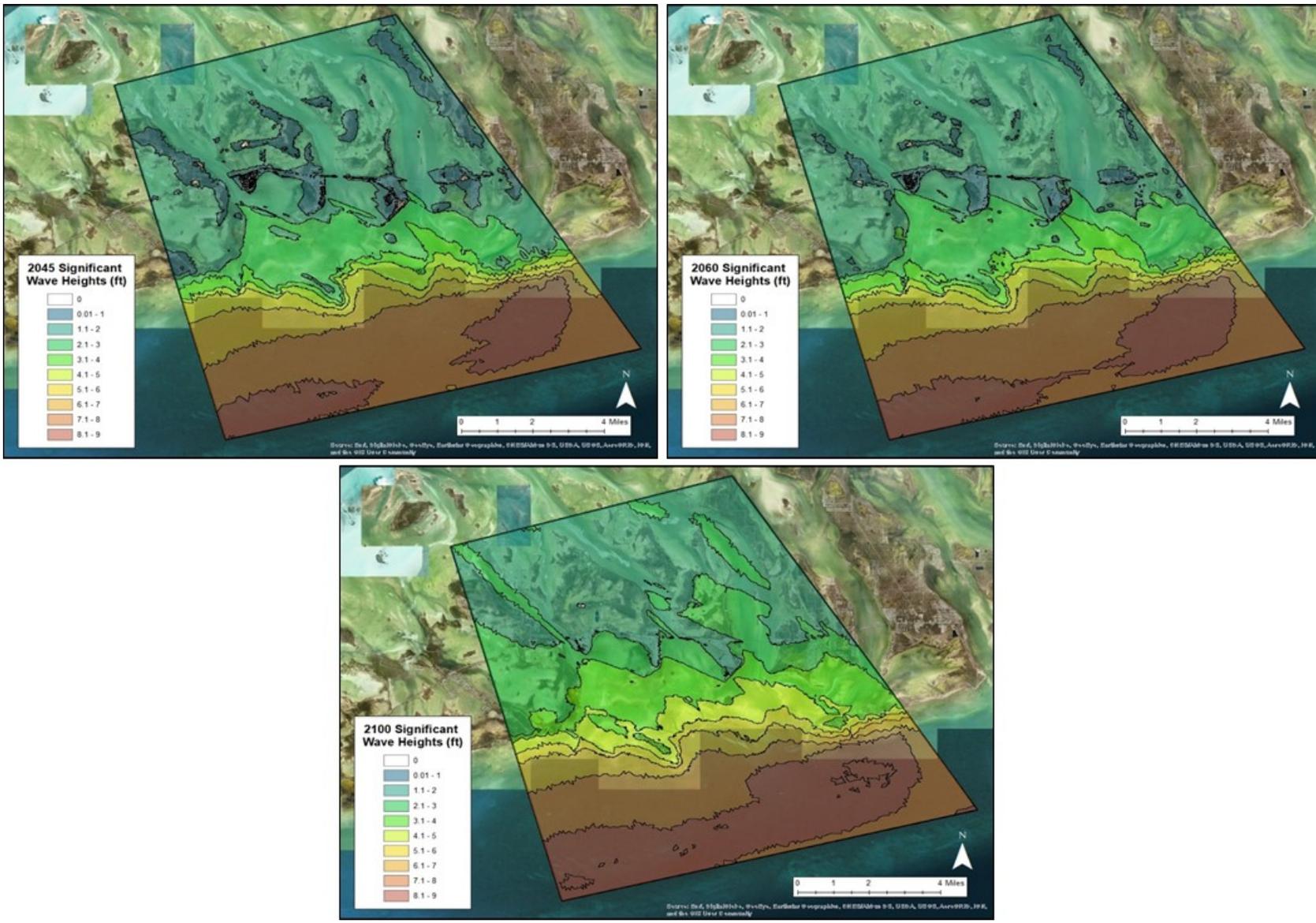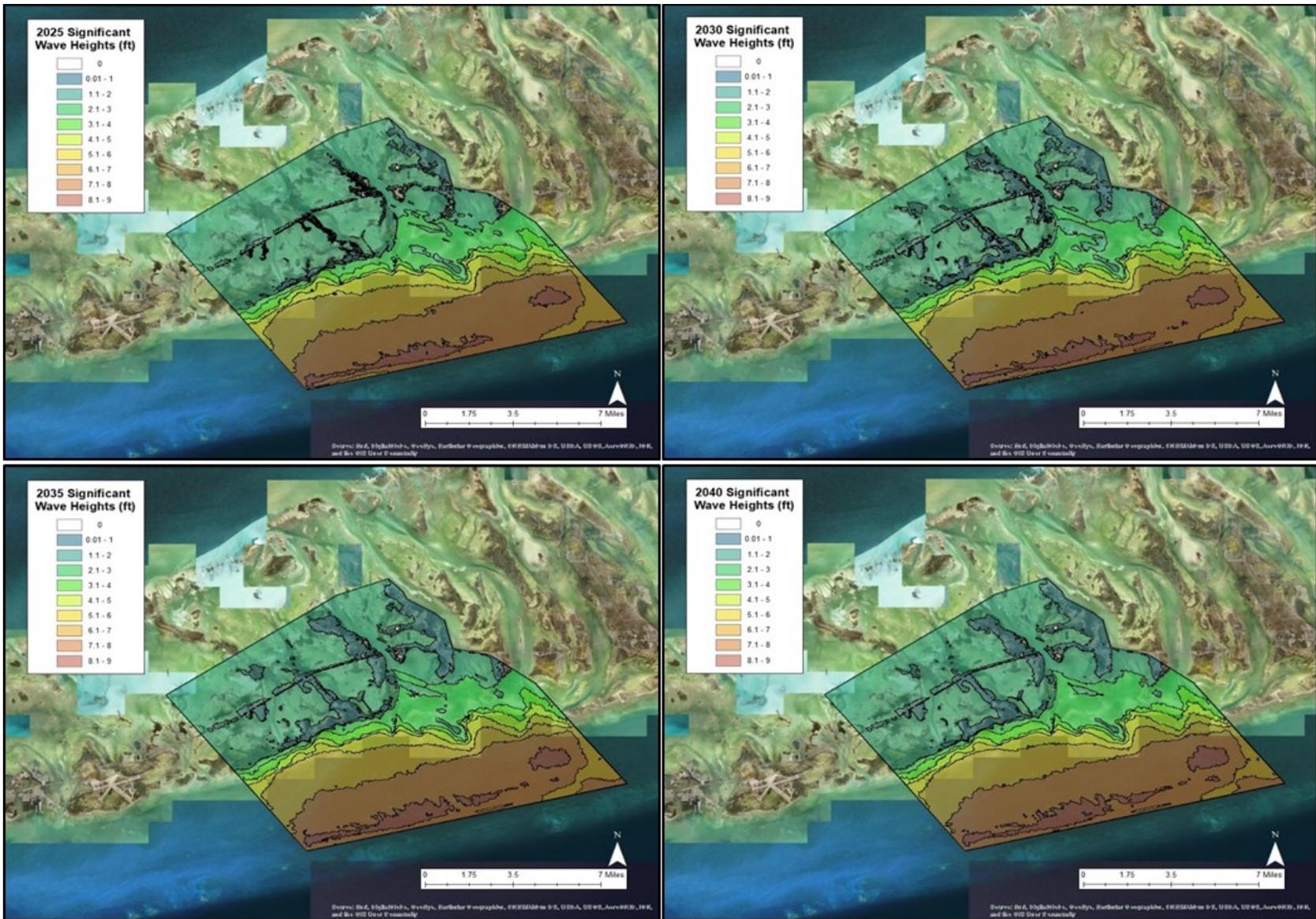**Figure D.2 - Significant wave heights of the North Key Largo nested domain from 2045 to 2100.**
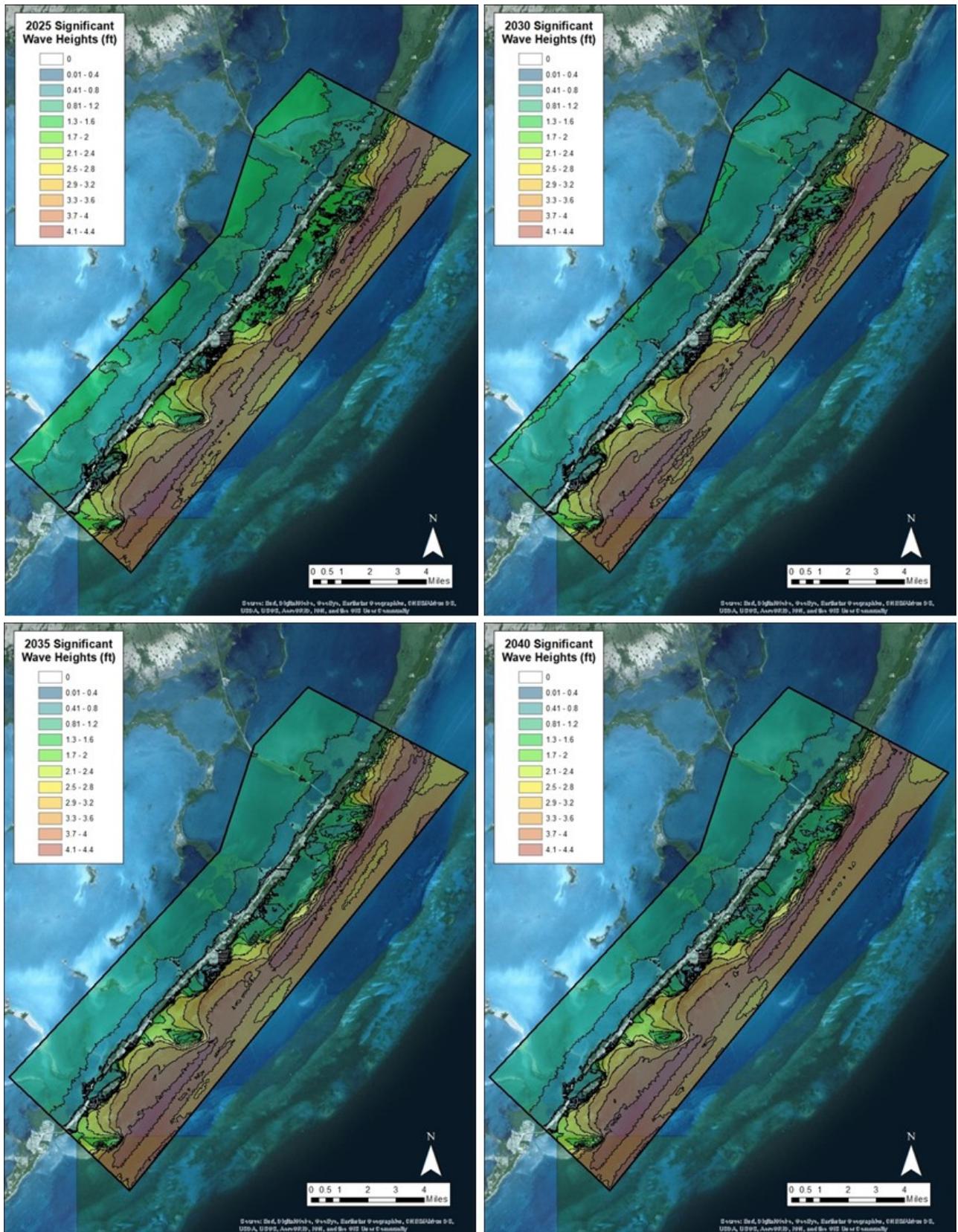
Figure D.3 - Significant wave heights for the Key Largo nested domain from 2025 to 2040.
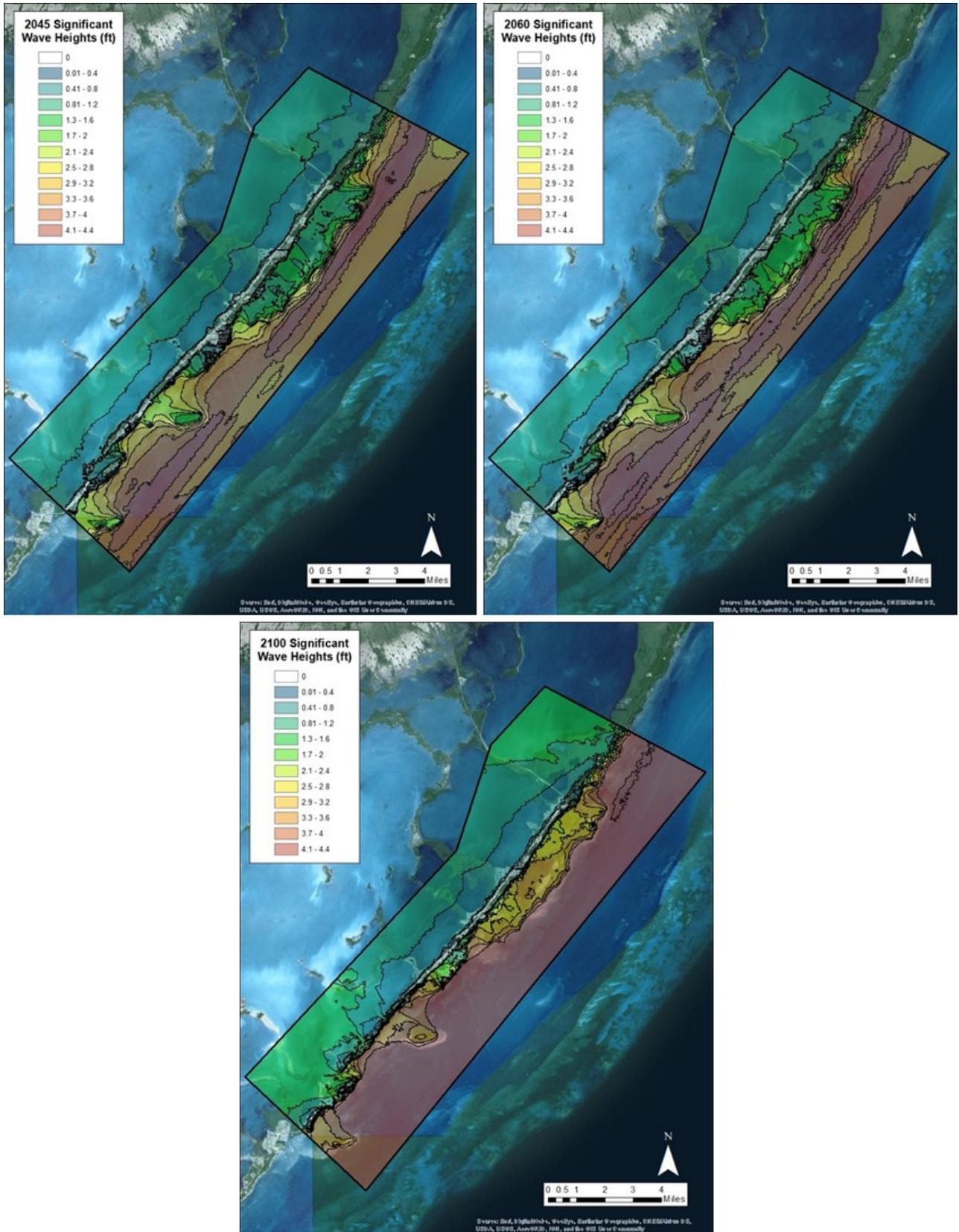
Figure D.4 - Significant wave heights for Key Largo nested domain from 2045 to 2100.
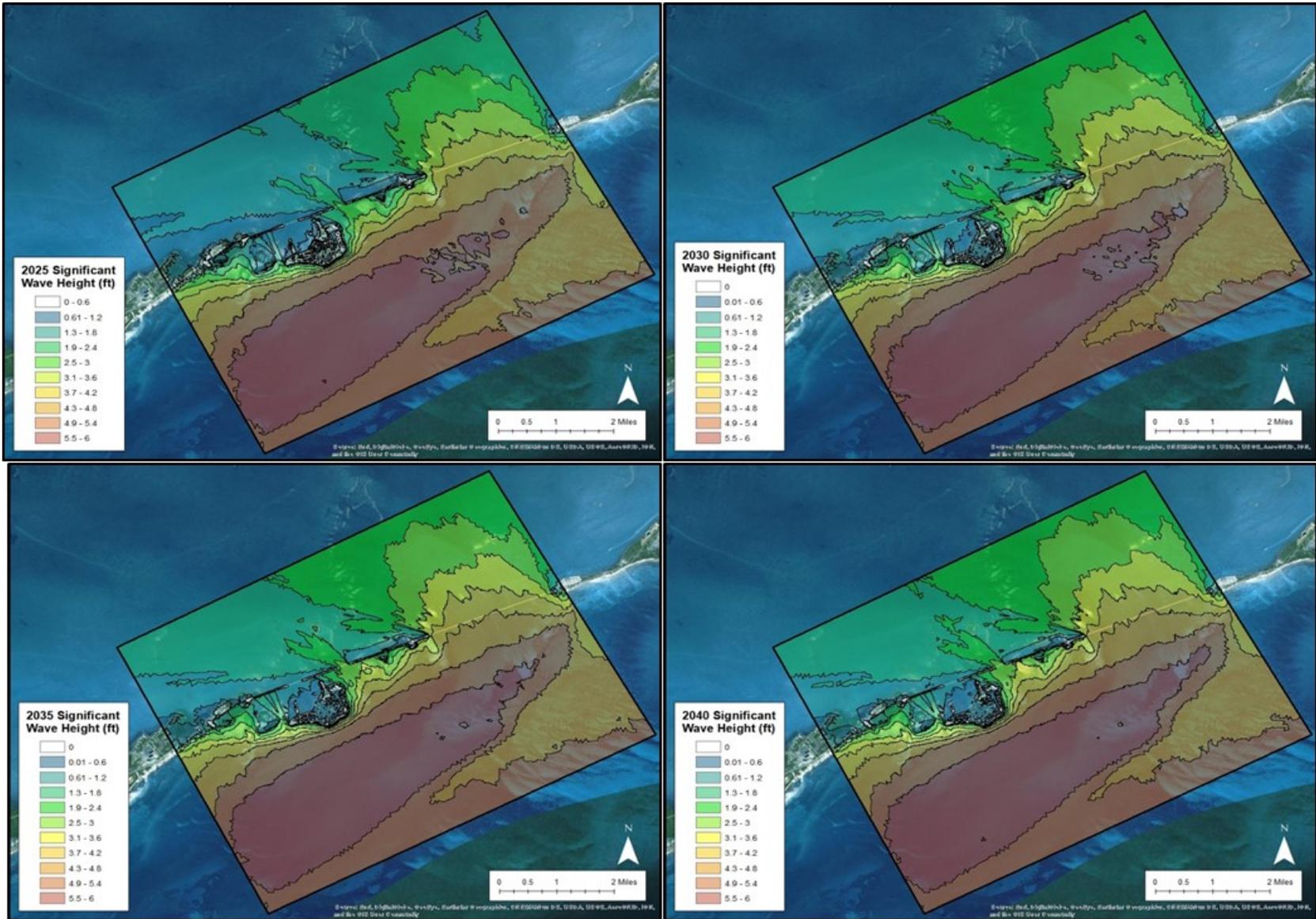
Figure D.5 - Significant wave heights of the Duck Key domain from 2025 to 2040
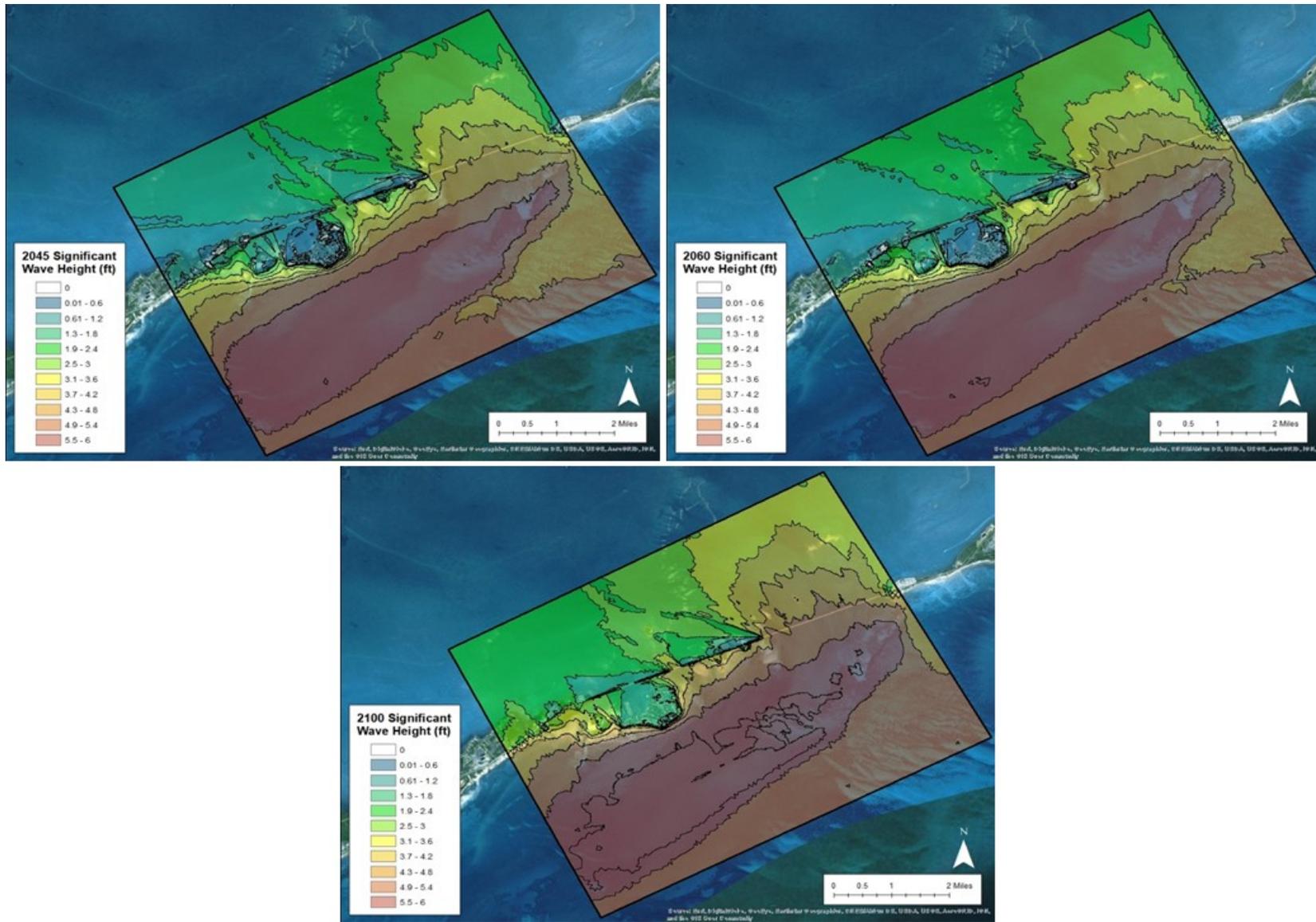
Figure D.6 - Significant wave heights of the Duck Key domain from 2045 to 2100
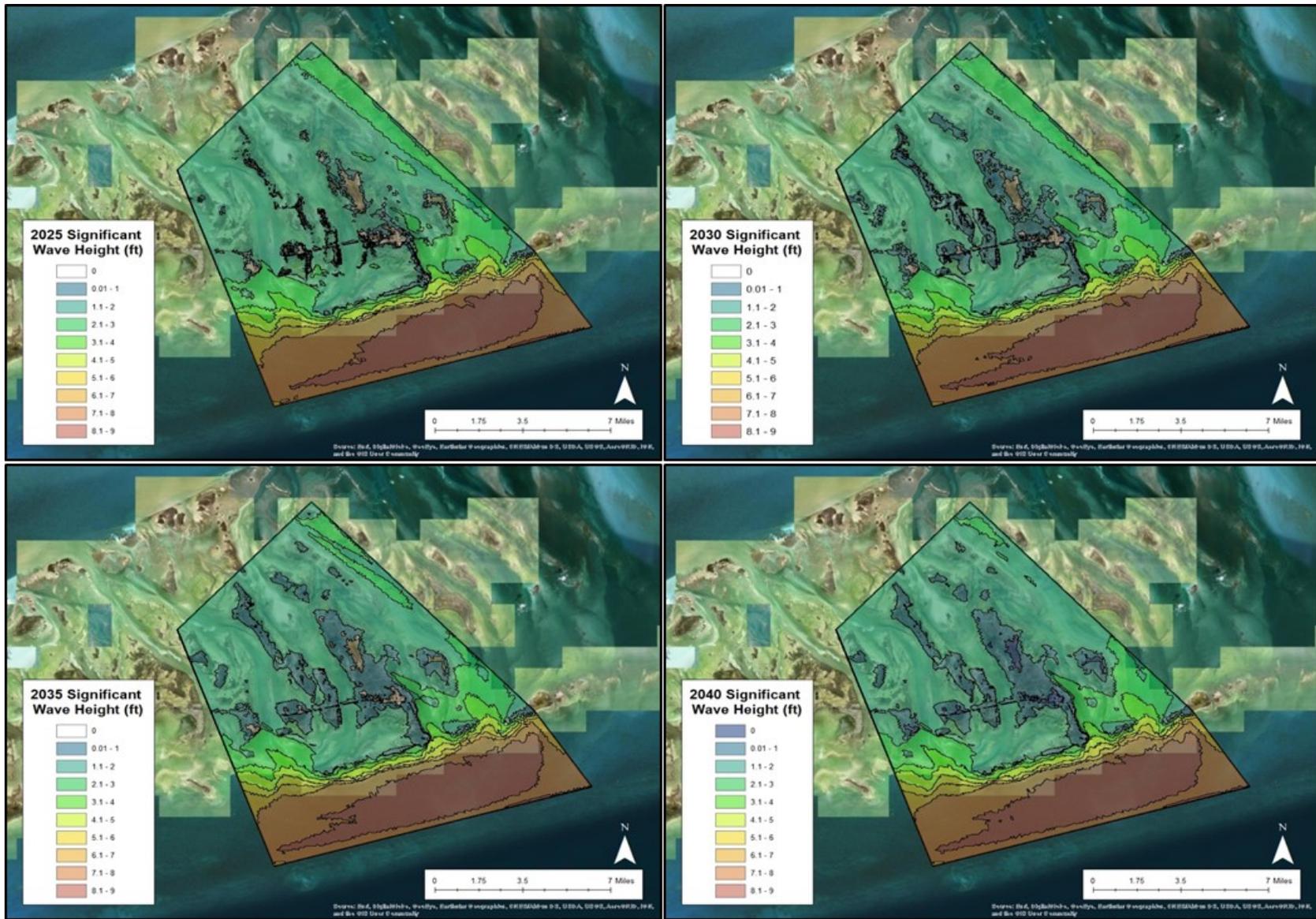
Figure D.7 - Significant wave heights for Big Pine Key (1) nested domain from 2025 to 2040
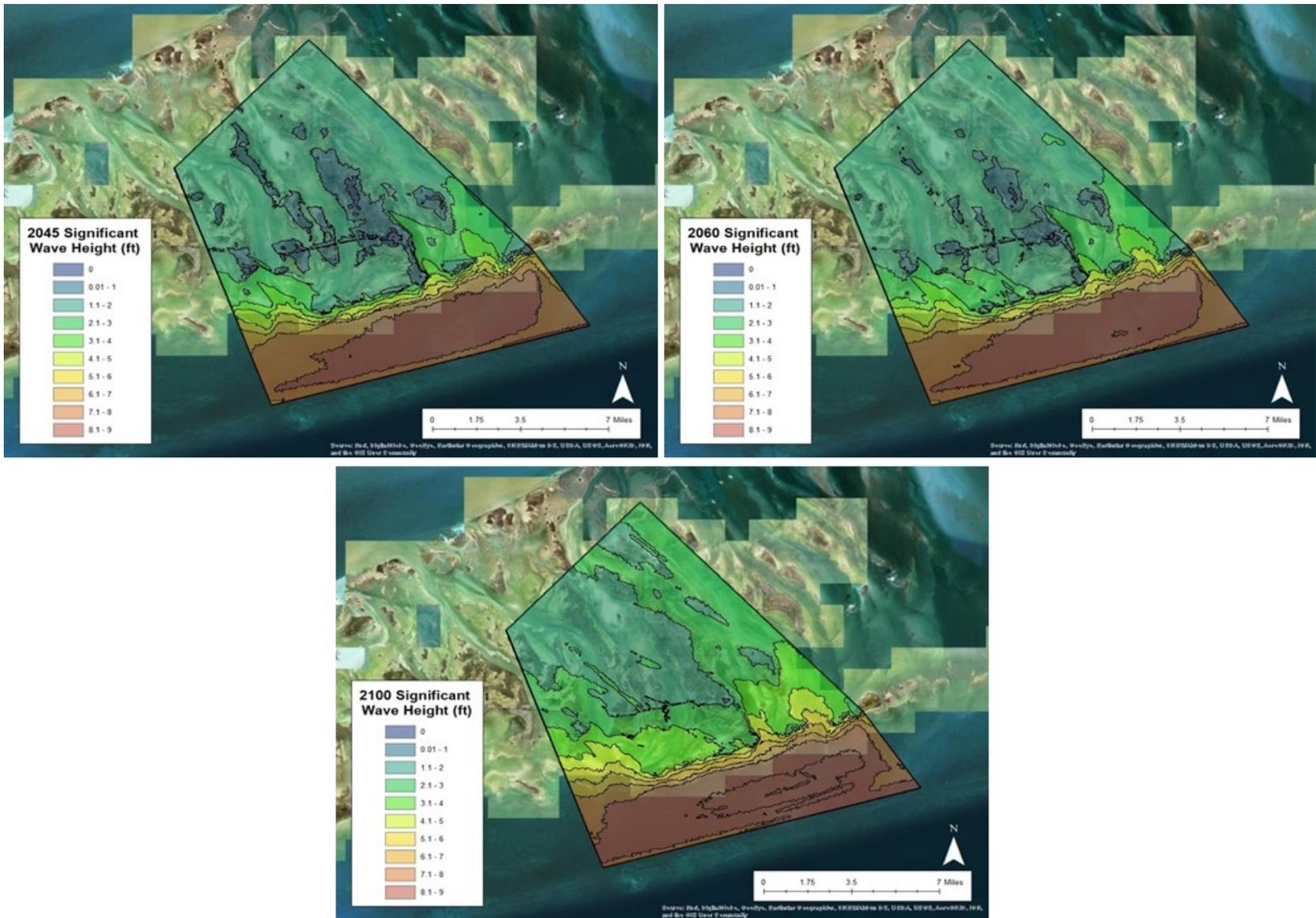
Figure D.8 - Significant wave heights for the Big Pine Key (1) nested domain from 2045 to 2100
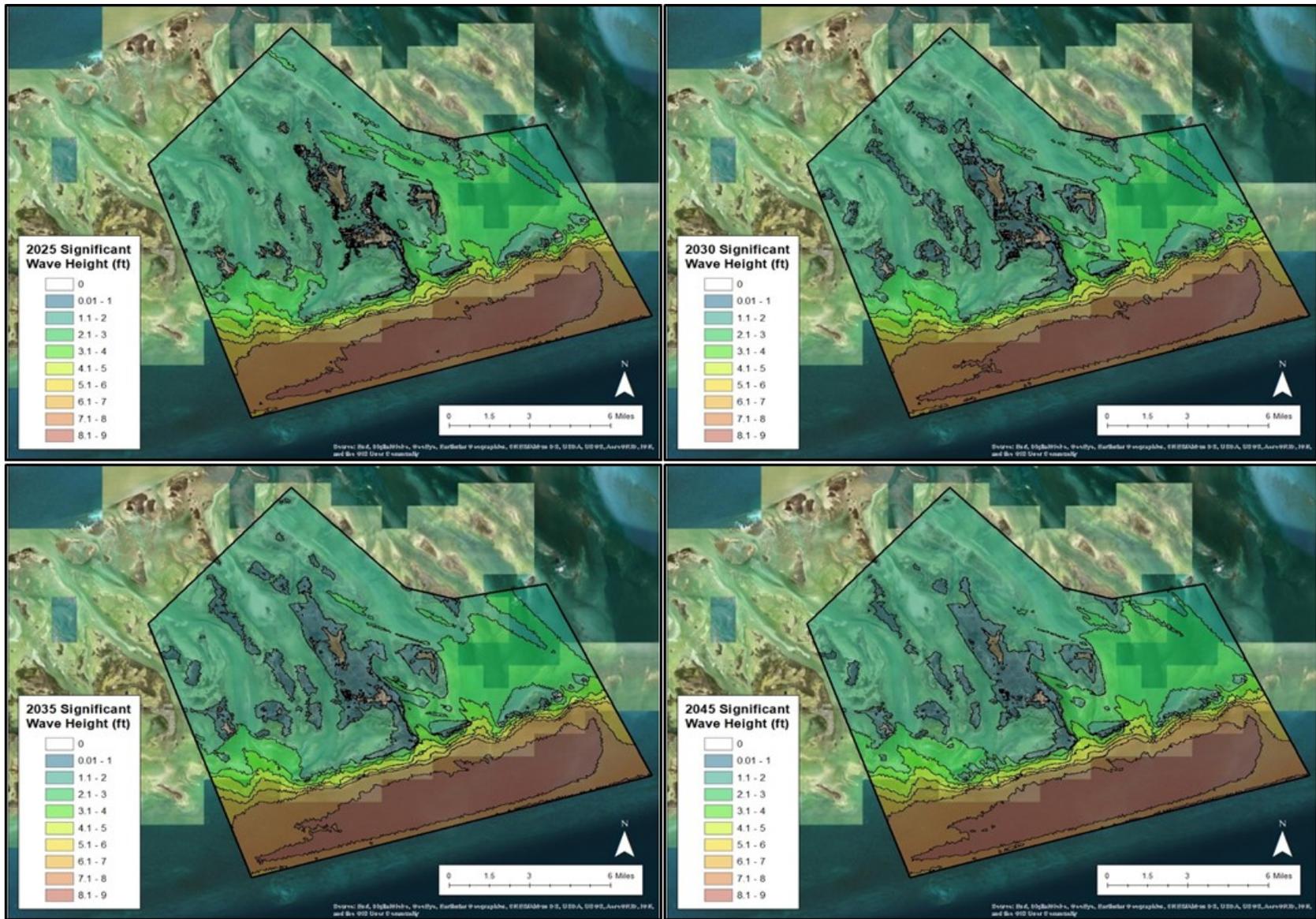
Figure D.9 - Significant wave heights for the Big Pine Key (2) nested domain from 2025 to 2040
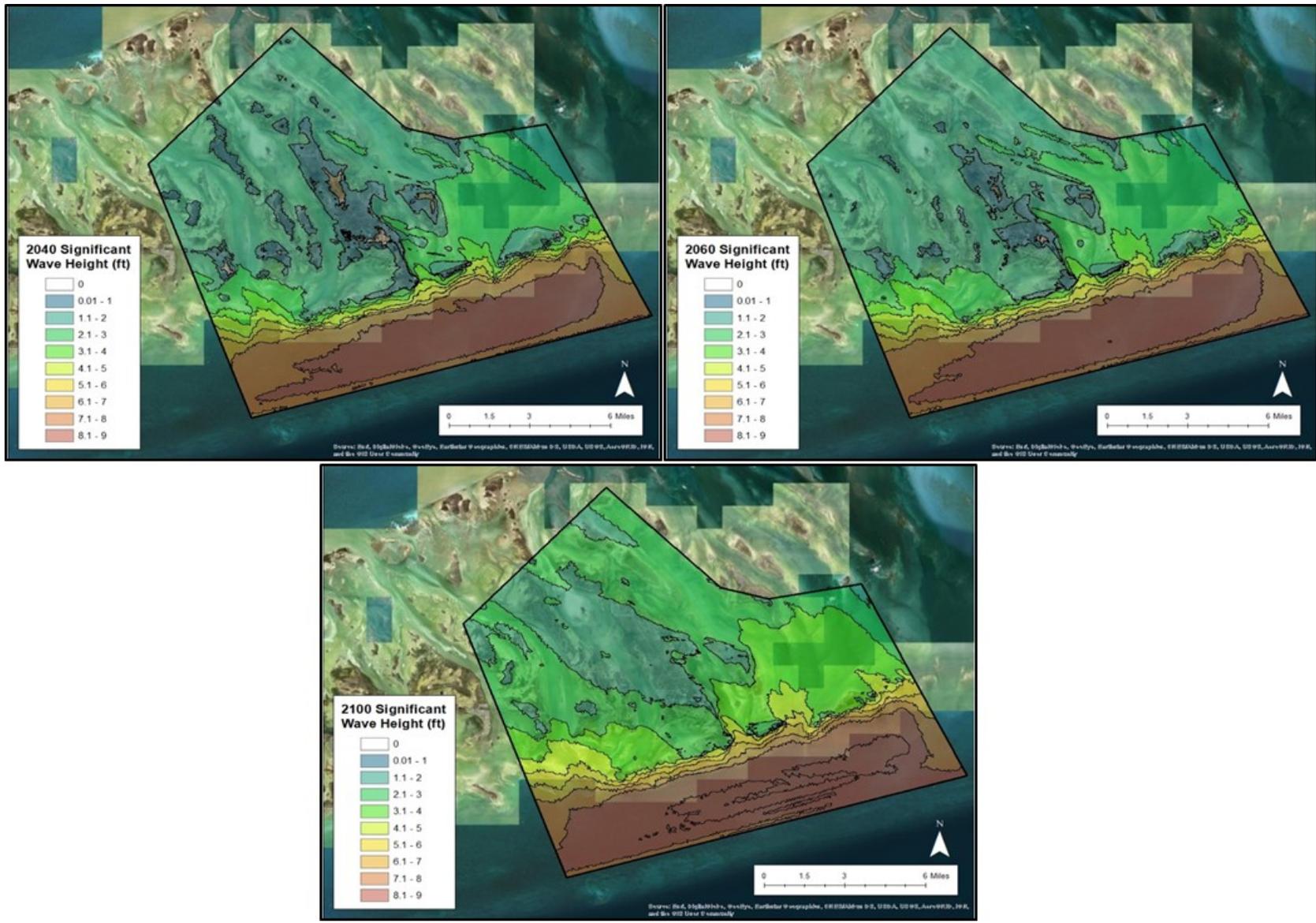
Figure D.10 - Significant wave heights for the Big Pine Key (2) nested domain from 2045 to 2100

Figure D.11 - Significant wave heights for the Summerland nested domain from 2025 to 2040

Figure D.12 - Significant wave heights for the Summerland nested domain from 2045 to 2100

Figure D.13 - Significant wave heights for the Sugarloaf nested domain from 2025 to 2040
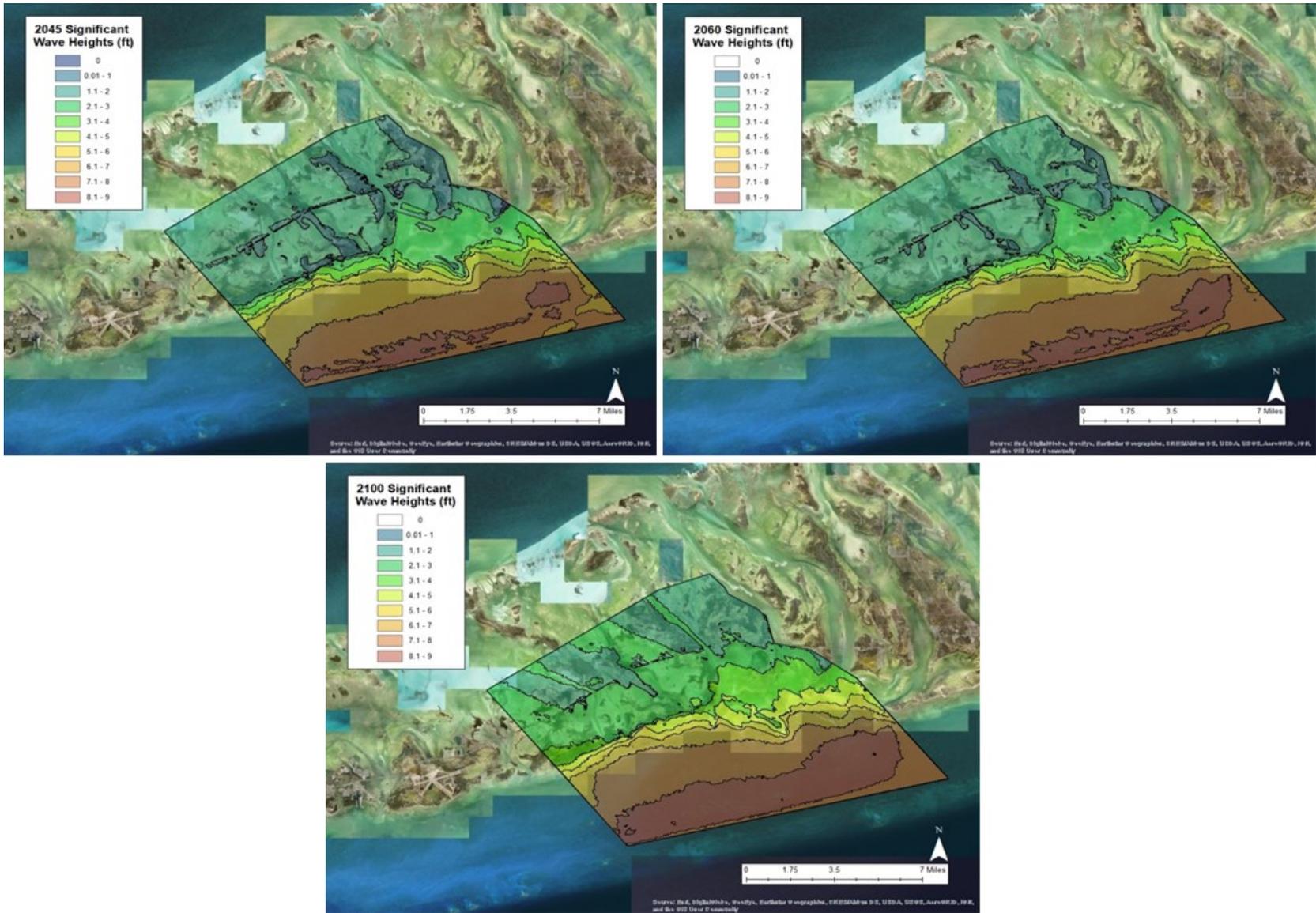
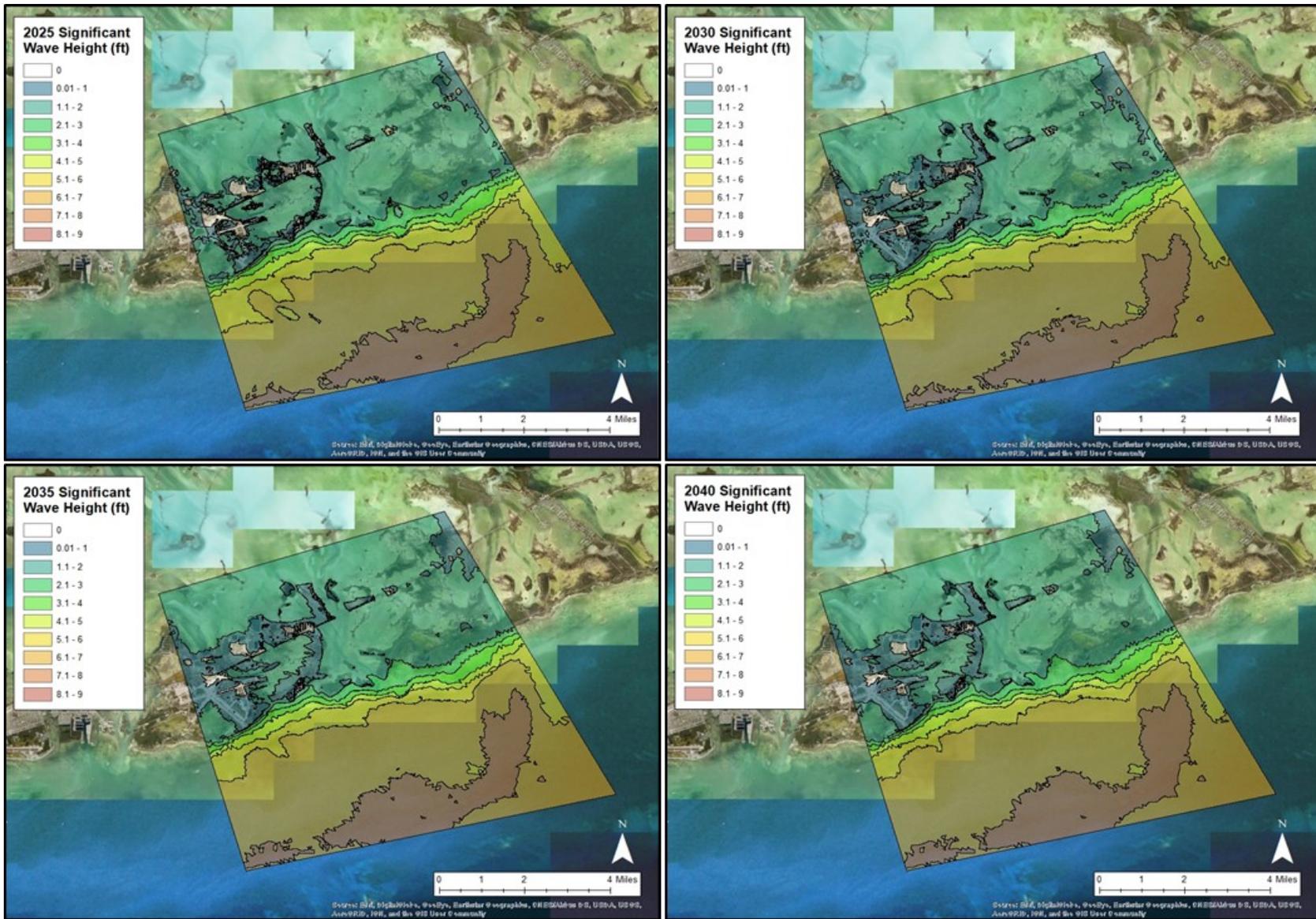**Figure D.14 - Significant wave heights for the Sugarloaf nested domain from 2045 to 2100**

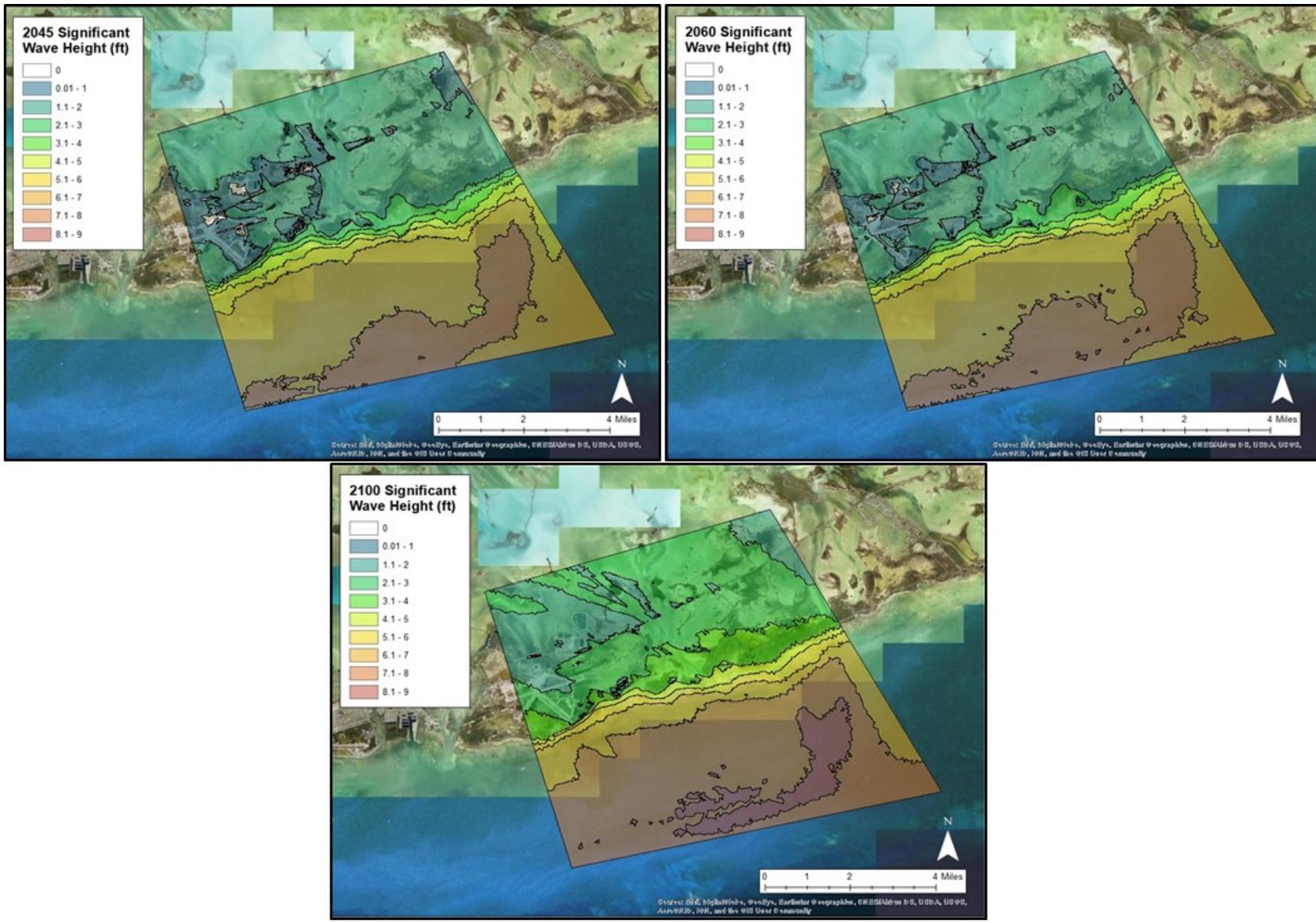**Figure D.15 - Significant wave heights for the Naval Air Station nested domain from 2025 to 2040**

Figure D.16 - Significant wave heights for the Naval Air Station nested domain from 2045 to 2100
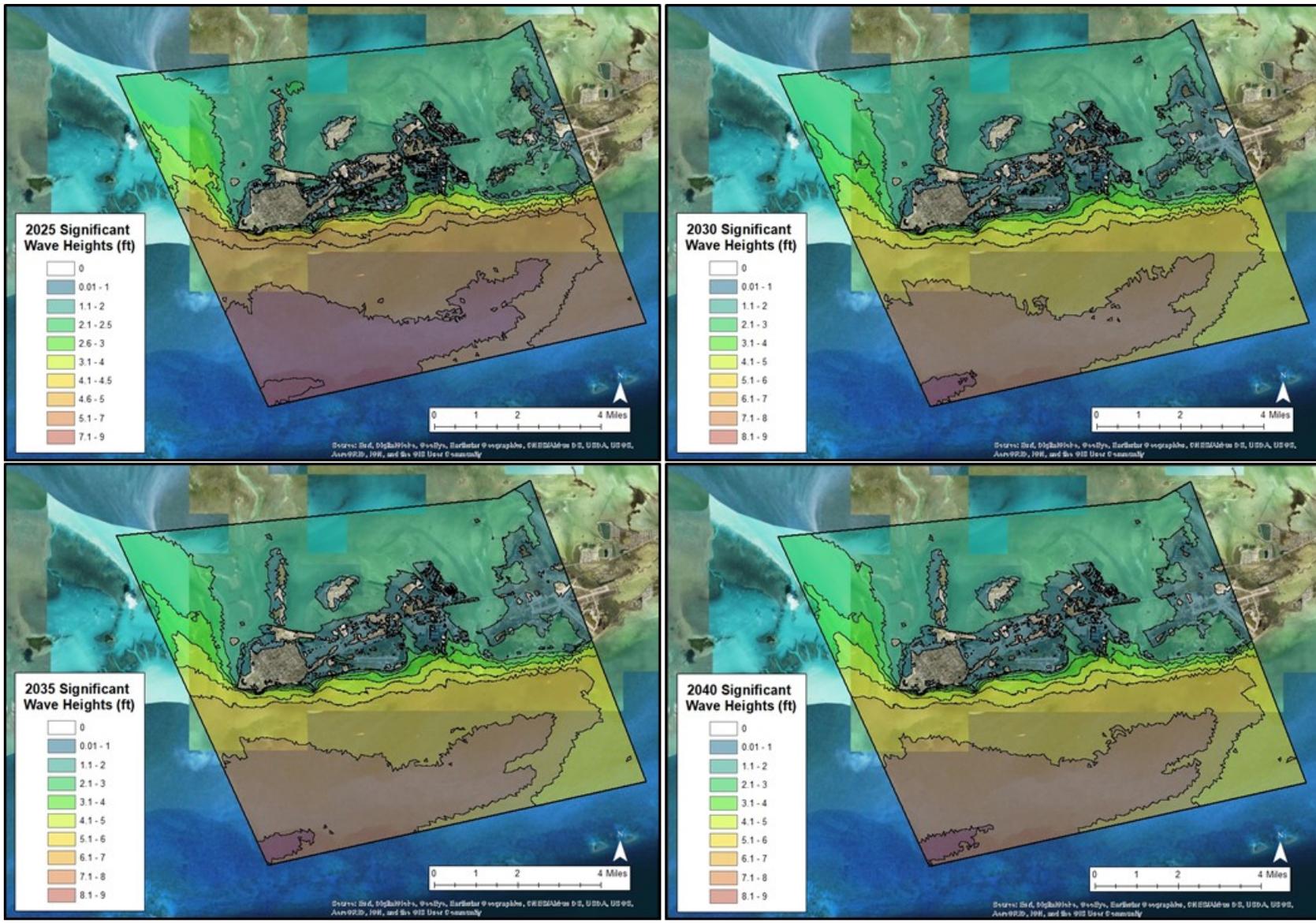
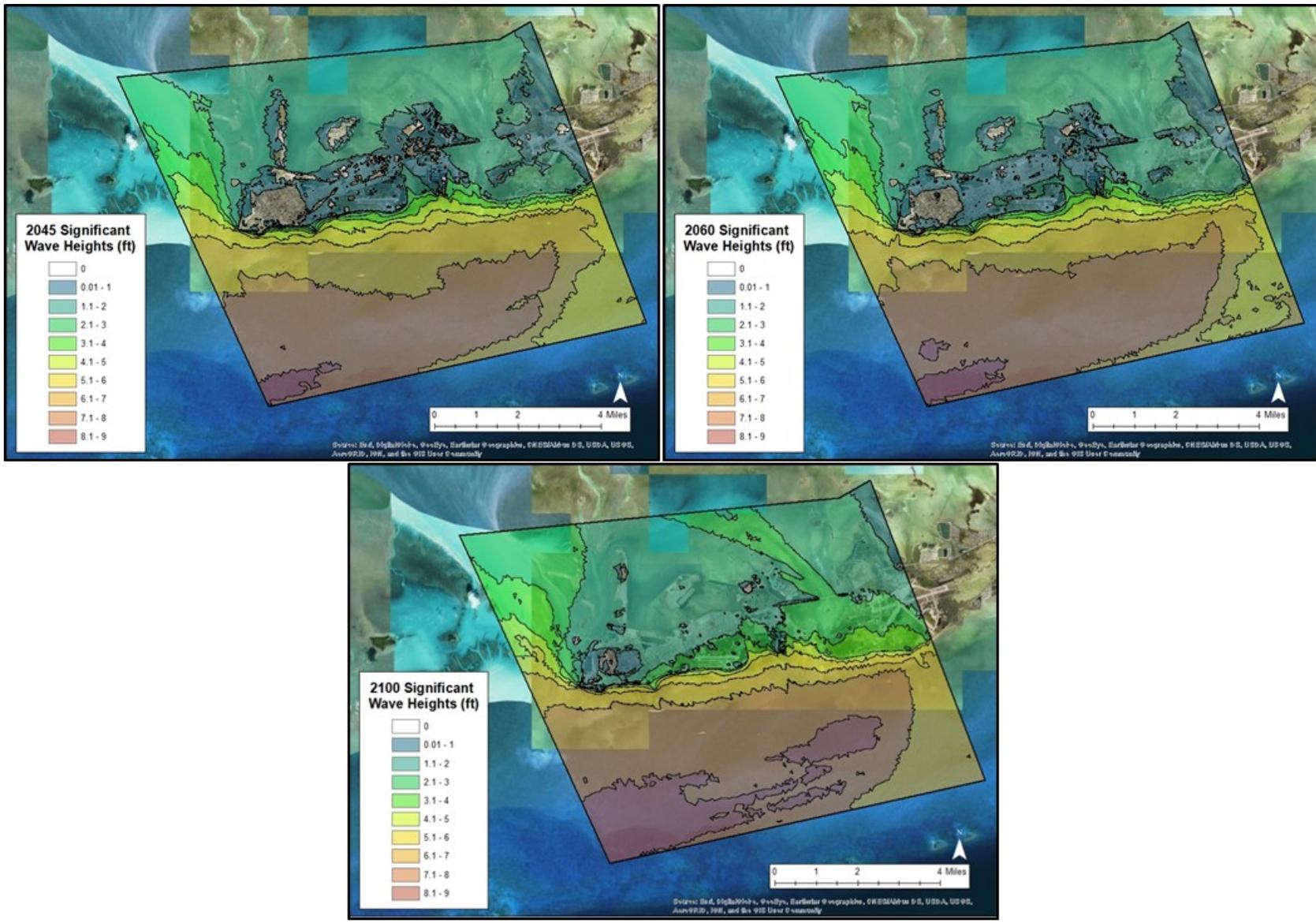**Figure D.17 - Significant wave heights of the Key West nested domain form 2025 to 2040**

Figure D.18 - Significant wave heights for the Key West nested domain from 2045 to 2100