GULF OF MEXICO
ALL-HAZARDS COASTAL RISK ASSESSMENT

FINAL REPORT

Prepared For:

Disaster Response Center
National Ocean Service
National Oceanic and Atmospheric Administration

Prepared By:

Research Planning, Inc.
1121 Park St.
Columbia SC 29201

30 September 2015

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INTRODUCTION

This project provides a detailed assessment of plausible risks to the Gulf of Mexico and the coastal region of the five states that border the Gulf of Mexico within the scope of the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) and Disaster Response Center's (DRC) mission priority for coastal preparedness, response, recovery, and resiliency to All-Hazards. The scope of all phenomena that could potentially be considered a hazard is very broad, so a set of criteria for including hazard scenarios in this assessment was identified as a first step. Hazards evaluated in the context of this report generally include phenomena that:

1) Involve significant increased risk to life, property or environment either through mechanism of increased physical energy or toxicity;
2) Are relatively infrequent, discrete events of fixed and limited (short to medium – days to months) duration; and
3) Require an event-specific or emergency response from NOAA.

These criteria generally excluded chronic problems that would not have an event-specific or emergency response from NOAA or NOAA-supported agencies. As such, phenomena like drought, famine, political instability, or chronic pollution have all been excluded. While these and other excluded hazards are of significant concern, the methods used to evaluate and compare relative risks are very different and, generally, would not require an event-specific response. The general categories of hazards considered here are included in Table 1. We distinguished between natural hazards generated by natural processes and anthropogenic (or technological) hazards.

Table 1. Natural and anthropogenic hazards included in this analysis**.**

Hazard Category	Hazard Type
Geophysical	Earthquake
	Volcanic Eruption
	Dry Mass Movement
	Tsunami
Meteorological	Tropical Storm
	Tornado
	Lightning
Hydrological	Riverine Flood
	Flash Flood
	Storm Surge/Coastal
Climatological	Wildfire
Biological	Harmful Algal Bloom

Hazard Category	Hazard Type
Oil/Chemical Spill	Vessel/Tanker
	Pipeline
	Vehicle
	Rail
	Facility
Nuclear/Radiological Release	Reactor
	Facility
	Vehicle
Biological	Sewage System

The list of hazards is quite broad and may seem initially counter-intuitive. Tsunamis and dry mass movement or landslides are not considered as commonly occurring hazards in the Gulf of Mexico. This work attempted to include an exhaustive list for two reasons: (1) some hazards may be infrequent on human time scales but actually pose significant risk (e.g., tsunamis) and (2) the methodology presented here can be applied for similar risk assessments that may examine a different suite of hazards, assets, regions, or combination of those three aspects.

The broad mandate of the DRC and NOAA implies that it is desirable to estimate risk to human populations and infrastructure, as well as to natural resources and the natural environment. As such we considered risk here as specific to four distinct assets: human population, human infrastructure, sensitive natural habitats, and threatened and endangered species. In this analysis, we treated these assets separately when evaluating risk because the vulnerability of an asset to a particular hazard varies both by the mechanism through which the hazard causes damage or harm and the attributes of a given asset type.

Multi-hazard risk assessments are generally either qualitative or quantitative. Here, we used a semi-quantitative framework to evaluate risk. We included quantitative rates of hazard event occurrence, amount of assets at risk, and quantitatively derived relative vulnerability estimates of assets to hazards of different severities. The final overall risk indices allowed for ranking and comparison of risks from multiple hazards over the area of interest, but the indices do not reflect any physical quantity.

The study area was comprised of 73 counties and parishes in Texas, Louisiana, Mississippi, Alabama, and Florida with coastlines on the Gulf of Mexico, or with significant estuaries that are hydrologically connected to the Gulf (Figure 1).

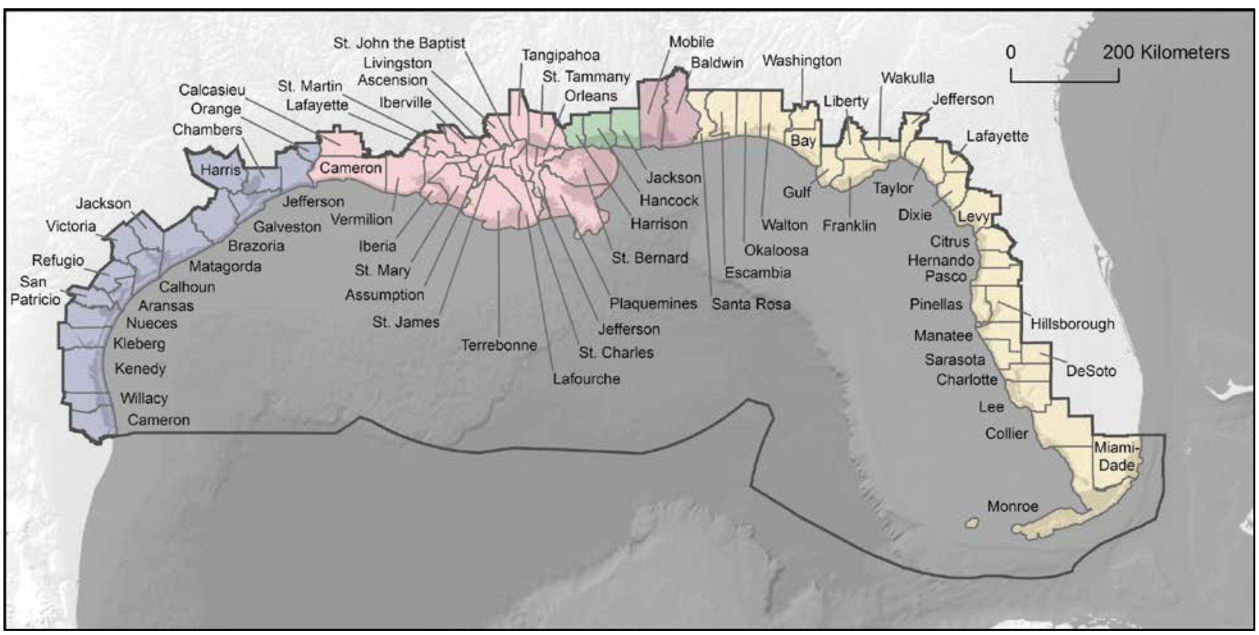

Figure 1. Counties and parishes comprising the study area**.**

RISK ESTIMATION OVERVIEW

The language used to define concepts such as risk, hazard, vulnerability, and similar concepts can be confusing, and may differ by discipline, so it is useful to explicitly define terms and concepts used in this analysis and the overall strategy adopted for evaluating risk. We considered risk to be both hazard- and asset-specific, reflecting the rate of hazard event occurrence, the amount of asset exposed, and the vulnerability of that asset to that hazard.

We considered the rate of hazard events as the most likely number of occurrences of a potentially damaging phenomena, event, or activity with the potential to cause harm to an asset over a fixed time interval. All rates have been presented as annual expected rates. We defined assets as human population, property, and natural resources that may be exposed to a hazard. We conceptualized vulnerability by assuming that a given event of a specific hazard type may have different severities, and that the relative impact of a hazard event to a specific asset differs by event severity. Frequency of an event of a given severity expressed the estimated likelihood that a hazard event will have a minor, moderate, or major impact on an asset given the occurrence of that hazard event. Relative impact defines the relative difference of harm a minor, moderate, or major hazard could cause to an asset. As such, we evaluate risk based upon the methodology in Figure 2.

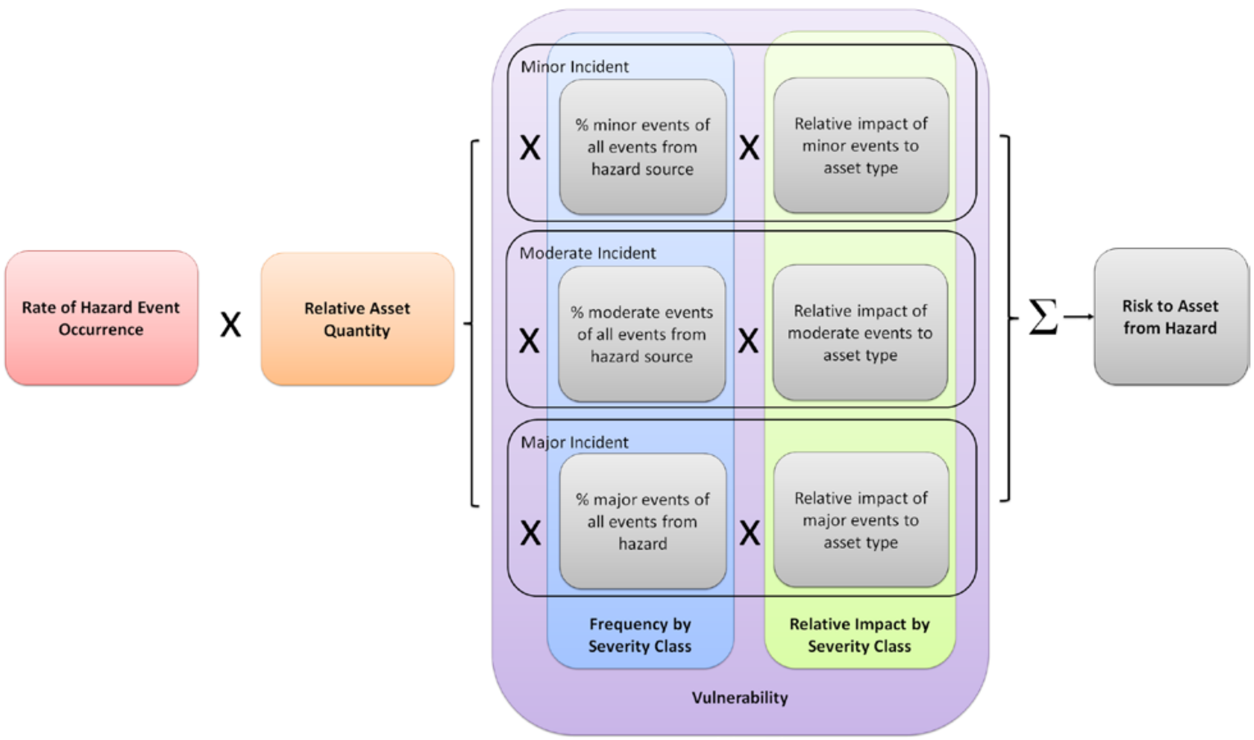

Figure 2. Overview of risk assessment methodology for each specific hazard and asset combination.

An overview for each of the terms used to define risk has been given below, with specific details on the methods and sources used throughout calculations provided separately in respective sections throughout the report.

***Rate of Hazard Event Occurrence* -** Within each county or parish, for each hazard type, rate of occurrence was computed as the average annual rate of a hazard event (e.g., storm, flood, or spill/release). Rates were calculated based on available datasets, reports, and published literature.

Relative Asset Quantity - Within each county or parish, for each asset category, we computed the total amount of both human and environmental assets in each identified category. We selected asset categories that were easily comparable among counties or parishes, and that spanned the full range of NOAA's mission to respond to natural and human disasters.

***Vulnerability* -** For each specific hazard and asset type, we estimated the relative vulnerability of that asset type to that hazard. We estimated vulnerability by apportioning hazard events into different severity classes (minor, moderate, and major) and estimating the differences in impact to an asset from a hazard event of each severity class. This process created severity classes that were unique to each specific combination of hazard type and asset type. For example, a major oil spill could have very large effects on sensitive habitats and species, but small effects on human populations. Between severity classes for each hazard and asset combination, we computed both the proportion of all events that fall within these severity classes and the relative difference in impact (with each set of methods described below).

***Severity Class* -** Severity classes were based upon *a priori* cutoff values for a single metric for each asset type including economic cost, human casualties (fatalities and injuries), and hazard event size. Event size as was approximated by spill volume for oil spills, evacuation radius for chemical, biological, and radiological spills/releases, and event footprint for natural hazards like floods, tornados, and tropical storms.

***Frequency by Severity Class* -** For most specific hazard types, we computed the relative proportion of all events that fall within severity classes by computing summary statistics from events recorded in long-term comprehensive databases. Where database records were insufficient or unavailable, we estimated hazard frequency by severity class using expert knowledge and/or the most recent information from published literature.

***Relative Impact of Severity Class* -** For each specific hazard category and asset type, we computed the relative impact between severity classes in a two-step process. First, we computed the mean damage or harm from all events within a severity class. Second, we normalized these values by dividing the mean values of each severity class by the mean impact from "major" hazard type severity class.

NATURAL HAZARDS

Natural hazards included in this analysis have been listed in Table 2. The hazard types included in this report have been chosen to reflect differences in the source of the hazard and the mechanism (e.g., wind, rain, tidal, riverine, tectonic, etc.) through which assets are put at risk. We note that many of these hazards will co-occur in relation to a singular root cause. For example, convective storms are likely to bring both convective storm winds and lightning, which is itself a frequent source for the sparks that can ignite wildfires (USFS, 2014), but the threats these hazards pose to assets are unique in the mechanism (wind, electricity, and heat) and the spatial scale at which they cause damage varies significantly. We differentiated hazard types with similar rates of occurrence but different mechanisms and/or scale by including vulnerability as a term that varies both by hazard type and asset type. Thus, when annual rates of occurrence of interrelated hazard types were similar, the risk indices between hazard types highlighted relative levels of risk among asset types.

Table 2. Natural hazards included in analysis and sources for probabilities/rates, frequency by severity class, and spatial footprint if applicable. Specific methods are described in the text.

Hazard Category	Hazard Type	Rate and Frequency by Severity Class Source	Footprint/Location Source
Meteorological	Tropical Storm Wind	NOAA IBTrACS	NOAA IBTrACS
	Convective Storm Wind	NOAA SPC SVRGIS database NOAA NCDC Storm Event Database	Estimated to affect a portion of a county or parish
	Tornado	NOAA SPC SVRGIS database NOAA NCDC Storm Event Database	NOAA SPC SVRGIS database NOAA NCDC Storm Event Database
	Lightning	NOAA NCDC NLDC gridded summary data	Estimated to affect a portion of a county or parish
Hydrological	Riverine Flood	NOAA NCDC Storm Event Database	FEMA DFIRM/Q3 flood risk data NOAA NCDC Storm Event Database
	Flash Flood	NOAA NCDC Storm Event Database	FEMA DFIRM/Q3 flood risk data NOAA NCDC Storm Event Database
	Storm Surge/Coastal Flood	NOAA NCDC Storm Event Database	FEMA DFIRM/Q3 flood risk data NOAA NCDC Storm Event Database
Geophysical	Earthquake*	USGS National Seismic Hazard Maps	Estimated to affect an entire county or parish
	Volcanic Eruption	VOGRIPA Database	After Jenkins *et al.* (2012)
	Landslide	NOAA NCDC Storm Event Database	Estimated to affect a portion of a county or parish
	Tsunami	USGS report	FEMA DFIRM/Q3 flood risk data
Climatological	Wildfire	USFS spatial wildfire occurrence data	USFS spatial wildfire occurrence data
Biological	Harmful Algal Bloom**	NOAA CSC (2004)	Estimated

*Infrastructure and casualty statistics of earthquakes were estimated from Vranes and Pielke (2009)
** Estimated as always having minor impacts to infrastructure and human populations.

Though beyond the scope of this report, we recognize many natural hazards have greater rates of occurrence in certain multi-year periods and during a certain times of year. For example, tropical storm winds, which are specific to the occurrence of tropical cyclones, have a greater likelihood of occurrence during a La Niña, also known as an El Niño-Southern Oscillation (ENSO) cold event, and occurs on a 2-7 year cycle, as well as during the annual Atlantic hurricane season (June 1 – November 30) (NHC, 2014b). As a result, annual rates of occurrence and the overall risk to assets are best interpreted in the context of these multi-year and annual cycles highlighted in each hazard's description.

Natural Hazard Rate

For all natural hazards, we estimated the rate of hazard event occurrence using available datasets, reports, and published literature. We described each dataset and methodology used to evaluate rate in detail in the hazard-specific subsections below.

Natural Hazard Severity

For most natural hazards, we estimated the frequency of an event by severity class and the relative impacts via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a), which included data on natural hazard events by human casualties and economic cost. Additional data to assess the damage and human casualty of earthquakes was added using U.S. events from 1980 to 2005 included in Vranes and Pielke (2009).The specific process of determining frequency and relative impact by severity class for assets has been described in more detail in the Vulnerability section.

The spatial extent of a natural hazard event ranges widely for various natural hazards. For example, a tropical cyclone making landfall in a particular county has the potential to affect nearly the entire county with hurricane-force winds. By contrast, a single lightning strike within a particular county is not likely to affect more than 100 square meters. In estimating spatial extents of a given natural hazard, they are generally considered to:

1) Affect the entire area of a county or parish with *approximately equivalent magnitude* (e.g., earthquake or volcanic ash fall).

2) Affect the partial area of a county or parish that may *randomly occur anywhere* within the county or parish (e.g., tornadoes, lightning strikes, or wildfires).

3) Affect a limited area of the county or parish that reflect known susceptible areas of a county or parish (e.g., flood zone areas for coastal flooding or coastal waters for harmful algal blooms).

Exact methods used to estimate the distribution of sizes of the spatial extent of each natural hazard are described in respective subsections of this report.

Tropical Storm Winds

Tropical storm winds are one of many natural hazards caused by tropical cyclones. When winds exceed 74 miles per hour (mph), cyclones in the Atlantic Ocean have are classified as hurricanes; tropical storm and tropical depression are terms used globally to describe weaker cyclones (NHC, 2014b). Increases in a cyclone's strength result from feedbacks between evaporating ocean water, heat generated from bands of thunderstorms, and upper level wind speeds. Tropical storm winds differ from convective storm winds and tornadoes because of their size, which can be hundreds of miles in diameter, and the frequency with which they occur. From 1970-2010, an average of 6 hurricanes and 11 tropical storms per season affected the Atlantic Ocean, Caribbean, and Gulf of Mexico (Blake *et al.*, 2011; CPHC, 2012).

The complexity of global air movements and a lack of long-term data describing air movement and temperature cycles limit our understanding and long-term forecasting abilities for these events. In general, the occurrence of tropical cyclones will have a greater likelihood of occurrence during both La Niña, also known as an ENSO cold event and occurs on a 2-7 year cycle and during the annual Atlantic hurricane season (June 1 – November 30) (NHC, 2014b). Large areas of lower-than-average vertical wind shear observed between 10^0 and 20^0 N can also contribute to a greater than average number of cyclones, as seen during the 2008 hurricane season (Brown *et al.*, 2009).

The damaging impacts of tropical storm winds occur in conjunction with the other natural hazards caused by tropical cyclones so that it is often difficult to assess the damage caused by a specific hazard (Blake *et al.*, 2011). Thus, the damages and costs linked to tropical storm winds reflect those of tropical cyclones and may include loss of life, damage to private property and public infrastructure, and interruption to services and economic sectors. Other damages and costs associated with hurricanes are reported by the NOAA National Hurricane Center (NHC) as they may be available and include: loss of crops and livestock, loss of power to businesses and homes, road and facility closures, number of people requiring evacuation, and number of people requiring rescue. Impacts to wildlife or other natural resources also occurs from cyclones, but the impacts from a storm event, if reported, are reported to a lesser degree than socioeconomic and human environmental damages (Blake *et al.*, 2011; Brown *et al.*, 2009; Keim and Muller, 2008). For this analysis, tropical storm wind events included any cyclonic storm of tropical origin, including those classified as tropical depressions where the 1-minute sustained wind speed is 33 knots (38 mph), or greater.

Hazard Rate

To estimate hazards posed by damaging tropical cyclone winds such as hurricanes and tropical storms, we extracted all storm tracks for storms classed as tropical depression or greater from the NOAA IBTrACS database (Knapp *et al.*, 2010a, b) within 100 km of the area of interest for the period from 1851 to 2012. The IBTrACS data consist of vector lines depicting the estimated or recorded storm center tracks. Each storm track was buffered by a distance equal to the median radius of damaging (>26 m/s) winds for the categorical storm intensity of that storm at the time, per the analyses of Kimball and Mulekar (2004; Fig. 3, top). We then summed the number of damaging wind polygons that intersected any portion of each county or parish and divided by the number years in the database to compute the annual rate of occurrence of damaging tropical/extratropical storm winds in each county or parish (Fig. 3, bottom).

Hazard Severity

We estimated the frequency and the relative impacts of damaging tropical cyclone winds by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for damaging convective storm wind events, we calculated the total area of the damaging wind footprint polygons in the area of interest for each of the 499 tropical cyclones in the area over the investigated period.

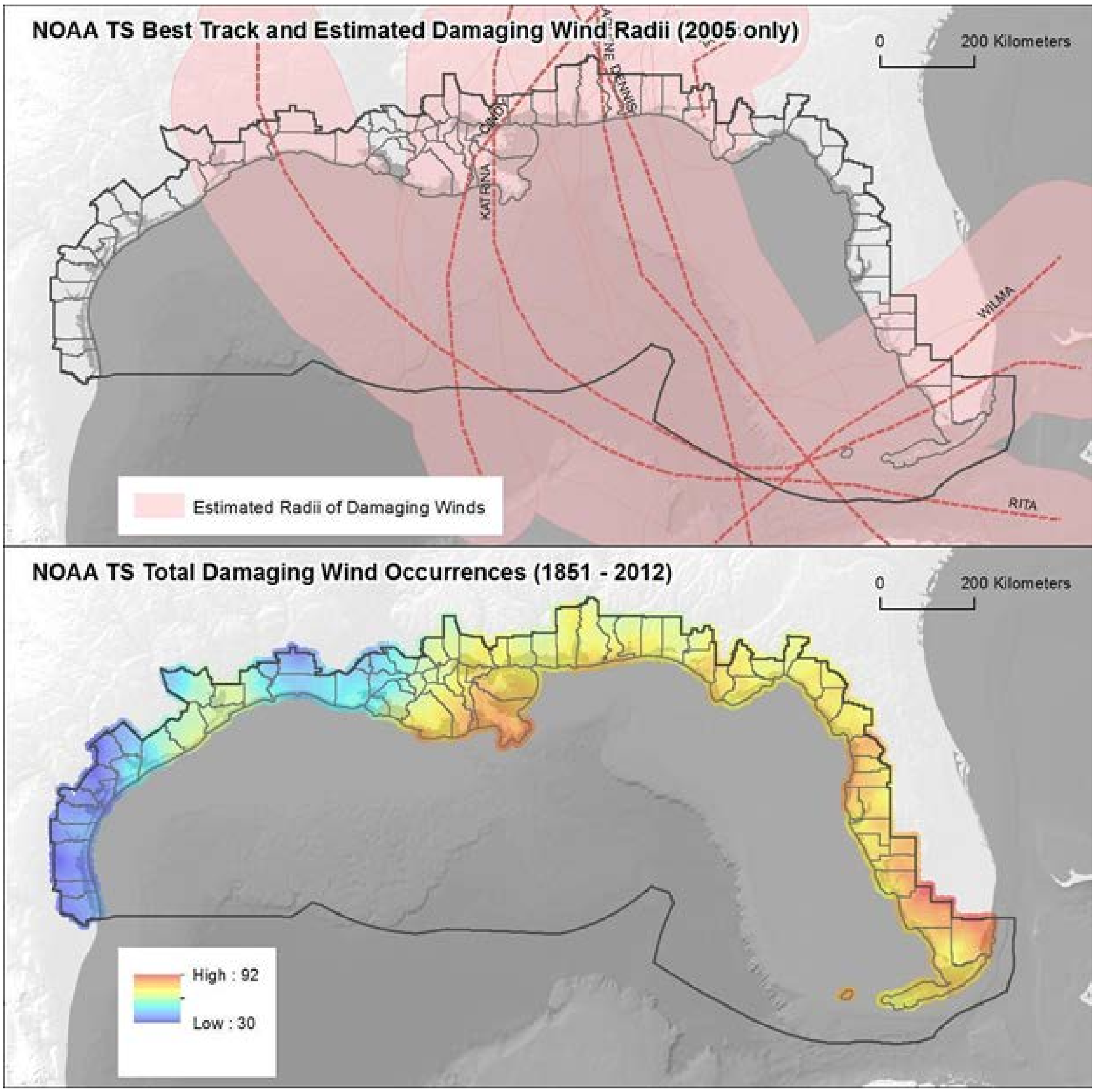

Figure 3. Tropical cyclone tracks and estimated damaging wind radii swathes for the 2005 hurricane season (top) and total estimated count of occurrences of damaging winds from tropical cyclones for 1851 through 2012 (bottom).

Convective Storm Winds

Damaging winds from convective storms (thunderstorms) are also significant hazards in the Gulf of Mexico. We consider all straight-line non-tornadic wind events associated with convective storms as part of this category including microbursts, macrobursts, and derecho events. Though associated wind speeds are generally less intense, convective storms are much more common than tropical storms. Convective storms are most frequent during the summer months (June-August), having a near-daily occurrence in the afternoon. Nationally, non-tornadic convective storm winds are responsible for approximately one in three wind-related deaths (Black and Ashley, 2010). The risk to human populations from convective storm winds is increased by the presence of large water bodies and/or numerous smaller water bodies (both common features in the area of analysis) as they contribute to increased boating-related fatalities (Black and Ashley, 2010).

Hazard Rate

To estimate hazards posed by convective storm winds, we extracted all damaging wind records from the NOAA National Weather Service Storm Prediction Center Severe Weather Geographic Information Systems Database (NOAA SPC, 2014). Hart and Janish (1999) provide additional details. These data consist of vector points of observed convective storm wind damage from 1950 to 2012 (Fig. 4). We summed the number of points that intersected any portion of each county or parish and divided by the number years in the database to compute the annual rate of occurrence any class of convective storm wind damage in each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of damaging convective storm winds by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). Little data exists on the distribution of event footprint sizes for damaging convective storm wind events, so we assumed an area of 10 km^2 were affected by each wind event.

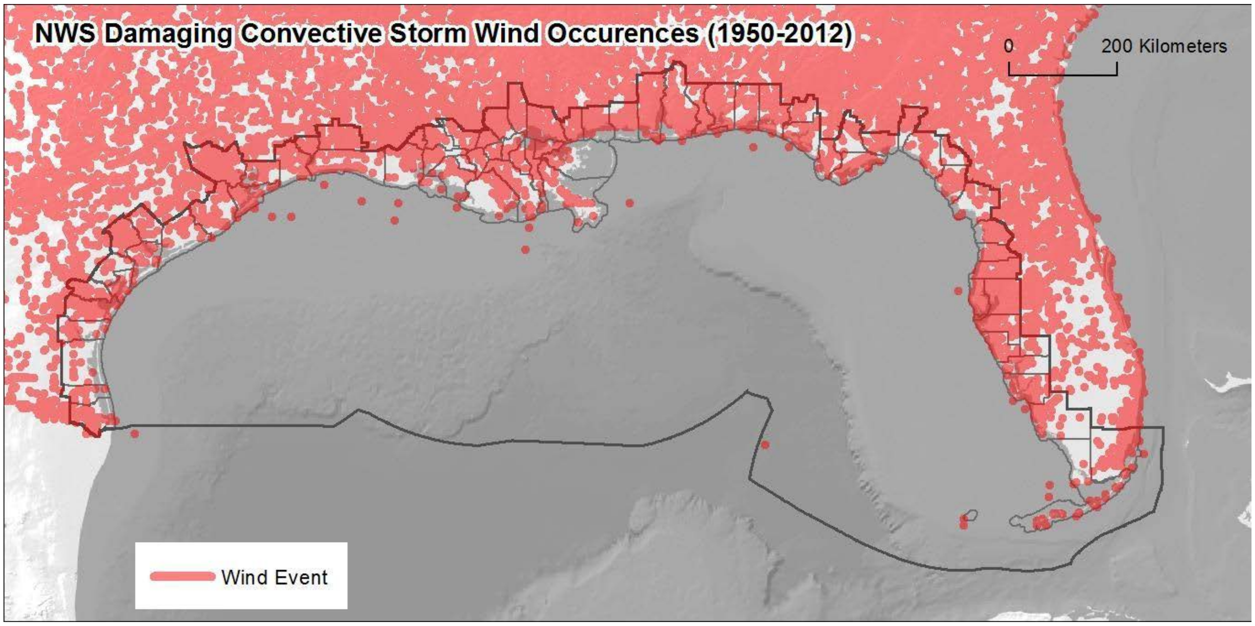

Figure 4. Damaging convective storm wind occurrences from 1950 to 2012.

Tornadoes

Tornadoes are a particular threat to the Gulf coast region because the potential for the atmospheric conditions that create tornadoes (strong vertical wind shear at mid- to low-altitudes) to occur both with tropical cyclones (potentially present May through October) and during the "cool season" (October through February) (Guyer *et al.*, 2006; Spratt *et al.*, 1997). The Gulf coast states have the most frequent and significant tropical cyclone tornadoes, typically F1 or F2 tornadoes on the Fujita scale of intensity, because at least one state is fully exposed to the right-front quadrant of the storm during landfall (Spratt *et al.*, 1997). During the cool season, the strength of tornadoes that impact the region may range from F1 up to F5 (Guyer *et al.*, 2006). We define tornadoes as violently rotating columns of air, extending to or from a cloud, to the ground, and visible as a funnel. Further, tornadoes must be in contact with the ground and extend to/from the cloud base, and observable effects on the ground. We compute hazards of tornadoes separately from tropical storm wind hazards for this analysis.

Hazard Rate

To estimate hazards posed by tornadoes, we extracted all tornado records from the NOAA National Weather Service Storm Prediction Center Severe Weather Geographic Information Systems (SVRGIS) Database (NOAA SPC, 2014). Hart and Janish (1999) provide additional details on methods used to assemble these data. These data consist of vector lines depicting the estimated or recorded path from the start to stop of observable ground effects of all tornadoes from 1950 to 2012 (Fig. 5). The SVRGIS database also contains estimates on the observed length and width of the observable ground damage or disturbance for each tornado. We summed the number of lines representing tornado paths that intersected any portion of each county or parish and divided by the number years in the database to compute the annual rate of occurrence any class of tornado damage in each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of tornadoes by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for tornadoes, we calculated the total area of all tornado paths over the investigated period in the SVRGIS Database.

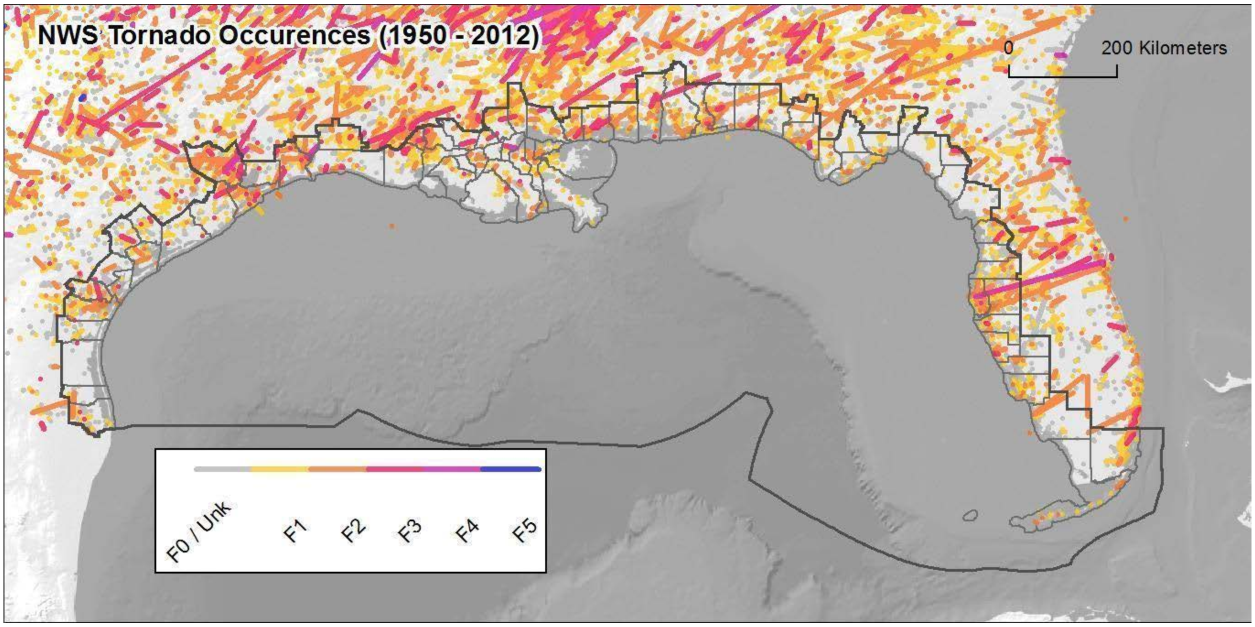

Figure 5. NWS tornado occurrences by intensity in the Fujita scale from 1950 to 2012.

Lightning

Lightning, measured by its flash density, has the highest national rates of occurrence across the Gulf coastal region, and in Florida, particularly (Roeder *et al.*, 2014; Holle *et al.*, 2010). Like convective storm winds, cloud-to-ground lightning strikes are most frequent during the summer months (June-August), having a near-daily occurrence in the afternoon (Holle *et al.*, 2010). As the third leading source of storm deaths in the U.S., it poses a direct threat to human life and can indirectly be responsible for the start of wildfires (Roeder, 2012; Roeder *et al.*, 2014). Fatality risks across the Gulf coastal region are particularly high where high flash occurrence overlaps with high density population areas, such as Tampa, FL; New Orleans, LA; and Houston, TX (Roeder *et al.*, 2014). We define lightning here as a sudden electrical discharge from a thunderstorm or other meteorological phenomena, resulting in a cloud-to-ground strike.

Hazard Rate

To estimate hazards posed by lightning strikes, we obtained annual gridded National Lightning Detection Network (NLDN) summary gridded data for the period from 1992-2012 (NOAA NCDC, 2014b). We then computed the average number of cloud-to-ground strikes per year in each grid cell over this period (Fig. 6). We then summed all grid cells within each county or parish to compute the average annual rate of cloud to ground lightning strikes for each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of lightning by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). Little data exists on the distribution of event footprint sizes for lightning strike events, so we assumed an area of 100 m^2 was affected by each individual lightning strike.

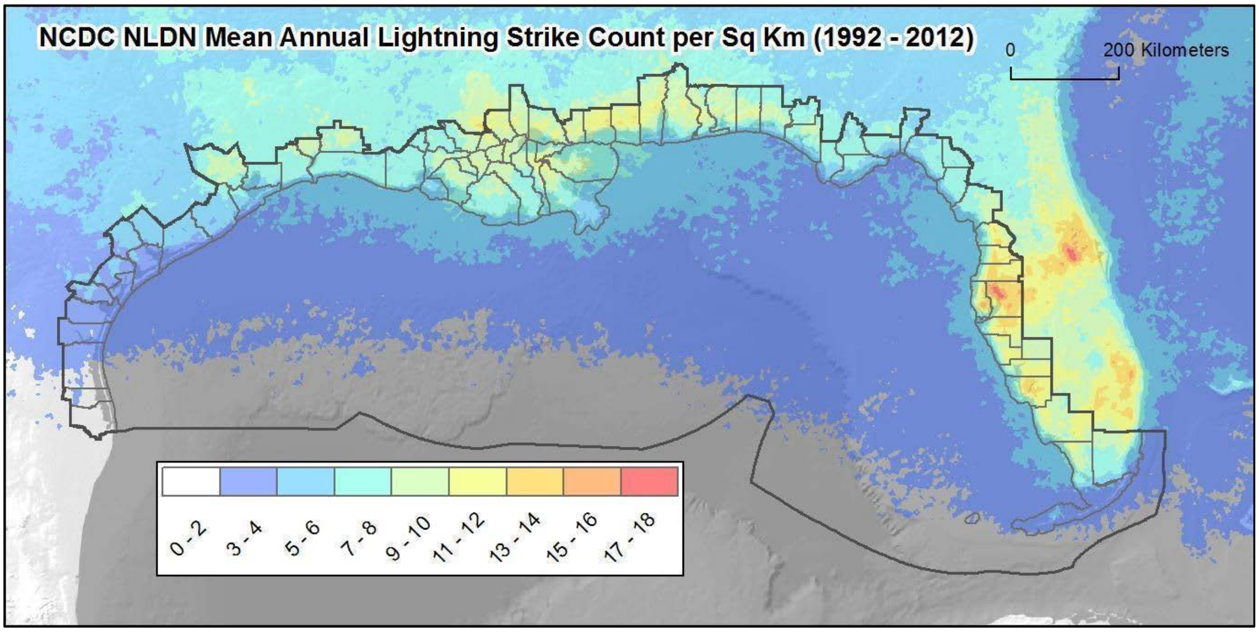

Figure 6. NCDC National Lightning Detection Network average annual count of lightning strikes per km^2 (1992-2012).

Coastal or Storm Flooding

In the Gulf Coast region, threat to life and property are at greatest risk from coastal or storm flooding (NHC, 2014a). While riverine and flash flooding events are more common, they are generally less destructive. This region is particularly vulnerable, with 72% of ports, 27% of major roads, and 9% of rail lines lay within at or below 4 feet of elevation. The depth and extent of coastal flooding can be devastating (CCSP, 2008). The breadth of such damage was exemplified by Hurricane Katrina in 2005.

During Hurricane Katrina, storm surge played a central role in the damage wrought to the gulf coast from both the wide range of the surge caused by the large size of the storm at the heights to which the surge exceeded. The worst of Katrina's storm surge occurred along the Mississippi coast, centered on St. Louis Bay, in which a stretch of shoreline about 20 mi wide, experienced storm surge of 24-28 feet. Continuing east of the bay to Pascagoula, MS, storm surge ranged between 17 feet and 22 feet with heights over 10 feet extending into Baldwin County, on the eastern side of Alabama. West of where the storm made landfall, which is along the weaker side of the hurricane, storm surge over 15 feet reached many parts of western New Orleans, while eastern New Orleans west to the western shores of Lake Pontchartrain experienced storm surge above 10 feet. In addition to the impact measured along the coastal shoreline, storm surge penetrated as far as 12 miles inland (Knabb *et al.*, 2006). As the water overtopped and breached levees and floodwalls, storm surge contributed to the flooding of New Orleans, where waters reached depths of 20 feet and were not fully removed until 43 days after Katrina made landfall (Knabb *et al.*, 2006).

Though an exact categorization of the casualties and damage brought by Katrina from storm surge versus strong winds, tornadoes, or other flooding cannot be made, the vast majority of the approximately 1,500 deaths and $108 billion of damage from flooding are thought to be from Katrina's storm surge (Knabb *et al.*, 2005). This damage included the complete destruction of several coastal communities nearest where the hurricane hit, with extensive damage to coastal homes occurring from where storm surge washed over Dauphin Island, AL; approximately 70 mi east of where the hurricane made landfall (Knabb *et al.*, 2005). In addition to the personal losses suffered by the victims of Katrina, the hurricane left a wake of environmental hazards (2,300 reported cases), including the release of 7 million gallons of oil, 118 million cubic yards of debris, flooding across three Superfund sites, and widespread contamination of drinking water facilities and wastewater treatment plants (USEOP, 2006). The impact to the economy was also severe, particularly to the region's fisheries and energy sectors. Nearly $145 million of loss were tallied across the region's fisheries, with over half of these losses from shrimp fisheries alone (LSU AgCenter, 2005). Both production and refinery facilities, including pipelines, were closed for days and damage to petroleum infrastructure ranged from broken infrastructure to an offshore platform being washed ashore in Alabama (Knabb *et al.*, 2005). Recalling the impacts of the Hurricane Katrina provides an important backdrop to assessing threats from storm surge since the occurrence of major hurricanes striking the gulf coast again remains a question of "when", rather than "if" (Keim, 2009).

Coastal or storm surge flooding is defined herein as flooding of coastal areas due to the vertical rise above normal water level caused by a storm of tropical origin (e.g., hurricane, typhoon, or tropical storm) or other meteorological event that generates strong, persistent onshore wind and/or low atmospheric pressure, resulting in damage, erosion, flooding, fatalities, or injuries. Coastal areas are defined as those portions of coastal land zones (coastal county/parish) adjacent to the waters and bays of the oceans. Terrain (elevation) features generally determine how far inland the coastal flooding extends. For this analysis, this hazard category encompasses coastal or storm surge related flooding due to tropical storms, cyclones, and hurricanes. Wind hazards due to tropical storms are considered separately in this analysis because the extent and locations of flood and wind damage from a given storm may differ widely from the impacts of flooding.

Hazard Rate

To estimate hazards posed by coastal and storm surge flooding, we first extracted all coastal and storm surge flood records from the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). These data consist of records of all reported flood events in these categories from 1996 to 2013. We further processed these data to remove events reported multiple times by different sources. Additionally, we removed flood events for a given county or parish that were found to be attributed to the incorrect county or parish (Fig. 7). The total number of records of coastal or storm generated flood events for each county or parish was summed and divided by the number of years contained in the database to compute the annual rate of coastal and storm surge flood events in each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of coastal and storm surge flooding by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for coastal and storm surge flooding, we estimated the total area of each coastal and storm surge events in the area of interest as described in Appendix A.

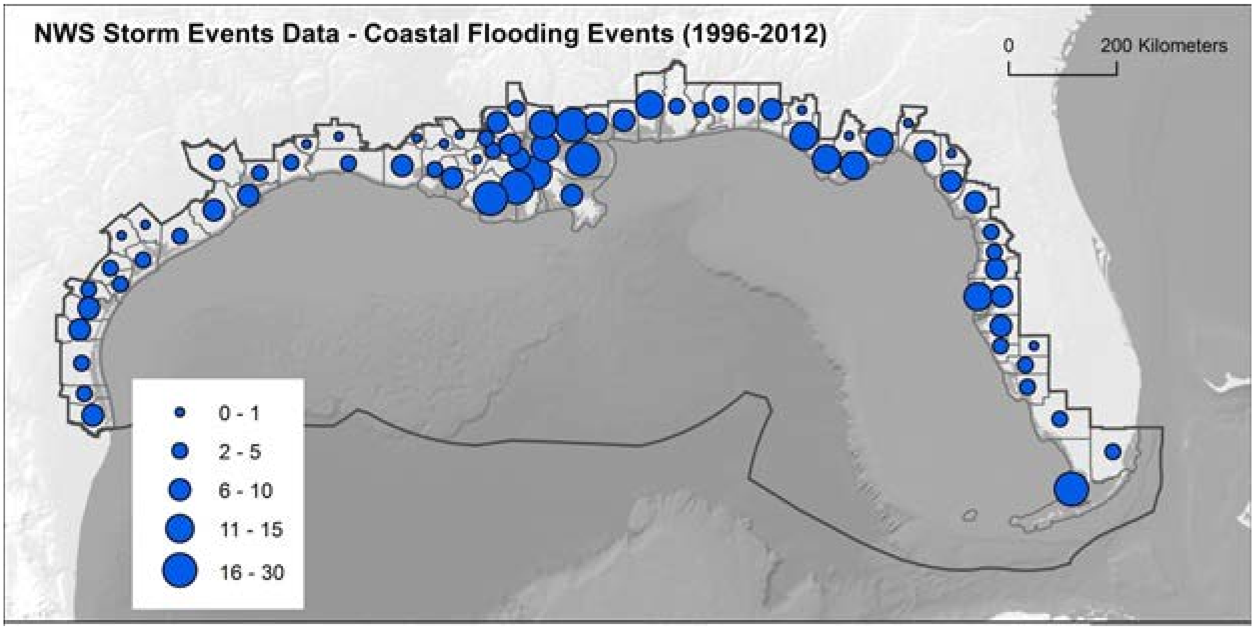

Figure 7. Counts of coastal flooding events from NWS Storm Events data (1996-2012) by county/parish.

Flash Flooding

Flash floods are a rapid and extreme flow of high water into a normally dry area, or a rapid rise in a stream or creek above a predetermined flood level, beginning within approximately six hours of the causative event (e.g., intense rainfall, dam failure, ice jam) (NWS, 2006). Flash floods can be more severe than riverine floods because of the speed with which flooding occurs, the high water velocity, and the large debris load carried by the flood waters (NFIP, 2005). Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters. Damages from flash flooding are compounded when the dense water flow breaches inadequate dams and levees. Generally flash floods do not persist beyond two or three consecutive days. Across the Gulf coast region, flash floods may be associated with the heavy rainfall brought by convective storms or tropical cyclones (NFIP, 2005).

Hazard Rate
To estimate the rate of occurrence of flash floods, we first extracted all flash flood records from the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). These data consist of records of all reported flood events in these categories from 1996 to 2013. As per coastal flooding described above, we further processed these data to remove events reported multiple times and events attributed to the incorrect county or parish (Fig. 8).

Hazard Severity
We estimated the frequency and the relative impacts of flash flooding by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for flash flooding, we estimated the total area of each flash flooding event in the area of interest as described in Appendix A.

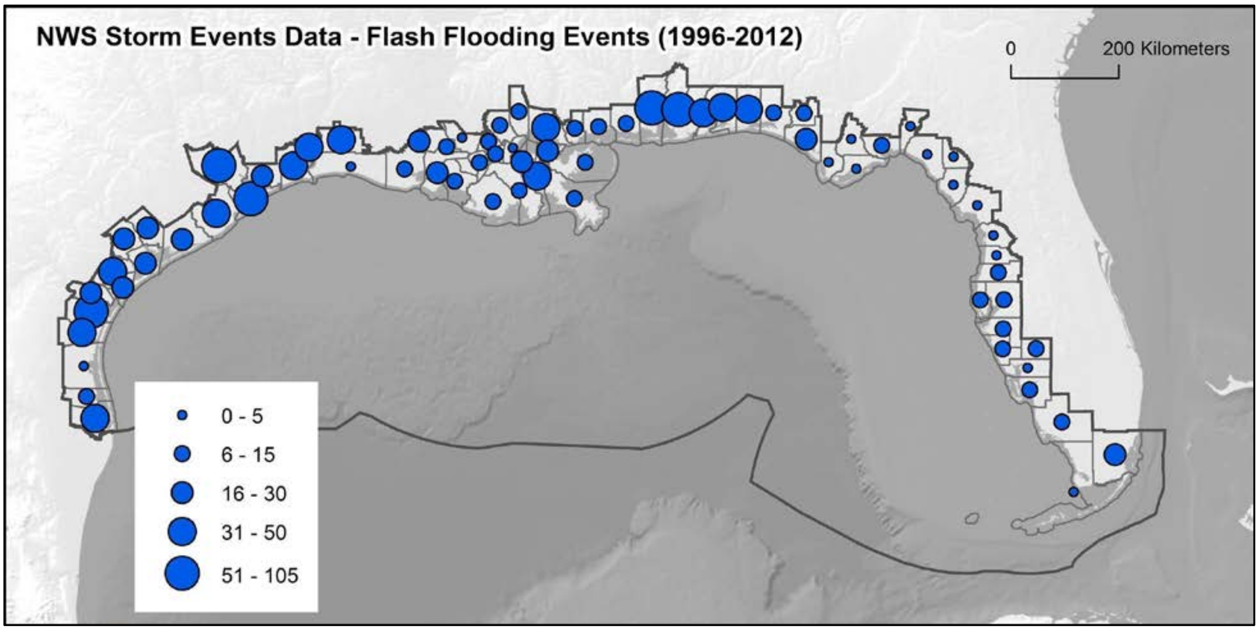

Figure 8. Counts of flash flooding events from NWS Storm Events data (1996-2012) by county/parish.

Riverine, Lake, or Other Flooding

Though flash floods will be the most frequent type of riverine flooding in smaller basins, flooding in large rivers is usually the result of large-scale weather systems generating prolonged rainfall over wide areas. In these cases, flooding may be tied to seasonal changes in rainfall and thus occur on a generally predictable and periodic basis (NFIP, 2005). On lakes, short-duration flooding from high rainfall events or dam and levee failures can occur; however, when flooding is associated with closed basin lakes or lakes with inadequate outlet channels, high water levels may persist for years. Other flooding may occur from problems related to urban drainage or ground failures. In flooding related to urban drainage, the cumulative effects of how stormwater runoff from urban areas is managed can lead to downstream flooding. Ground failures include mudfloods, mudflows, subsidence, and liquefaction. Mudfloods and mudflows, the flow of water with high percentages of sediment (including large debris), are most often associated with mountainous topography, though heavy rainfall on recently denuded soils can facilitate these events even in less steep areas. Subsidence is the lowering of the ground surface and can increase flooding risk by creating a lower area more prone to flooding or altering drainage patterns in a way that causes deeper or unexpected flooding (NFIP, 2005).

This hazard category is defined herein as any high flow, overflow, or inundation by water that causes or threatens damage, as well as flooding of lakeshore areas due to the vertical rise of water above normal level caused by strong, persistent onshore wind and/or low atmospheric pressure, resulting in damage, erosion, flooding, fatalities, or injuries. Lakeshore areas are defined as those portions of land zones (coastal county/parish) adjacent to the waters of the Lake Okeechobee, Lake Pontchartrain and Lake Maurepas. In general, this would mean the inundation of a normally dry area caused by an increased water level in an established watercourse, or ponding of water, generally occurring more than 6 hours after the causative event, and posing a threat to life or property. This type of hazard can be on a widespread or localized basis.

Hazard Rate

To estimate hazards posed by riverine, lake and other flooding, we first extracted all riverine, lake, and other flood records from the NOAA NCDC Storm Events database (NOAA NCDC, 2014a). These data consist of records of all reported flood events in these categories from 1996 to 2013. As per coastal flooding described above, we further processed these data to remove events reported multiple times and events attributed to the incorrect county or parish (Fig. 9). The total number of records of riverine, lake, and other flood events for each county or parish were summed and divided by the number of years contained in the database to compute the annual rate of these flood events in each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of riverine, lake and other flooding by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for riverine, lake and other flooding, we estimated the total area of each riverine, lake and other flooding event in the area of interest as described in Appendix A.

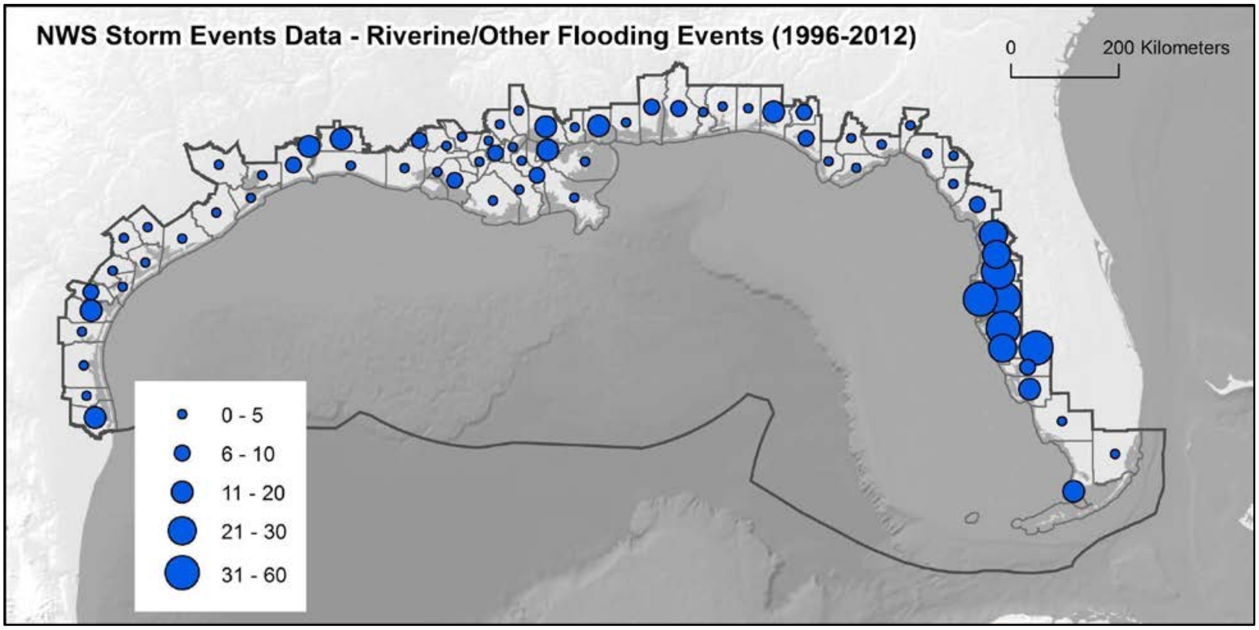

Figure 9. Counts of riverine, lake, and other flooding events form NWS Storm Events data (1996-2012) by county/parish.

Wildfires

Wildfires are uncontrolled fires of combustible vegetation that occur in wilderness or undeveloped areas (USFS, 2014). Across the Gulf Coast states, wildfires occur relatively frequently due to rapid forest growth rate and accumulation of fuels within a favorable fire climate with a fire-return rate of 3-5 years for most parts of the region. Seasonally, wildfires are more frequent in the summer months, June through August, when there is a rise in the daily number of lightning strikes, which may ignite accumulated fuels. Under a changing climate, it has been estimated that a future fire potential has the largest projected increase along the western coastal area of the Gulf of Mexico. For people living in fire-prone areas, socioeconomic impacts may include loss of life, increased morbidity, loss of property, and the necessity of making investments to reduce fire-related risks (Liu *et al.*, 2014).

Hazard Rate

We estimated the rate of occurrence of wildfires by obtaining the U.S. Forest Service (USFS) wildfire occurrence data (Short, 2014) from 1992 to 2012 shown in Figure 10. These data consist of vector points representing the known or reported locations of wildfires compiled from federal, state and local agency databases. The USFS data also contained information on size of each wildfire. We summed the number of wildfire locations that were located each county or parish and divided by the number years in the database to compute the annual rate of occurrence wildfires in each county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of wildfires by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC)

Storm Events database (NOAA NCDC, 2014a). To estimate the distribution of event footprint sizes for wildfires, we calculated the total area of all wildfires over the investigated period in the USFS Database in each county or parish.

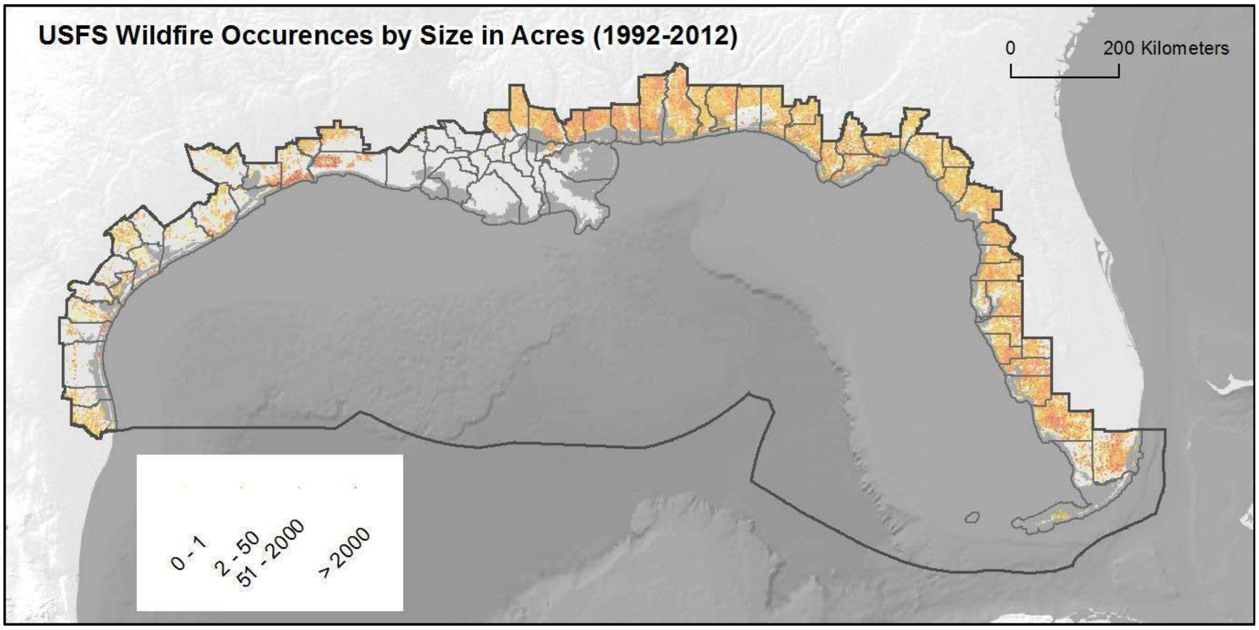

Figure 10. USFS database wildfire occurrence by fire size in acres.

Dry Mass Movement (Landslide / Debris Flows)

Landslides are the sudden and catastrophic downward movements of unconsolidated soils and sediments or other material. Debris flows are fast moving and highly destructive due to the amount of material being carried with the flow. Large boulders, trees, and massive amounts of sediment can be carried in a debris flow. Areas with low slopes, which includes the majority of the coastal plain region occurring across the Gulf Coast states, generally have a low or negligible risk of experiencing landslides (FGS-FDEP, 2014). A recent study for the contiguous U.S. examined landslide susceptibility and hazard and concluded that broad regions of negligible hazard (Fig. 11) were present across the Gulf coast region (Godt *et al.*, 2012). The limited landslide hazards that are present in the Gulf coastal plain and lower Mississippi alluvial valley are almost entirely slumps and bank failures along alluvial river valleys, coastal bluffs, and dredged waterways, including the Houston ship channel (Radbruch-Hall *et al.*, 1982).

Hazard Rate

To estimate hazards posed by debris flows, we extract all debris flow records from the NOAA NCDC Storm Events database (NOAA NCDC, 2014a). These data consist of records of all debris flow events from 1996 to 2013. During this period, there was only a single example within the study area in Baldwin County, AL. As such, we considered the annual rate of landslides in Baldwin County, AL to adequately represent the same annual rate of occurrence for every county or parish.

Hazard Severity

We estimated the frequency and the relative impacts of debris flow events by severity class in terms of human casualties and economic cost via the NOAA National Climatic Data Center (NCDC) Storm Events database (NOAA NCDC, 2014a). Little data exist on the distribution of event footprint sizes for debris flow events, so we assumed an area of between 100 and 1,000 m^2 was affected by each individual debris flow event.

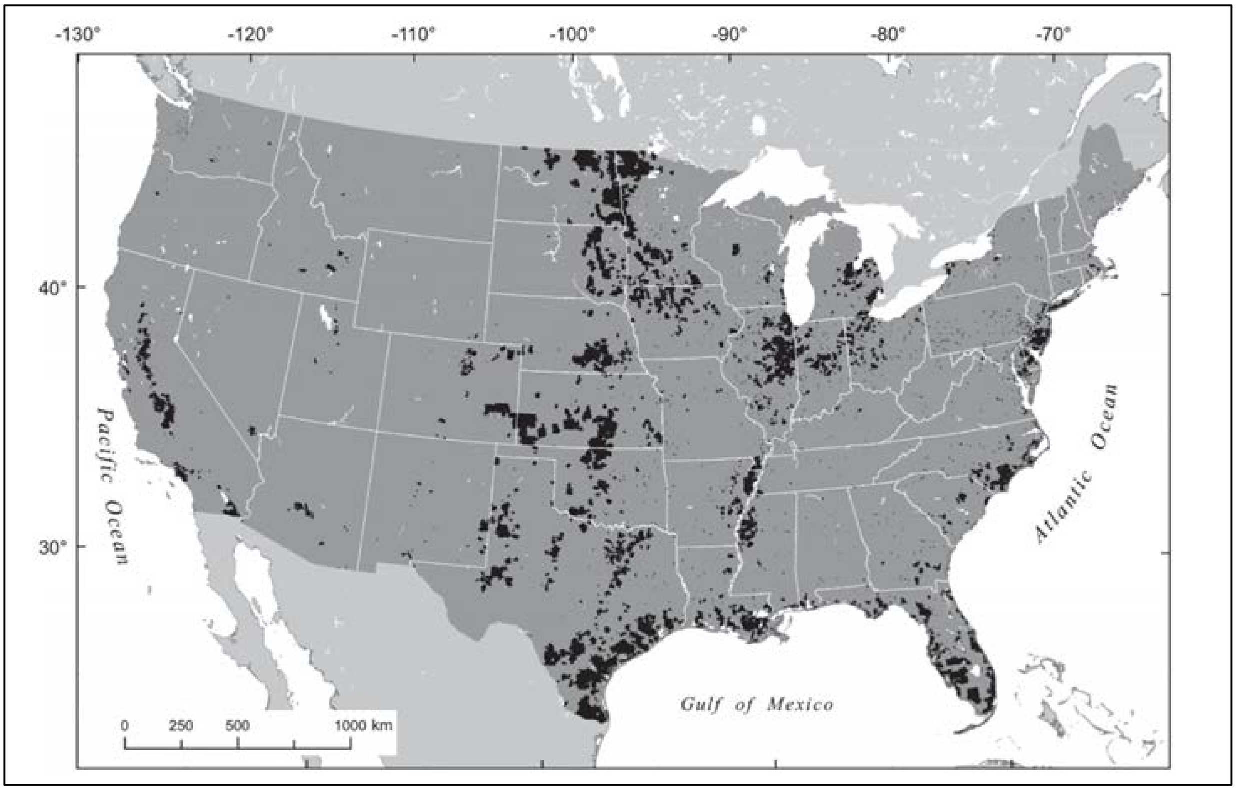

Figure 11. Prototype map showing Zip Code Tabulation Areas (ZCTAs) in the conterminous U.S. with negligible (black) landslide hazard. Reprinted from Godt *et al.* (2012).

Earthquakes

Earthquakes, and especially larger magnitude earthquakes (<6.0), are most likely to occur along the boundaries of tectonic plates. However, even in mid-plate and trailing regions, such as the Gulf of Mexico, earthquakes of modest magnitudes (6.0) can occur (Russo, 2006). Overall, the Gulf of Mexico represents an area of low risk for larger magnitude earthquakes, but does experience infrequent moderate earthquakes (Russo, 2006; FGS-FDEP, 2014). The most recent moderate seismic events in this region were in 2005/2006 with a 5.9, and 5.3 earthquake recorded centered offshore in the Gulf and near Houma, LA (Lovett, 2006; Earthquake Tracker, 2014). With these events, low or no damages were reported (Lovett, 2006). The greatest threat to people and infrastructure in the region would occur from an earthquake of moderate magnitude causing the collapse of unstable sediments that might then trigger a tsunami (Russo, 2006).

Hazard Rate
To estimate hazards posed by earthquake, we computed the cumulative annual rate of an earthquake of magnitude 5.0 or greater on the Richter scale for the centroid of each county or parish in the study area using the USGS online hazard mapping tool (USGS, 2009), as in Figure 12. A detailed explanation of the tool's modeling processes are given in Peterson *et al.* (2008).

Hazard Severity
For calculating the frequency of event by severity class to infrastructure and human casualties, we incorporated U.S. earthquakes events from 1980 to 2005 presented in Vranes and Pielke (2009). We assumed any earthquake would affect natural resource assets across an entire county or parish.

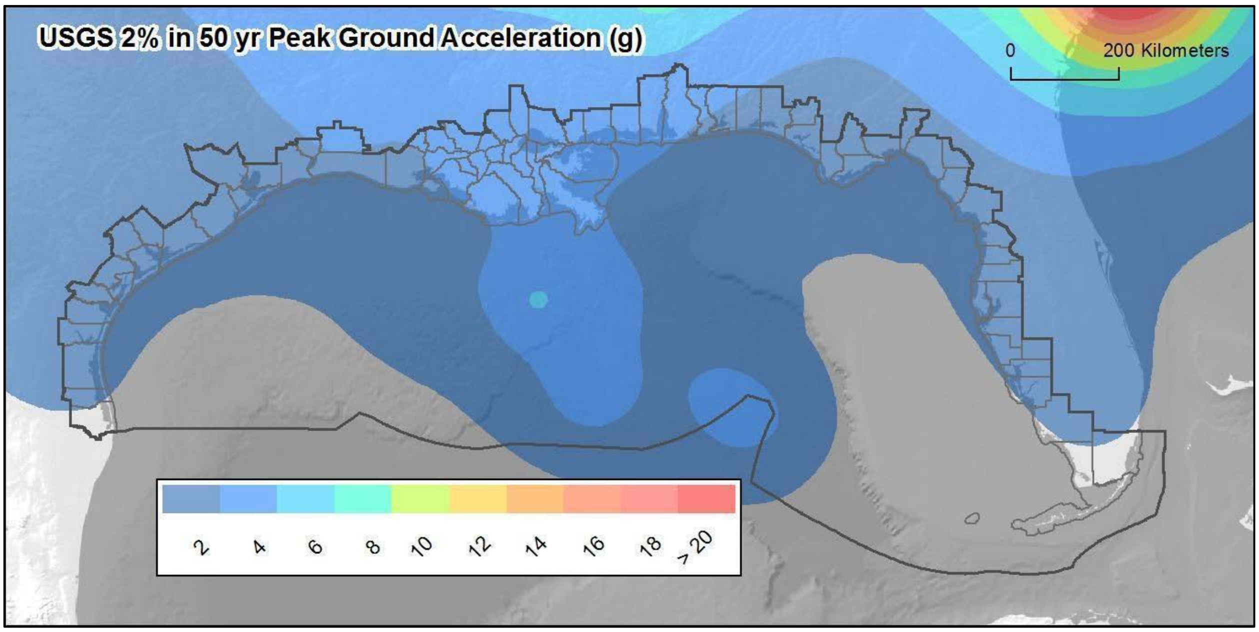

Figure 12. Peak ground acceleration (g) expected for an earthquake with an expected 2% in 50-year recurrence interval (data from Peterson *et al.*, 2008).

Volcanic Eruption/Ash Fall

There are no known dormant or active volcanoes located in the study area or in the northern Gulf of Mexico in general. However, there are a number of volcanoes within 1,000 km of the study areas located along the Pacific Coast of Mexico with recorded eruptions as recently at 1945 (Crosweller *et al.*, 2012). These volcanoes have the potential to affect the counties in the study area via ash plumes: fine particles of mineral matter from a volcanic eruption which can be dispersed long distances by winds aloft, resulting in fatalities, injuries, damage, or a disruption of transportation and/or commerce. Even relatively thin ash falls of around 1 mm are capable of disrupting vital lifelines such as transport, water supply, telecommunications, and electricity.

Hazard Rate

To estimate rate of occurrence posed by volcanic eruption ash fall, we followed a method greatly simplified from, but conceptually related to, Jenkins *et al.* (2012). We extracted all volcanoes from the VOGRIPPA v.2014 database (Crosweller *et al.*, 2012) within 1,000 km of the study area with at least one recorded eruption in the Holocene (11,700 years before present), as in Figure 13. Of these 7 volcanoes, there were 31 eruptions within the past 11,700 years. Assuming a Poisson distribution, we estimated the individual volcano annual eruption probability was 0.03%. Because detailed stochastic modeling (per Jenkins *et al.*, 2012) of atmospheric transport is not within the scope of this project, we estimated ashfall probability given an eruption. Because no volcano in the database is closer than 700 km away from the study area, we assumed that there a 1% chance of ashfall in any county or parish within 1000 km given an eruption, yielding a conditional probability of ashfall of 0.0003% for each volcano within 1,000 km. We summed the number of volcanoes within 1,000 km of each county or parish and multiplied this count by the conditional probability of ashfall exposure to compute the annual rate of volcanic ashfall occurrence in each county or parish.

Hazard Severity

We assumed any volcanic ashfall would affect an entire county or parish equally and thus, any ashfall event would have a major impact sensitive habitats and species as well as infrastructure, but a low impact on human populations, which could be evacuated. .

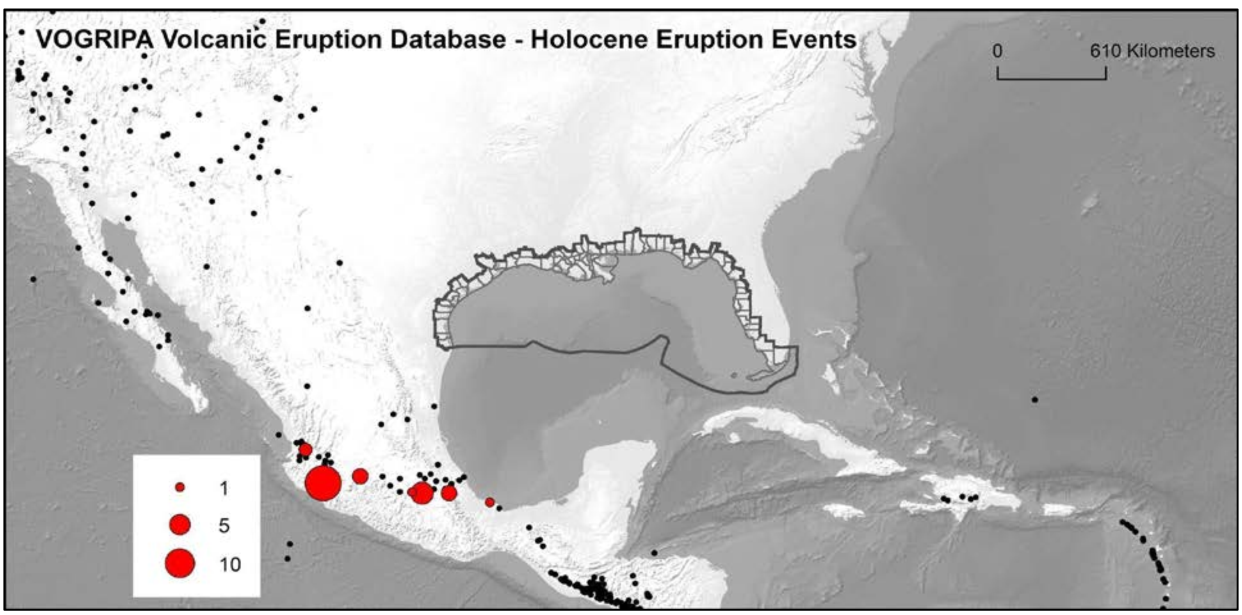

Figure 13. VOGRIPA volcanic eruption event database for southern North America. Volcanoes with eruption events recorded in the Holocene symbolized in red by number of eruptions.

Tsunami

A tsunami is a series of very long waves generated by any rapid, large-scale displacement of the seafloor (e.g., an underwater earthquake, landslide, volcanic eruption, or combination thereof) resulting in a fatality, injury, or damage. When the wave reaches the coast, a tsunami may appear as a rapidly rising or falling tide, a series of breaking waves, or even a bore. Recent investigations by the USGS (ten Brink *et al.*, 2009) determined that, despite recent activity within the Gulf Mexico in the last 100 years, there were no significant earthquake sources likely to generate tsunamis. Similarly, the report concluded that earthquake sources in tectonically active areas outside of the Gulf of Mexico (e.g., the Panama Convergence Zone, Northern South America, Cayman Trough, the Puerto Rico trench, and the Gibraltar area) generally do not present a tsunami threat because the amplitude of a tsunami would be constricted by the narrow and shallow passages into the Gulf of Mexico. However, the possibility of a submarine landslide generating a tsunami is considered to be a present day tsunami hazard with potential landslide areas in the northwest Gulf of Mexico, Mississippi Canyon and Mississippi fan, and the Florida/Campeche Margin.

Evidence along the Mississippi fan suggests a large submarine landslide 7,000 to 11,000 years before present. Using estimates of sediment deposits created by the landslide, modeled predictions of an East Breaks landslide suggest the possibility of subsequent ~15 feet (~5 meters) wave intersecting the northwestern shore of the Gulf, which would be similar in size to storm surge generated by major hurricanes. Today, slope steepening and increased fluid pore pressure in this area continue to build through increased sediment supply, especially from the Mississippi River, making it vulnerable to over-pressurization and slope failure. Along the northern Gulf of Mexico continental shelf seismic records suggest active small-scale landslides, but more data are needed to validate this hypothesis. Although there are no records in the U.S. that report damages and costs linked directly to a tsunami, it is possible to imagine impacts to communities and human-built infrastructure on par with major hurricane-related storm surge fatalities and damage through similarly sized waves. It should be noted that coastal communities and facilities would have significantly less preparation times, hours instead of days, compared to the approach of a major hurricane.

Hazard Rate
To estimate hazards posed by tsunamis, we estimated an annual recurrence frequency of tsunamis in the Gulf of Mexico as once every 5,000 years after ten Brink *et al.* (2009).

Hazard Severity
We estimated frequency of event by severity class from tsunami events in the NOAA NCDC database from 1996-2013. The approximate footprint area of a given tsunami as the total area of the area of the FEMA 100-year coastal flooding zones in each county or parish.

Harmful Algal Blooms

Harmful Algal Blooms (HABs) are defined as a rapid increase of the concentration of one or more phytoplankton species in the water column with potentially harmful or detrimental effects that has a defined spatial extent and persists through time. Concerns about HABs have increased over the last decade largely because of the perceived increase in the number and duration of events. The toxins produced by these species cause finfish and shellfish poisoning and mortality of marine animals, including mammals and birds. In the Gulf of Mexico, the red tide species, *Karenia brevis*, routinely occurs along the southwest coast of Florida in the late summer and early fall and can persist for up to three months. This type of bloom has occurred in the Florida panhandle, Texas, and as far north as the barrier islands of North Carolina. Aquatic organisms are affected either by the neurotoxin itself or by the reduced water quality that results from a bloom. In 1996, a bloom was responsible for the death of 10 percent of the manatee population (NOAA CSC, 2004). In addition, human health is compromised by the presence of dead and decaying fish in the waters and on the beach and by the production of aerosols that cause asthma-like symptoms. The blooms also impact fisheries and tourist industries by inducing neurotoxic shellfish poisoning. In the 2002-2003 HAB season, the Florida shellfish aquaculture and oyster industries lost $6 million in dockside sales alone, and up to 20 percent of the planted clams (NOAA CSC, 2004).

Hazard Rate

To estimate hazards posed by HABs, we used historical records of HAB occurrences by county from data provided by the Florida Fish and Wildlife Conservation Commission (as presented in NOAA CSC, 2004). These data consist of maps of counts of years with HABs events across coastal regions in the Gulf of Mexico from 1957 to 2004. HABs in these data are defined more specifically as *Karenia brevis* bloom locations where concentrations exceeded 5×10^3 cells l^{-1}.We divided the number of years with occurrences the number years in this time span to compute the annual rate of occurrence of one or more HABs in each county or parish.

Hazard Severity

We estimated frequency of event by severity by assuming HABs present minor threats to infrastructure and populations. We estimated the approximate footprint area of each HAB as the area of inland and coastal waters of each county or parish.

ANTHROPOGENIC HAZARDS

We considered anthropogenic hazards listed in Table 3 for inclusion in this analysis. Generally, we considered fixed facilities to have a single annual spill occurrence of oil, chemical, radiological or biological spill/release. Thus, for a given county or parish, spill hazard occurrence was a function of the number of facilities within the county or parish and the spill probability for that type of facility. Oil, chemical or radiological spill/release hazard rates from transportation of materials by vehicle, railroad, vessel or pipeline for a county or parish are a function of the modeled flow of a material along respective transportation routes, the length of those transportations routes in the county or parish, and the spill rates per given flow volume.

Table 3. Anthropogenic hazards included in analysis and sources for probabilities/rates and spatial footprint if applicable. Specific methods are described in the text.

Hazard Category	Hazard Type	Data Source(s)	Rate/Probability Source
Oil/Chemical Spill	Vessel/Tanker	USACE Waterway Network USACE Waterborne Commerce of the United States USDOT FHSA FAF3 Commodity Flow Database	Anderson *et al.*, 2012 API, 2009 Etkin, 2006
	Pipeline	Multiple pipeline datasets USDOT FHSA FAF3 Commodity Flow Database	Anderson *et al.*, 2012 API, 2009 Etkin, 2006
	Vehicle	USDOT FHSA FAF3 Freight Traffic Analysis Network USDOT FHSA FAF3 Commodity Flow Database	Anderson *et al.*, 2012 API, 2009 Etkin, 2006
	Rail	USDOT FRA Rail Network USDOT FHSA FAF3 Commodity Flow Database	Anderson *et al.*, 2012 API, 2009 Etkin, 2006
	Facility	BOEMRE Offshore Production Platforms EIA Refineries EIA Ethylene Crackers US EPA Facility Registration Service US EPA Toxics Release Inventory Facilities	Anderson *et al.*, 2012 API, 2009 Etkin, 2006
Nuclear/ Radiological Release	Reactor	USNRC Reactor/Site data	Lelieveld *et al.*, 2012
	Facility	US EPA RADInfo Facilities	Multiple
	Vehicle	DOT FHSA FAF3 Freight Traffic Analysis Network	Multiple
Biological Release	Sewage System	EPA CWNA/NPDES Sanitary Sewer Overflows	EPA Report to Congress on the Impacts and Control of CSOs and SSOs

Anthropogenic Hazard Rate

For all anthropogenic hazards, we estimated the rate of hazard event occurrence using available datasets, reports, and published literature. Anthropogenic hazards are further classified as local or non-local, based on the potential for a non-local hazard event to have effects in a particular county or parish. Non-local hazards are those that are likely to have impacts substantially offset from the location at which they occur. In this analysis, we assume that offshore petroleum and chemical spills from production platforms, tanker, tank barge, or pipeline transportation are the primary anthropogenic hazards with significant potential for non-local effects. For these hazards, we explicitly compute the conditional probability that an event occurs at the source, and that it has an impact at the county or parish level using methods described in the hazards' respective subsections. Additionally, we assume that a nuclear/radiological release from a reactor has significant non-local effects and the data we use to compute rate of occurrence for these hazards incorporate these effects. We describe each dataset and methodology used to evaluate rate in detail in the hazard-specific subsections below.

Anthropogenic Hazard Severity

For all anthropogenic hazards, we estimated the frequency of event and the relative impacts by severity class from the USCG National Response Center data compiled for 1994-2013 (USCG, 2014) which includes data on human casualties, economic cleanup cost, spill volume, and evacuation radius by incident, material, and spill/release source. The methods used for these calculations have been described in more detail in the Vulnerability section below.

Oil and Chemical Spills/Releases from Offshore Tanker Transportation

The Gulf of Mexico is home to the majority of the U.S. refinery capacity, extensive historical and current onshore and offshore petroleum production, as well as associated chemical and petrochemical processing and manufacturing infrastructure. Nearly all of the import/export volume of crude and refined petroleum products and associated petrochemicals is transported into and out of the region via tanker. Transportation of oil and chemical products by offshore tanker transport represents roughly 29% and 19% respectively of the total annual product tonnages moved regionally (FAF3, 2010). Spills of oil by tanker transportation are quite rare, per unit volume-distance, but individual spills tend to be larger than all other modes save pipelines (API, 2009; Anderson *et al.*, 2012). Separate statistics are not compiled for chemical spills, but these incidents are likely similar in magnitude and volume per unit volume-distance. Tankers carrying oil as cargo spilled an average of 3,600 barrels of oil annually in the U.S. between 1998 and 2007 (API, 2009). Rates of oil, and presumably chemical, spillage have been declining both in absolute terms and relative to the amount of oil or chemicals transported over the past three decades (API, 2009; Anderson *et al.*, 2012).

Hazard Rate

To evaluate rates of oil or chemical spills from offshore tanker transportation, we first estimated the total annual flows in tons of all petroleum (crude and refined products) and chemical products by waterway both nationally and regionally using the U.S. Department of Transportation (USDOT) Freight Analysis Framework v3 (FAF3, 2010) database. In computing total volume of materials shipped in metric tons, we summed that all material flows originating or terminating within an FAF zone in the study area. The FAF3 database does not distinguish between types of vessel or route for waterway transportation, so to estimate the proportions of regional waterway transportation of petroleum products by vessel class, we used data from the U.S. Energy Information Administration (EIA) summarizing annual petroleum import, export, and regional movements for 2013 (EIA, 2014). The FAF3 database itself makes extensive use of EIA petroleum import, export, and regional waterway shipping to estimate flows of these commodities. We assumed that all waterborne shipments of petroleum products within the Gulf of Mexico, or between the Gulf of Mexico and the east coast of the U.S. are via barge, and that all waterborne shipments of petroleum products to or from foreign destinations or the West Coast of the U.S. are via tanker. While the FAF3 database includes accurate estimates of tonnage of petroleum products imported or exported by waterborne modes, it only includes ton-kilometer (km) summaries for the portion of international import or export waterway transport that takes place on domestic waterways – not the portions that occur on open-ocean routes offshore in the Gulf of Mexico. Similarly, the U.S. Army Corps of Engineers (USACE) National Waterway Network (NWN) link commodity flow estimates (USACE, 2012a) estimate the flow of waterborne petroleum and chemical products by route but only for domestic commodity flows. Some portion of domestic waterborne transport takes place offshore in the Gulf of Mexico, but nearly all of this transportation is by barge rather than tanker.

To remedy this, we assumed that all foreign import/export of petroleum and chemical products by waterway took place via tanker, and that the average distance shipped by tanker within the Exclusive Economic Zone (EEZ) in the Gulf of Mexico was equal to the average distance domestic oil and chemical cargoes are shipped by all waterway: 350 km. We then computed the total estimated volume of shipping of petroleum and chemical products by offshore tanker by multiplying the total foreign import/export and long distance domestic volume by this average distance. We apportioned the volume of petroleum and chemical products being imported or exported into or from the study area, as estimated above to the offshore portions of USACE NWN using the Bureau of Ocean Energy Management (BOEM) Automatic Identification System (AIS) data (BOEMRE, 2012). We assumed that all open-ocean routes in the USACE NWN in the EEZ represent potential shipping routes for import/export petroleum and apportioned all import/export and other waterway transportation of petroleum and chemical products to the individual segments of these routes using a weighting scheme based on the proportion of AIS vessel counts occurring along those segments. Figure 14 shows the results of this analysis.

We estimated the annual rate of petroleum product spill events per ton-km using national spill rates from Anderson *et al.* (2012) and the national offshore tanker shipping estimates from the EIA (2014) and USACE Waterborne Commerce of the United States (WCUS) data (2012) at 0.0009 per million ton-km. We estimated the total spill rate from offshore tanker transport in each offshore BOEM spill launch location as the product this value and the total estimated material shipments in ton-km by tanker in each offshore launch location. For each county or parish, we then took the product of the tanker transport spill rates in each offshore BOEM spill launch location and the probability that a spill in that launch location would impact that county or parish (as described in Appendix B). We estimated the annual rate of exposure to spills/releases from offshore tankers for each county or parish as the sum of all launch area conditional rates.

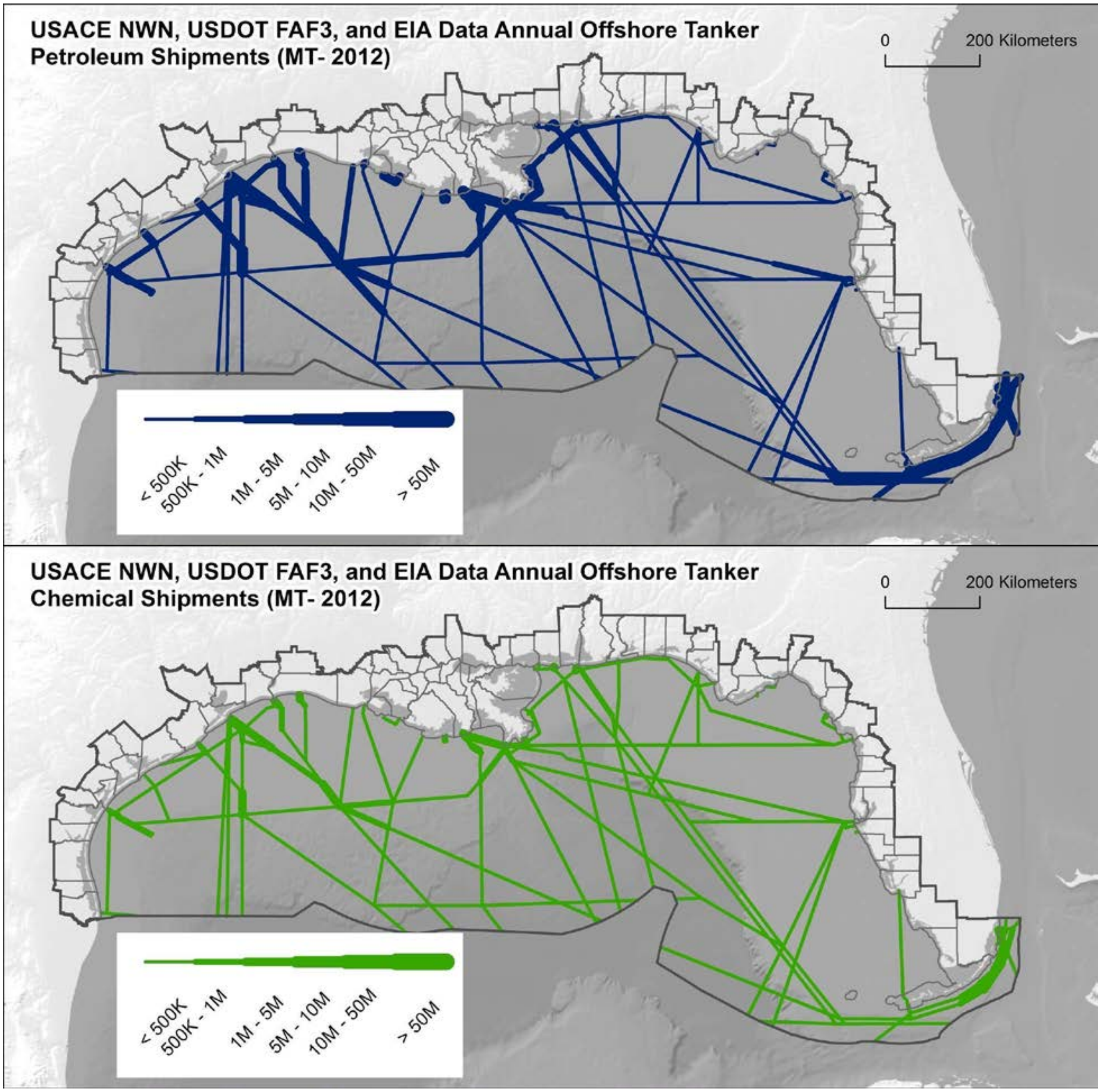

Figure 14. USACE National waterway network data by averaged domestic annual flows of petroleum (top) and chemical (bottom) products in tons (2001-2012) for inland and coastal routes.

Oil Spills from Offshore Oil/Gas Production Facilities

The western Gulf of Mexico is the site of substantial offshore petroleum production. Offshore oil and gas production and exploration platforms spilled an average of 1,773 barrels of oil annually in the U.S. between 1998 and 2007 (API, 2009). Rates of oil spillage from offshore production and exploration had been declining both in absolute terms and relative to the amount of oil produced over the past three decades prior to the Macondo well spill in 2010 (Anderson *et al.*, 2012). Anderson *et al.* (2012) provides an update of rates of spillage after the *Deepwater Horizon*, which dramatically reversed this trend for volumes of oil spilled, though not for spill rates overall. It is clear that changes in offshore deep-water production technology have resulted in different likelihoods for spills from offshore production, but insufficient data exist at present to fully understand these changes.

Hazard Rate

To evaluate rate of oil spills from offshore production and exploration, we extracted all offshore production facilities from the Bureau of Safety and Environmental Enforcement data (BSEE, 2015) that were active and were producing or handling either liquid oil or condensate (Fig. 15). We then computed the annual spill rate per platform from the number of spills from offshore platforms in the U.S. between 1996 and 2010 (Anderson *et al.*, 2012) and the number of active platforms in the U.S (USEIA, 204) at 0.008 per platform. While platforms are continually being placed online and removed from service, we assume that the number of active platforms in any given year is relatively constant. We estimated the total spill rate from offshore platforms in each offshore BOEM spill launch location as the product of the per-platform spill rate and the count of platforms in that spill launch location. For each county or parish, we then took the product of the offshore facility spill rates in each offshore BOEM spill launch location and the probability that a spill in that launch location would impact that county or parish (as described in Appendix B). We estimated the annual rate of exposure to an oil spill from an offshore platform or facility for each county or parish as the sum of all launch area conditional rates.

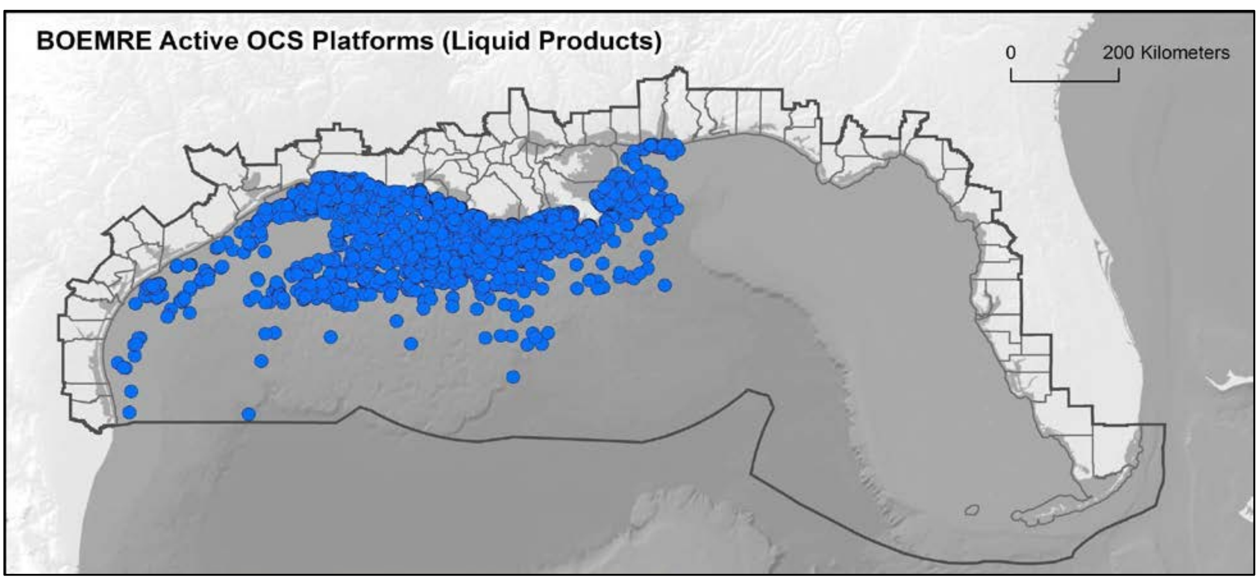

Figure 15. BSEE Active OCS production platforms producing or handling oil or gas condensate.

Oil Spills from Offshore Pipeline Transportation

Nearly all the oil and gas produced offshore in the Gulf of Mexico is transported to land for storage and processing via pipelines on the seafloor (Fig. 16). Spills of liquid petroleum products from offshore pipelines are relatively common as compared with tankers and barges, per unit volume-distance, and individual spills are similar to these other modes (API, 2009; Anderson *et al.*, 2012). Pipelines transporting oil and gas produced offshore spilled an average of 2,614 barrels of oil annually in the U.S. between 1998 and 2007 (API, 2009).

Hazard Rate

The USDOT Freight Analysis Framework v3 (FAF3, 2010) database contains data on oil transport by pipeline, but does not distinguish between offshore and onshore pipeline transport. To evaluate probability of oil spills from onshore pipeline transportation, we estimated annual offshore production in the Gulf of Mexico for 2013 as 64 million tons (USEIA, 2014) and assumed that all offshore production was transported onshore by pipeline. We estimated the average transportation distance in km of a given ton of petroleum products (crude and refined products) by pipeline regionally as 190 km using the USDOT Freight Analysis Framework v3 database (FAF3, 2010). We then estimated the total annual flow of liquid petroleum in offshore pipelines in the region as 12 million ton-km by multiplying the total annual volume of oil transported by the estimated average transportation distance of a given ton. We used data from BSEE (2013) describing the location of pipelines on the Outer Continental Shelf (OCS) and filtered these data to include only active pipelines transporting either liquid oil or condensate. Because the BSEE pipeline data do not distinguish between pipelines based on flow rates or volume, we apportioned all regional offshore pipeline flow in ton-km to the pipeline network equally by dividing the total length of offshore pipelines by the estimated total flow to derive the average annual flow rate per unit pipeline length in t/km.

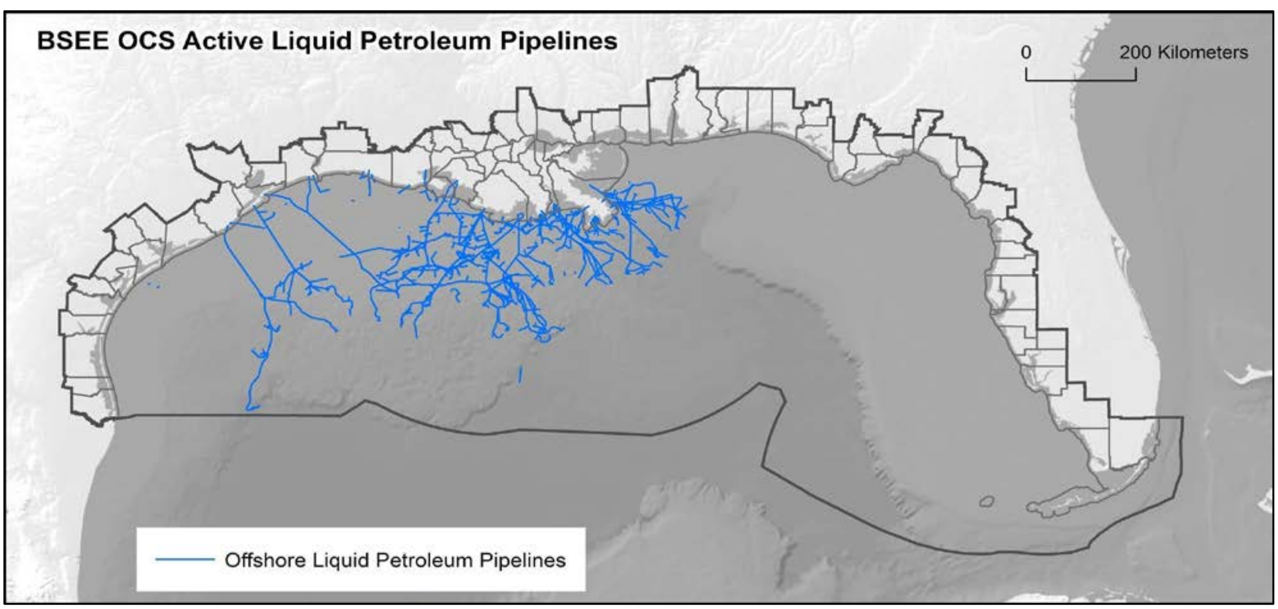

Figure 16. Offshore and onshore pipelines transporting liquid petroleum products or gas condensate.

We estimated the annual rate of petroleum product spill events per ton-km using national spill rates from Anderson *et al.* (2012) and the national offshore pipeline material estimates from the USEIA (2014) similar to those above at 0.001 per million ton-km. We estimated the total spill rate from offshore pipelines in each offshore BOEM spill launch location as the product this value and the total estimated material shipments in ton-km by pipeline in each offshore launch location. For each county or parish, we then took the product of the offshore facility spill rates in each offshore BOEM spill launch location and the probability that a spill in that launch location would impact that county or parish (as described in Appendix B). We estimated the annual rate of exposure to an oil spill from offshore pipelines for each county or parish as the sum of all launch area conditional rates.

Oil and Chemical Spills/Releases from Inland and Coastal Waterborne Transportation

A substantial portion of the domestic flow of crude and refined petroleum products and associated petrochemicals is transported into and out of the region via inland and coastal waterways either along the Gulf Intracoastal Waterway (GICWW), the Mississippi River, or other rivers and coastal routes. These products are moved by river barge, articulated tank barge, or other ocean-going barge, rather than by tanker. Transportation of oil and chemical products by inland and coastal waterway transport represents roughly 13% and 15%, respectively, of the total annual product tonnages moved regionally (FAF3, 2010). Spills of oil by barge transportation are more common than by tanker, per unit volume-distance, but individual spills tend to be smaller (API, 2009; Anderson *et al.*, 2012). Separate statistics are not compiled for chemical spills, but these incidents are likely similar in magnitude and volume per unit volume-distance. Barges carrying oil as cargo spilled an average of 3,600 barrels of oil annually in the U.S. between 1998 and 2007 (API, 2009). Rates of oil, and presumably chemical, spillage/releases have been declining both in absolute terms and relative to the amount of oil or chemicals transported over the past three decades (API, 2009; Anderson *et al.*, 2012).

Hazard Rate

To evaluate probability of oil or chemical spills from coastal or inland waterway tanker and tank barge transportation, we estimated the total annual flows in tons and ton-km of all petroleum (crude and refined products) and chemical products by waterway both nationally and regionally using the USDOT Freight Analysis Framework v3 (FAF3, 2010) database. In computing total volume of materials shipped in metric tons, we summed that all material flows originating or terminating within an FAF zone in the study area. In computing total flows of materials in ton-km, we assumed all material flows both originating and terminating within any FAF zones in the regional study area represented flows where the whole shipment took place on transportation routes entirely within that regional study area. For material flows either originating or terminating outside that FAF zones in the regional study area, we assumed that the proportion of that flow taking place within the regional study area was equivalent to the ratio of the average ton shipping distance within the regional study area to the total shipping distance of that shipment.

We estimated the annual rate of petroleum product spill events per ton-km using national spill rates from Anderson *et al.* (2012) and total national shipping flow estimates by mode from USDOT National Transportation Statistics (USDOT, 2014b) data at 0.6 per billion ton-km. We assumed similar spill rates for chemical products. We then computed the estimated annual spill/release rate using this value and the total estimated material shipments in ton-km by inshore/coastal tanker/tank-barge along routes in each county or parish. The results of this analysis are shown in Figure 17.

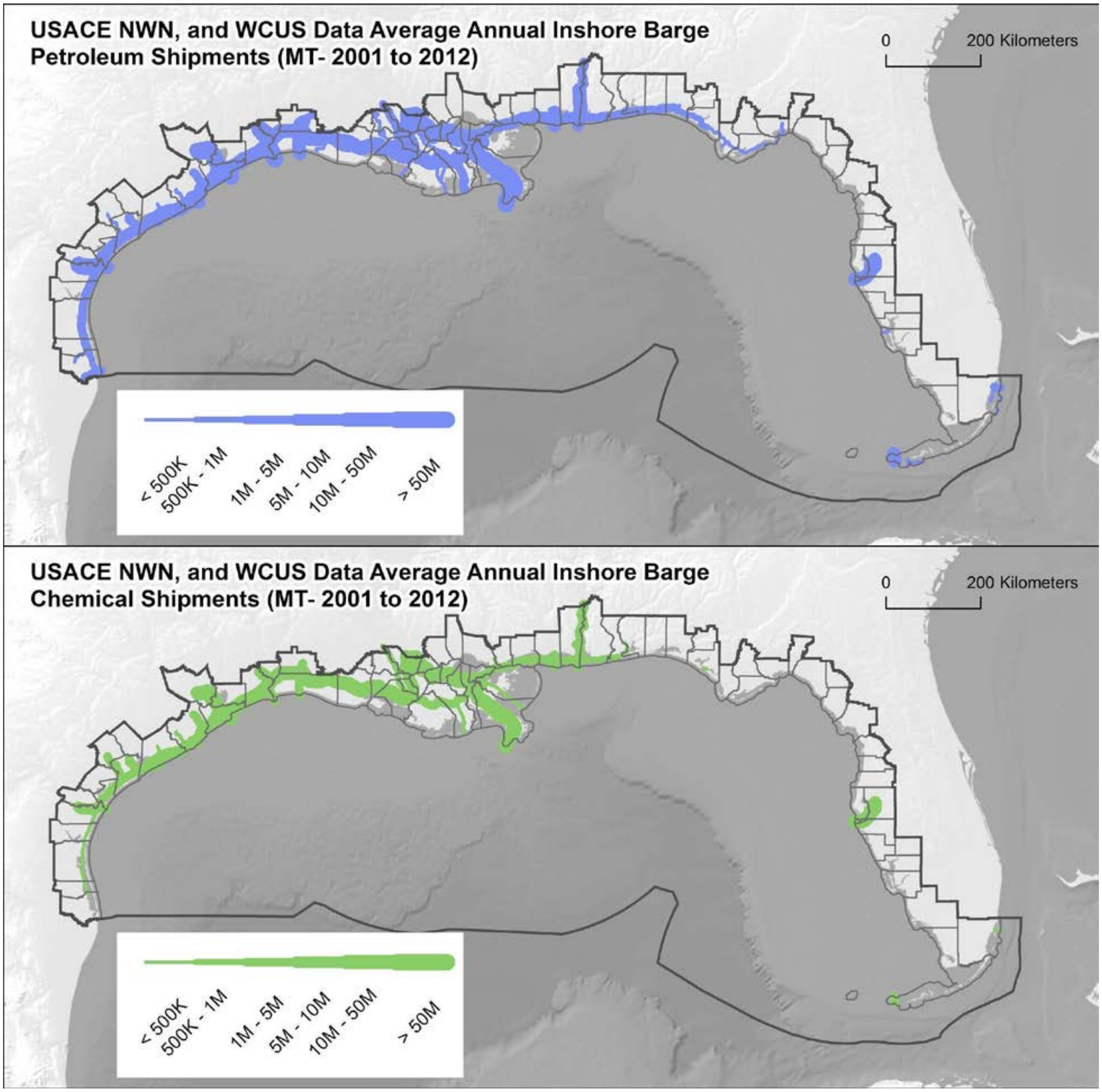

Figure 17. USACE National waterway network data by averaged domestic annual flows of petroleum (top) and chemical products (bottom) in tons (2001-2012) for inland and coastal routes.

Oil and Chemical Spills/Releases from Onshore Pipeline Transportation

Onshore pipelines move the largest percentage of crude and refined petroleum products transported into, out of, and within the region annually. A minor portion of chemical products are also transported regionally via pipeline. Transportation of oil and chemical products by pipeline represents roughly 43% and 10%, respectively, of the total annual product tonnages moved regionally (FAF3, 2010). Spills of oil by onshore pipeline are quite rare, per unit volume-distance, but individual spills are on average larger than spills from any other mode (API, 2009; Anderson *et al.*, 2012). Separate hazard rate statistics are not compiled for chemical spills, but these incidents are likely similar in magnitude per unit volume-distance.

Hazard Rate

To evaluate rate of oil or chemical spills from onshore pipeline transportation, we estimated the total annual flows in tons and ton-km of all petroleum products (crude and refined products) and chemical products by pipeline both nationally and regionally using the USDOT Freight Analysis Framework v3 (FAF3, 2010) database. In computing total volume of materials shipped in metric tons, we summed that all material flows originating or terminating within an FAF zone in the study area. In computing total flows of materials in ton-km, we assumed all material flows both originating and terminating within any FAF zones in the regional study area represented flows where the whole shipment took place on transportation routes entirely within that regional study area. For material flows either originating or terminating outside that FAF zones in the regional study area, we assumed that the proportion of that flow taking place within the regional study area was equivalent to the ratio of the average ton shipping distance within the regional study area to the total shipping distance of that shipment. The estimated total annual volume and flow in onshore pipelines in the region are 525 million tons and 105 billion ton-km of liquid petroleum products and 40 million tons and 3 billion ton-km of chemical products.

We generated data describing onshore liquid commodity pipeline locations by digitizing publicly available county summary graphics from the USDOT National Pipeline Mapping System (USDOT, 2014a) in Florida, Alabama, Mississippi, and Louisiana, and supplemented with pipeline data for the state of Texas (TXFRC, 2014) to generate an onshore pipeline network dataset for the study area. We filtered these data to include only active pipelines transporting either liquid oil, condensate, or other liquid chemicals (Fig. 18). Because the available pipeline data do not distinguish between pipelines based on flow rates or volume, we apportioned all regional onshore pipeline shipments in ton-km to the pipeline network equally by dividing the total length of pipelines in the network by the estimated total shipments to derive the average annual flow per unit pipeline length in t/km. We estimated the annual rate of petroleum product spill events per ton-km using national spill rates from Anderson *et al.* (2012) and total national shipping flow estimates by mode from USDOT National Transportation Statistics (USDOT, 2014b) data at 0.2 per billion ton-km. We assumed similar spill rates for chemical products. We then computed the estimated annual spill/release rate using this value and the total estimated material shipments in ton-km by pipeline in each county or parish.

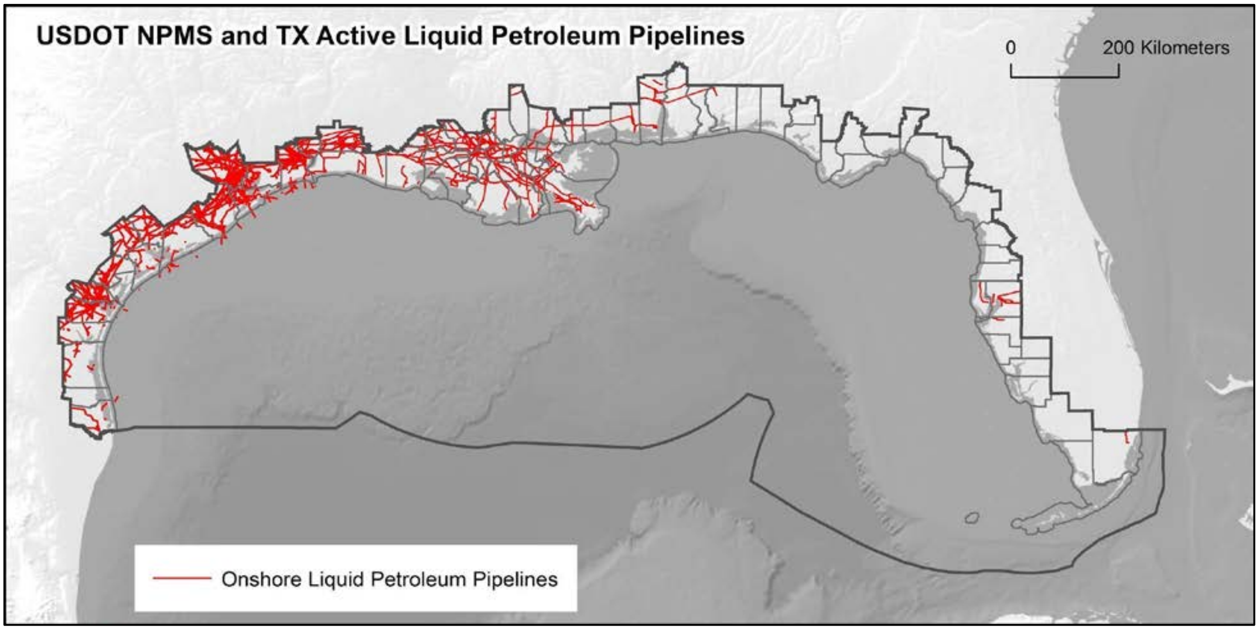

Figure 18. Onshore pipelines transporting liquid petroleum or chemical products, including gas condensate.

Oil and Chemical Spills/Releases from Roadway Transportation

Transportation of oil and chemical products by vehicle represents roughly 15% and 33%, respectively, of the total product tonnages moved regionally (FAF3, 2010). Spills of oil by road transportation are most common, per unit volume-distance, than any other mode of transport, but individual spills tend to be smaller than other modes (API, 2009; Etkin, 2006). Separate hazard rate statistics are not compiled for chemical spills, but these incidents are similar in magnitude. Tanker trucks carrying oil (usually fuels) as cargo spilled an average of 9,200 barrels of oil annually in the U.S. between 1999 and 2009 (API, 2009). Most of these spill incidents are handled by local emergency response personnel, such as fire departments. Spills from tanker trucks often go to pavements and are less likely to directly impact waterways or sensitive habitats. In this analysis we consider only oil and chemical spills of products transported by vehicles on roadways, rather than spills of fuel or other materials related to operation of vehicles, which are generally small.

Hazard Rate

To evaluate the annual rate of spills from onshore roadway transportation, we estimated the total annual flows in tons and ton-km of all petroleum (crude and refined products) and chemical products by roadway both nationally and regionally using the USDOT Freight Analysis Framework v3 (FAF3, 2010) database. As described above, we summed all flow originating or terminating with the FAF zones comprising the study area, while separately accounting for material flows occurring only within the study area and those originating or terminating outside. The estimated total annual volume and flow by vehicles on roadways in the region are 184 million tons and 35 billion ton-km of liquid petroleum products and 128 million tons and 33 billion ton-km of chemical products. We used the USDOT Freight Analysis Framework Network (FAFN) from the National Transportation Atlas Database (USDOT, 2014; FAF3, 2010) which represents the National Highway System as well as state primary and secondary roads to derive location of roadways in the study area. The FAFN data attribute all segments within this road network with modeled total annual flows of all freight in kilotons. For this purpose, we use the estimated 2012 updates to these estimated flows (Fig. 19). To estimate total petroleum and chemical product flows we performed a Closest Facility Transportation Network Analysis of the National Highway System with FAF zones and the study area counties/parishes as originating and terminating routes. Flow distance for within FAF zones was estimated using a standard distance calculation based on within FAF county/parish centroids. Finally, flow rates were estimated from FAF to the county level with a disaggregation model.

We estimated the annual rate of petroleum product spill events per ton-km using national spill rates from Anderson *et al.* (2012) and total national shipping flow estimates by mode from USDOT National Transportation Statistics (USDOT, 2011) data at 10 per billion ton-km. We assumed similar spill rates for chemical products. We then computed the estimated annual spill/release rate using this value and the total estimated material shipments in ton-km by roadway in each county or parish.

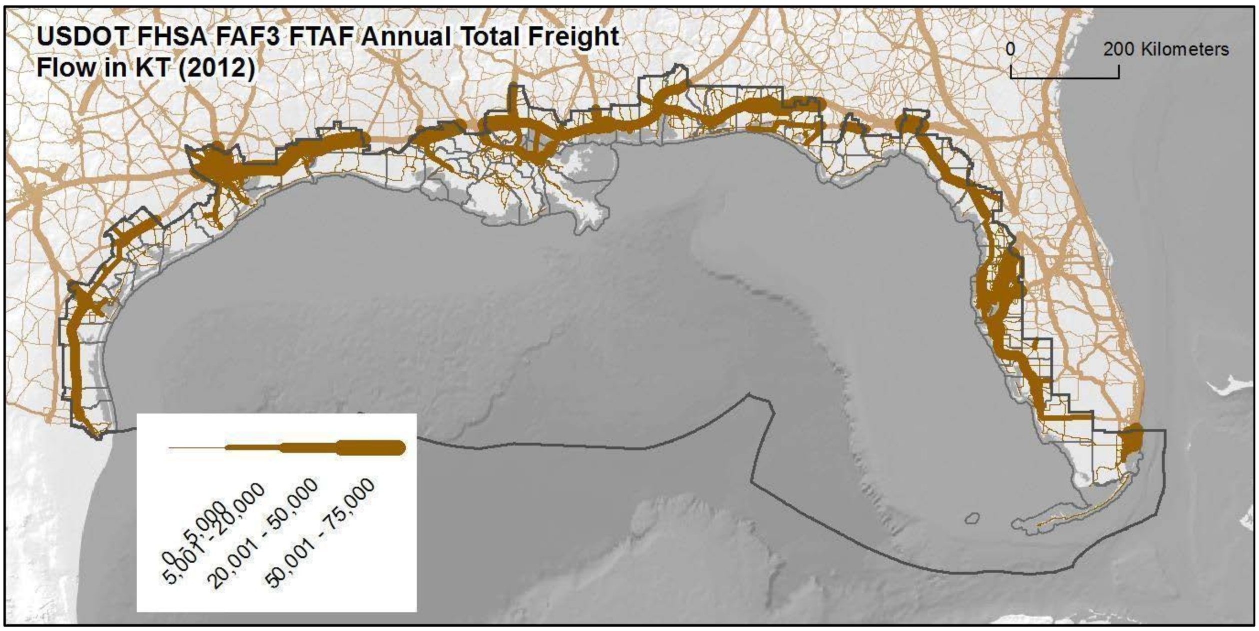

Figure 19. USDOT/FAF3 road network by modeled annual flows of all freight in kilotons.

Oil and Chemical Spills/Releases from Rail Transportation

Rail transportation of oil and chemical products represents the smallest overall fraction of transportation of these products by mode, even accounting for recent increases in transportation of oil by rail from North American and Canadian shale fields (FAF3, 2010). Spills of oil and chemical products by rail transportation are less common, per unit volume-distance, than by road and more common than by pipeline or waterborne mode of transport. Individual spills from rail transport tend, on average, to be larger than by road transport, while smaller than by pipelines or waterborne modes (API, 2009; Etkin, 2006).

Hazard Rate

To evaluate annual rate of spills from onshore railway transportation, we estimated the total annual flows in tons and ton-km of all petroleum (crude and refined products) and chemical products by railway both nationally and regionally using the USDOT Freight Analysis Framework v3 (FAF3, 2010) database. As described above, we summed all flow originating or terminating with the FAF zones comprising the study area, while separately accounting for material flows occurring only within the study area and those originating or terminating outside. The estimated total annual volume and flow by rail in the region are 2 million tons and 441 million ton-km of liquid petroleum products and 89 million tons and 40 billion ton-km of chemical products. We used the Federal Railroad Administration (FRA) Class 1 Rail Line Network data from the National Transportation Atlas Database (USDOT, 2014), which represents the major regulated Class 1 rail corridors to derive location of railways in the study area. To estimate total petroleum and chemical product flows we performed a Closest Facility Transportation Network Analysis of the Rail Line Network with FAF zones and the study area counties/parishes as originating and terminating routes. Flow distance for within FAF zones was estimated using a standard distance calculation based on within FAF county/parish centroids. Finally, flow rates were estimated from FAF to the county level with a disaggregation model. The FRA data classify all segments within this rail network with estimated total annual flows of all freight in megatons. We found that the estimated total petroleum and chemical product flows occurred on this network in relative proportion to the mid-point of the range of estimated total freight flows represented by these categories (Fig. 20). We estimated the annual rate of petroleum product spill events per ton-km using national spill rates Anderson *et al.* (2012) and total national shipping flow estimates by mode from USDOT National Transportation Statistics (USDOT, 2011) data at 0.4 per billion ton-km. We assumed similar spill rates for chemical products. We then computed the estimated annual spill/release rate using this value and the total estimated material shipments in ton-km by railway in each county or parish.

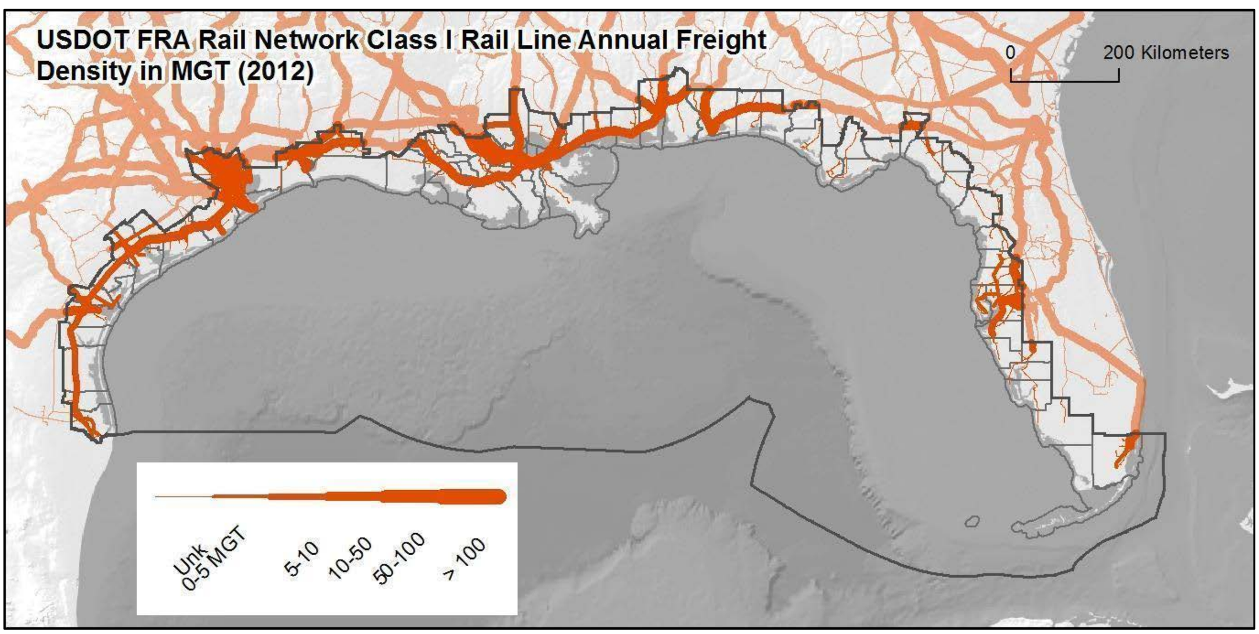

Figure 20. USDOT/FRA Class 1 rail network classified by overall annual flow of all freight in megatons.

Oil and Chemical Spills/Releases from Onshore Facilities

The study area is home to a high density of petroleum and chemical handling and storage facilities related to refinery infrastructure and associated chemical and petrochemical processing and manufacturing infrastructure in the region. Onshore petroleum refineries spilled an average of 12,136 barrels of oil annually in the U.S. between 1998 and 2007 (API, 2009) or roughly 6% of the total volume of oil spilled over this period. Over this same period, non-refinery inland EPA-regulated facilities spilled an average of 59,676 barrels annually or roughly 30% of all oil spilled. Compiled statistics are not available for chemical products but we assume overall spill rates are similar. Rates of oil spillage from onshore storage and handling have been declining both in absolute terms and relative to the amount of oil produced over the past three decades; however, these facilities remain as some of the largest single sources of oil and chemical spills/releases (API, 2009).

Hazard Rate

To evaluate annual rate of oil and chemical spills/releases from onshore facilities, we compiled all active EPA Spill Prevention Control and Countermeasures/Facility Response Plan (SPCC/FRP) facilities and EIA refineries (USEPA, 2015; USEIA, 2015) that were active and were producing or handling either liquid oil or condensate. We also compiled at EPA Toxic Release Inventory (TRI) facilities and EIA ethylene crackers (USEPA, 2015; USEIA, 2015). Maps of both are shown in Figure 21. We then computed the annual spill rate per facility and refinery from the number of spills from both refineries and SPCC/FRP facilities in the U.S. between 1998 and 2007 (API, 2009) and the number of active refineries and facilities in the U.S (USEPA, 2015; USEIA, 2014) at 2.13 per refinery and 0.06 per facility. We assumed per-facility spill rates of chemical spills from both TRI facilities and ethylene crackers were equivalent. We estimated the total spill rate per county or parish as the product of the per-facility spill rate and the count of facilities.

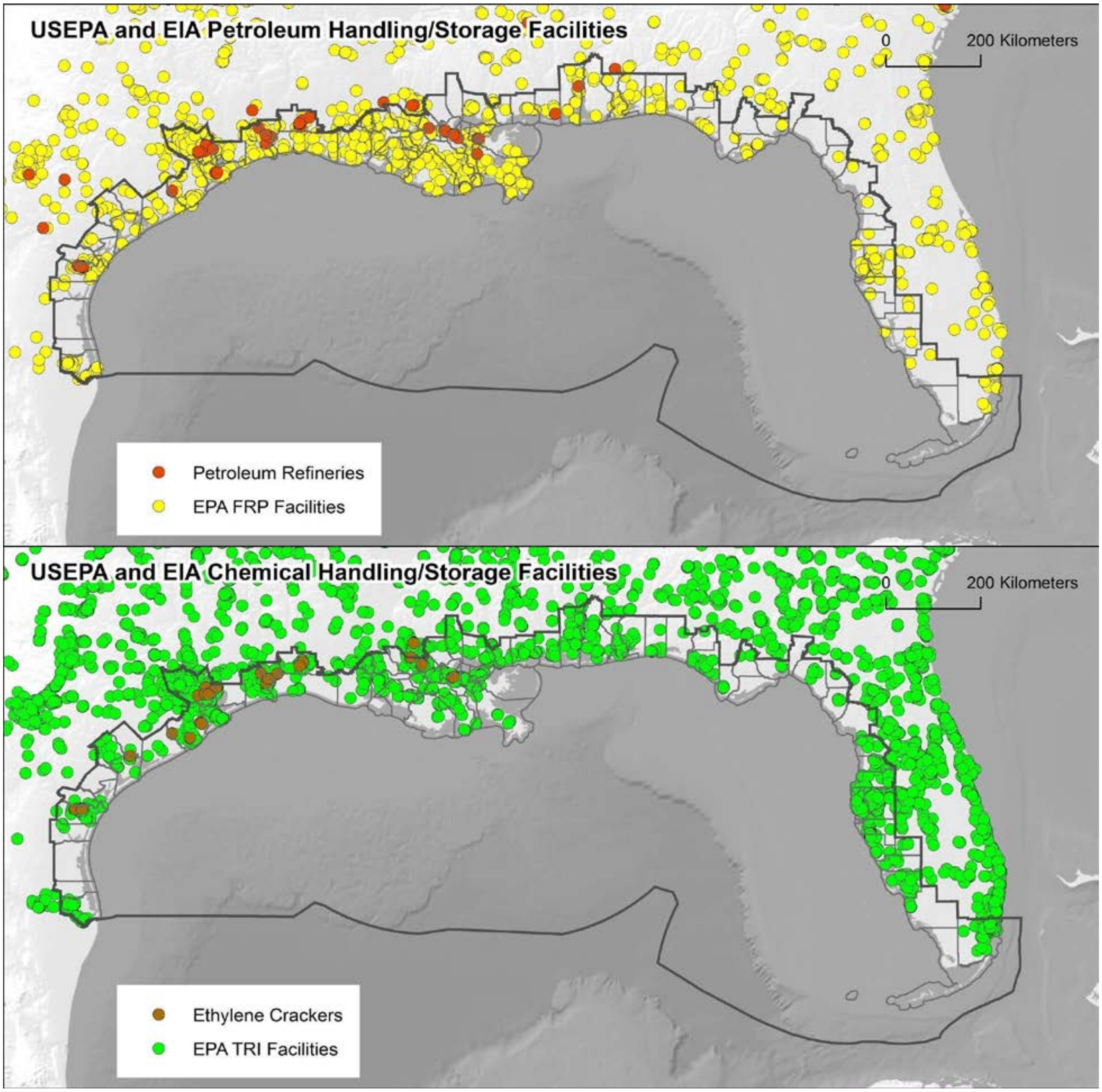

Figure 21. Potential onshore facility spill sources for petroleum products (top) from EPA FRP facilities and EIA petroleum refineries and for chemical products (bottom) from EPA TRI facilities and EIA ethylene cracker facilities.

Radiological Release from Nuclear Reactor

Major reactor accidents of nuclear power plants are rare, yet the consequences are catastrophic. Here, we consider a radiological release from a nuclear reactor to be any accident, generally associated with damage to the reactor core caused by the failure of the cooling systems, such that radioactive gases or particulate matter are released to the atmosphere. There are a number of nuclear reactors operating in the region for the purpose of generating electrical power (USNRC, 2015), as shown in Figure 22 (top).

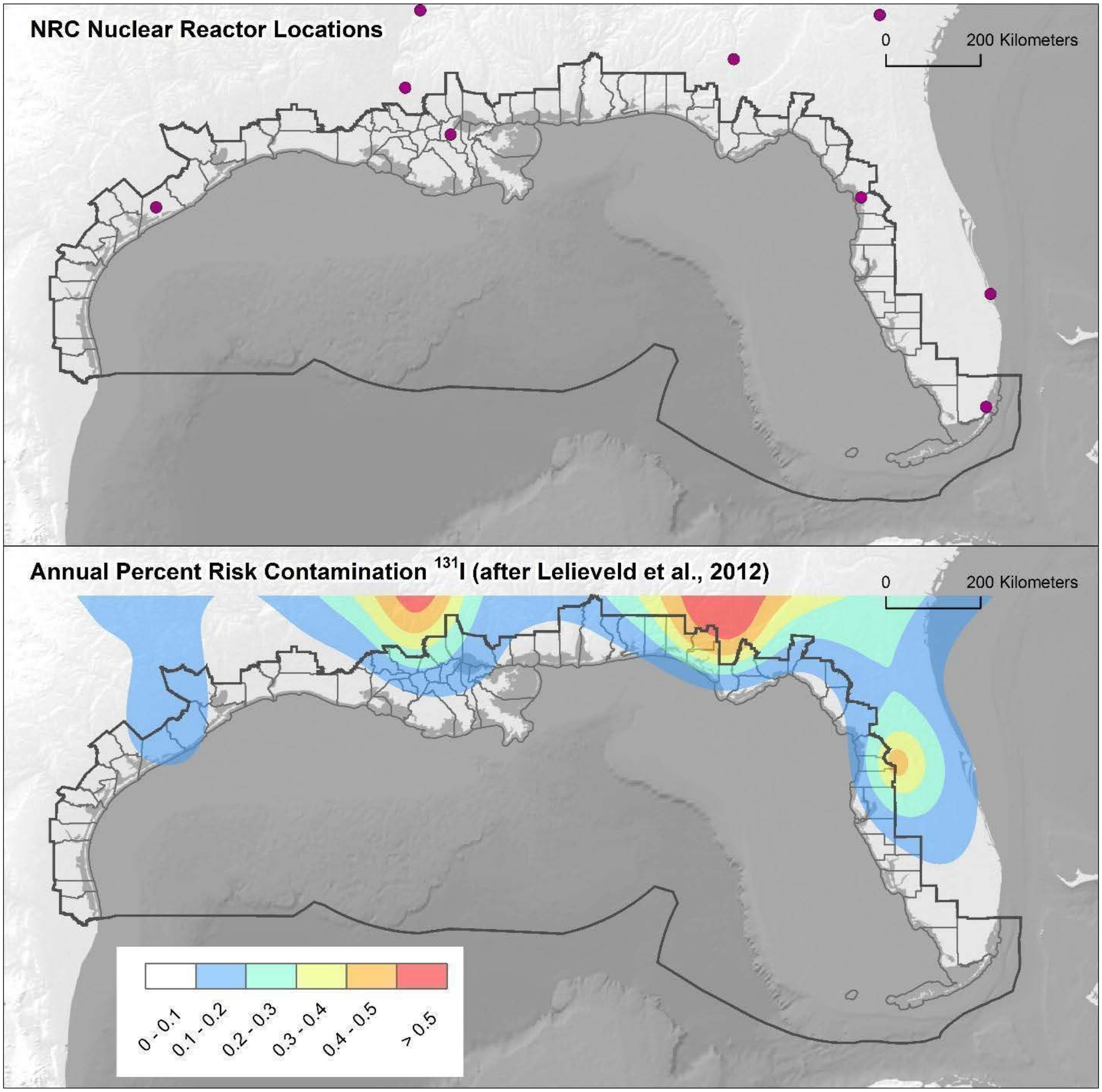

Figure 22. Active nuclear reactors in study area (top) and annual risk of ^{131}I contamination from fallout from a nuclear reactor incident after Lelieveld *et al.* (2012).

Hazard Rate

To evaluate annual rate of radiological release from a nuclear reactor, we follow Lelieveld *et al.* (2012) who generated probabilistic risk maps of fallout deposition from reactor sites based on stochastic simulations of atmospheric transport (Fig. 22, bottom). We extracted annual probability of exposure to ^{131}I as a proxy for both particulate and gaseous radioactive material fallout exposure risk from a nuclear reactor accident as a single averaged value for each county or parish. We then assumed that such incidents would follow a Poisson distribution and computed annual rate from annual probability.

Hazard Severity

Due to a lack of data to calculate the explicitly frequency of event by severity class for radiological reactor releases, the estimates of minor, moderate, and major radiological reactor release frequencies reflect the estimates for chemical facility spills calculated from the NRC database from 1994-2013.

Radiological Release from Facility

Spills or releases of radiological materials from processing or handling facilities are a rare occurrence, and there are little data with which to estimate their frequency.

Hazard Rate

To evaluate annual rates of a radiological releases from a facility, we compiled all active EPA RADInfo facilities handling radiological materials in the region (USEPA, 2015), shown in Figure 23. We also compiled at EPA TRI facilities and EIA ethylene crackers (USEPA, 2015; USEIA, 2015). We then estimated the annual spill rate per facility as similar to the rate of petroleum spills from SPCC/FRP facilities at 0.06 per facility and the total estimated spill rate per county or parish as the product of the per-facility spill rate and the count of facilities.

Hazard Severity

Due to a lack of data to calculate the explicitly frequency of event by severity class for radiological facilities, the estimates of minor, moderate, and major radiological facility release frequencies reflect the estimates for chemical facility spills calculated from the NRC database from 1994-2013.

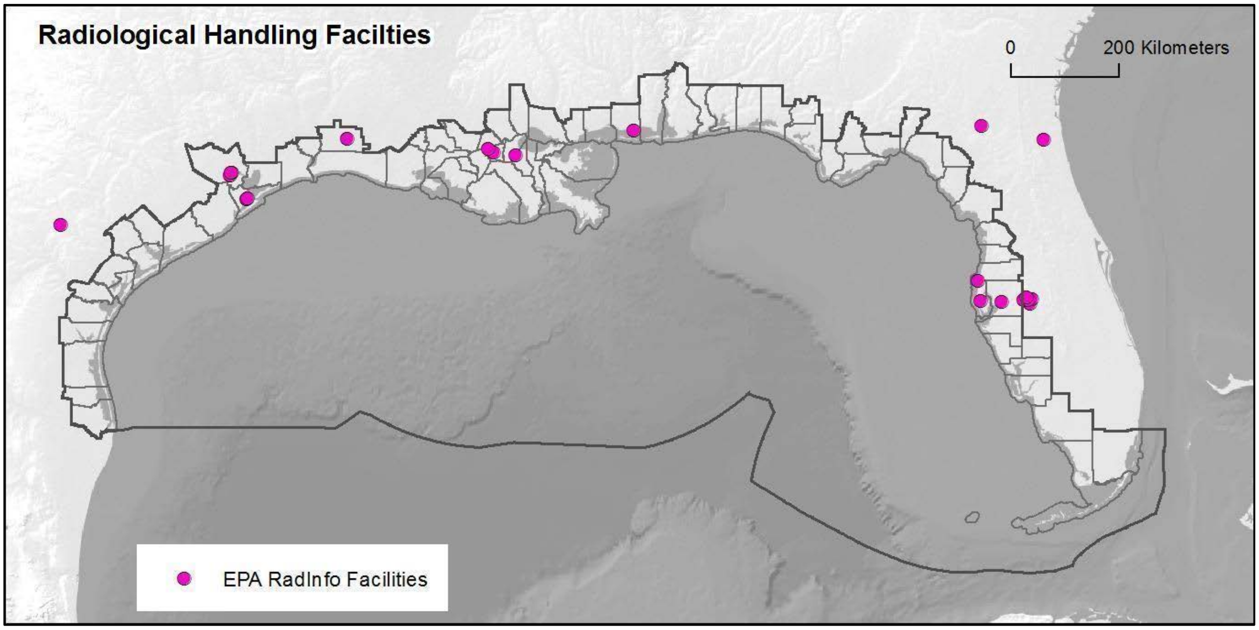

Figure 23. Radiological material handling facilities from EPA RADInfo database (USEPA, 2015).

Radiological Release from Roadway

The U.S. Nuclear Regulatory Commission estimates that about 3 million packages of radioactive materials are shipped each year by highway, rail, air, or water transportation. Accidents during shipping have occurred; however, according to the World Nuclear Association website, there has never been one in which a container of highly radioactive material has been breached (World Nuclear Association 2014). For this analysis we estimate the amount of radiological hazardous material transported in the 73 counties included in this analysis by ground transportation on the U.S. road system and the chance of an accident occurring during shipment.
The amount of radiological hazardous materials transported per year for each of the Gulf States were estimated based on data from the 2012 Economic Census for Hazardous Materials, a subset of data from the Commodity Flow Survey (CFS) (USDOT, 2015).

Hazard Rate
To evaluate annual rates of radiological releases from roadway transportation, we estimated the total annual flows in ton-km of radioactive materials by roadway nationally using the CFS database as described above as 35 million ton-km. We used the USDOT Freight Analysis Framework Network (FAFN) from the National Transportation Atlas Database (USDOT, 2014; FAF3, 2010) and the estimated 2012 updates to total freight flows. We assumed that the estimated total radioactive material flows occurred on this network in relative proportion to the modeled total freight flows. We assumed that the annual rate of radioactive material releases from roadway transportation per ton-km is the same as for chemical spills for roadway transportation. We then computed the estimated annual spill/release rate using this value and the total estimated material shipments in ton-km by roadway in each county or parish.

Biological Release from Sanitary Sewer Overflow

Nearly all municipalities in the study area have sanitary sewer systems (SSS). An SSS is municipal wastewater collection system that conveys domestic, commercial, and industrial wastewater, and limited amounts of infiltrated groundwater and stormwater, to a publicly owned treatment works. SSSs are not designed to collect large amounts of stormwater runoff from precipitation events. Areas served by SSSs often have a municipal separate storm sewer system to collect and convey runoff from rainfall and snowmelt. Untreated or partially treated discharges from SSSs are commonly referred to as sanitary sewer overflows (SSOs). SSOs have a variety of causes including blockages, line breaks, sewer defects that allow excess stormwater and groundwater to overload the system, lapses in sewer system operation and maintenance, inadequate sewer design and construction, power failures, and vandalism. An SSO is defined for this analysis as any release of untreated, or partially treated, sewage from a SSS.

Hazard Rate

To evaluate annual rates of sewage release from SSS for each county or parish, we extracted all SSO facilities from the EPA National Pollutant Discharge Elimination System (NPDES) database (USEPA, 2014) in the study area (Fig. 24). We then computed the annual SSO/release rate per SSS from the number of releases from all SSOs in the U.S. between 2003 and 2003 (USEPA, 2004) and the number of SSSs in the U.S. We estimated the expected annual rate of SSO per county or parish as the expected annual rate per SSS multiplied by the count of SSS per county or parish.

Hazard Severity

Due to a lack of data to calculate the explicitly frequency of event by severity class for biological facilities, the estimates of minor, moderate, and major biological facility release frequencies reflect the estimates for chemical facility spills calculated from the NRC database from 1994-2013.

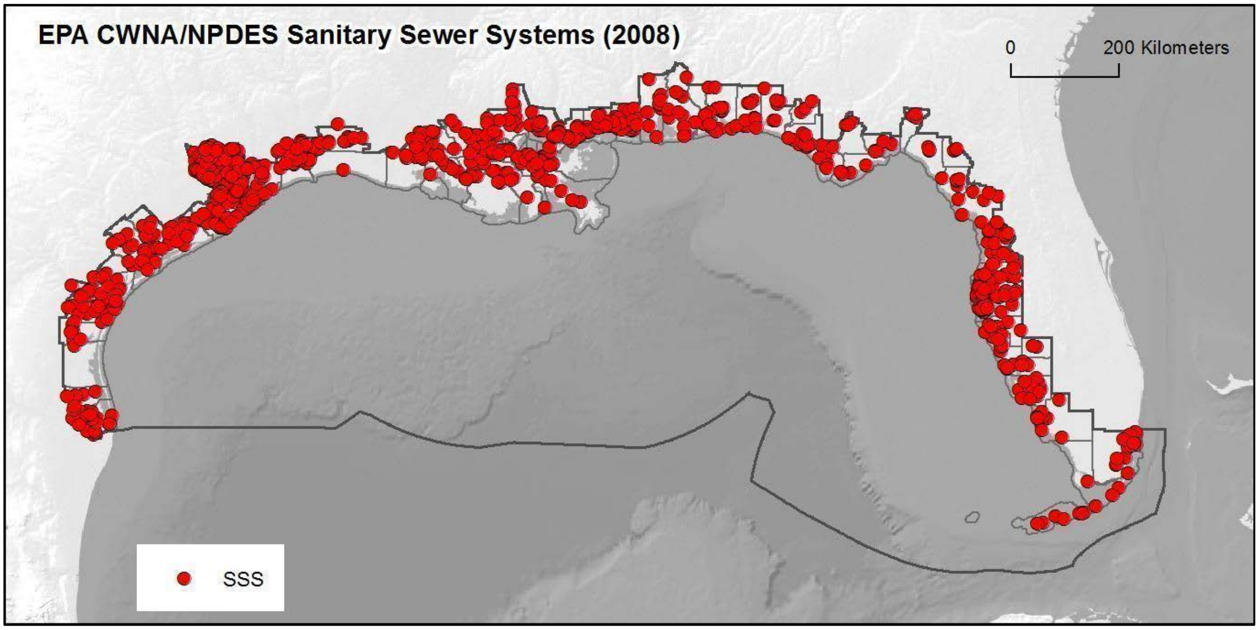

Figure 24. Sanitary sewers systems (SSS) in the study area from USEPA NPDES (2014).

Conditional Hazards

Conditional hazards are defined here as damaging anthropogenic events (e.g., oil and chemical spills, releases of biological wastes, and exposure to radiological material) that would not have occurred if not for an immediately preceding damaging natural phenomena. Across the Gulf coast region, the probability of a conditional hazard occurrence is most closely tied to the natural hazards accompanying tropical cyclones. During a tropical cyclone, strong winds and heavy rainfall may combine to damage assets and trigger conditional hazards in the form of one or many of five natural hazards discussed in this report: tropical storm winds, flooding (coastal, flash, and riverine), and tornadoes (Blake *et al.*, 2011). To better understand the complexity of events that occurs from a tropical cyclone, we have included examples of the conditional hazards, their causes, and impacts for the back-to-back category-2 hurricanes, Gustav and Ike, which affected the Gulf coast in September 2008.

Hurricane Gustav made landfall in Louisiana on 1 September 2008. It caused storm surge above 12 feet, brought as much as 21 inches of rain, and was associated to a total of 29 tornadoes that stretched from Louisiana to the Florida panhandle (Beven and Kimberlain, 2009). Eight days later, on September 9, Hurricane Ike made landfall on the north end of Galveston Island, Texas bringing storm surge up to 20 feet and causing higher-than-normal water levels across virtually the entire Gulf coast. Rainfall of up to 18 inches was recorded near Houston, Texas and 29 tornadoes were reported between Texas, Louisiana, and Florida (Berg, 2009).

By October 1, 2008, the Unified Command had received more than 200 pollutant reports associated with the winds, flooding, and tornadoes produced by the two cyclones (Berg, 2009). Hurricane Ike destroyed 52 of the approximately 3,800 oil platforms in the Gulf of Mexico, damaged 32 more, and damaged several large pipelines. Eight chemical facilities in the area were severely damaged by Ike with all but one having four to ten feet of salt water inside the plants (EIA, 2009; Berg, 2009). Including closures and damages, Gustav and Ike affected approximately 2,127 of the 3,800 natural gas platforms, 97 natural gas processors, and 28 pipelines, including 11 interstate pipelines. Petroleum production, refining, and pipelines received similar impacts affecting 2,277 platforms, 14 refineries, and at least 7 pipelines (EIA, 2009).

At least 33 oil spills required attention in the wake of Hurricane Gustav, ranging in distribution and volume from simple sheens to 8,000 gallon spills (Beven and Kimberlain, 2009). In relation to conditional hazards from Ike, Texas Parks and Wildlife Department (TPWD) and the U.S. Fish and Wildlife Service responded to a spill at the J.D. Murphree Wildlife Management Area (WMA), the Bessie Heights Marsh (Nelda Stark Unit) of the Lower Neches WMA, and also the Anahuac, McFaddin and Sabine National Wildlife Refuges. On the refuges alone, it was estimated that approximately 500-2,000 acres of national wildlife refuge were impacted. In the High Island area, approximately 3,000 acres had visible oil sheening and staining. Additionally, these areas were also impacted by marine debris with 70 acres of mixed debris on the J.D. Murphree WMA and over 30 acres of debris from the Bolivar Peninsula that covered much of the Candy Abshier WMA at Smith Point. Oiled wildlife was reported following at least one of the spills and a combination of spills and saltwater intrusion may have contributed to the 200 incidents of fish kills that occurred in tidal streams and rivers (FEMA, 2009).

We computed the joint probability of all anthropogenic hazard incidents being caused by specific natural hazards. We began by compiling all data from the USCG National Response Center (NRC) spill/release databases for 1994-2013 (USCG, 2014). We grouped all incidents by a simplified source scheme relevant to this study, and by the cause of the incident for all incidents caused by distinguishable natural phenomena. We were unable to distinguish between flooding caused by different hydrological phenomena used in this study. We filtered this database to only include incidents in the study area, incidents that involved a release to land or water, and tabulated all incidents in the database to compute the number of spills and releases from each source caused by each natural hazard.

We then estimated the number of events of each natural hazard type across the study area over the period covered by the spill database using the data sources described above and computed the annual rate of spill/releases based upon these counts and the number of spill sin each category. Finally, we estimated the annual probability of one or more spills/releases occurring in the study area given the occurrence of a natural hazard event by considering spills/releases as a Poisson process and computing the cumulative probability distribution from the expected rate per event type (Table 4).

These probabilities include any spill/release of any material from a given source, but exclude biological releases and radiological releases from nuclear reactors because these events are not captured in the NRC database. Likewise, we also exclude volcanic ashfall, tsunamis, landslides and earthquakes from this analysis because there are either no events or an insufficient number of events in the NRC database attributed to these causes. We also excluded HABs they were assumed to lack a mechanism by which to cause a spill/release.

It is evident that tropical storm winds (and the associated storm surge and waves) are by far the largest natural hazard that generates spills/releases in the region. A given tropical storm is more than 99% likely to generate one or more spills from offshore platforms and onshore facilities and quite likely to generate additional spills from vessels and pipelines. The use of the Poisson distribution given the computed rates can also be used to generate probabilities for events that generate larger number of spills. For example, these data suggest a probability of 0.69 that a given tropical storm will cause 10 or more spills from onshore facilities.

Table 4. Estimated probability of one or more of spills/releases in the study area from each spill source given the occurrence of a natural hazard event. Probabilities presented with two significant digits. Cells shaded by relative value.

	Facility (All)	Vehicle	Pipeline	Platform	Railroad	Vessel (All)
Flooding (Any)	0.005	0.000002	0.000003	0.001	0.00000001	0.0003
Lightning	0.00000000002	0.00	0.00	0.00	0.00	0.000000000003
Convective Storm Winds	0.00001	0.000000009	0.00	0.00002	0.00	0.00001
Tornado	0.0006	0.00001	0.000003	0.00	0.00	0.00002
Tropical Storm Winds	0.99	0.01	0.56	1.00	0.003	0.93
Wildfire	0.000000002	0.00	0.00	0.00	0.00	0.0000000001

HAZARD SUMMARIES

Summaries of county/parish-wise hazard rates are presented in Figures 25-27. Figure 25 presents the distribution of county/parish hazard event rates for all hazards. Most natural hazards have rates between 10 events annually to one event every 25 or 50 years. The notable exceptions are lightning strikes at one extreme, with annual rates around 10,000 per year, and earthquakes, volcanoes, and tsunamis at the other extreme with recurrence intervals of thousands to tens of thousands of years. Anthropogenic hazard rates generally range from several per year for common spill/release sources like vehicles and facilities, to recurrence intervals of many decades or hundreds of years for uncommon spill/release sources. Note that some counties/parishes have zero annual rate estimates for some hazards due to methods used to estimate hazard event rates.

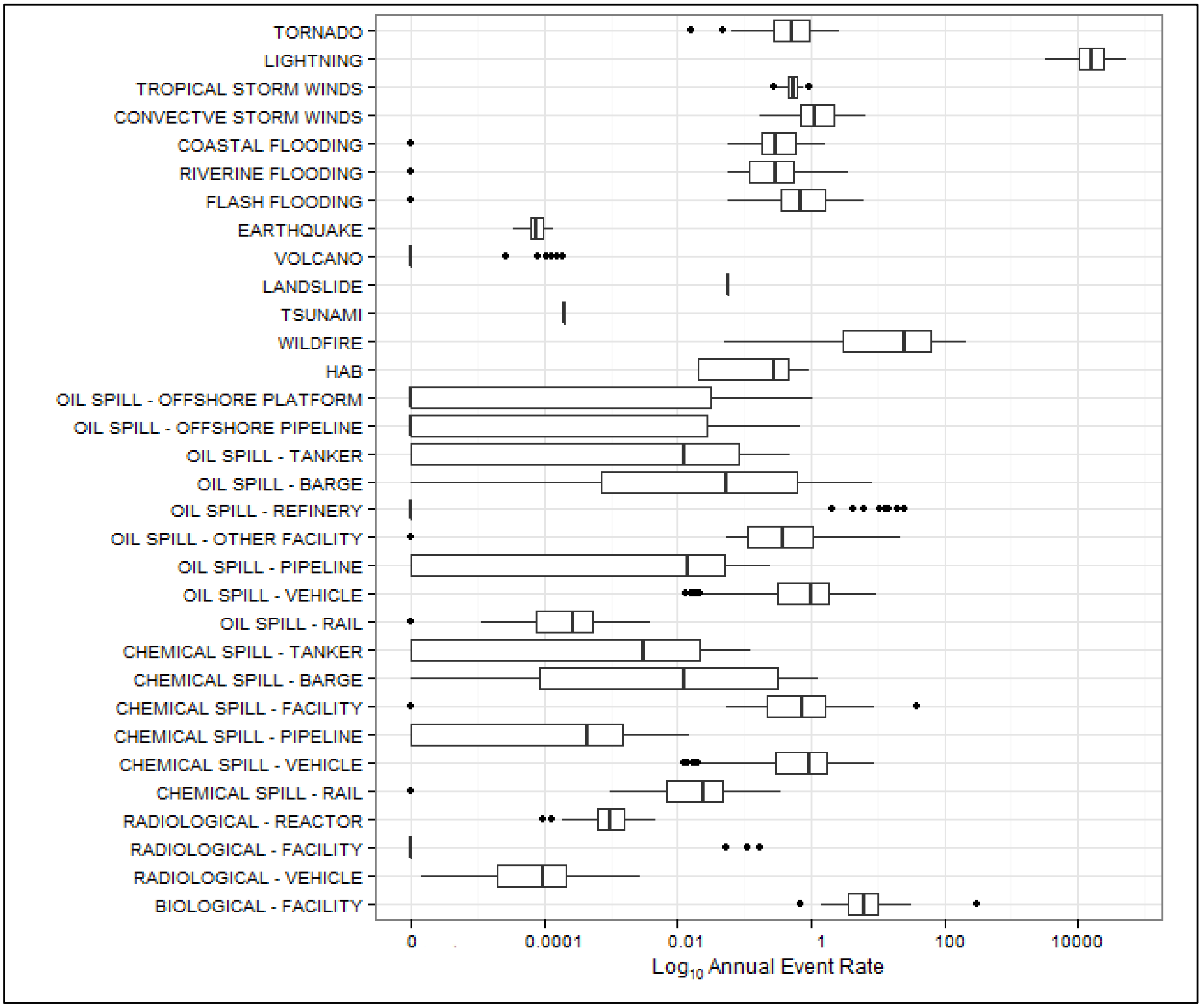

Figure 25. Boxplots of distribution of natural and anthropogenic hazard event rates for all counties/parishes. All counties/parishes have the same rate estimated for landslides and tsunamis. Note $\log_{10}$ scale.

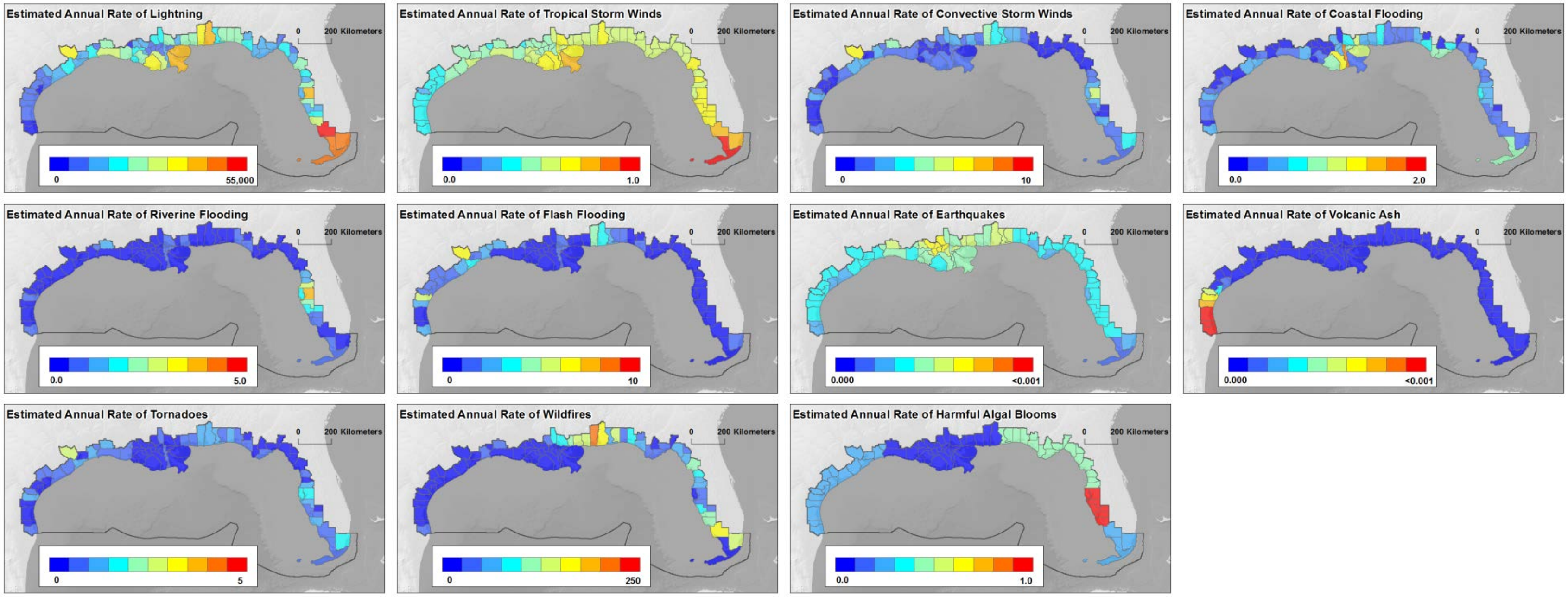

Figure 26. Annual natural hazard event rates by county or parish. Note that map values vary widely in scale and maps for tsunamis and landslides have not shown because all county/parish values were identical. High-resolution images of the above maps have been included within Appendix C.

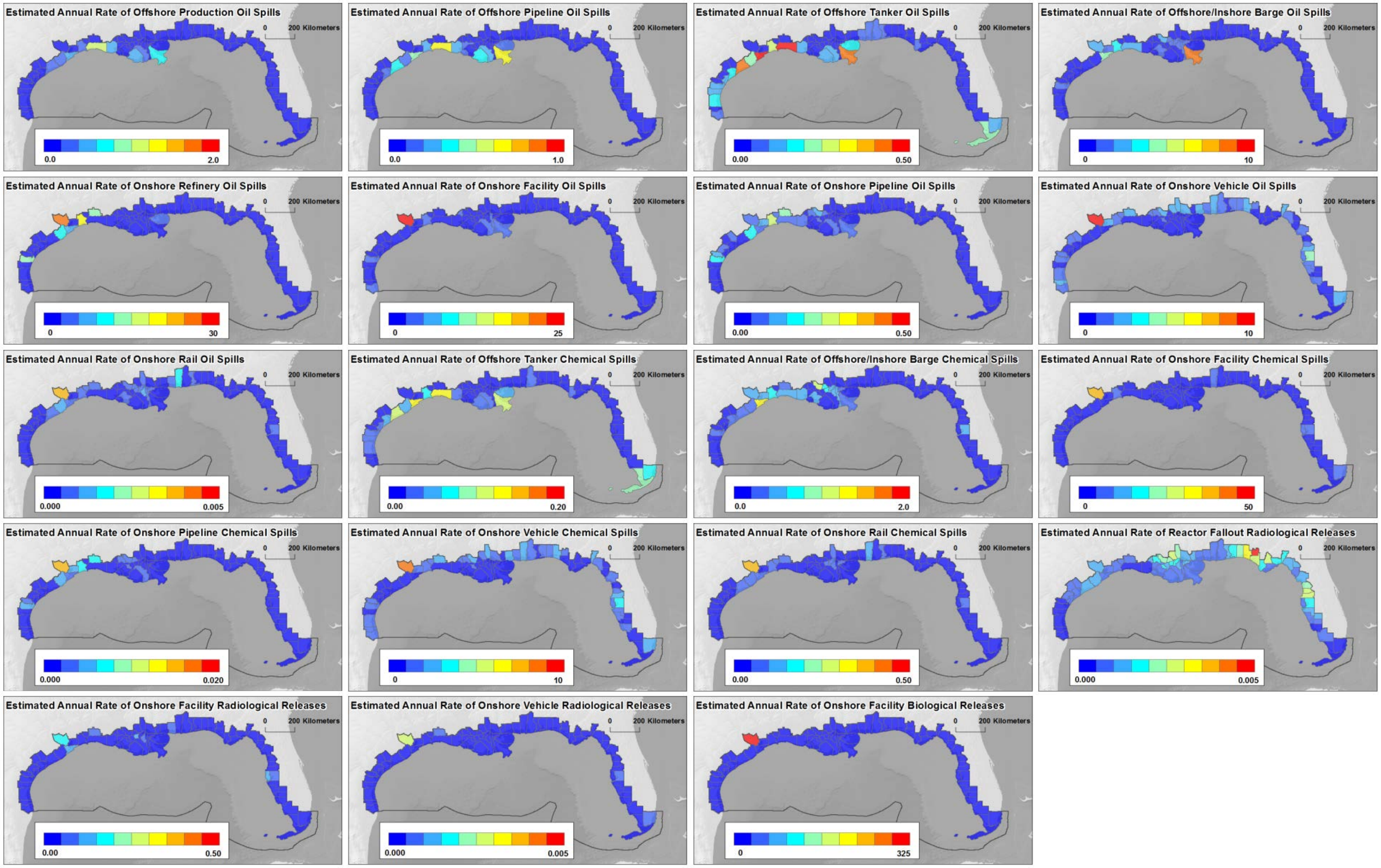

Figure 27. Annual anthropogenic hazard event rates by county or parish. Note that map values vary widely in scale. High-resolution images of the above maps have been included within Appendix D.

ASSETS AT RISK

We considered the asset categories and types listed in Table 5 for inclusion in this analysis.

Table 5. Environmental and human assets evaluated for each county or parish. Specific methods are described below.

Asset Category	Asset Type	Data Source
Human Population	Population	US Census 2010
Infrastructure	Waterways	USACE Waterway Network
	Pipelines	Multiple pipeline datasets
	Road network	USDOT FHSA FAF3 Freight Traffic Analysis Network
	Rail	USDOT FRA Rail Network
	Facilities	Multiple datasets described above
Natural Resources	Wetland	NWI wetland area
	T&E Species	ESI T&E Species

Human Population

We estimated human population density from the 2010 US Census county/parish (Fig. 28).

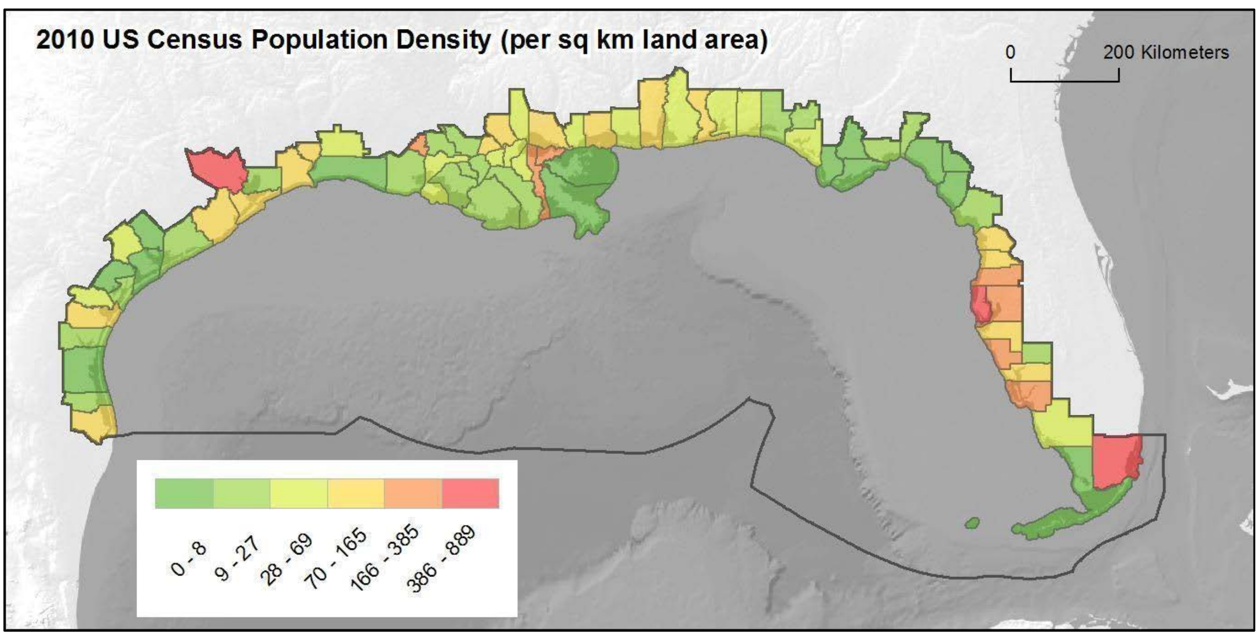

Figure 28. Human population density (count per km^2) from U.S. 2010 Census.

Infrastructure

For each of the infrastructure categories used to evaluate anthropogenic hazards described above, we computed the count (for oil refineries and oil chemical, radiological, and biological facilities) or linear density (for waterways, pipelines, roads, and rail lines) per unit area for each county or parish. Each infrastructure category was then ranked from zero to one based on a county's or parish's value of the category divided by the maximum value of the category across all counties and parishes. The ranked values across the nine infrastructure categories was averaged and ranked again to generate a zero-to-one county-level infrastructure index score.

Wetlands

We estimated the amount of wetland present in each county or parish as a percentage of total land area (Fig. 29). Total wetland area was derived from U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) data (USFWS, 2014). We converted all wetland types present in the NWI data to a simplified scheme based on the methods used by the Sea Level Affecting Marshes Model (SLAMM) after Clough *et al.* (2012). The SLAMM crosswalk was modified to include classes that were present in the 2014 NWI but were not included in the currently available version of the SLAMM crosswalk. All fresh marsh, salt marsh, scrub/shrub (swamp and mangrove), tidal marsh, and forested wetlands were included in the model as wetland classes. All marine, estuarine, and riverine deep water classes (unconsolidated bottom, rocky reef, etc.) were removed along with tidal flats and unconsolidated shoreline. The remaining wetland classes were then combined and the total area was calculated by county or parish. This area was used with the total land area of the county or parish to derive percentages.

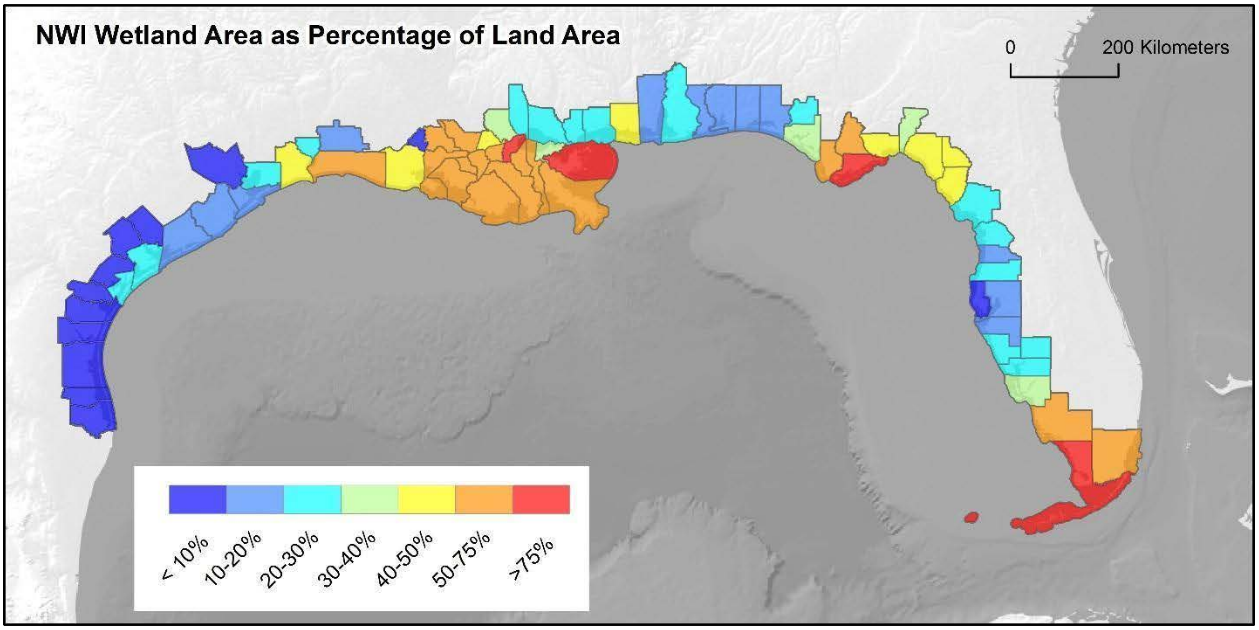

Figure 29. Wetland (NWI) as percentage of land area for each county or parish.

Threatened and Endangered Species

As a proxy for the quantity of sensitive species, we computed the number of threatened and endangered species in each county or parish (Fig. 30). Data were derived from NOAA Environmental Sensitivity Index (ESI) atlases for Northern Texas, Louisiana, Alabama, Mississippi, and Florida (NOAA, 2007, 2009, 2012, 2013a,b,c). We compiled the total number of unique State- or Federally listed species present in these data in each county or parish. Listed vascular plant species were irregularly included in these data (generally only in Florida), so plant species were excluded from species counts. Digital spatial data were not available for Southern Texas so we derived species counts manually from available hardcopy map products (TGLO, 1997).

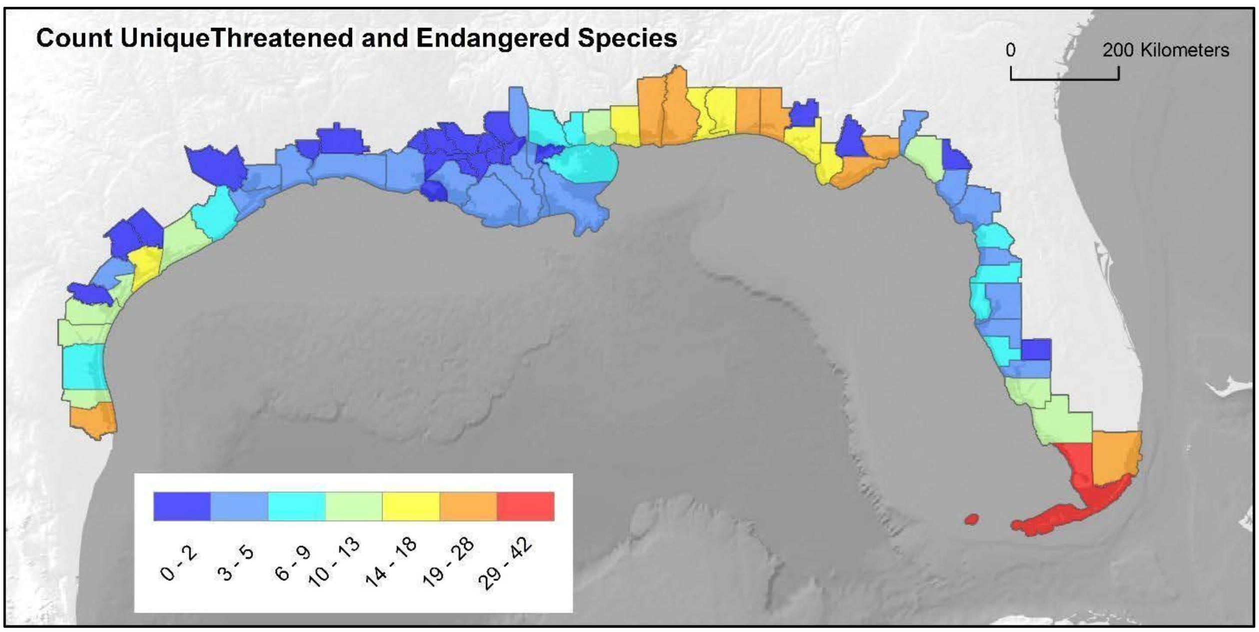

Figure 30. Count of unique non-plant state and federally listed Threatened and Endangered species from NOAA ESI data by county or parish.

VULNERABILITY

Rates of hazards and quantities of assets can demonstrate differences in risk for a single hazard type across counties and parishes, but the two metrics alone are limited in their ability to demonstrate differences in risk among hazard types, even hazard types within the same category. A clear example would be to compare the risk to wetlands from lightning versus the risk to wetlands from tropical storm winds. The comparison is poor because counting each lightning strike equal to each record of a tropical storm through hazard rate and asset quantity alone grossly ignores the differences in severity and size between the two events. In a more complicated example, again considering wetlands, comparing impacts from oil pipeline spills with impacts from oil refinery spills requires that both the frequency of minor, moderate, and major spills be considered as well as scale of the difference between a minor, moderate, or major spill.

Vulnerability, as calculated here, was not a county or parish specific measure, but when integrated with county-level rates of hazard occurrence and asset quantities, it addressed the problem described above and allowed for relative risk to an asset to be compared across hazard types for a single county or parish, in addition to across counties. As shown in Figure 2, vulnerability combined the severity of a hazard event, the frequency an event occurs at a given severity, and the relative difference in the harm or damage done to an asset from a hazard type at different severities.

Severity classes were determined by asset for measures of property damage, human casualties (injuries and fatalities), and size of an event, which reflect impacts to infrastructure, populations, and natural resources, respectively. Cutoffs between severity classes were set *a priori* (Table 6) and reflect the range and distribution of past harm or damage recorded in national datasets or summaries in published data. Frequencies of hazards at a given severity impacting an asset were calculated for each hazard type as the number of recorded events that fell within the predefined thresholds (Table 7). Relative impacts of hazards to an asset were derived in a two-step process for each hazard category (natural hazards, oil spills, chemical spills, radiological releases, and biological releases). First, the average value harm or damage amount recorded for all hazard events of a hazard category in a severity class was calculated (Table 8). Second, this value was normalized by the average harm or damage of a major event so that all measures of relative impacts for major events were equal to one and moderate and minor events were scaled proportionally from zero to a value less than one (Table 8).

In most cases, we were able to generate statistics for frequency and relative impact scales from records of past hazard events (e.g., natural disasters and oil/chemical spills) and their recorded impacts (USD of damage, injuries/fatalities, and size of event). For natural hazards, these statistics were largely generated from the NCDC database from 1993-2013. For anthropogenic hazards, these statistics were generated from the NRC database from 1994-2013. In both cases, events in the databases with no recorded damage or harm to any asset were considered too minor for the scope of this analysis and excluded.

In applying the metrics used to evaluate asset harm or damage, values of property damage were adjusted for inflation to 2015 USD using implicit price deflators for gross domestic product (U.S.

Bureau of Economic Analysis, 2015). The casualty metric was formed as an index using recorded injuries and deaths where two injuries are equivalent to one fatality and the adjusted injury and fatality measures are summed. Methods to calculate size of event for anthropogenic hazards vary by hazard category, with spill volume used to measure oil spill event sizes and evacuation radius used to measure all chemical, radiological, and biological spills/releases. Specific methods used to calculate size of events for natural hazards vary based on available data and are described in more detail within those hazards' respective sections above. For some hazard severity classes, lack of data for certain hazard types (e.g., volcanic ash fall or radioactive reactor releases) necessitated that frequencies and relative impacts across assets be estimated from similar hazard types, defined from published literature, or assumed from expert knowledge.

Table 6. Severity metric thresholds across asset types for minor, moderate and major severity classes. Note that the metric used to evaluate impact to natural resources is measured in square kilometers for all categories except oil spills, where the units are in barrels.

Asset	**Metric**	**Severity Classes**		
		Minor	**Moderate**	**Major**
Infrastructure	Cost (USD*)	<10,000	10,000-100,000	>100,000
Population	Human casualties** (fatalities and injuries)	<1	1	>1
Natural Resources	Hazard Event footprint (km2)	<3	3-13	>13
	Volume (bbl) for oil spills only	<1,000	1,000-10,000	>10,000

* Values adjusted to 2015 USD

** Casualties are calculated as one half the total number of injuries plus the total number of fatalities

Table 7. Estimated frequency of minor, moderate, and major event severity classes given occurrence of a hazard event for all natural and anthropogenic hazards estimated from natural hazard records and spill occurrence data for impacts to infrastructure, human populations, and natural resources.

Hazard		Infrastructure			Population			Natural Resources		
		Min.	Mod.	Maj.	Min.	Mod.	Maj.	Min.	Mod.	Maj.
Natural Hazards	Biological (HAB)	100.00	0.00	0.00	100.00	0.00	0.00	0.00	100.00	0.00
	Coastal/Storm Flooding	19.63	30.22	50.15	96.99	1.46	1.55	33.33	25.25	41.41
	Convective Storm Wind	59.11	35.05	5.83	98.90	0.58	0.52	0.00	100.00	0.00
	Lightning	45.91	37.33	16.77	89.06	6.11	4.83	100.00	0.00	0.00
	Tornado	18.32	39.17	42.51	88.21	3.10	8.69	92.01	5.87	2.11
	Dry Mass Movement	45.31	31.25	23.44	96.88	1.56	1.56	100.00	0.00	0.00
	Earthquake	0.00	0.00	100.00	60.34	6.90	32.76	0.00	0.00	100.00
	Flash Flood	29.23	43.81	26.97	96.41	2.17	1.42	85.84	8.50	5.66
	Riverine Flood	26.46	38.19	35.36	97.00	1.92	1.08	53.96	22.90	23.13
	Tropical Storm Winds	16.02	23.05	60.93	93.16	3.80	3.03	0.00	0.00	100.00
	Tsunami	12.50	18.75	68.75	81.25	12.50	6.25	0.00	0.00	100.00
	Volcanic Eruption	0.00	0.00	100.00	100.00	0.00	0.00	0.00	0.00	100.00
	Wildfire	30.10	26.51	43.39	79.67	7.29	13.04	99.11	0.71	0.17
Chemical Spill/Rel.	Offshore Tanker	97.65	0.00	2.35	56.47	15.29	28.24	97.65	2.35	0.00
	Offshore/Inshore Barge	97.65	0.00	2.35	56.47	15.29	28.24	97.65	2.35	0.00
	Onshore Facility	97.28	1.28	1.44	57.82	16.11	26.07	95.58	4.20	0.22
	Onshore Pipeline	72.93	23.31	3.76	67.67	16.54	15.79	94.74	4.51	0.75
	Onshore Rail	78.51	1.13	20.36	68.50	19.06	12.44	95.64	4.04	0.32
	Onshore Vehicle	95.85	2.91	1.23	65.30	21.27	13.43	98.77	1.18	0.05
Oil Spill/Rel.	Offshore Pipeline	98.90	0.95	0.15	99.91	0.03	0.07	97.49	2.35	0.16
	Offshore Production	99.76	0.18	0.06	99.65	0.21	0.14	99.02	0.86	0.11
	Offshore Tanker	99.63	0.12	0.25	98.73	0.61	0.66	98.79	0.58	0.63
	Offshore/Inshore Barge	99.63	0.12	0.25	98.73	0.61	0.66	98.79	0.58	0.63
	Onshore Facility	99.76	0.18	0.06	99.65	0.21	0.14	99.02	0.86	0.11
	Onshore Pipeline	98.90	0.95	0.15	99.91	0.03	0.07	97.49	2.35	0.16
	Onshore Rail	97.99	0.32	1.69	95.60	2.51	1.90	99.86	0.14	0.00
	Onshore Refinery	99.76	0.18	0.06	99.65	0.21	0.14	99.02	0.86	0.11
	Onshore Vehicle	98.90	0.71	0.39	91.48	5.60	2.92	99.99	0.01	0.00
Rad. Rel.	Onshore Facility	97.28	1.28	1.44	57.82	16.11	26.07	95.58	4.20	0.22
	Onshore Vehicle	95.85	2.91	1.23	65.30	21.27	13.43	98.77	1.18	0.05
	Reactor Fallout	97.28	1.28	1.44	57.82	16.11	26.07	95.58	4.20	0.22
Bio. Rel.	Onshore Facility	97.28	1.28	1.44	57.82	16.11	26.07	95.58	4.20	0.22

Table 8. Relative differences in severity of minor, moderate and major severity classes across assets for different types of hazards. Note that the metric used to evaluate impact to natural resources is measured in square kilometers for all categories except oil spills, where the units are in barrels.

Hazard	Infrastructure			Population			Natural Resources		
	Min.	**Mod.**	**Maj.**	**Min.**	**Mod.**	**Maj.**	**Min.**	**Mod.**	**Maj.**
Oil spill	5	49,080	523,980	0	1	2	23	2,632	151,060
Biological release	39	49,654	542,923	0	1	4	0.02	1.44	226.36
Chemical spill/release	39	49,654	542,923	0	1	4	0.02	1.44	226.36
Radiological release	39	49,654	542,923	0	1	4	0.02	1.44	226.36
Natural hazard event	3,305	29,944	23,777,673	0	1	7	0.06	2.27	1,411.73

RISK SUMMARIES

For each of the asset metrics, we computed an index of the relative amount of assets of each type in each county or parish. Each metric was normalized such that the values ranged from zero to one for all counties and parishes and the values reflected the percentage of the maximum county/parish value. These index values represent the relative quantity of each category of asset in that county or parish as compared with all counties or parishes in the study area. We then computed overall risk indices for each hazard category in the same manner based upon rates of hazard occurrence in each county or parish.

As a final step, we computed final risk indices per the methodology outlined in Figure 2. For each combination of hazard category and asset category, a component risk index was calculated as the sum over each hazard severity class of the product of the hazard index values specific hazard category, the relative asset index value for that asset type, the frequency of the hazard severity class for that hazard and hazard source, and the relative impact of that severity class for that hazard and asset combination. These indices were normalized such that the values ranged from zero to one for all counties and parishes and the values reflected the percentage of the maximum county/parish value. Maps of all these hazard-asset risk index values are presented in Figures 31-38.

A few trends are immediately apparent. South Florida has high risk values reflecting the high relative environmental asset index values there as well as large numbers of facilities and adjacent vessel traffic. Louisiana and northern coastal Texas also have high risk values reflecting the large amount of petroleum and petrochemical industry and transportation. Harris County in Texas stands out as a hotspot in nearly all risk index maps involving human population or infrastructure due to its very high concentration of population, infrastructure and transportation. For natural hazards, Harris County is also high in nearly every hazard index for the same reasons. Patterns generally reflect the overall distribution of hazard probability over the study area moderated by population and industrial centers. Coastal flooding and tsunami risk index value distributions are very similar reflecting the strong controls of topography and elevation on these hazards.

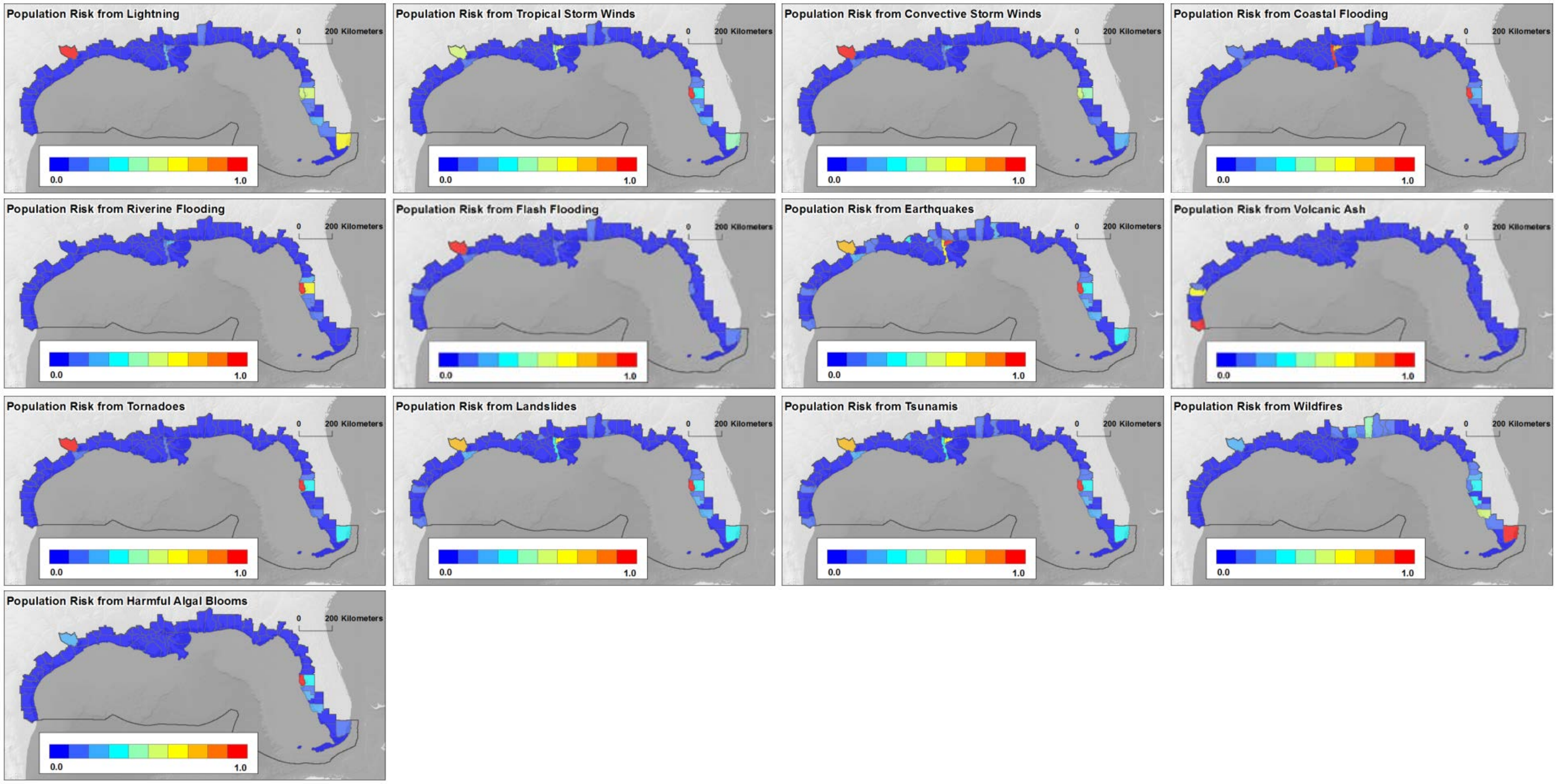

Figure 31. Natural hazard ranked risk index values to human population by county or parish. High-resolution images of the above maps have been included within Appendix E.

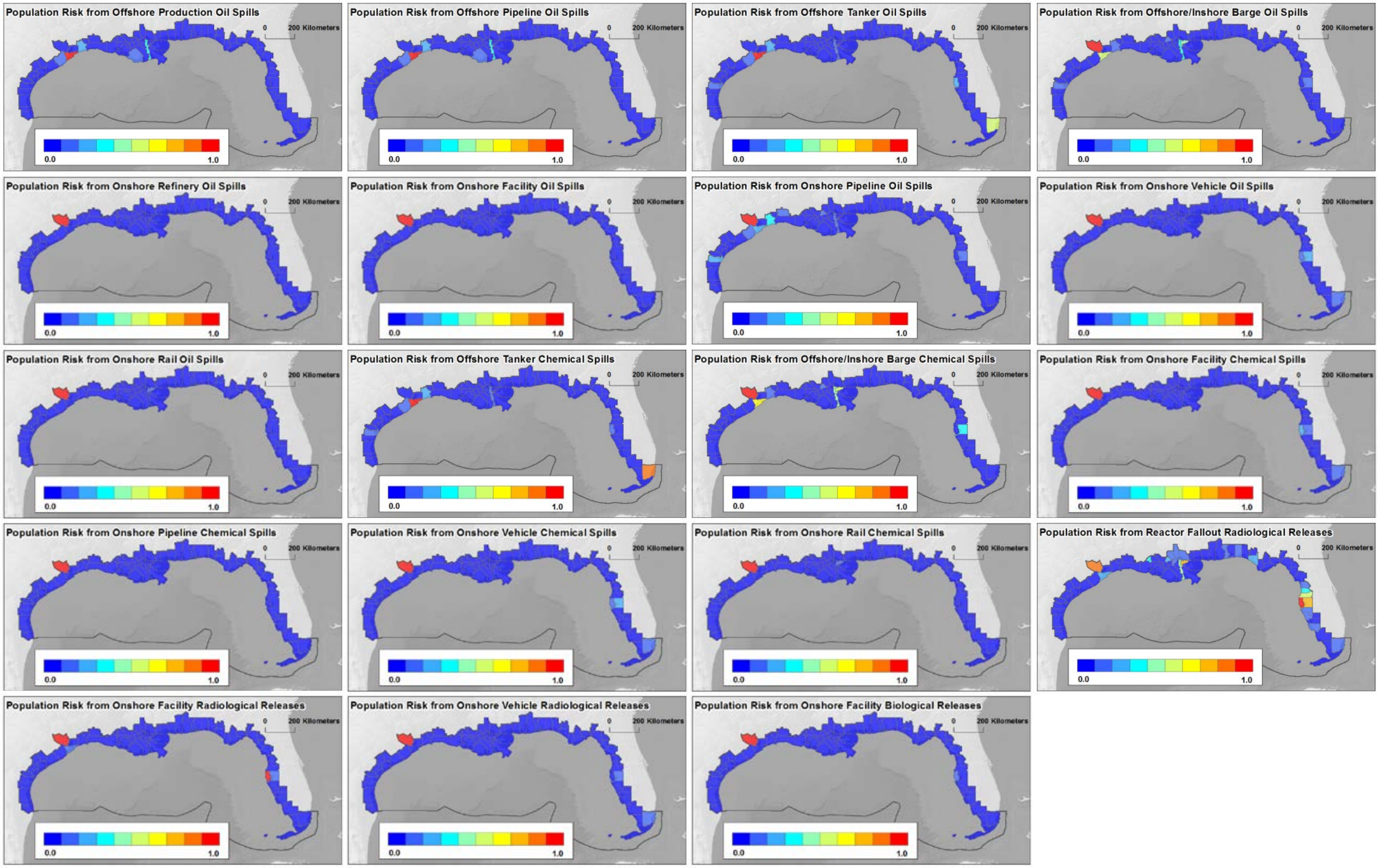

Figure 32. Anthropogenic hazard ranked risk index values to human population by county or parish. High-resolution images of the above maps have been included within Appendix F.

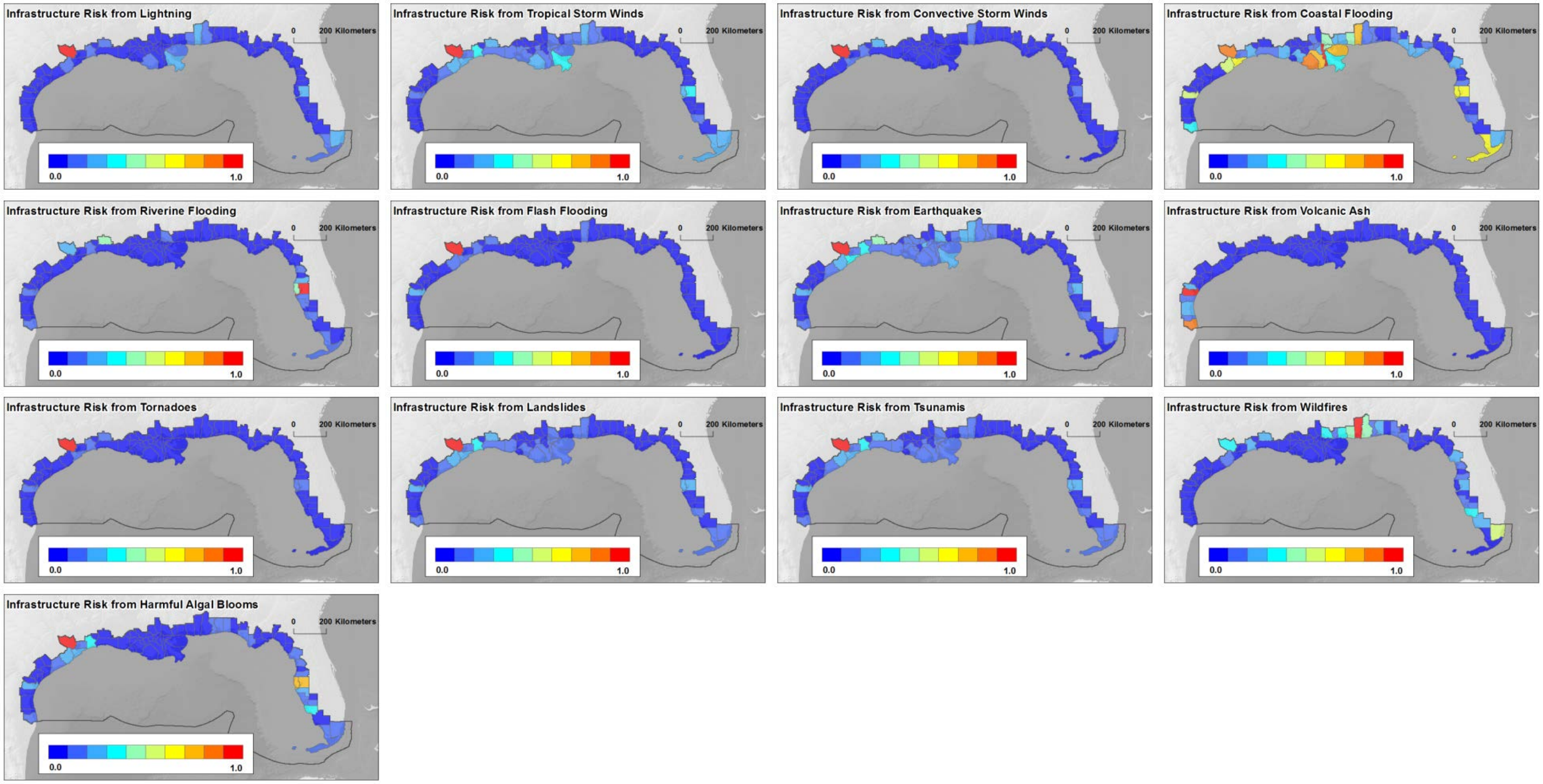

Figure 33. Natural hazard ranked risk index values to infrastructure by county or parish. High-resolution images of the above maps have been included within Appendix G.

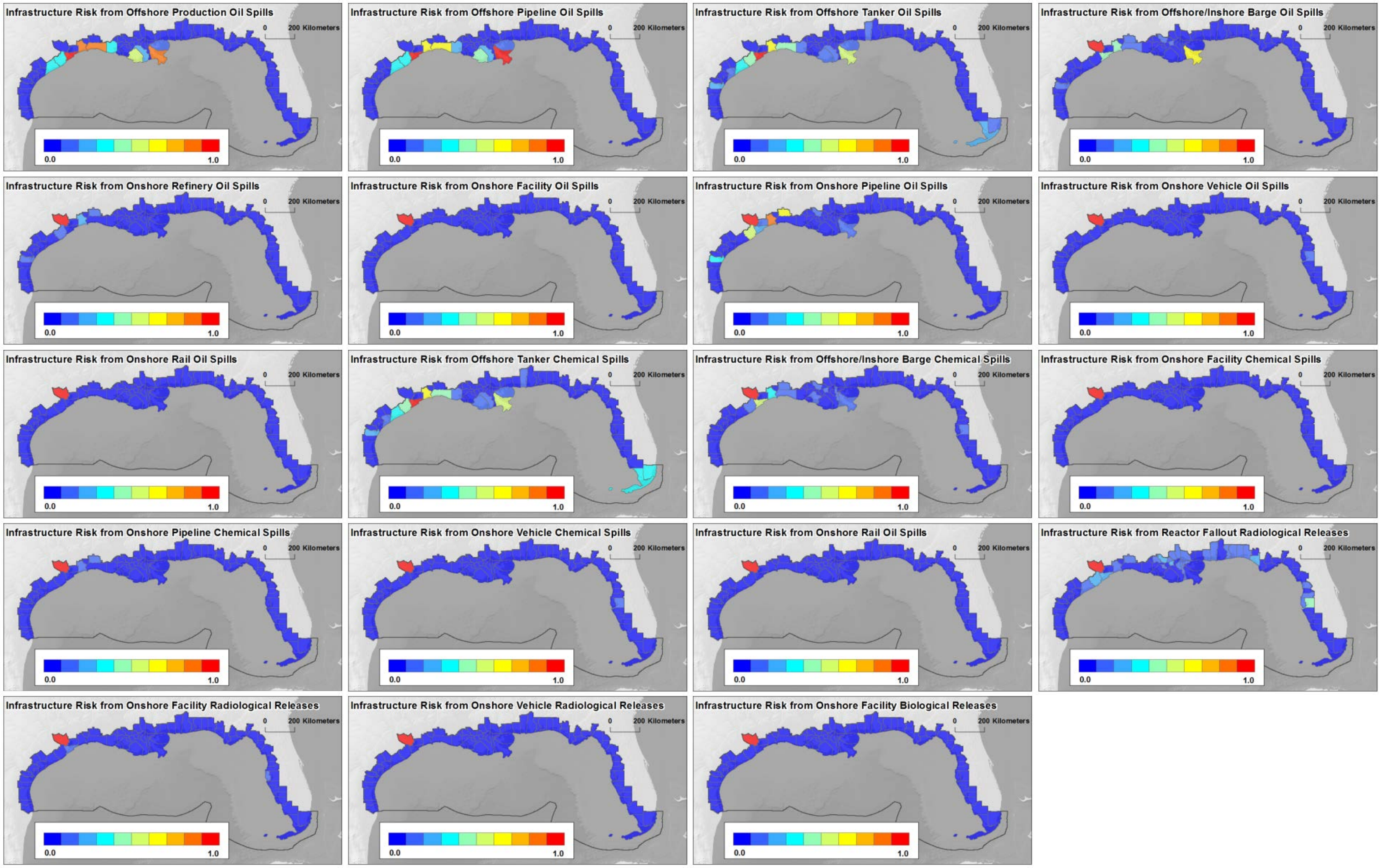

Figure 34. Anthropogenic hazard ranked risk index values to infrastructure by county or parish. High-resolution images of the above maps have been included within Appendix H.

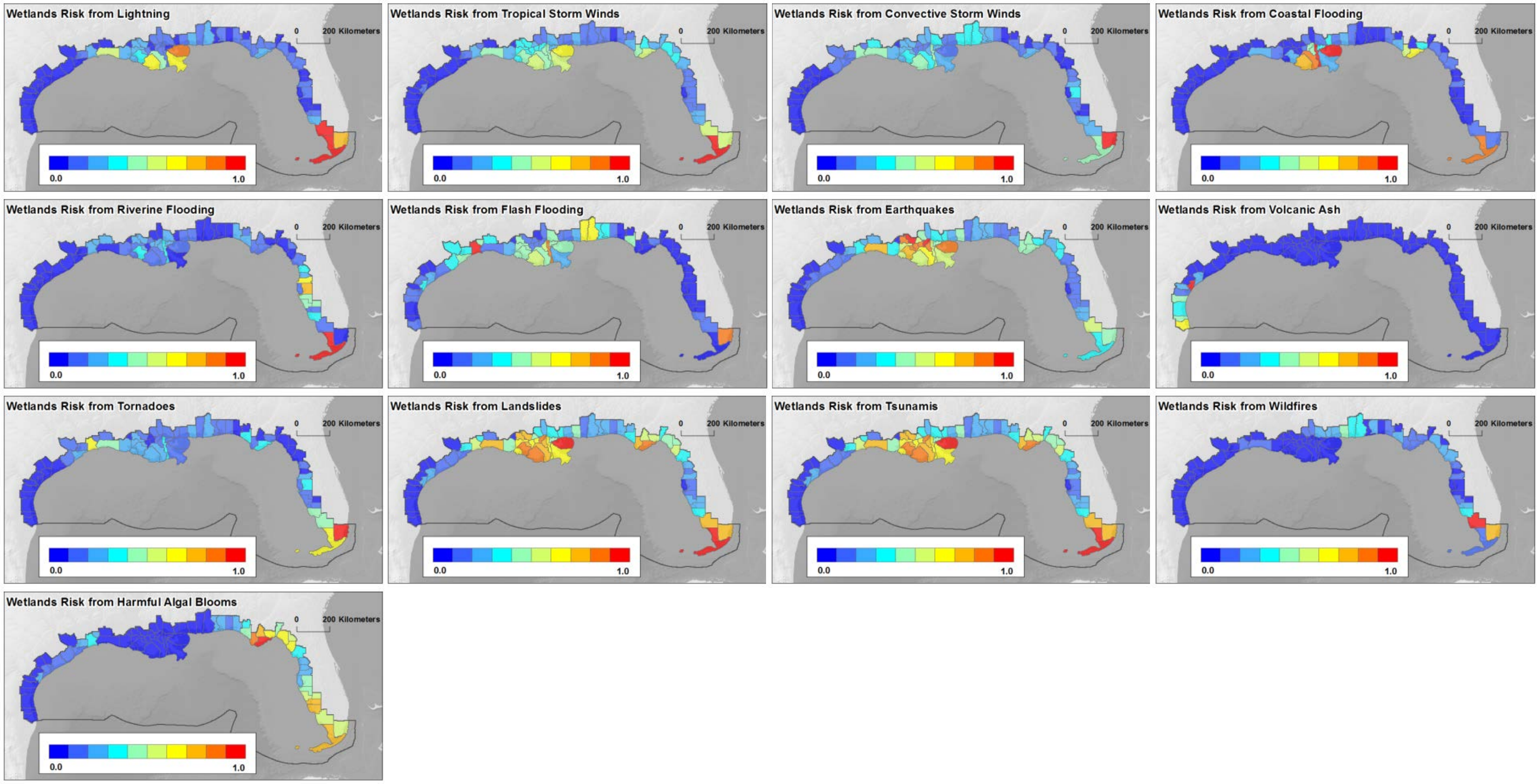

Figure 35. Natural hazard ranked risk index values to sensitive habitat by county or parish. High-resolution images of the above maps have been included within Appendix I.

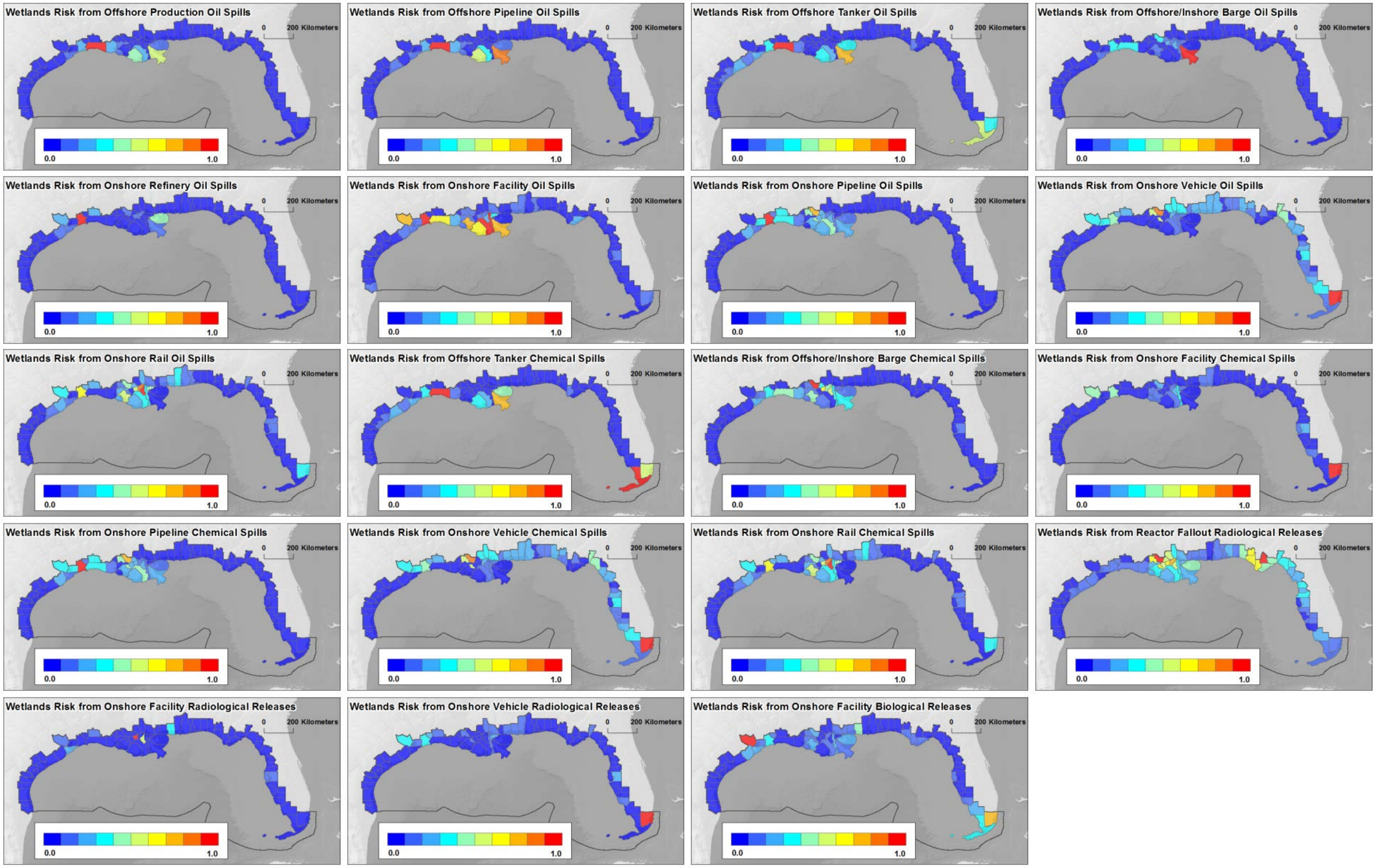

Figure 36. Anthropogenic ranked hazard risk index values to sensitive habitat by county or parish. High-resolution images of the above maps have been included within Appendix J.

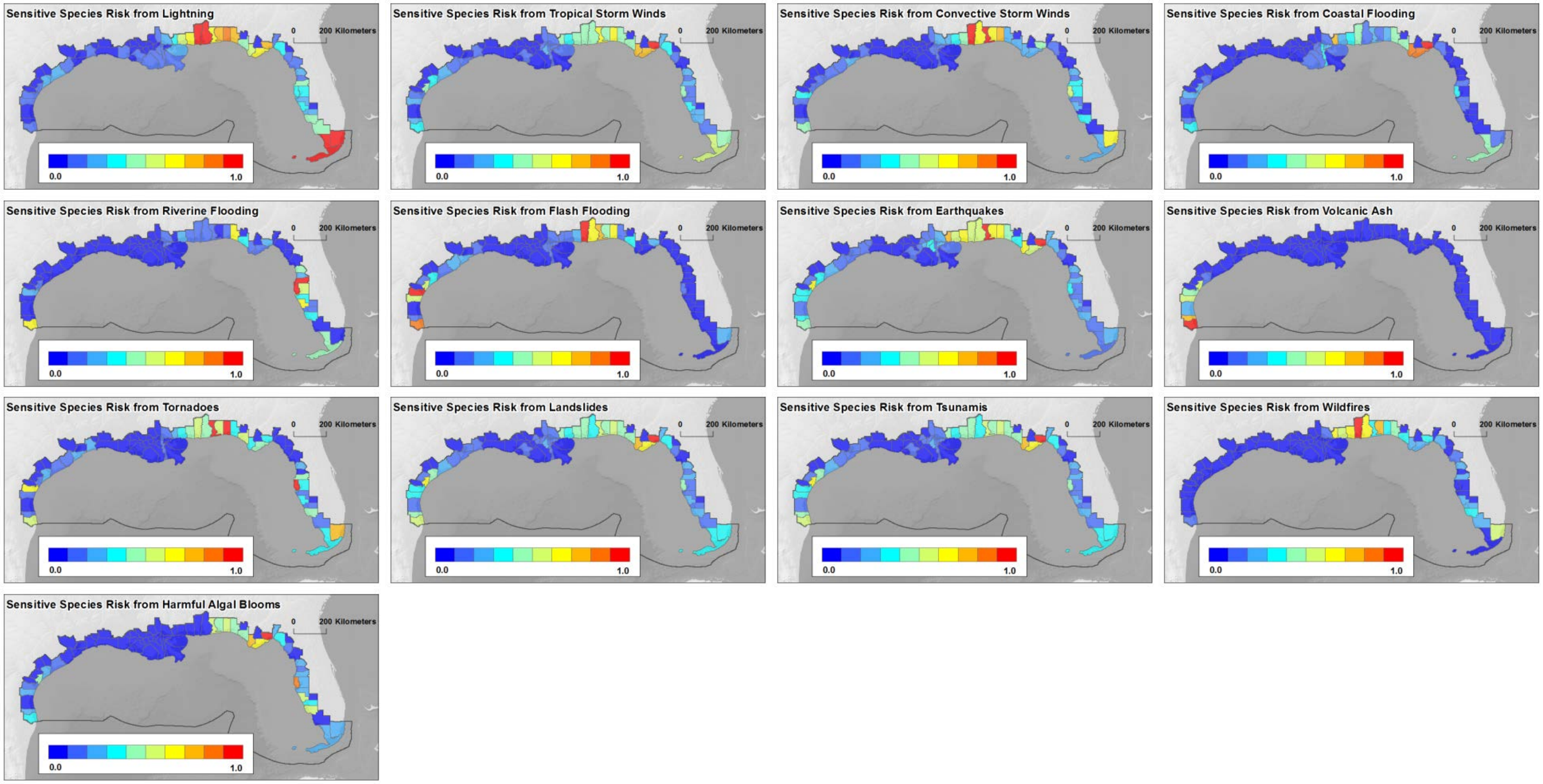

Figure 37. Natural hazard ranked risk index values to sensitive species by county or parish. High-resolution images of the above maps have been included within Appendix K.

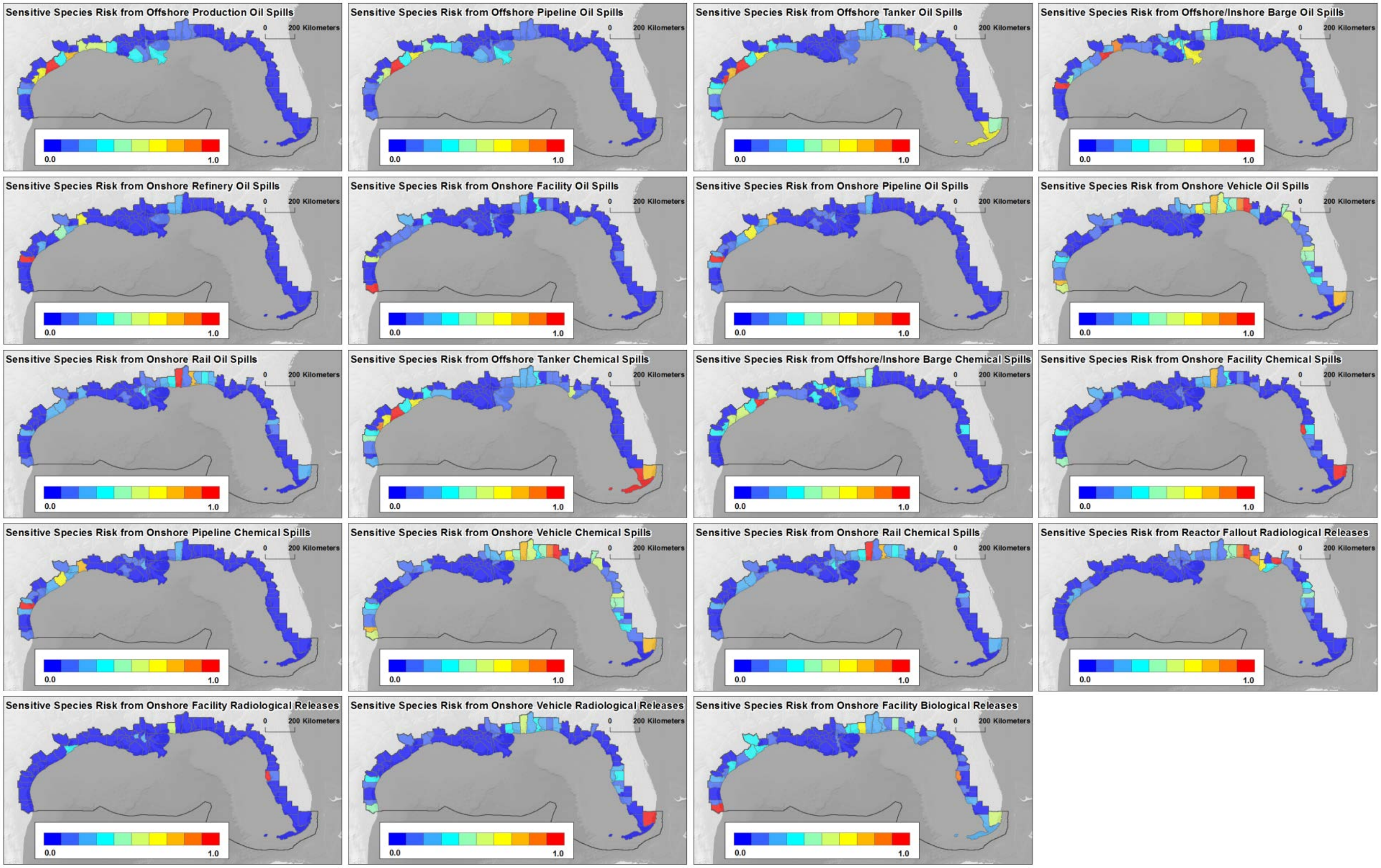

Figure 38. Anthropogenic hazard ranked risk index values to sensitive species by county or parish. High-resolution images of the above maps have been included within Appendix L.

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APPENDIX A

Methodology Used To Derive Flood Event Footprint Areas

While the NCDC database (NOAA NCDC, 2014a) describes individual flood events at the county/parish level via multiple metrics, there are no national or regional data available that summarize the spatial extent of large numbers of individual flood events. We required estimates of the distribution of sizes of individual flood events across the region of interest as one of the methods of evaluating the relative severity of these events as compared with other hazards, in addition to human casualties and economic cost. To accomplish this, we compiled the best available data describing the possible extent of flood events (e.g., flood zone areas) across the area of interest, and combined this with best estimates of the spatial scale of specific individual events to estimate the distribution of actual flood event footprint sizes.

We began by combining Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) and Q3 flood zone data (FEMA, 2014). FEMA flood zone data describe potential flood zones based upon elevation and locally varying base flood elevation FEMA digital (DFIRM) flood maps were available for 58 of the 73 county/parishes in the study area in either effective (49) or preliminary (9) formats. For the 15 counties without available DFIRM data, we supplemented this dataset with older digital Q3 maps (FGDL, 2014). Because the digitized versions of the Q3 maps did not have the coastal flooding zones (V zones) included separately (except for Sarasota County, FL), we digitized the V zones for the remaining 14 counties using georeferenced versions of the digital Q3 panels. The final digitized flood zones were then clipped using a digital shoreline and polygonal waterbodies (Wessel and Smith, 1996; USGS, 2013) to remove open water areas from the flood zones. All FEMA “A” flood zones in the compiled database (A, AH, AE and AO) were dissolved into a combined “A” zone. All “V” zones in the compiled database (V and VE) were dissolved into a single “V” zone and all 500-year flood zones (X500 and X/0.2 percent chance of flood hazard) were dissolved into a single X500 zone by county or parish (Fig. A-1). This analysis was interested only in “A” Zones and “V”’ Zones, which show 100-year flood zones and 100-year flood zones impacted by wave action respectively. “A” Zones were assigned to riverine floods, flash floods, and other flood events while ‘V’ Zones were assigned to coastal and storm surge flooding. Note that the FEMA data products downloaded for this analysis use FEMA’s Application Programming Interface (API), but are not endorsed by FEMA. FEMA Q3 data products that were modified for this analysis for this study are also not endorsed by FEMA.

Individual flood events in the NCDC database are not assigned explicit areas, but are characterized by a descriptive spatial footprint type indicative of the scale of the event: county/parish wide, large portion or zone within parish or county, small portion or zone within parish or county, and town or other small geography. We obtained a subset of more recent, more spatially-explicit data from the NWS flash flood polygons (NOAA NWS, 2014), and compared this with the footprint type assigned to the same subset of events in the NCDC database. We calculated the average proportions of the county or parish total area represented by each event type for this subset of data, as follows:

County/parish-wide – 50% of county or parish flood zones
Portion (large), and Zone – 20% of county or parish flood zones
Portion (small) – 10% of county or parish flood zones
Other – 5% of county or parish flood zones

We then assigned every flood event in the NCDC database an area based on these average proportions, and the area of the relevant flood zones in the county/parish in question. We used the area of "A" zones for riverine floods, flash floods, and other flood events, and the area of "V" zones for coastal and storm surge flooding.

Town events were not assigned an area based on proportion of the area of flood zones in the county. Because Town events have implied coordinate locations, each of these events was geocoded to the town center location. We buffered these locations to yield polygons with the area of the average flood footprint in that county/parish, calculated the area of FEMA flood zones within that polygon, and assigned the resulting area to each flood event.

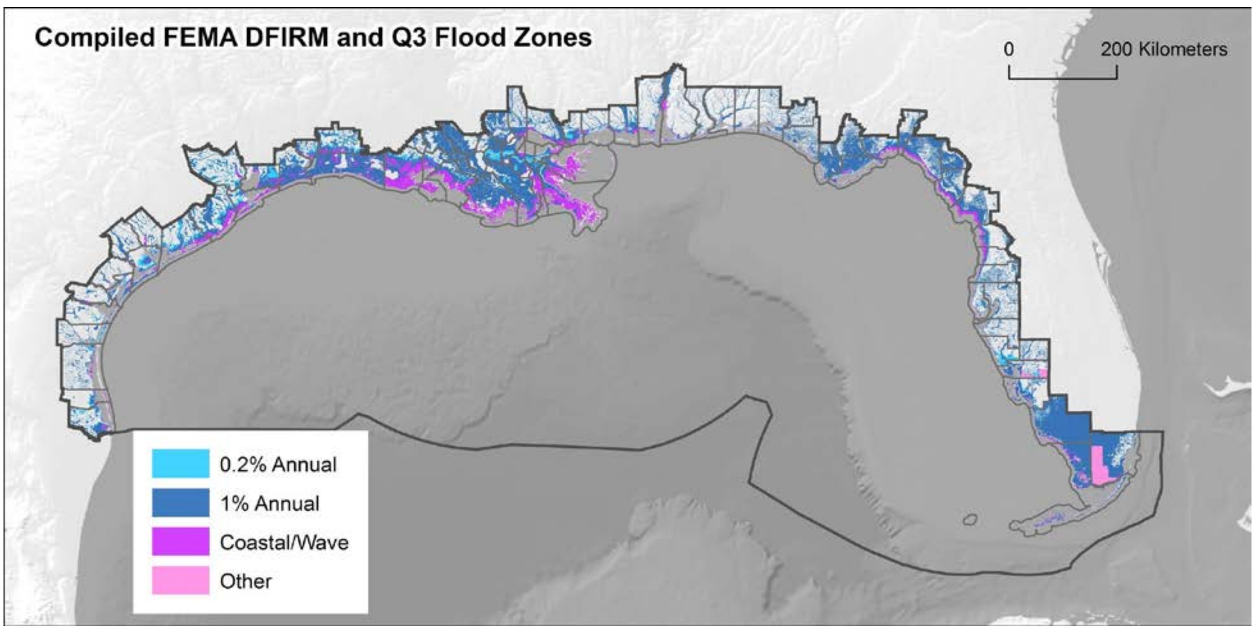


Figure A-1. Extents of compiled FEMA flood zones from DFIRM and Q3 data.

Based on these results, each flood event in the NCDC database was assigned an areal extent based on the flood event type, the reported NCDC footprint type, and the compiled FEMA data in the county in which the event took place.

APPENDIX B

Methodology Used To Evaluate Impacts from Offshore Hazards to Coastal Counties/Parishes

Spills/releases from offshore tanker traffic, pipeline transport, and production facilities do not occur within the boundaries of the counties/parishes within our study area but may have substantial non-local effects that impact counties/parishes that are far from the hazard event location. For these hazards, we computed the estimated the probability that a spill/release in each offshore spill planning areas utilized by BOEM within the US Exclusive Economic Zone (EEZ) across the entire Gulf of Mexico would impact each of the counties/parishes in the study area.

For launch areas in the western Gulf of Mexico with active oil and gas development, we adopted the BOEM generated estimates of the probability of a given offshore spill/release in those launch areas making landfall in different coastal counties or parishes (Fig. B-1, top) via summaries of stochastic trajectory model runs (Ji *et al.*, 2002a, 2002b). No similar estimates exist for launch areas in the eastern Gulf of Mexico, but our analysis still needed to account for spill/releases from tanker traffic in these areas. We extended this model to the eastern Gulf of Mexico by obtaining five years of monthly NOAA OSCAR surface current data (NOAA NESDIS, 2014) and advecting particles from the centroids of each launch area within this velocity field (e.g., Fig. B-1, bottom). We computed the number of particle intersections with each coastal county or parish, as well as the distance from each launch area to each coastal county or parish and used these data as inputs to a boosted regression tree model (Ridgeway, 2006; Friedman *et al.*, 2000) that predicts probability of landfall for each county or parish from each launch area. This model was trained using the BOEM stochastic trajectory data for the western Gulf, and used to make similar predictions for the launch areas in the eastern Gulf.

These landfall probabilities are used to compute rates of impact from offshore spills and releases on coastal counties/parishes as a function of both the rate of spill release in offshore spill launch areas, and conditional probabilities of spill/release landfall in each county/parish.

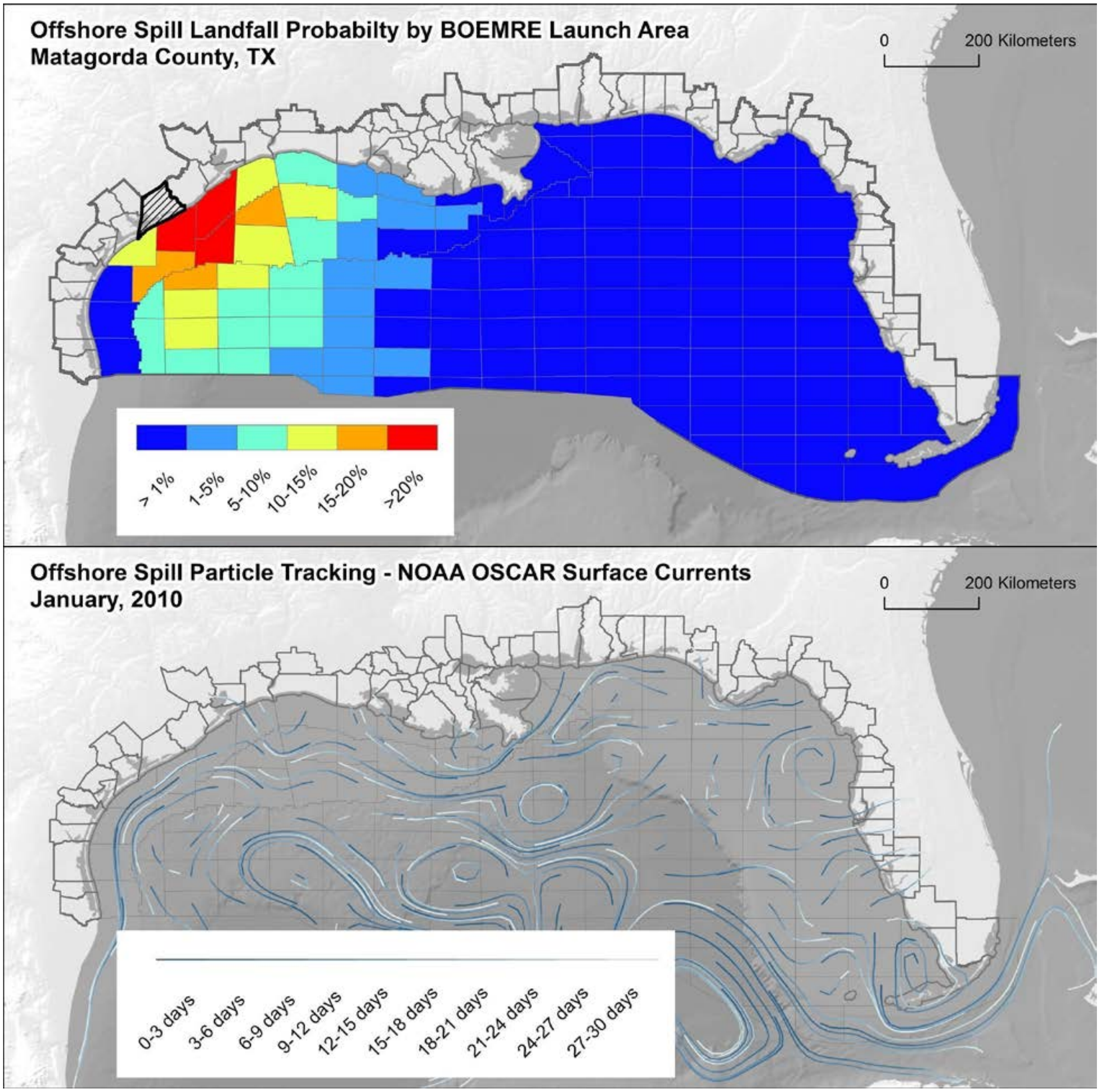
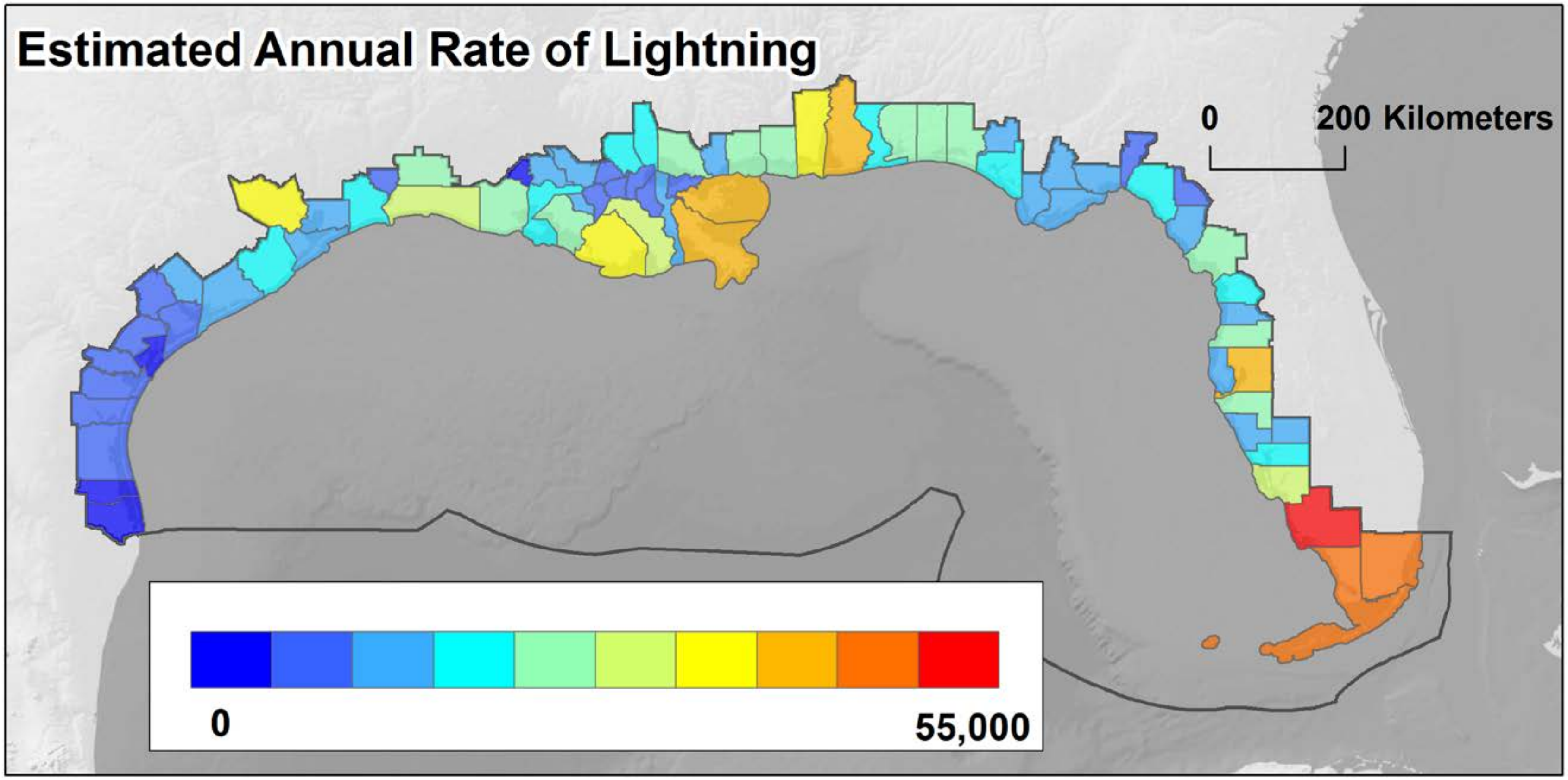


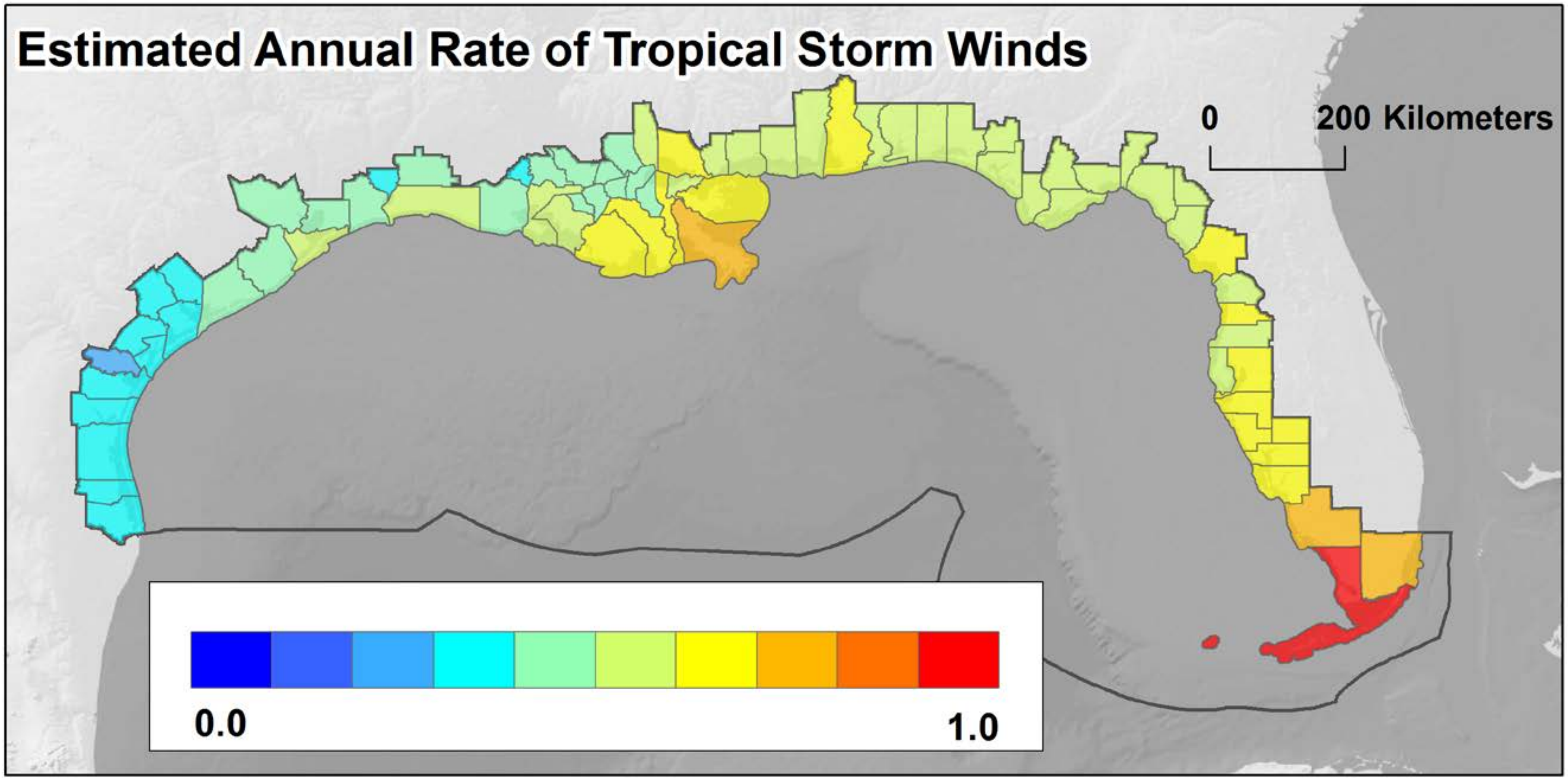
Figure B-1. Example of BOEM-calculated oil spill landfall probability oil spill in offshore launch areas in western Gulf of Mexico for Matagorda County in Texas (top) and 30-day particle trajectories advected using average NOAA OSCAR surface currents in the Gulf of Mexico for January 2010 (bottom) used as inputs to machine learning model for predicting similar landfall probabilities for BOEM launch areas in eastern Gulf of Mexico.

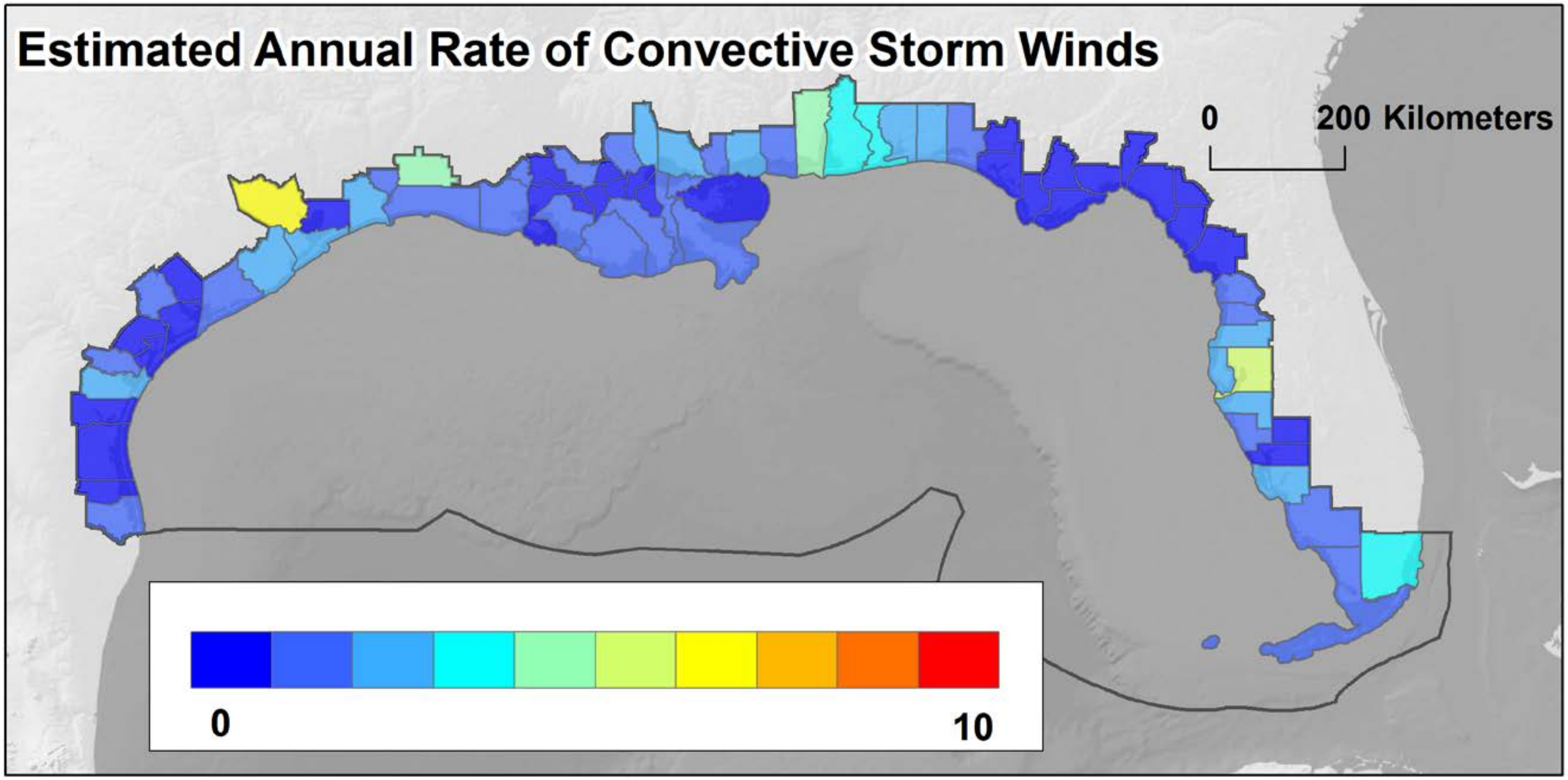
APPENDIX C
Annual Natural Hazard Event Rates

Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 27 and display annual natural hazard event rates by county or parish for the hazard indicated in the title of the map. Note that scales vary widely across maps and maps for tsunamis and landslides have not been included because all county/parish values are identical.

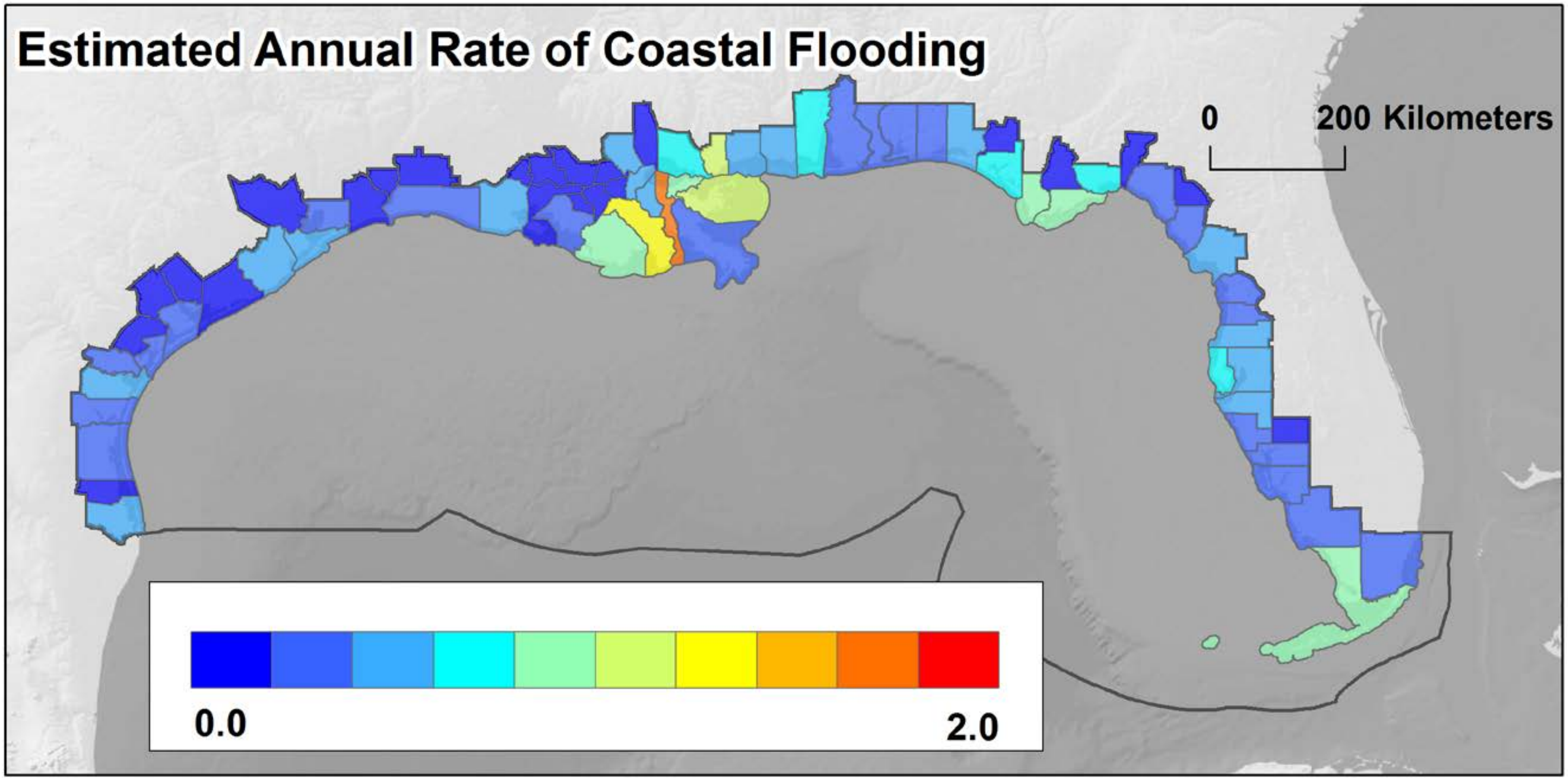


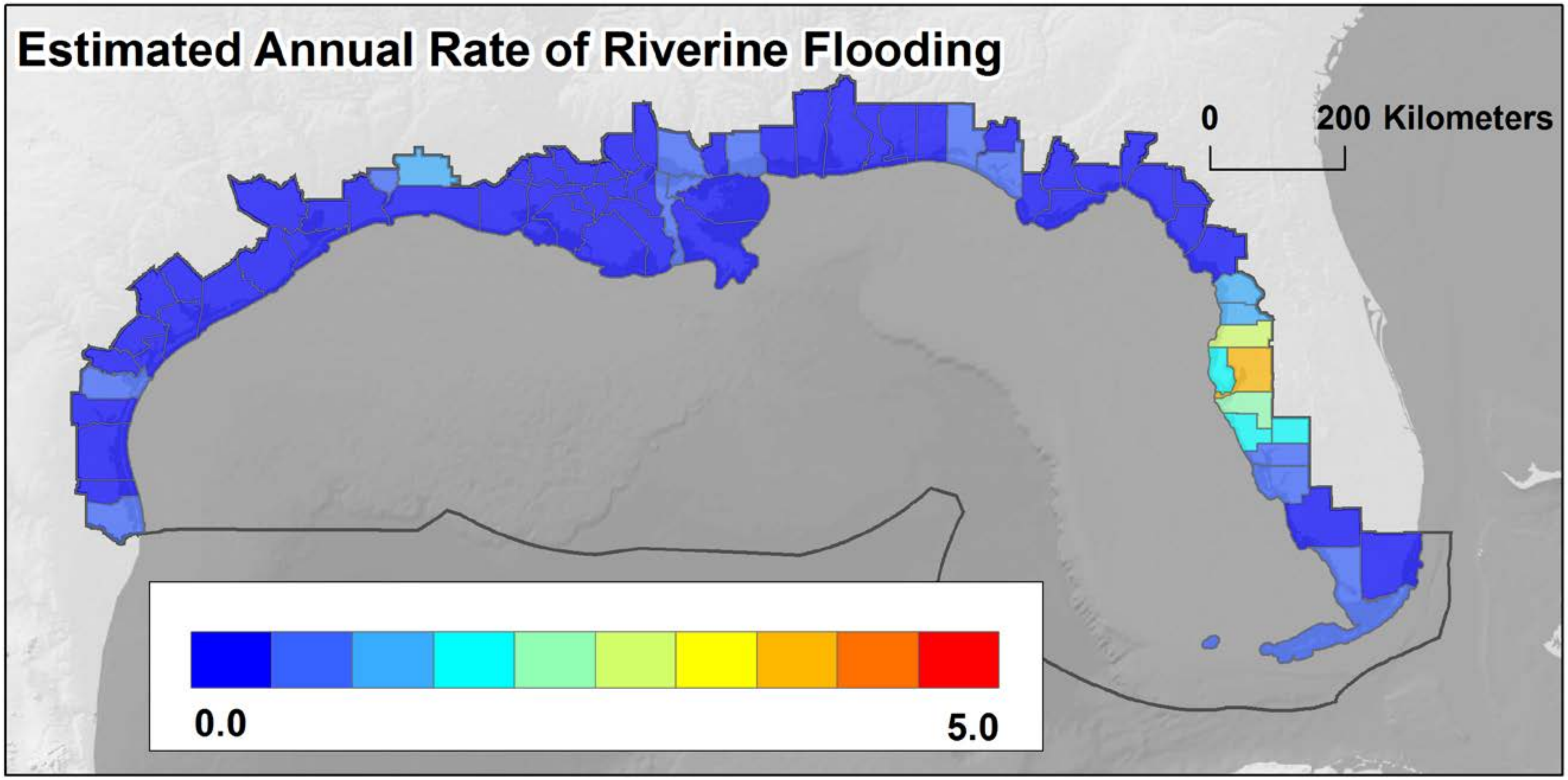
Estimated Annual Rate of Lightning
0
200 Kilometers
0
55,000

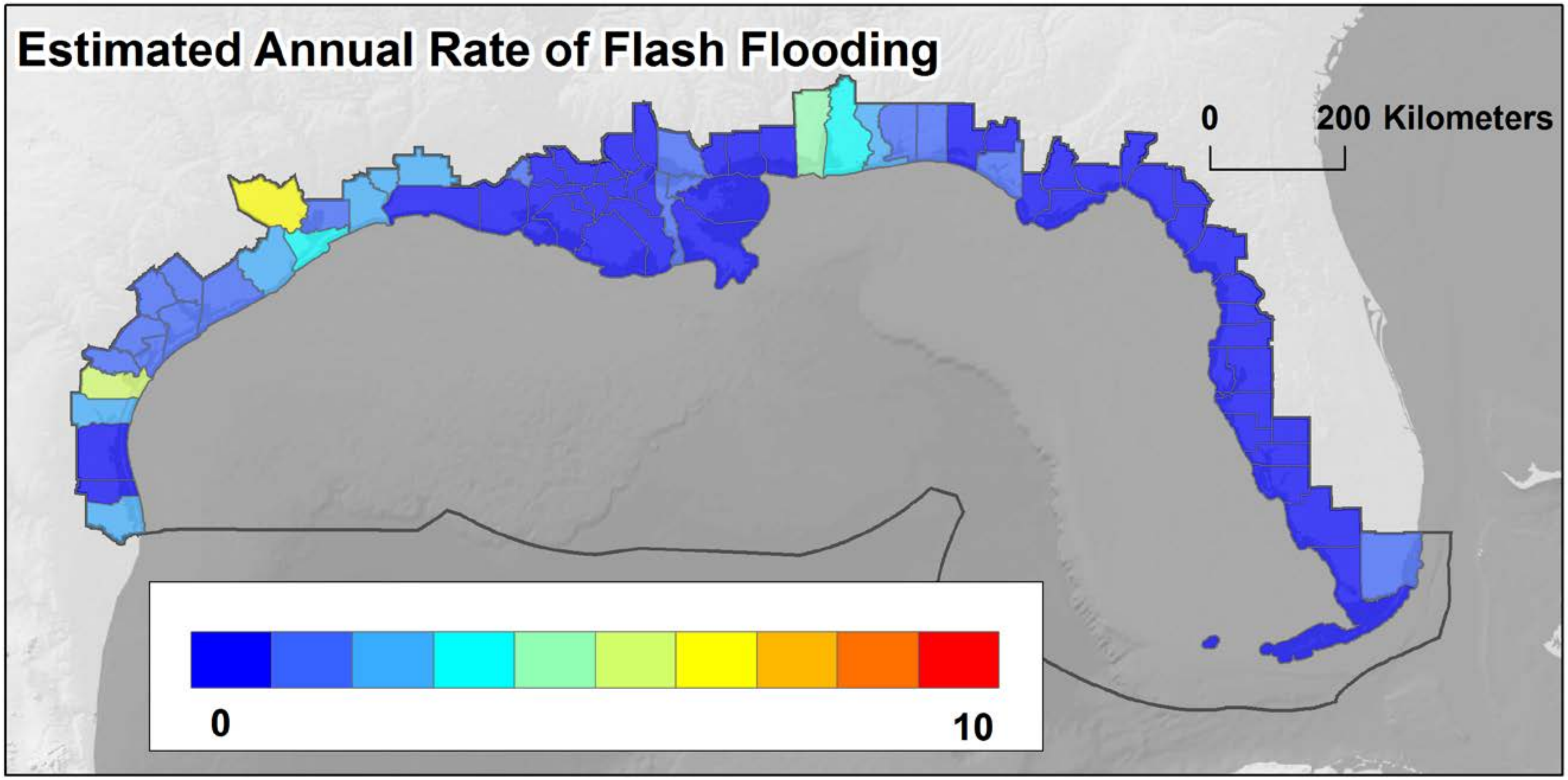

Estimated Annual Rate of Tropical Storm Winds
0
200 Kilometers
0.0
1.0

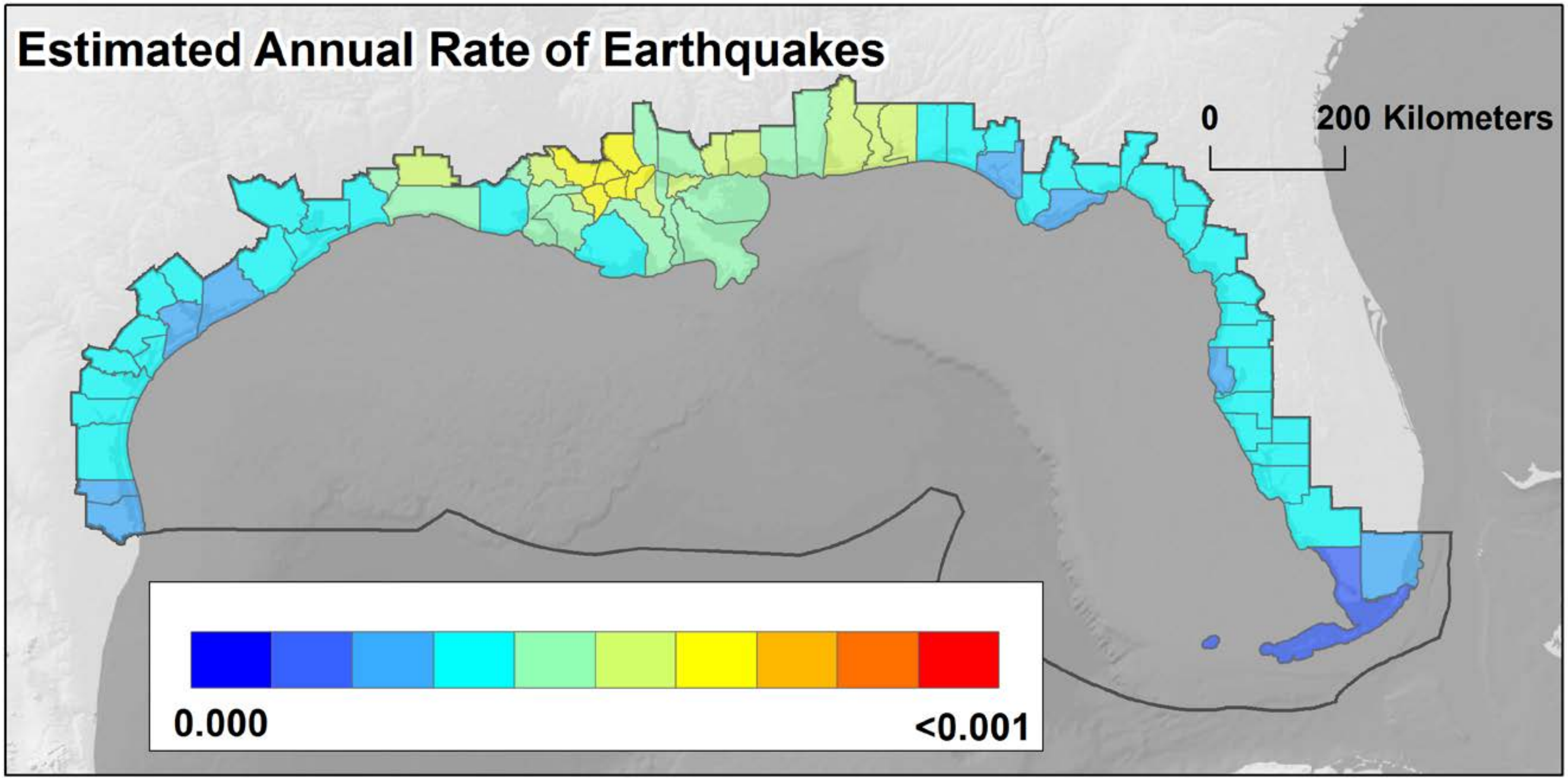


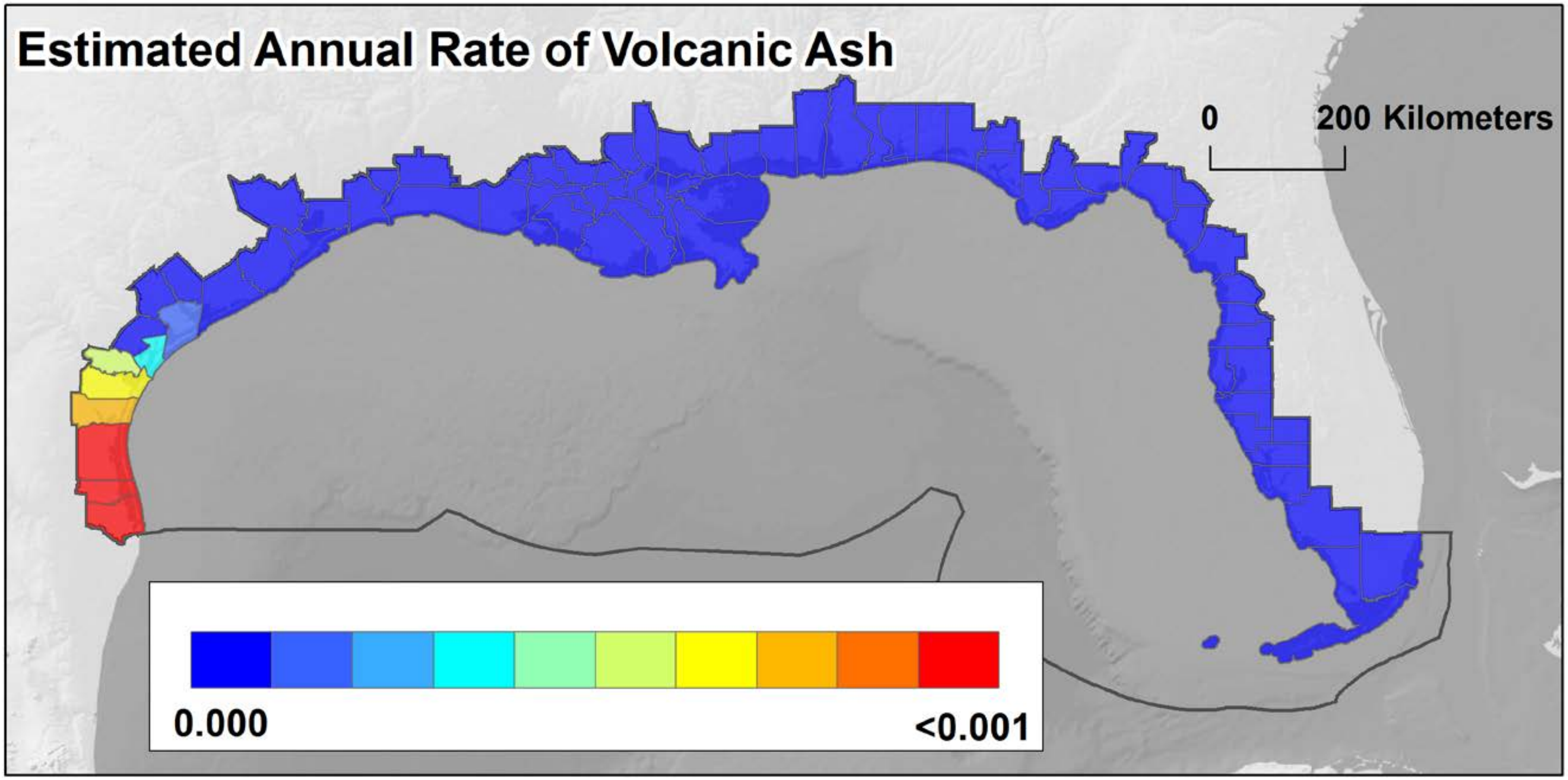
Estimated Annual Rate of Convective Storm Winds
0
200 Kilometers
0
10

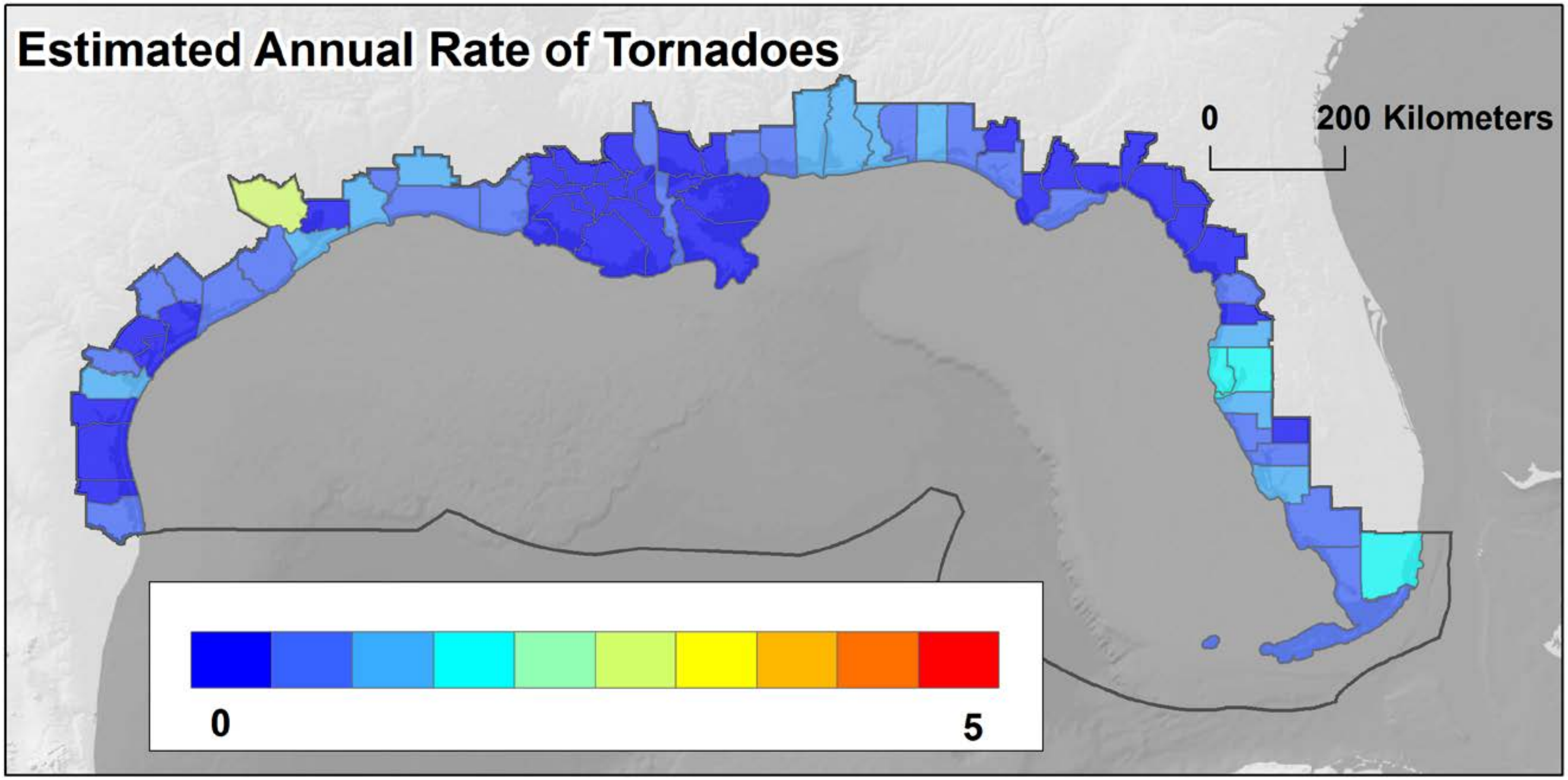

Estimated Annual Rate of Coastal Flooding
0
200 Kilometers
0.0
2.0

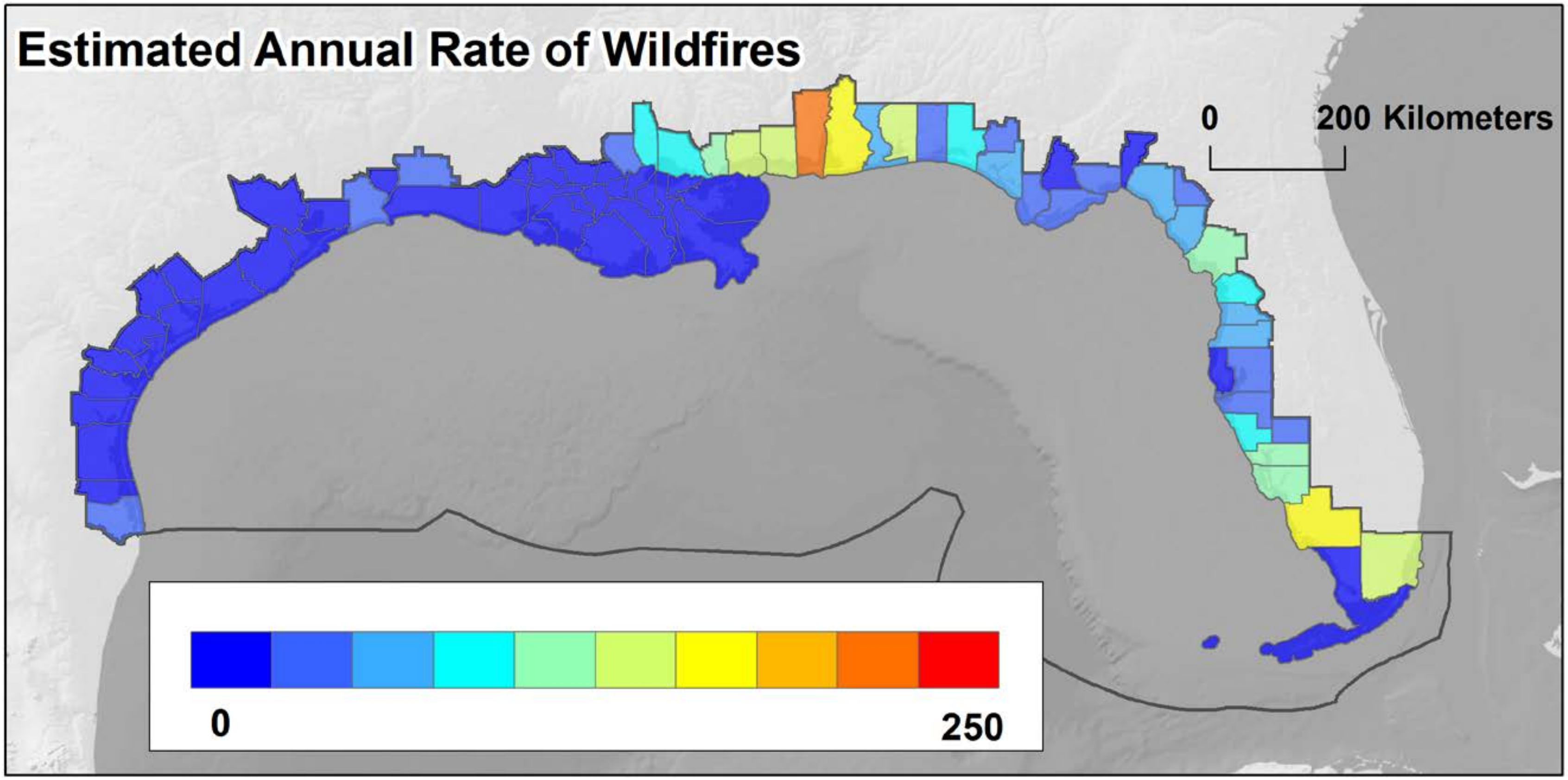

Estimated Annual Rate of Riverine Flooding
0
200 Kilometers
0.0
5.0

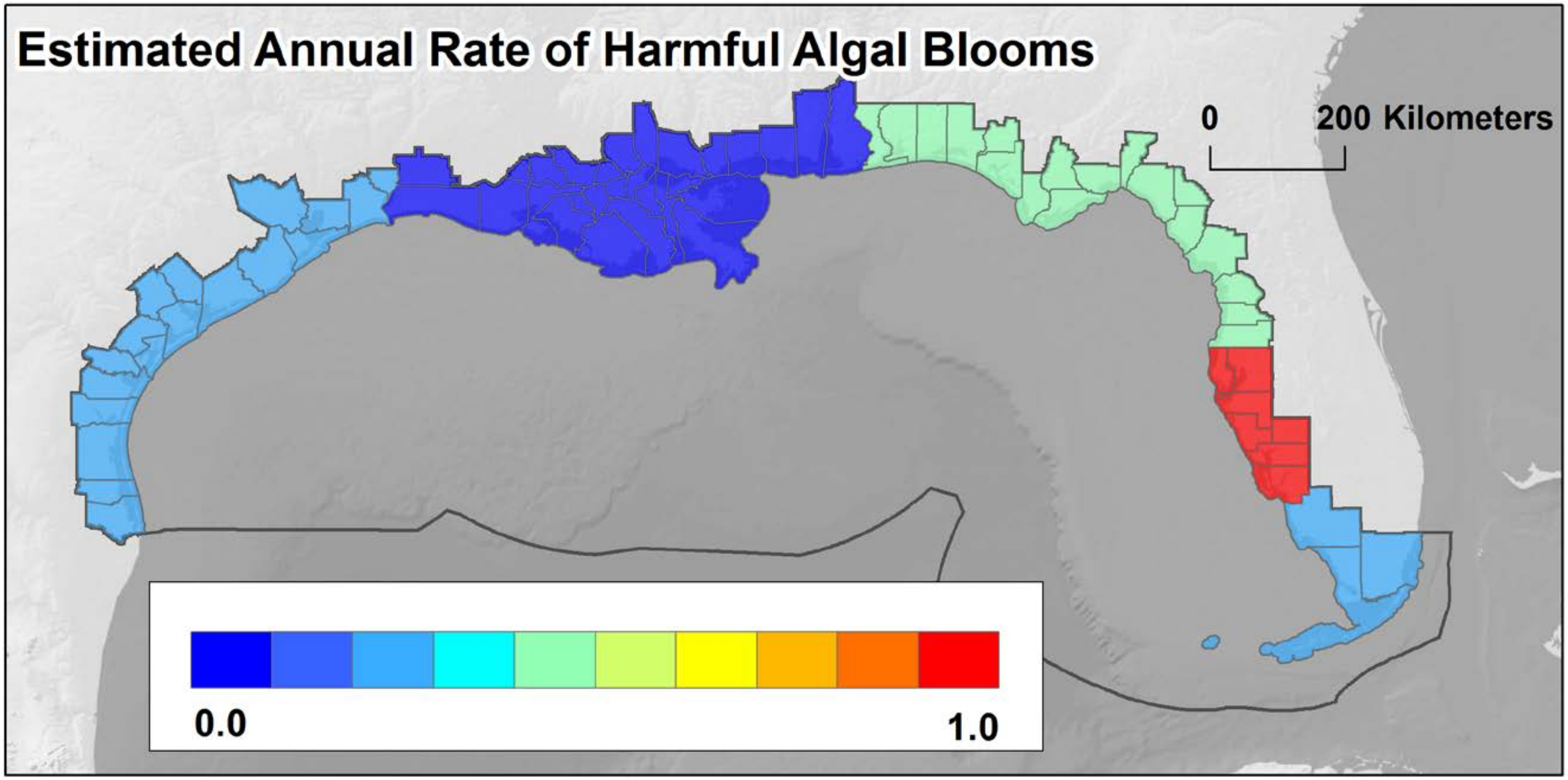

Estimated Annual Rate of Flash Flooding
0
200 Kilometers
0
10


Estimated Annual Rate of Earthquakes
0
200 Kilometers
0.000
<0.001


Estimated Annual Rate of Volcanic Ash
0
200 Kilometers
0.000
<0.001


Estimated Annual Rate of Tornadoes
0
200 Kilometers
0
5

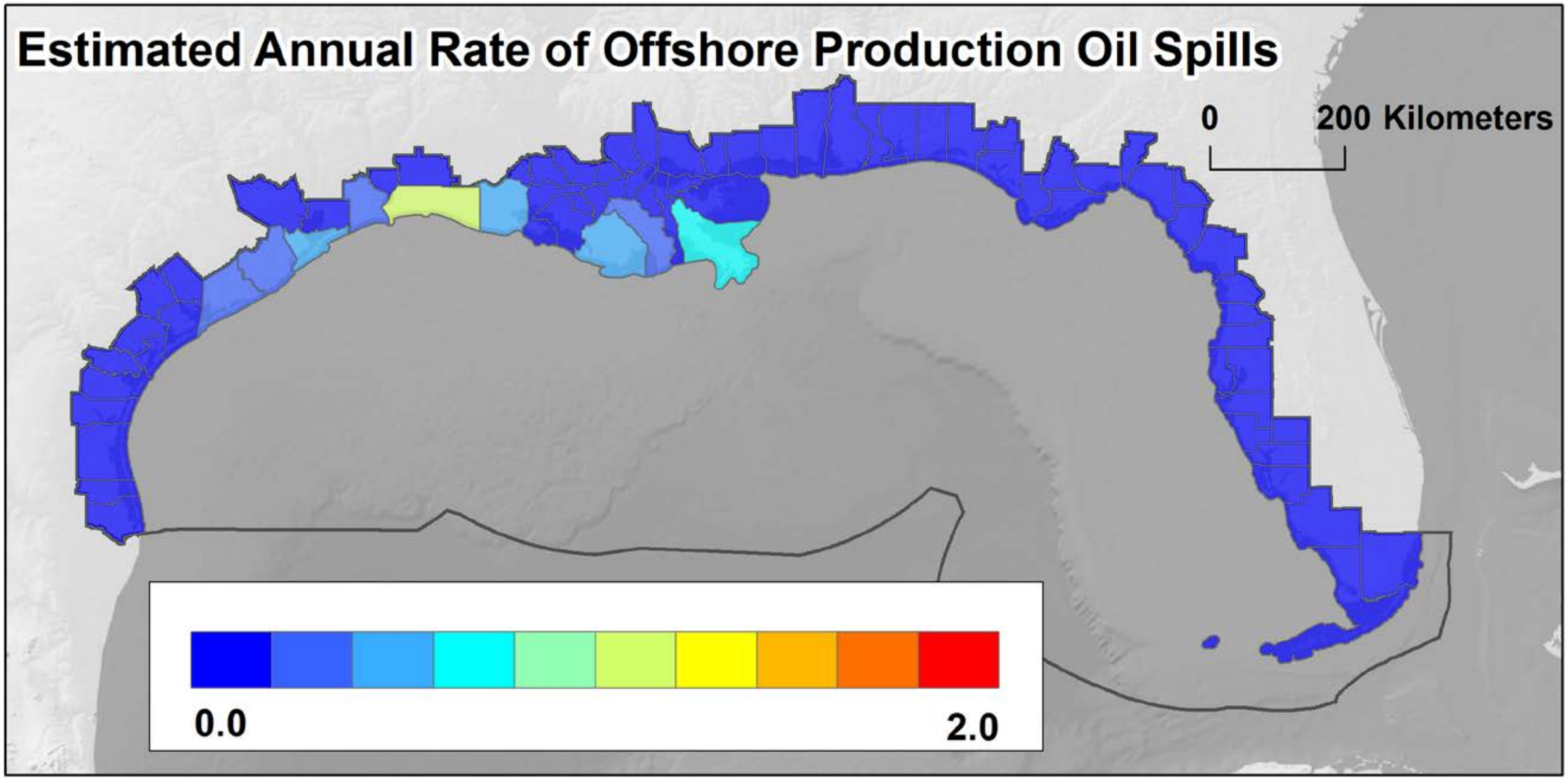

Estimated Annual Rate of Wildfires
0
200 Kilometers
0
250

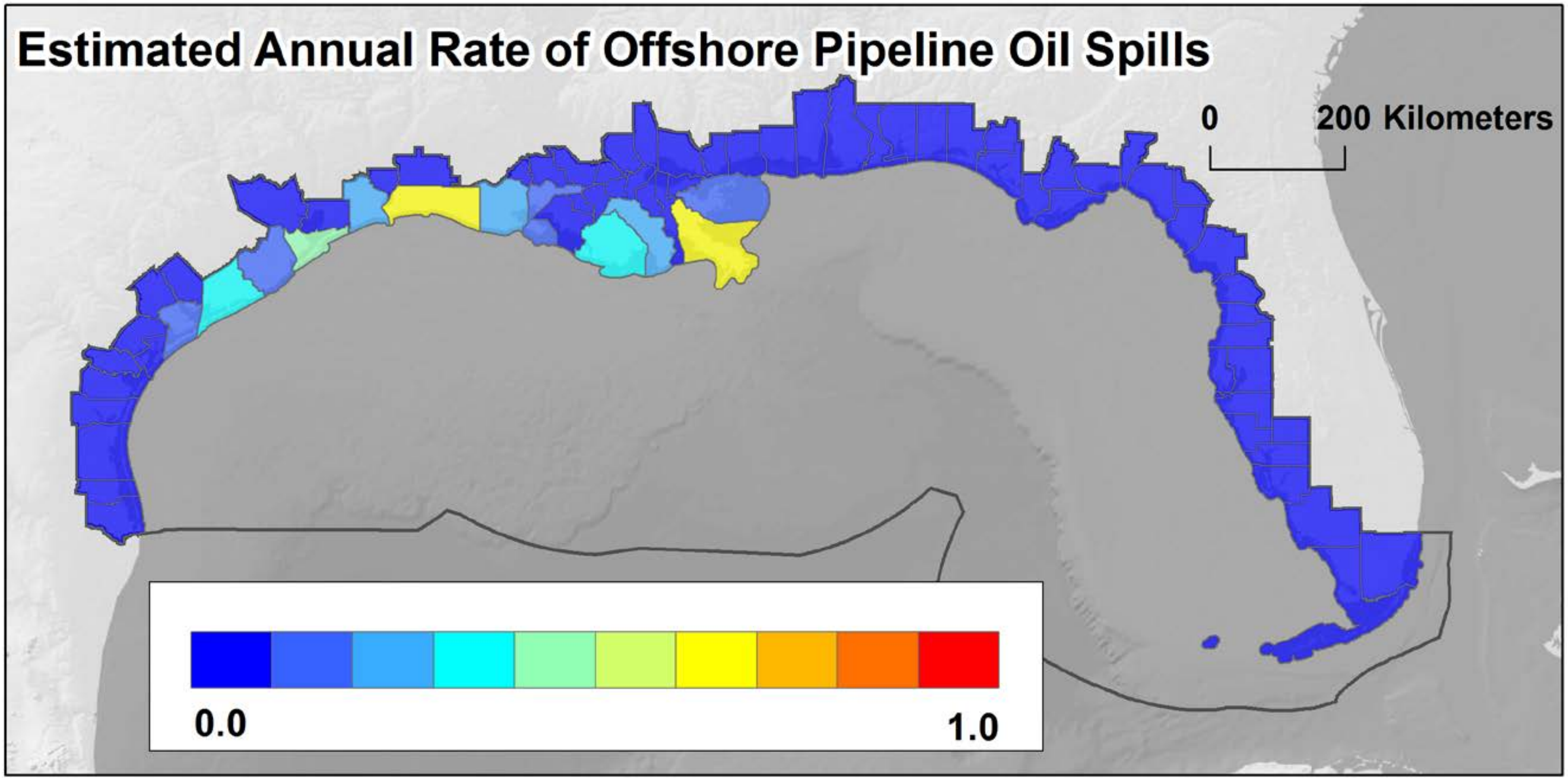


Estimated Annual Rate of Harmful Algal Blooms
0
200 Kilometers
0.0
1.0

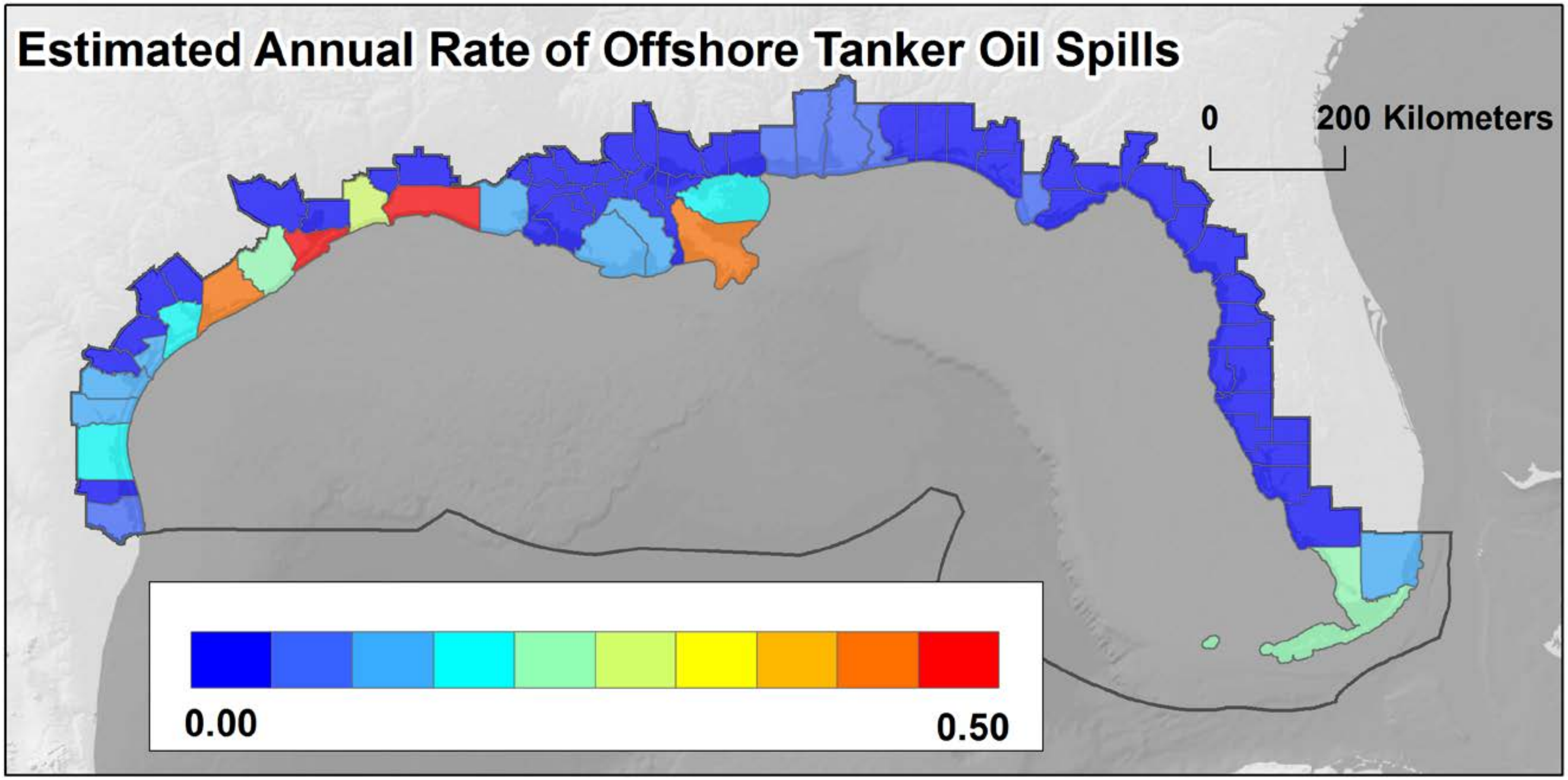
APPENDIX D
Annual Anthropogenic Hazard Event Rates

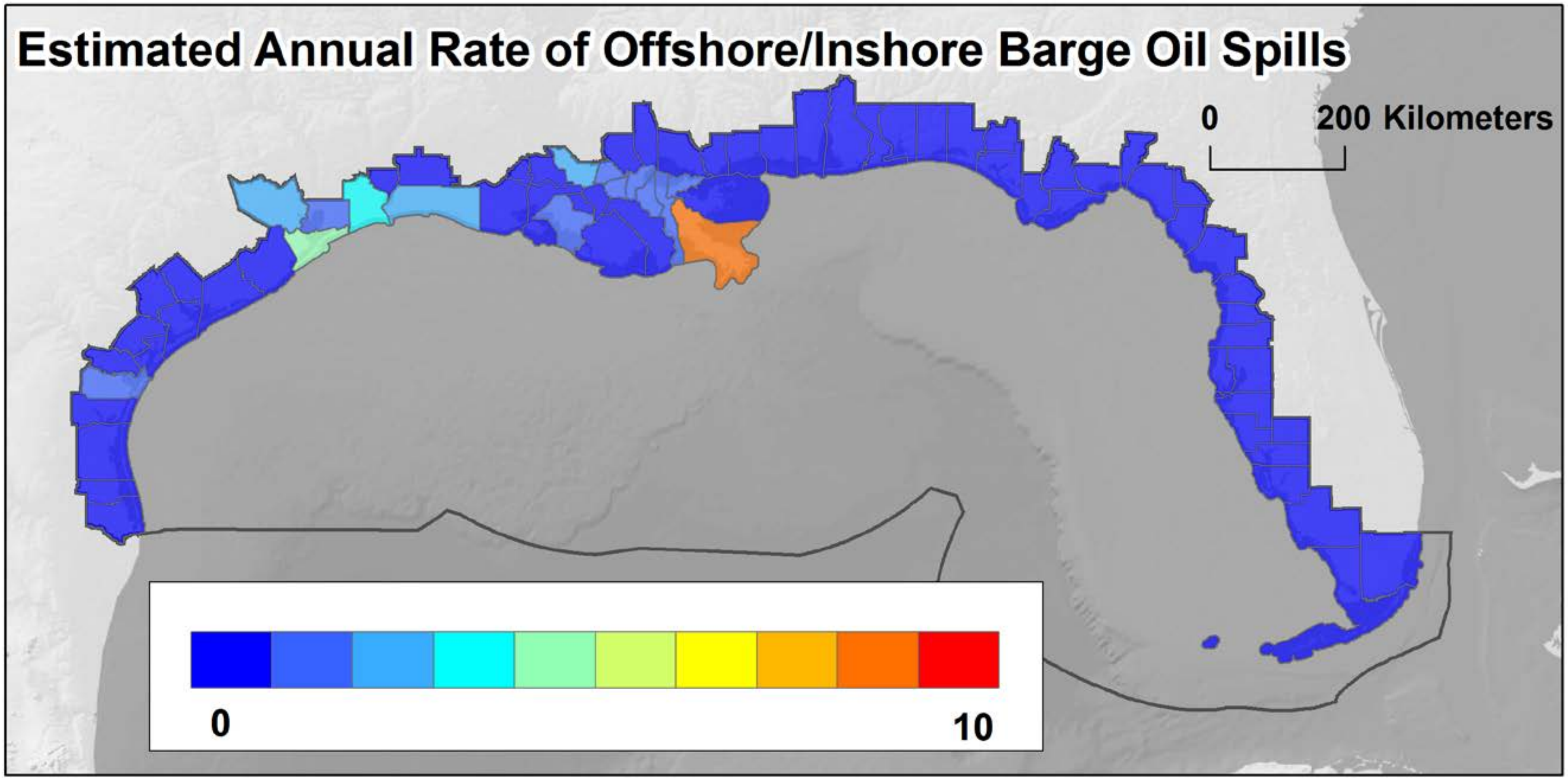
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 28 and display annual anthropogenic hazard event rates by county or parish for the hazard indicated in the title of the map. Note that scales vary widely across maps.

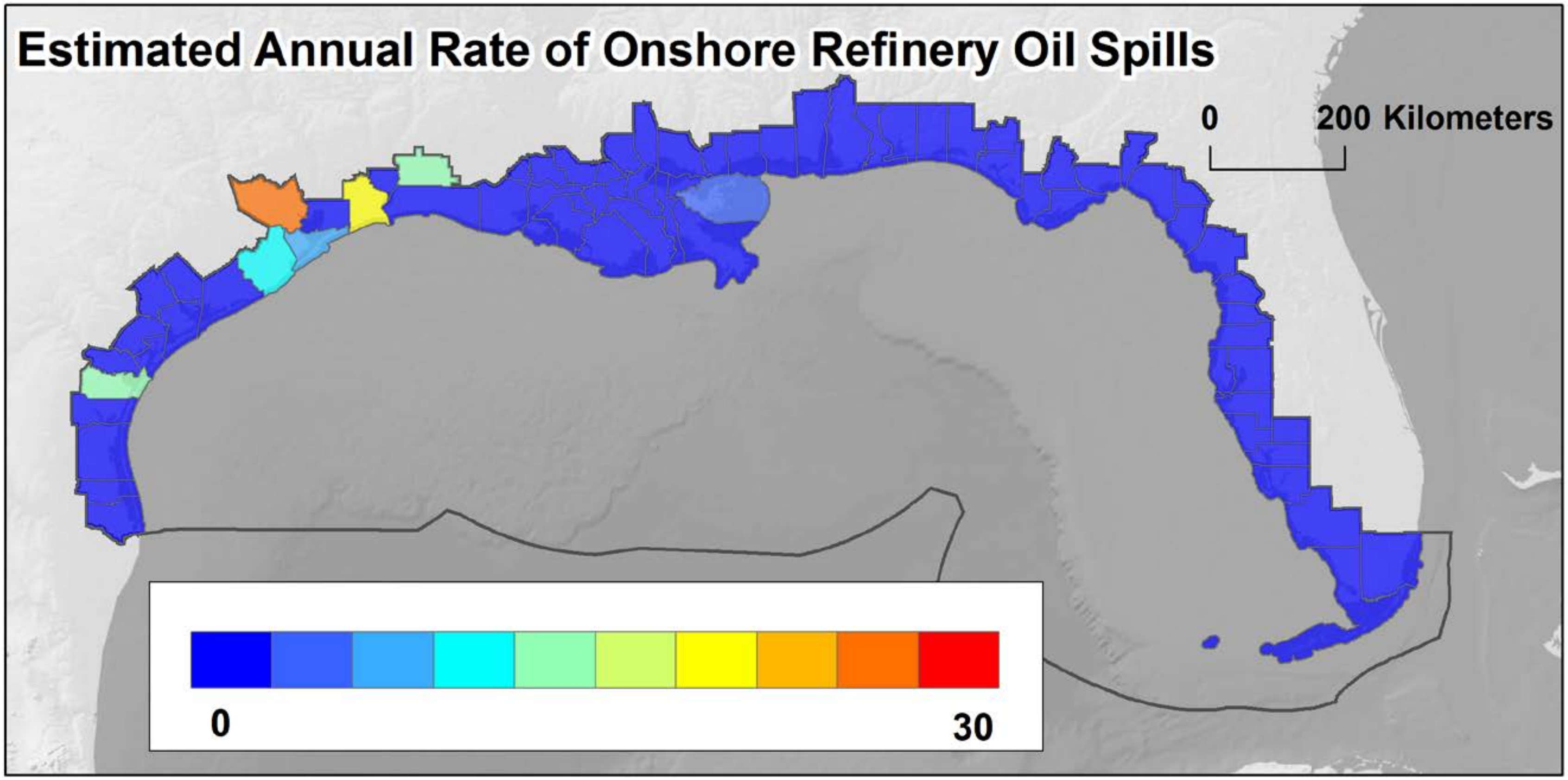

Estimated Annual Rate of Offshore Production Oil Spills
0
200 Kilometers
0.0
2.0

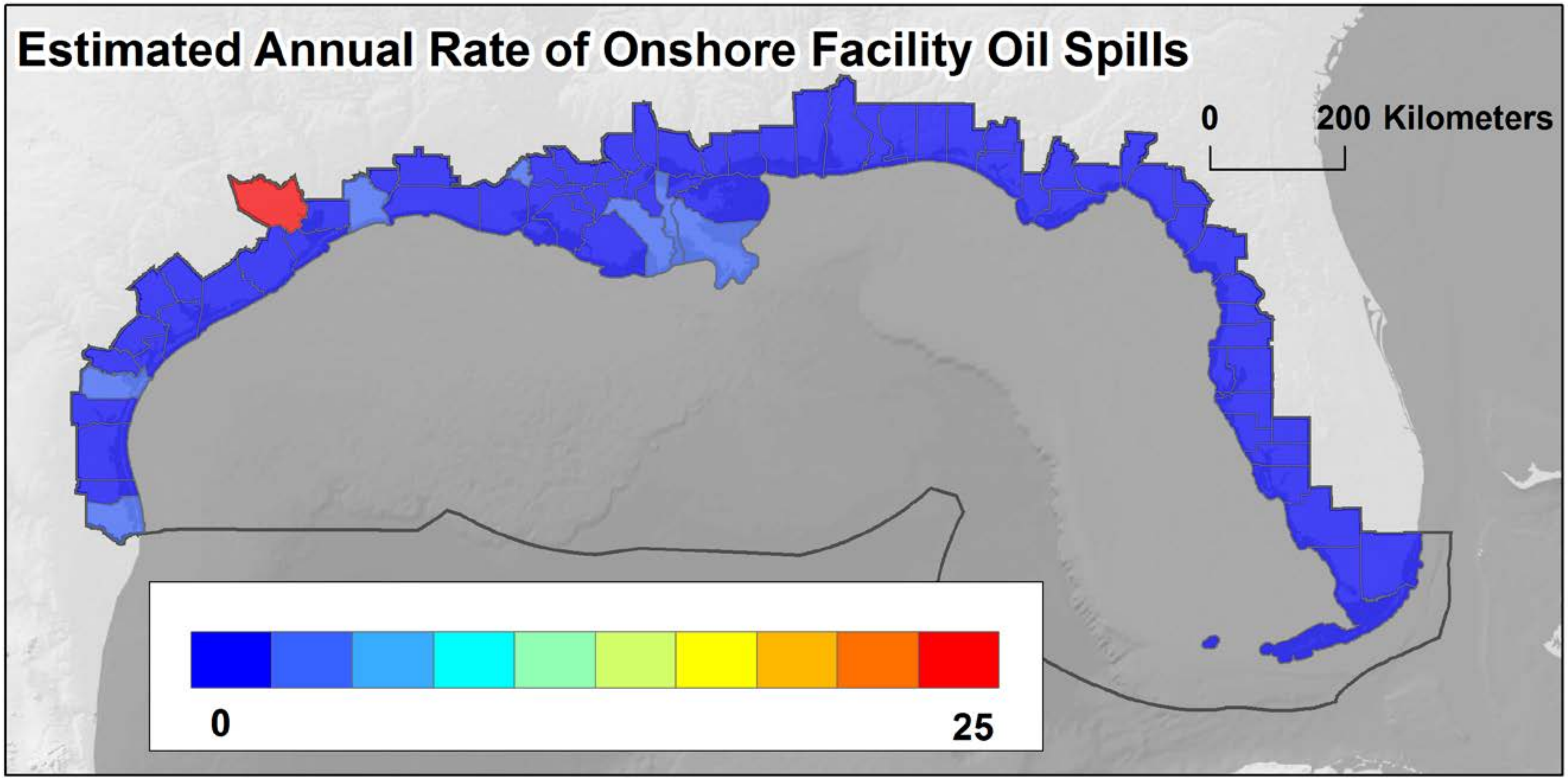


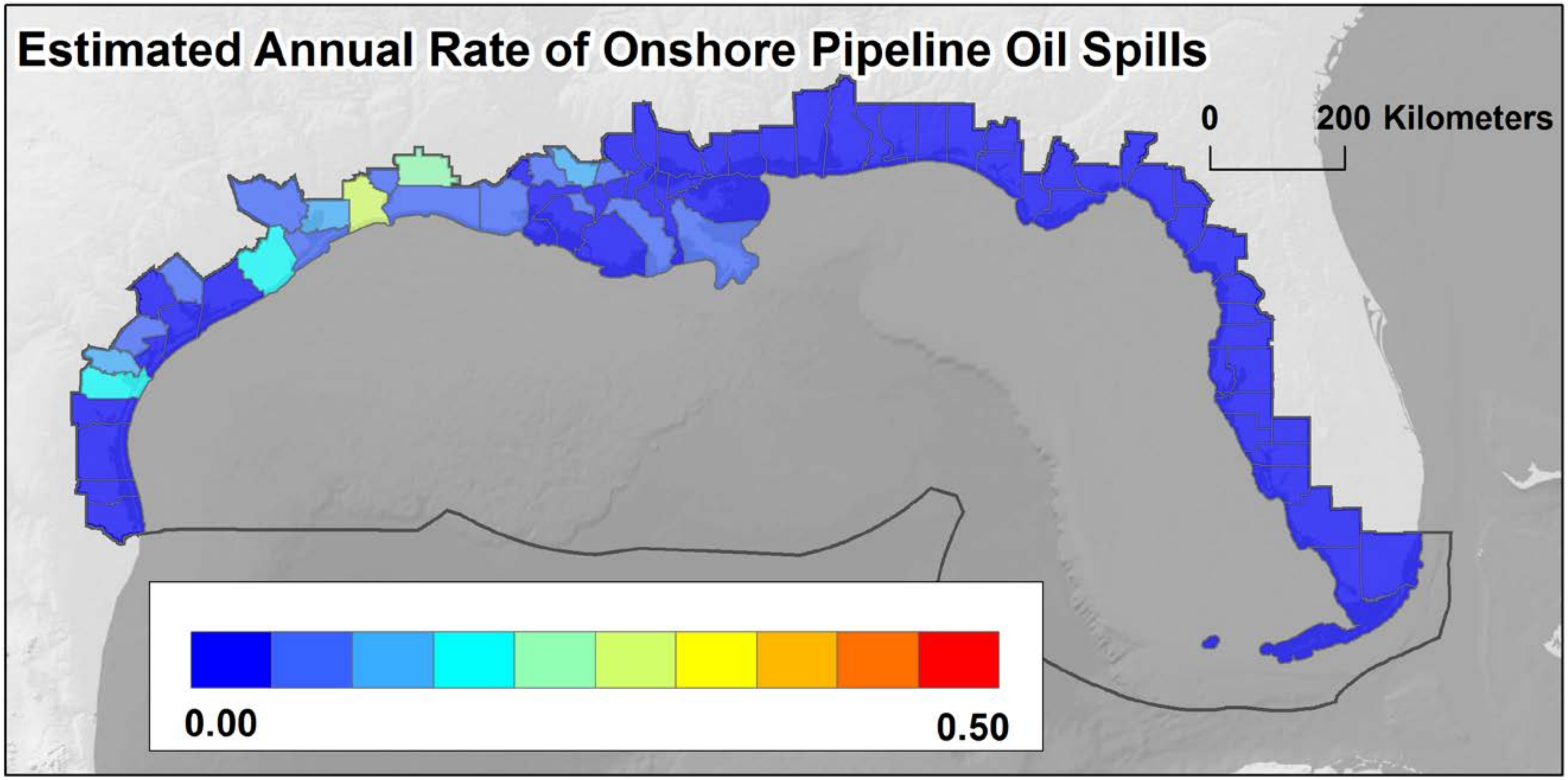
Estimated Annual Rate of Offshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

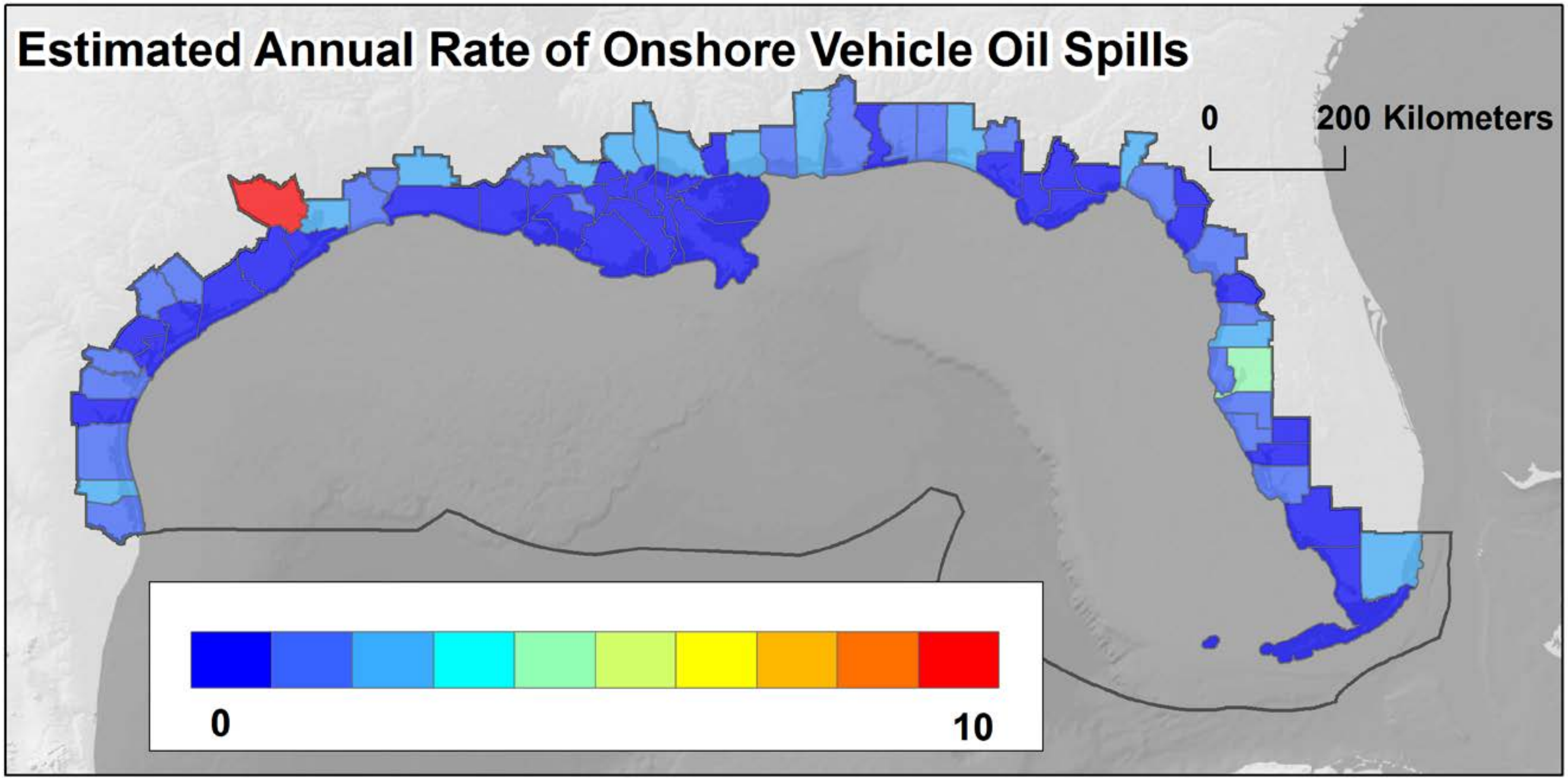

Estimated Annual Rate of Offshore Tanker Oil Spills
0
200 Kilometers
0.00
0.50

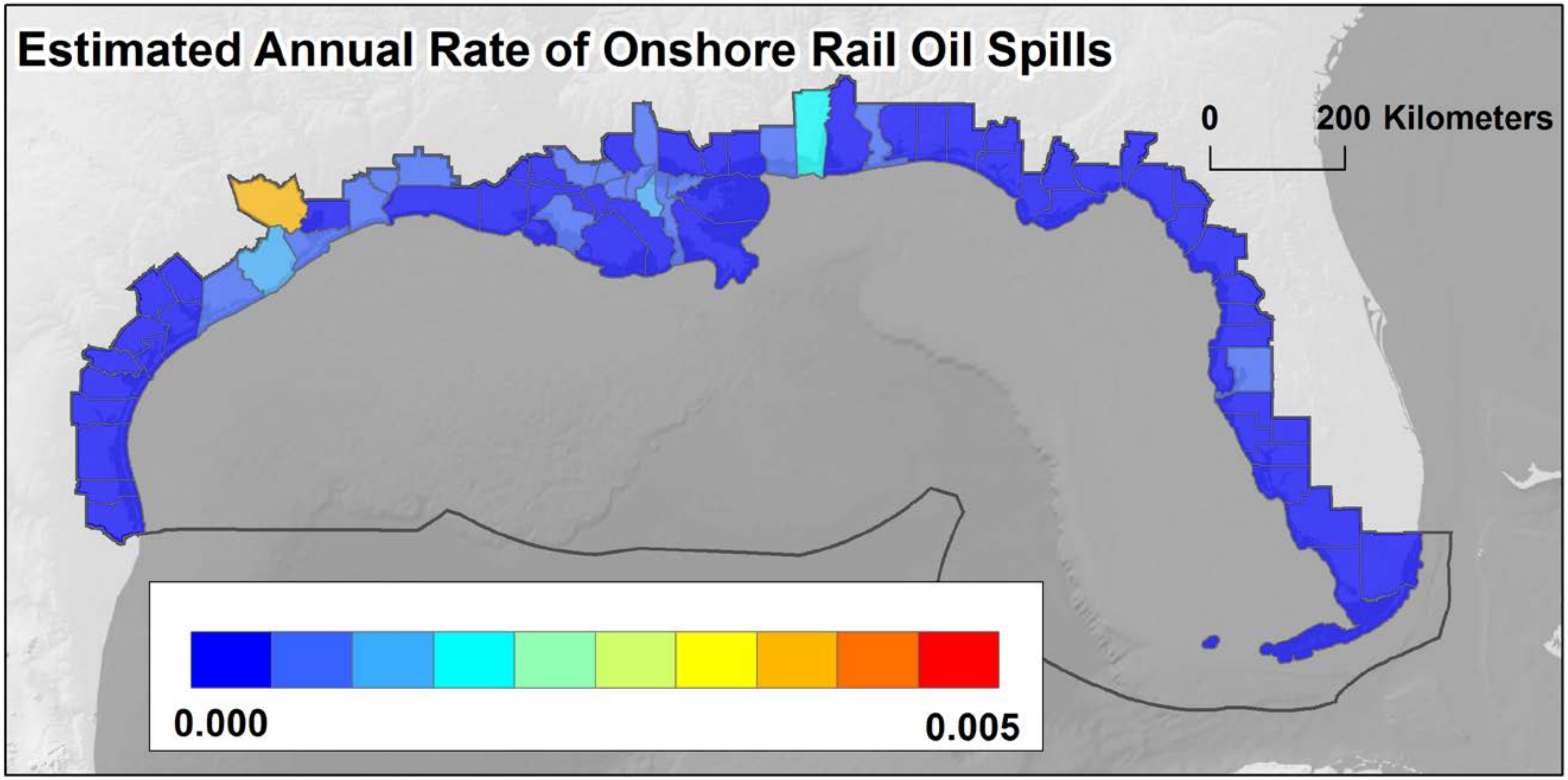

Estimated Annual Rate of Offshore/Inshore Barge Oil Spills
0
200 Kilometers
0
10

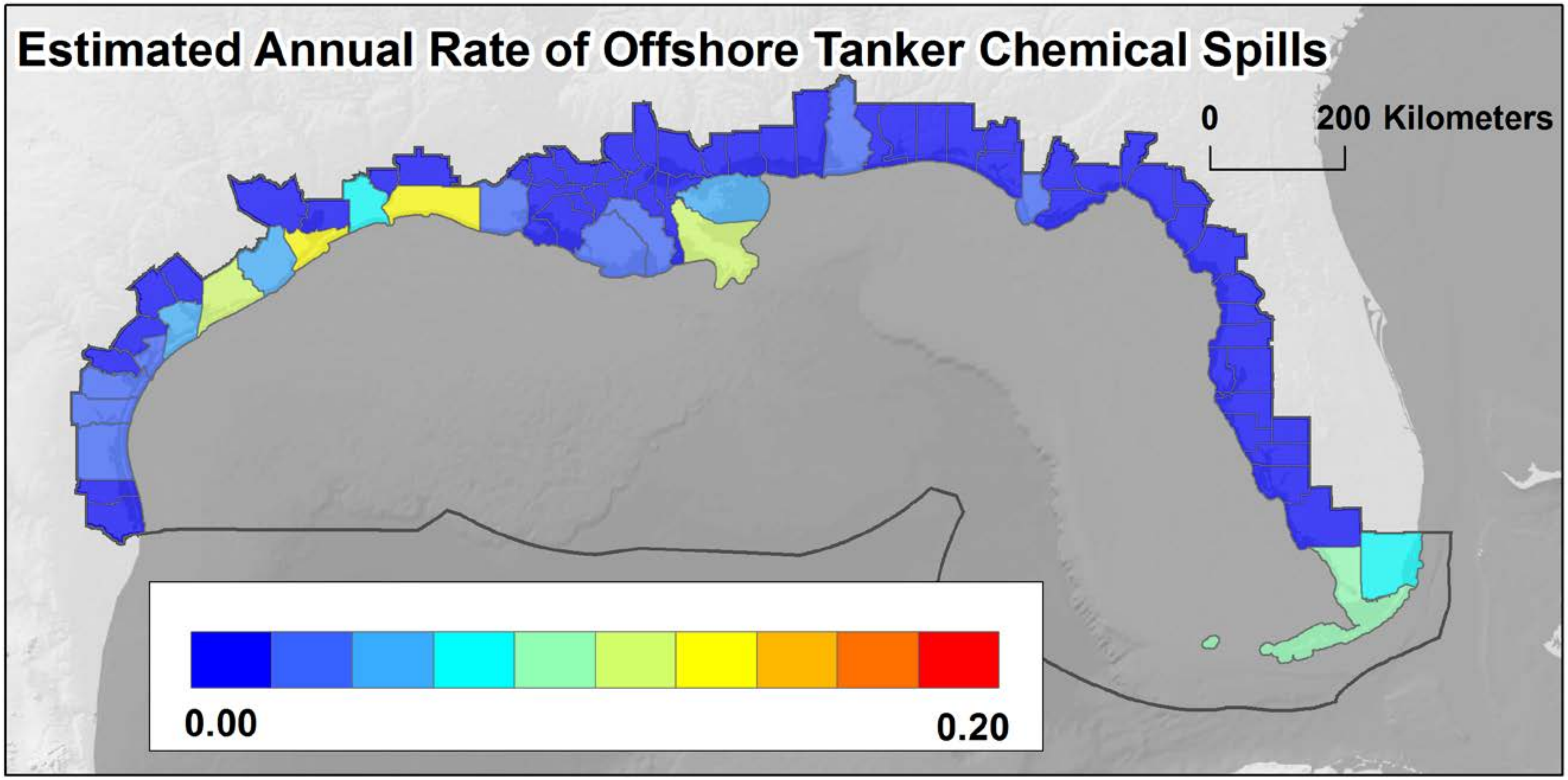

Estimated Annual Rate of Onshore Refinery Oil Spills
0
200 Kilometers
0
30

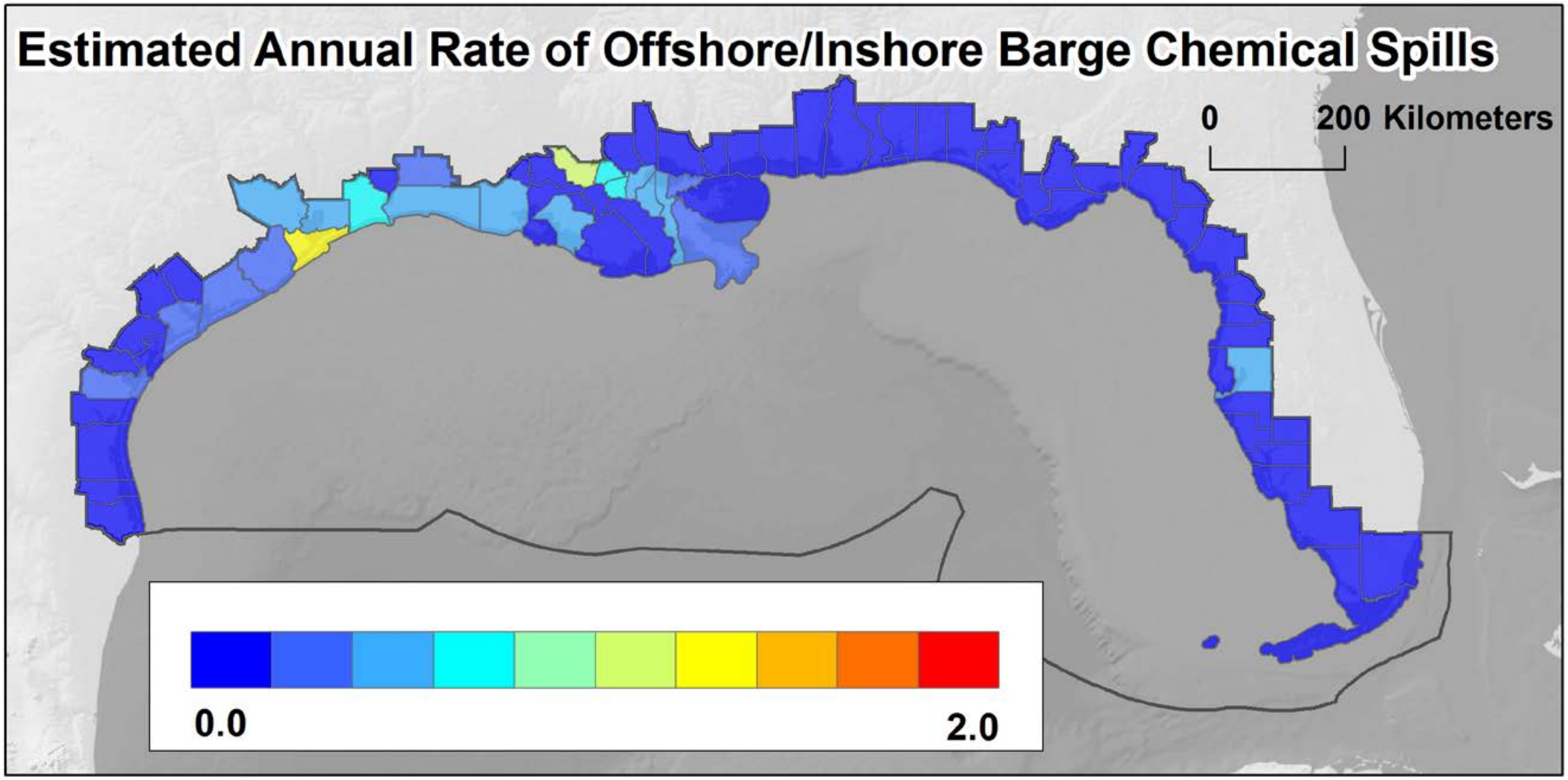

Estimated Annual Rate of Onshore Facility Oil Spills
0
200 Kilometers
0
25

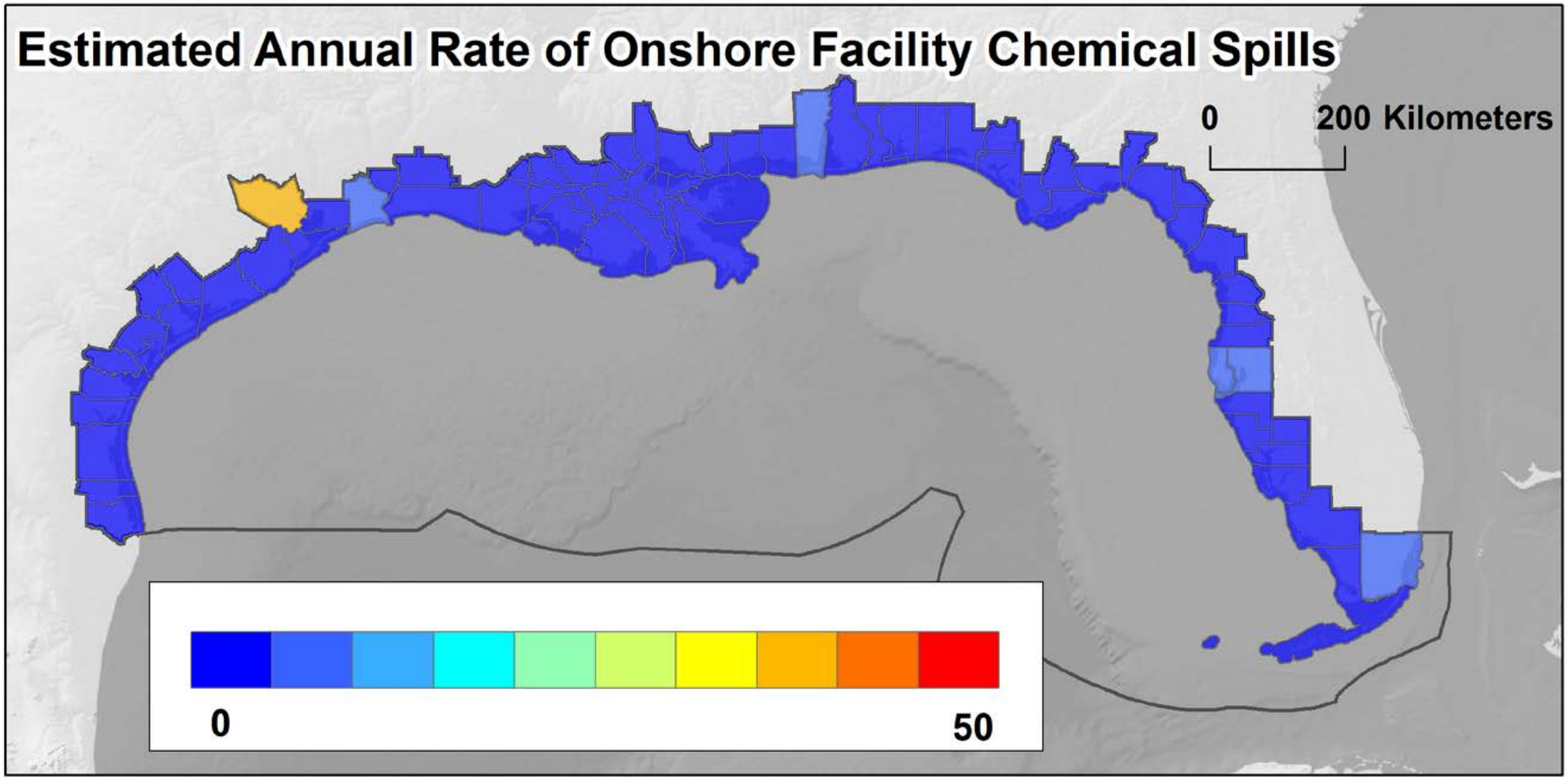

Estimated Annual Rate of Onshore Pipeline Oil Spills
0
200 Kilometers
0.00
0.50

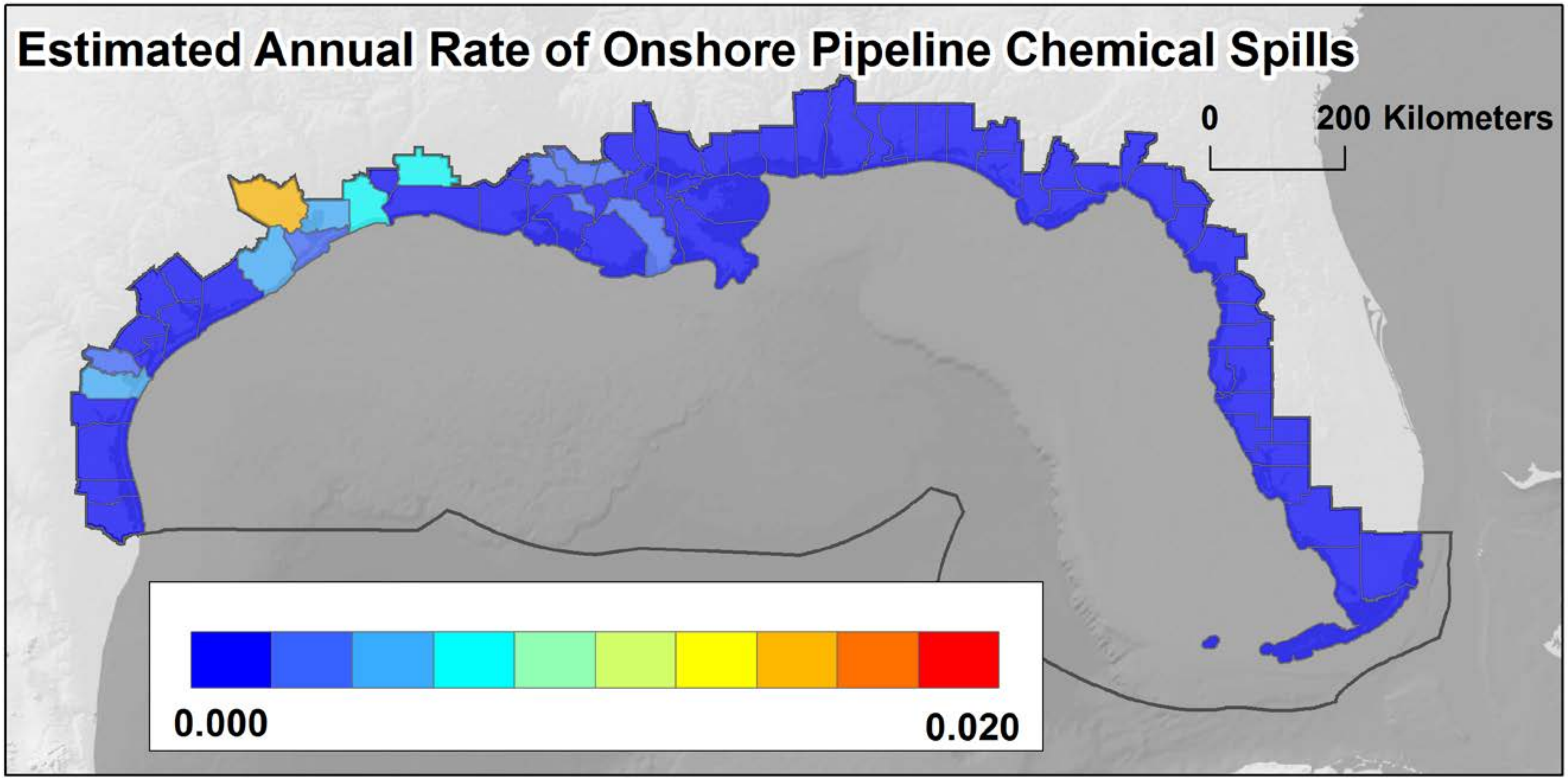

Estimated Annual Rate of Onshore Vehicle Oil Spills
0
200 Kilometers
0
10

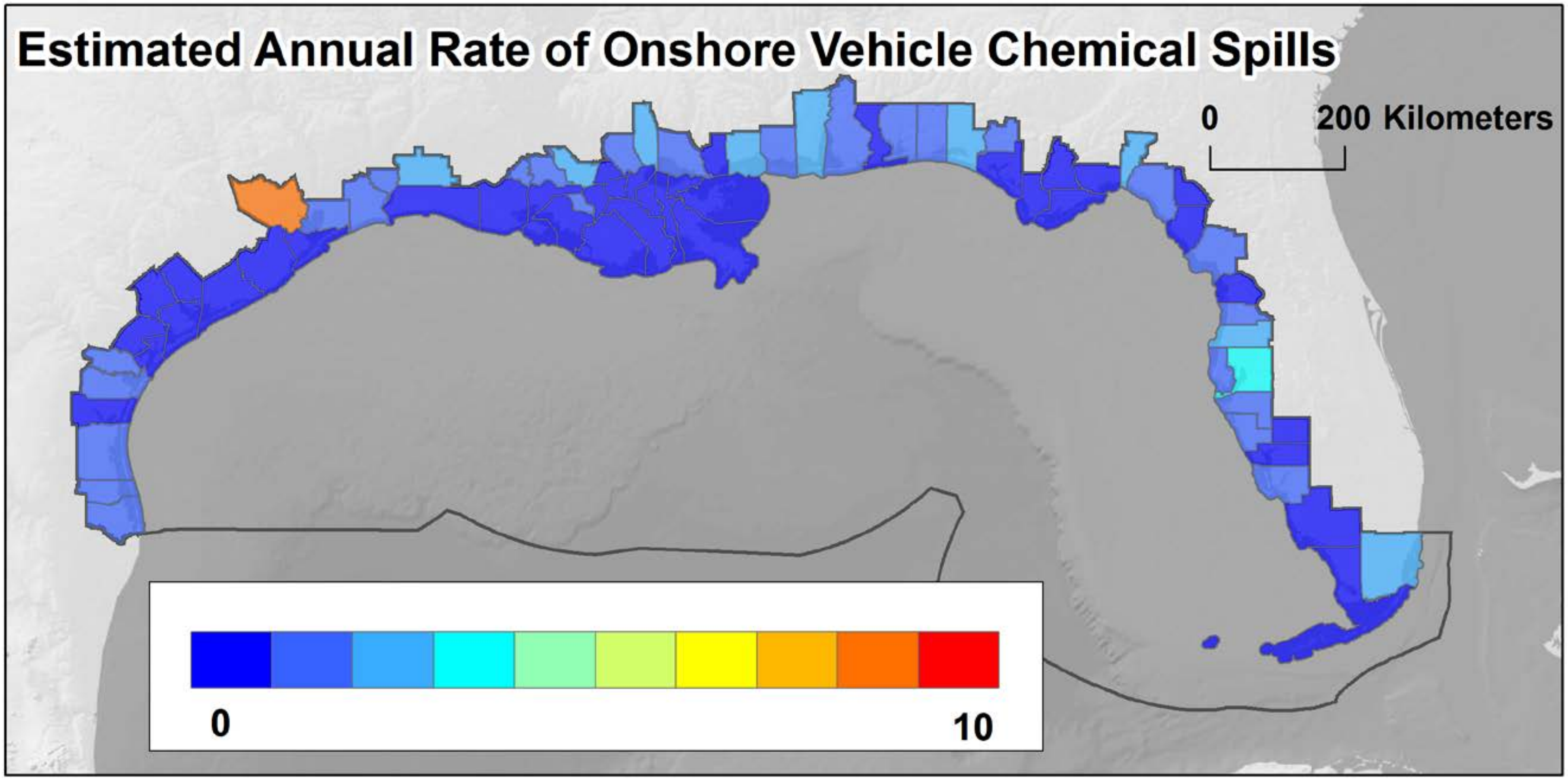

Estimated Annual Rate of Onshore Rail Oil Spills
0
200 Kilometers
0.000
0.005

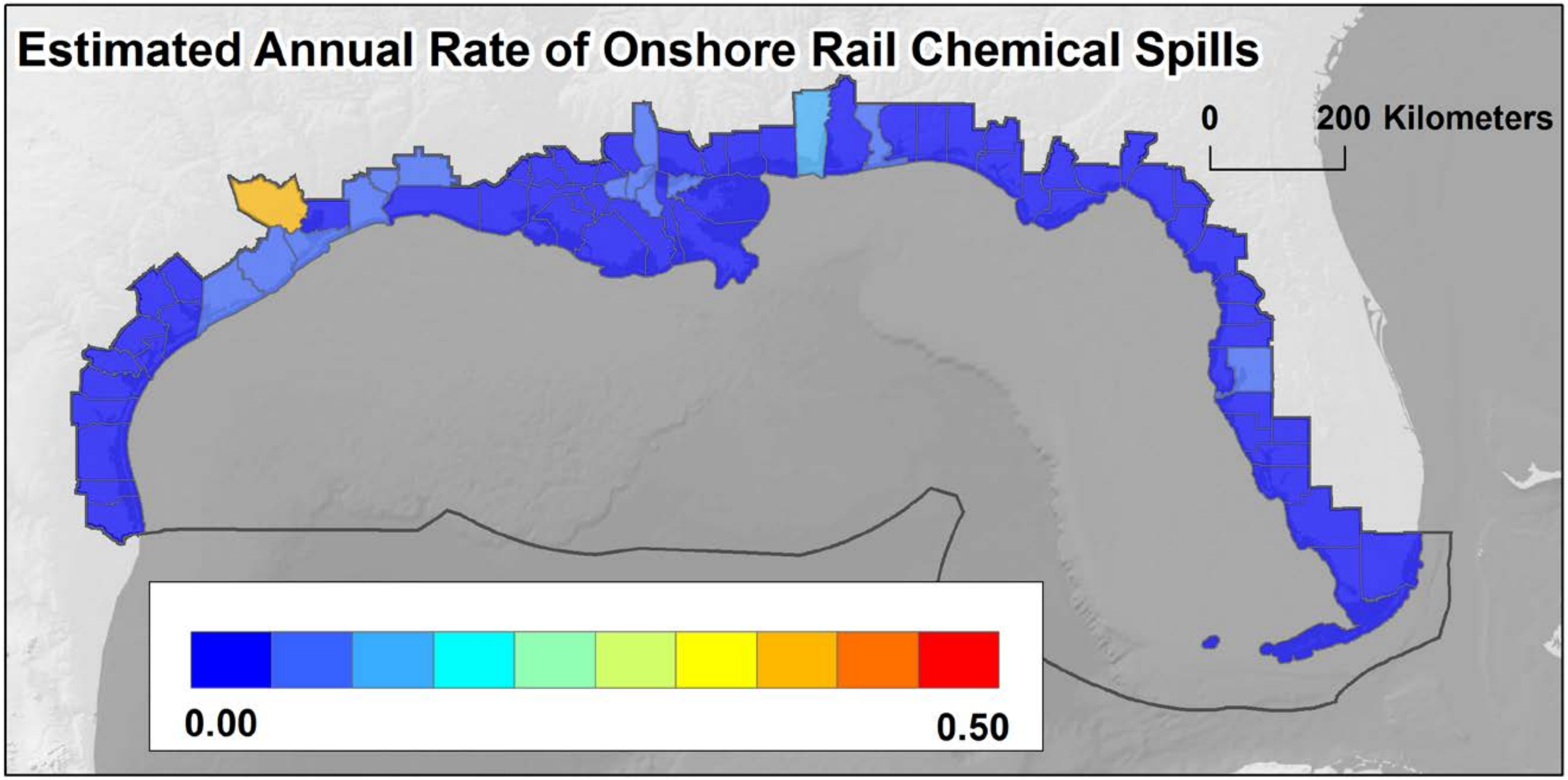

Estimated Annual Rate of Offshore Tanker Chemical Spills
0
200 Kilometers
0.00
0.20


Estimated Annual Rate of Offshore/Inshore Barge Chemical Spills
0
200 Kilometers
0.0
2.0

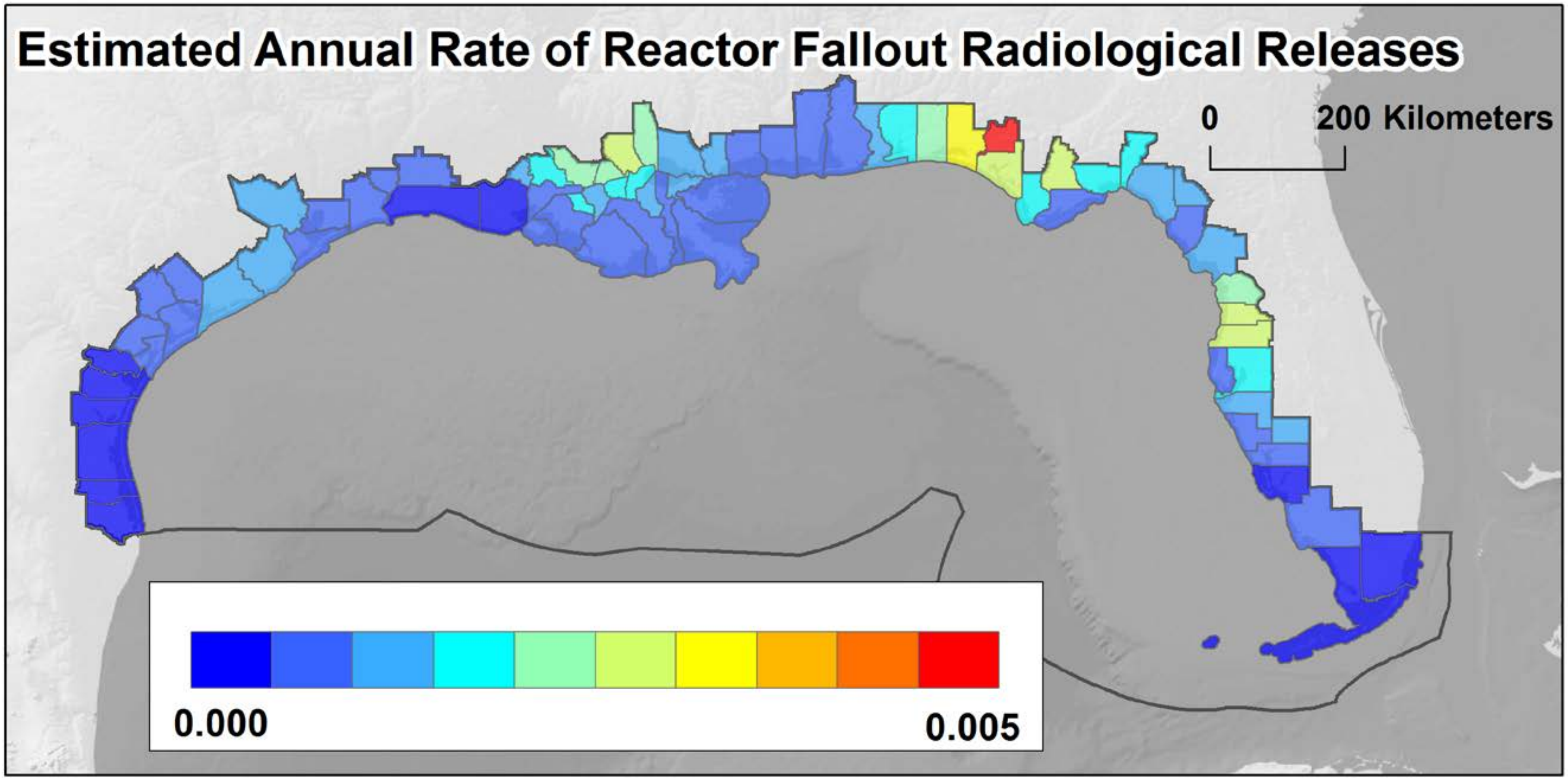

Estimated Annual Rate of Onshore Facility Chemical Spills
0
200 Kilometers
0
50

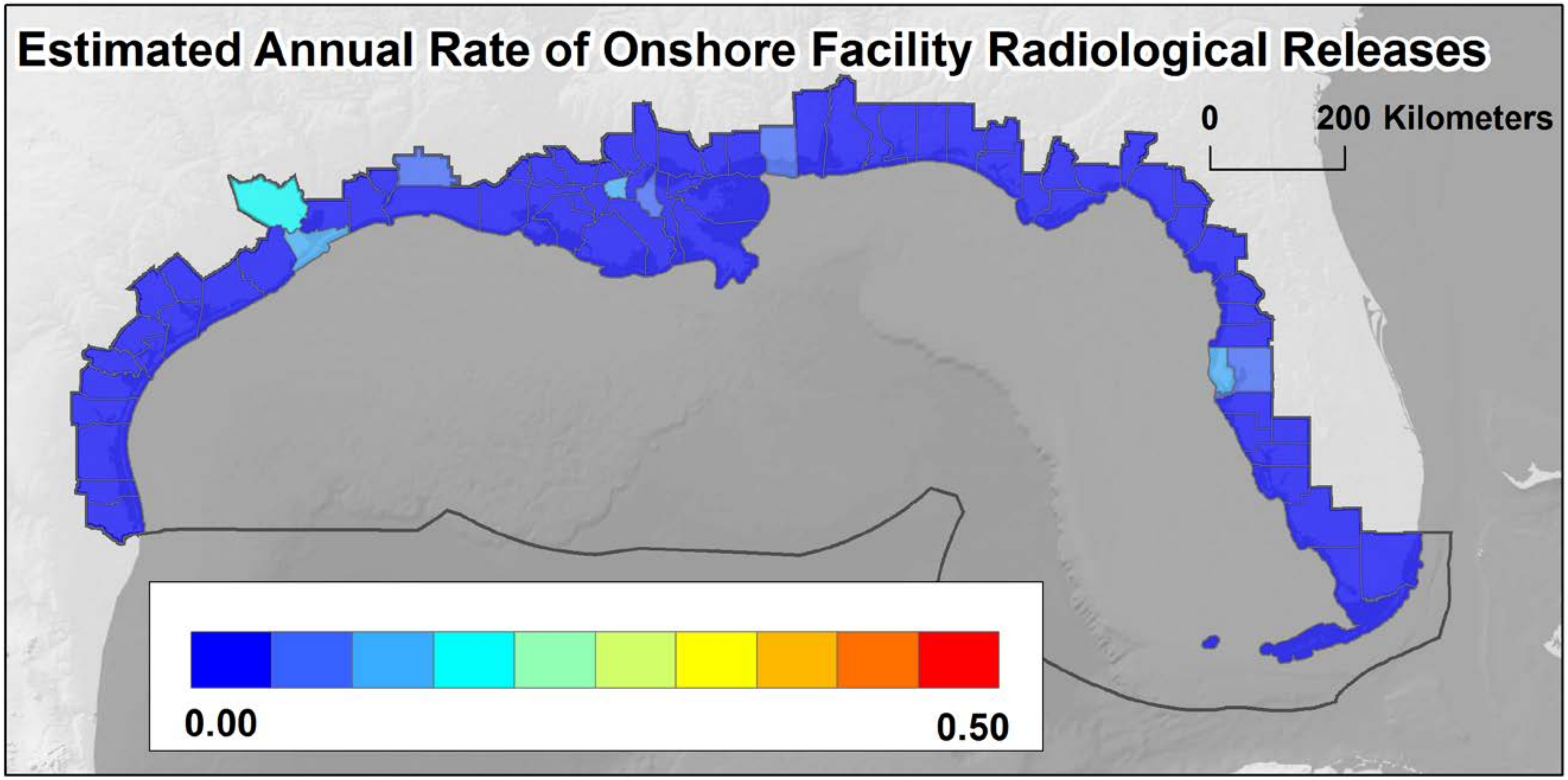

Estimated Annual Rate of Onshore Pipeline Chemical Spills
0
200 Kilometers
0.000
0.020

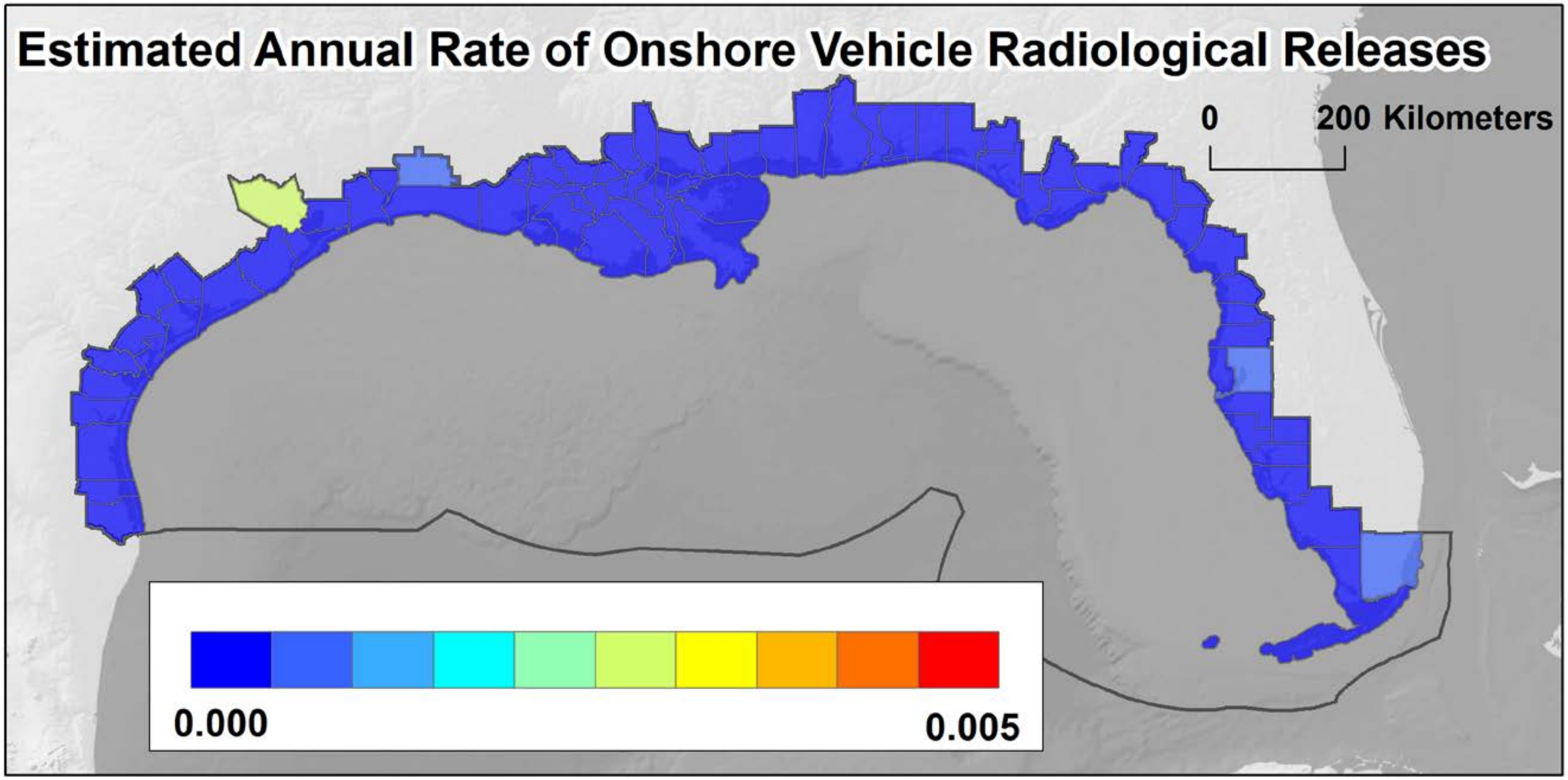

Estimated Annual Rate of Onshore Vehicle Chemical Spills
0
200 Kilometers
0
10

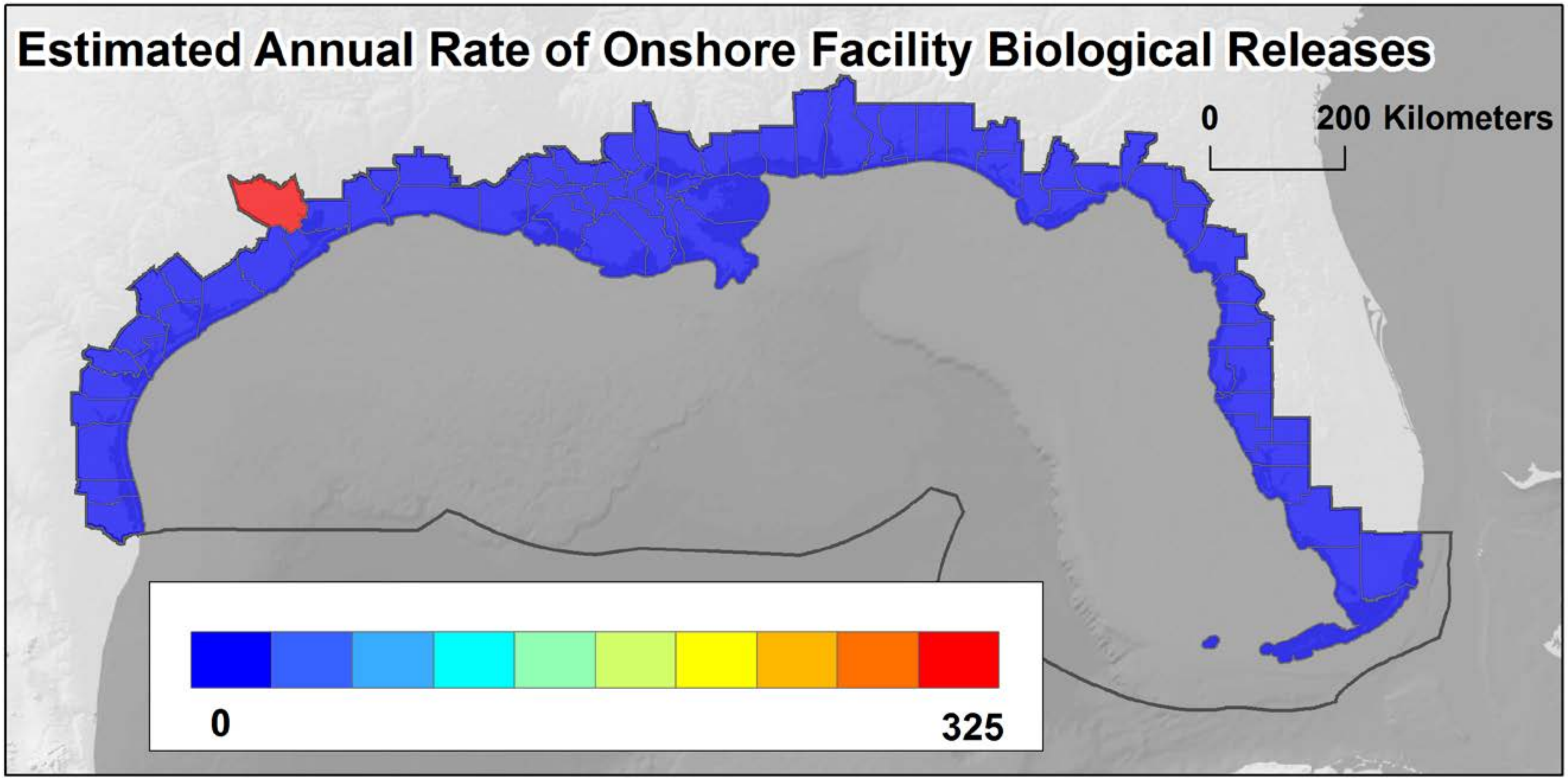


Estimated Annual Rate of Onshore Rail Chemical Spills
0
200 Kilometers
0.00
0.50


Estimated Annual Rate of Reactor Fallout Radiological Releases
0
200 Kilometers
0.000
0.005


Estimated Annual Rate of Onshore Facility Radiological Releases
0
200 Kilometers
0.00
0.50

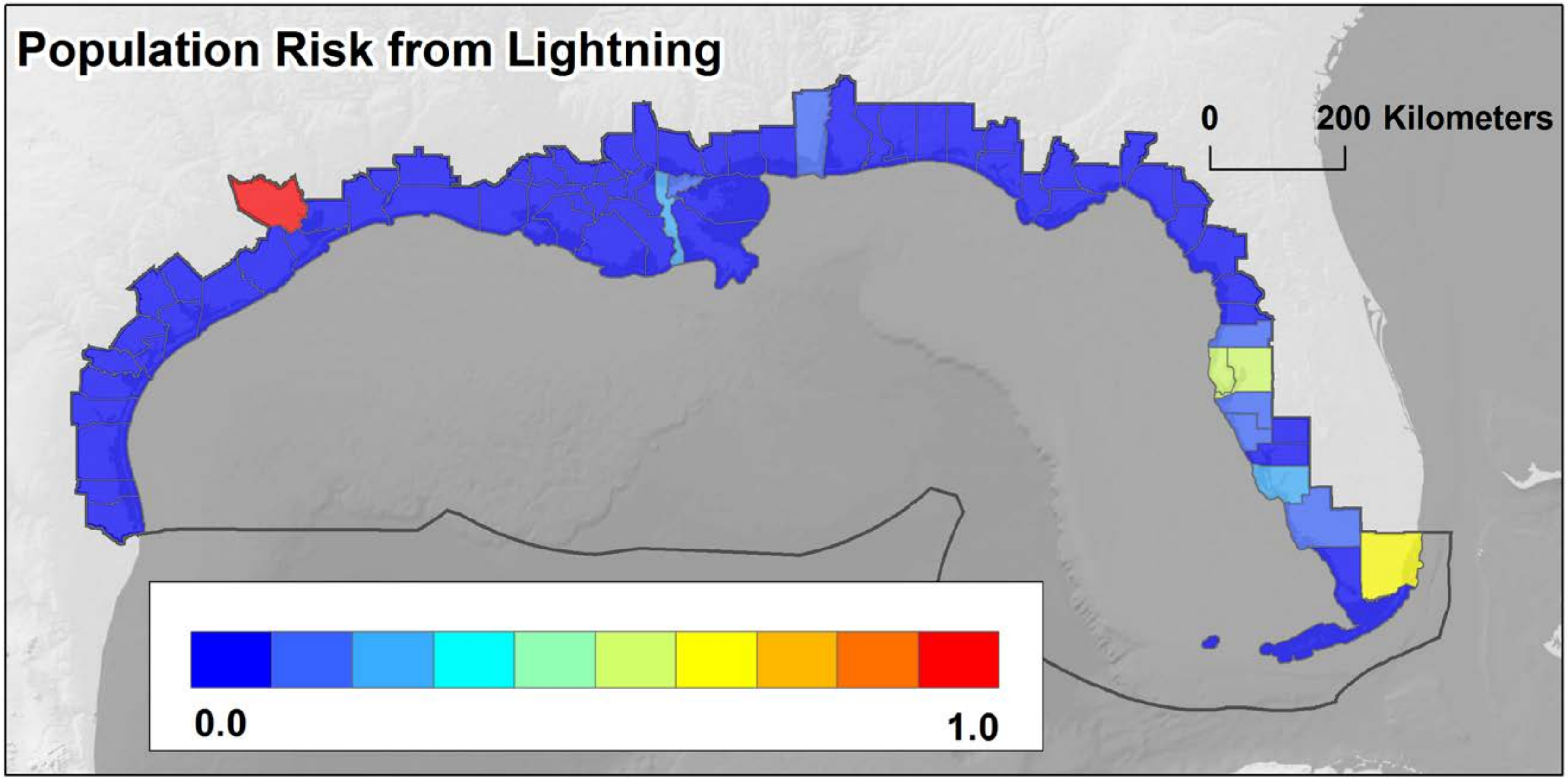

Estimated Annual Rate of Onshore Vehicle Radiological Releases
0
200 Kilometers
0.000
0.005

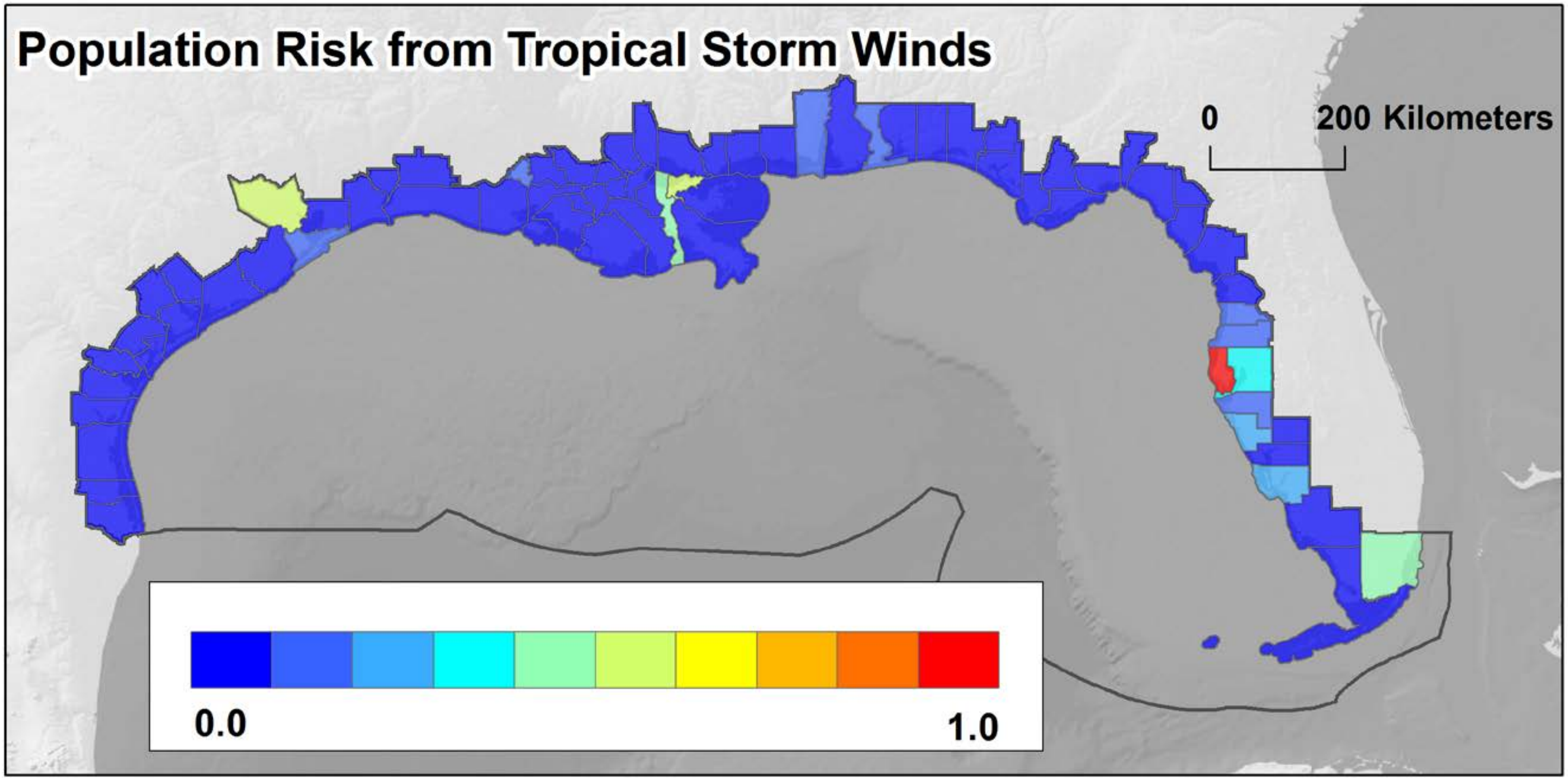

Estimated Annual Rate of Onshore Facility Biological Releases
0
200 Kilometers
0
325

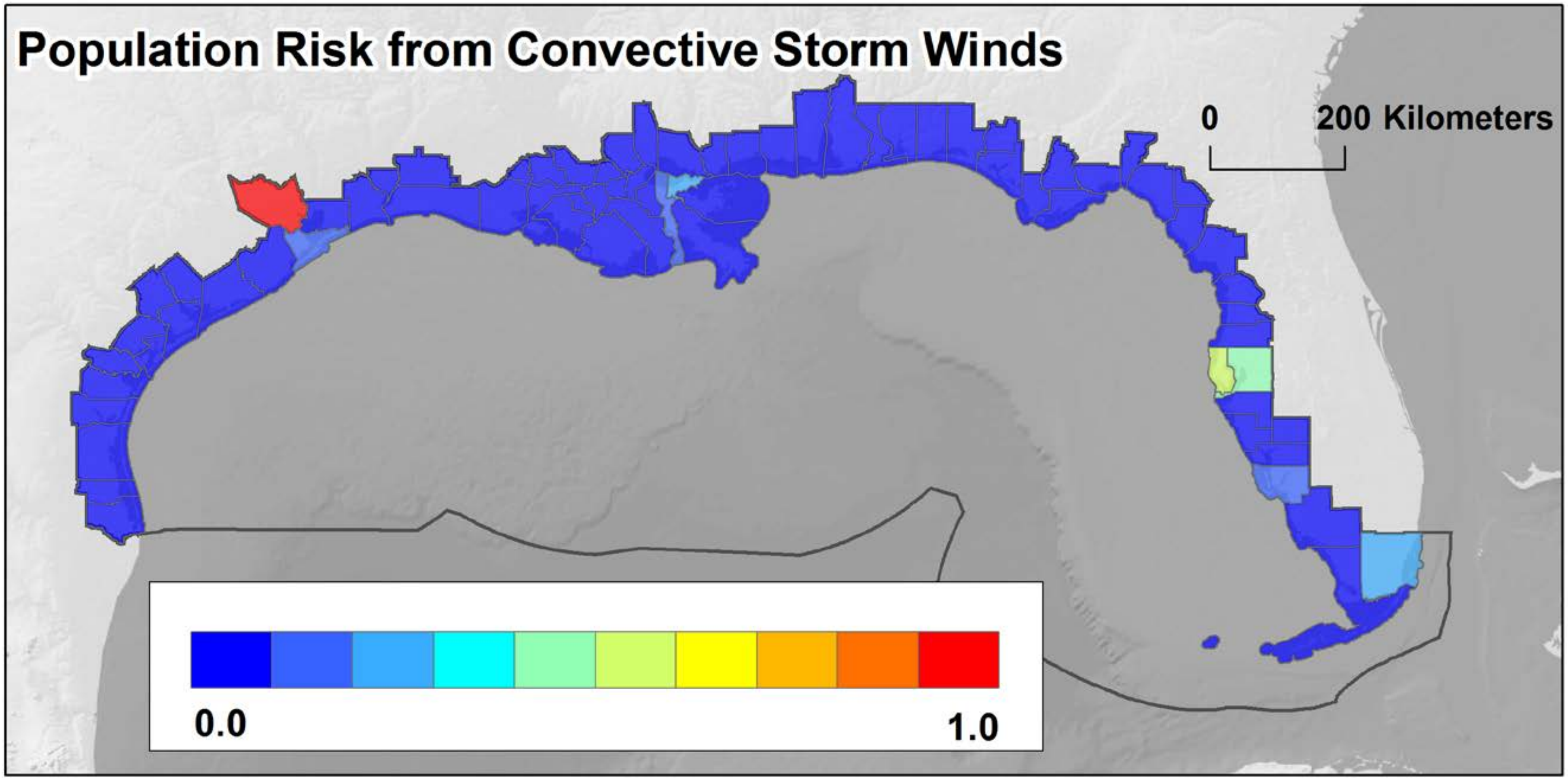
APPENDIX E

Risk to Human Population from Natural Hazards

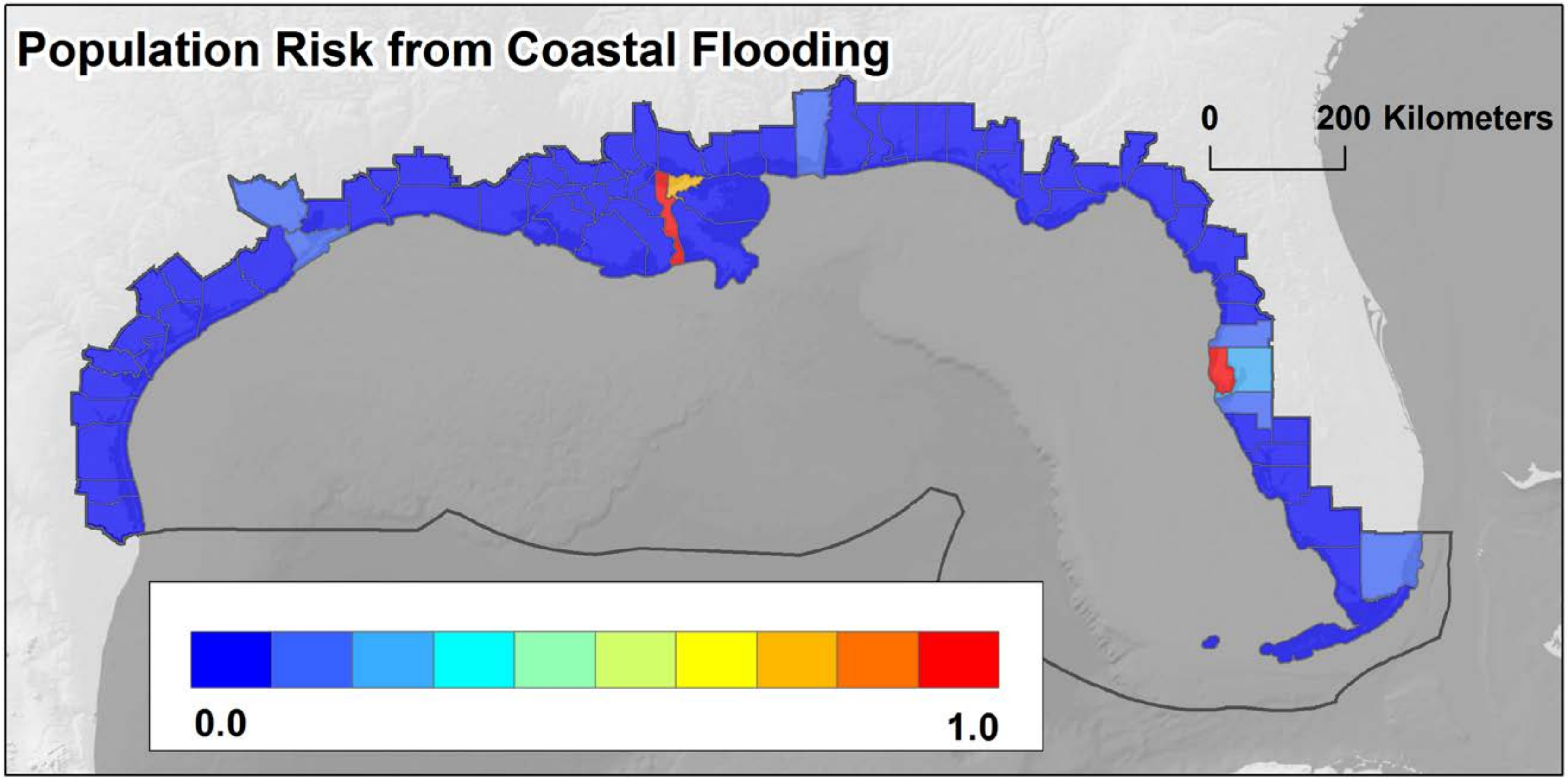
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 31 and display ranked risk index values to human population by county or parish for all natural hazards.

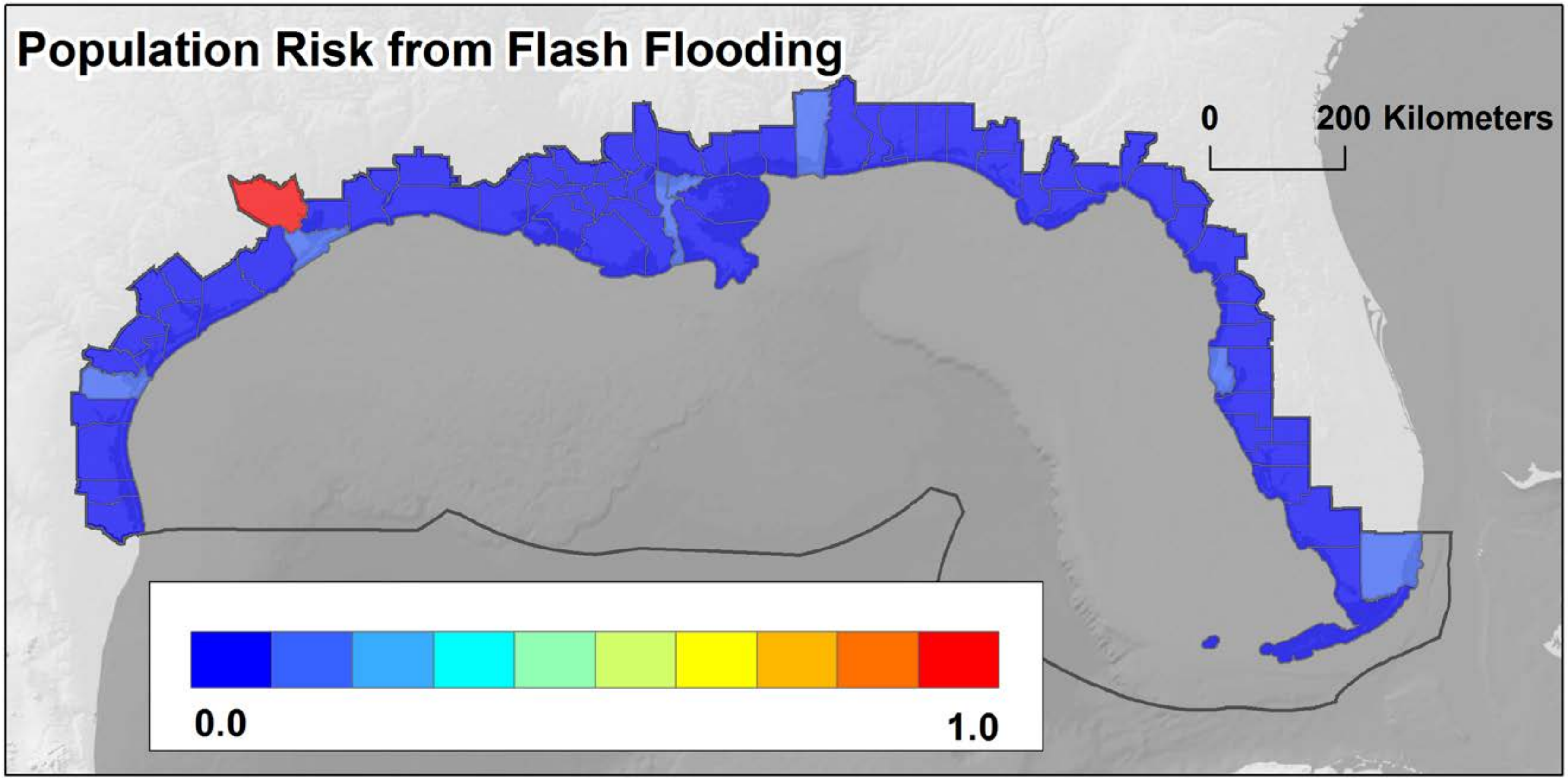

Population Risk from Lightning
0
200 Kilometers
0.0
1.0


Population Risk from Tropical Storm Winds
0
200 Kilometers
0.0
1.0

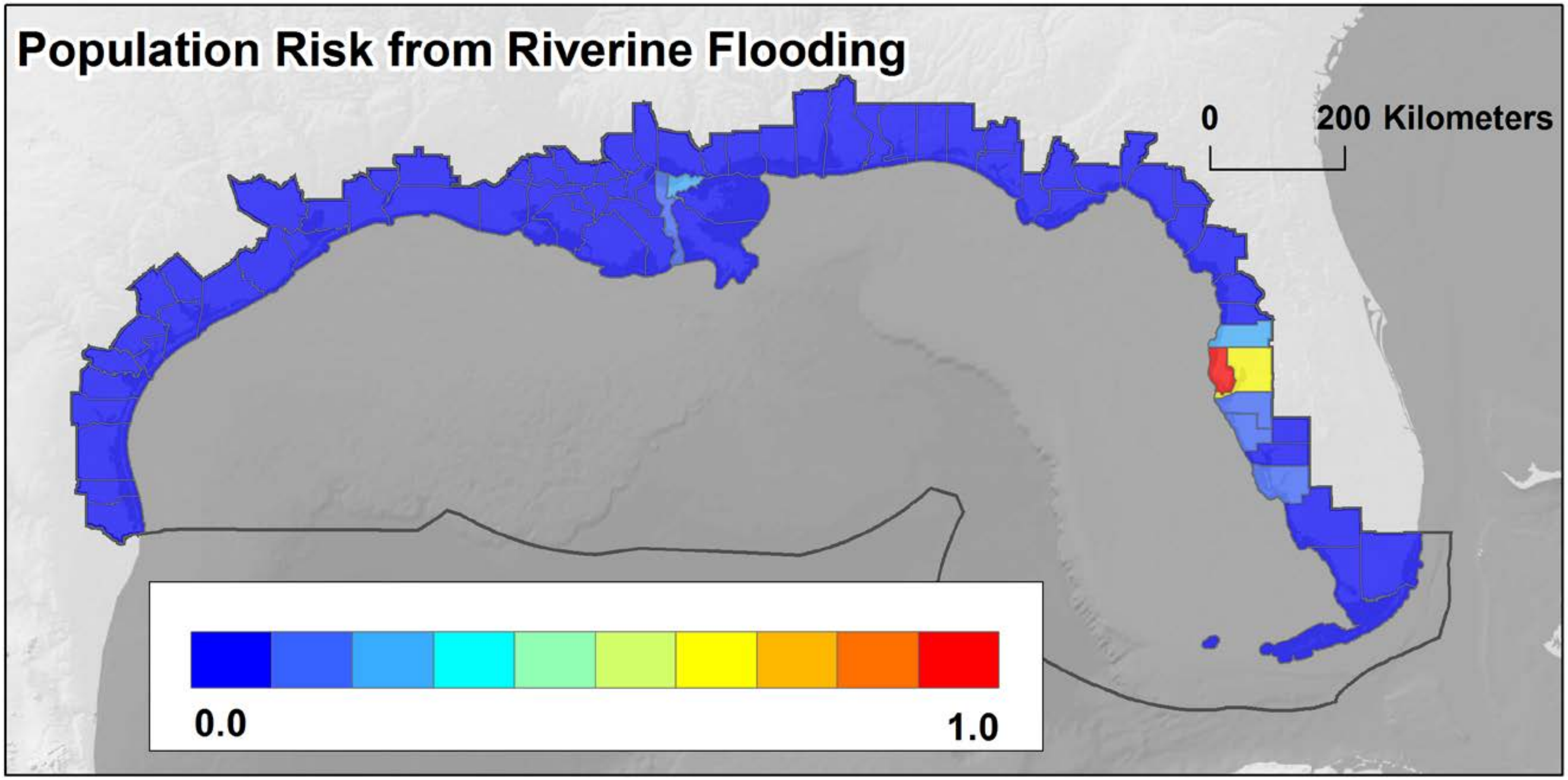


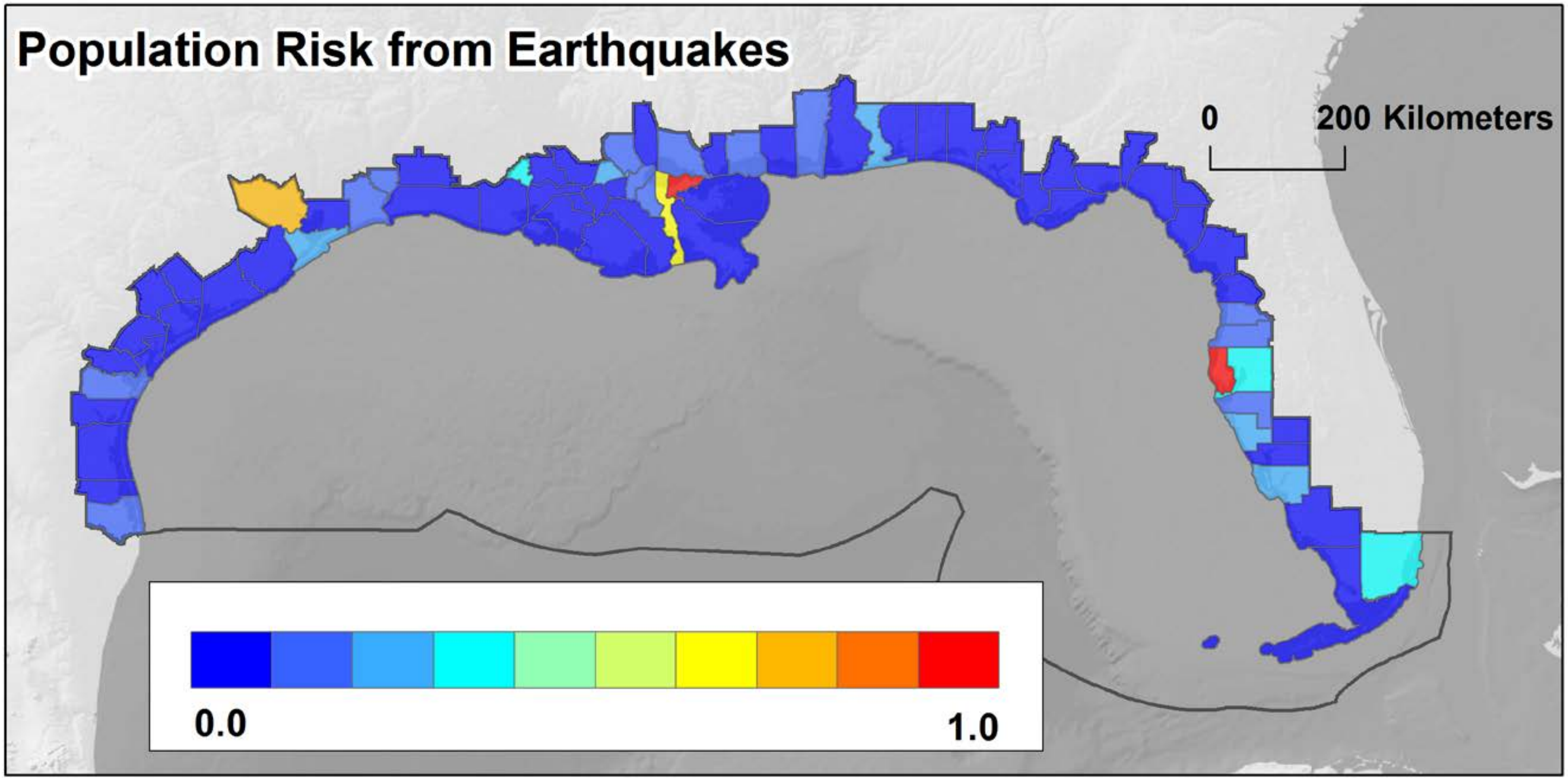
Population Risk from Convective Storm Winds
0
200 Kilometers
0.0
1.0

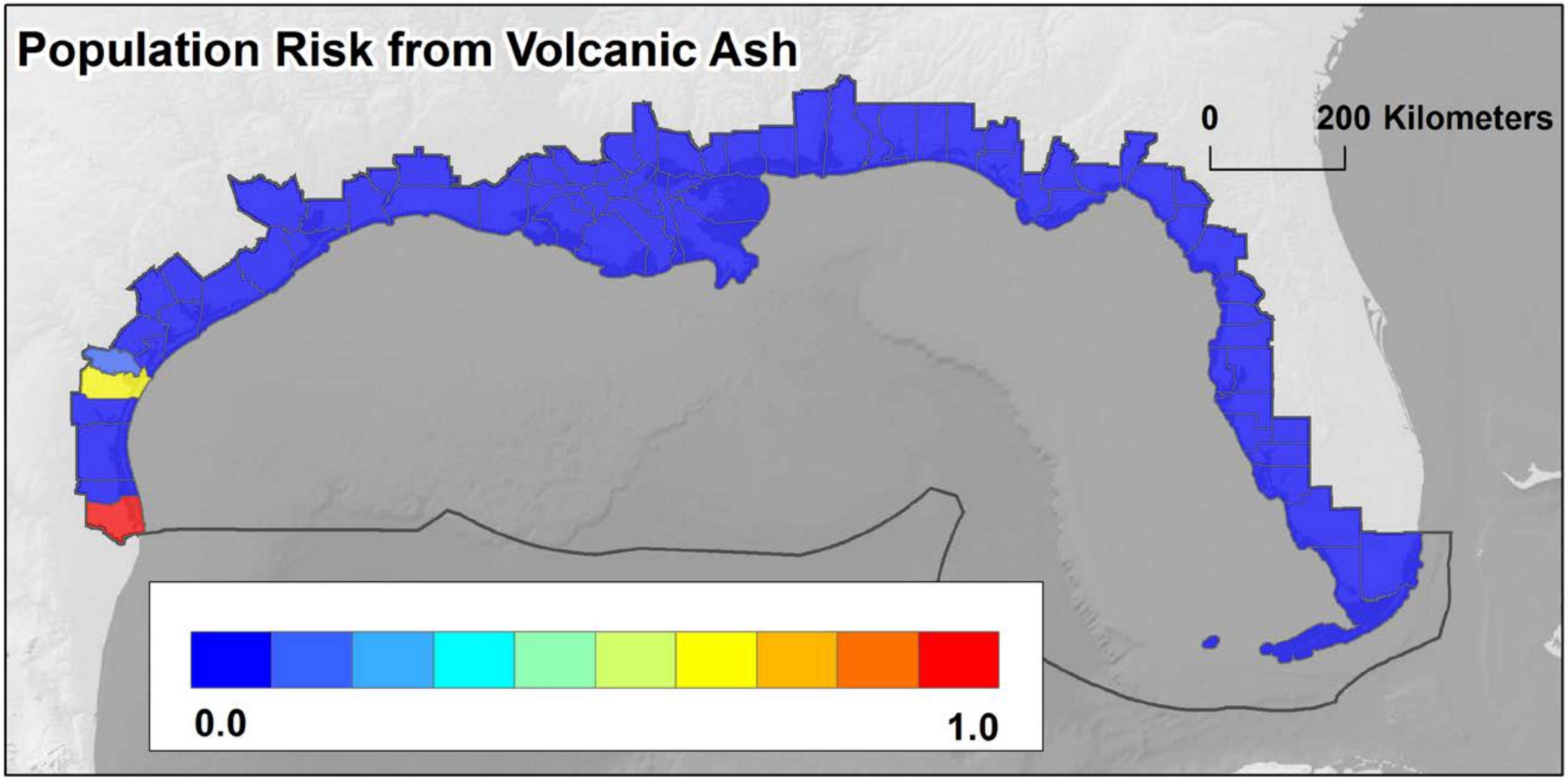

Population Risk from Coastal Flooding
0
200 Kilometers
0.0
1.0

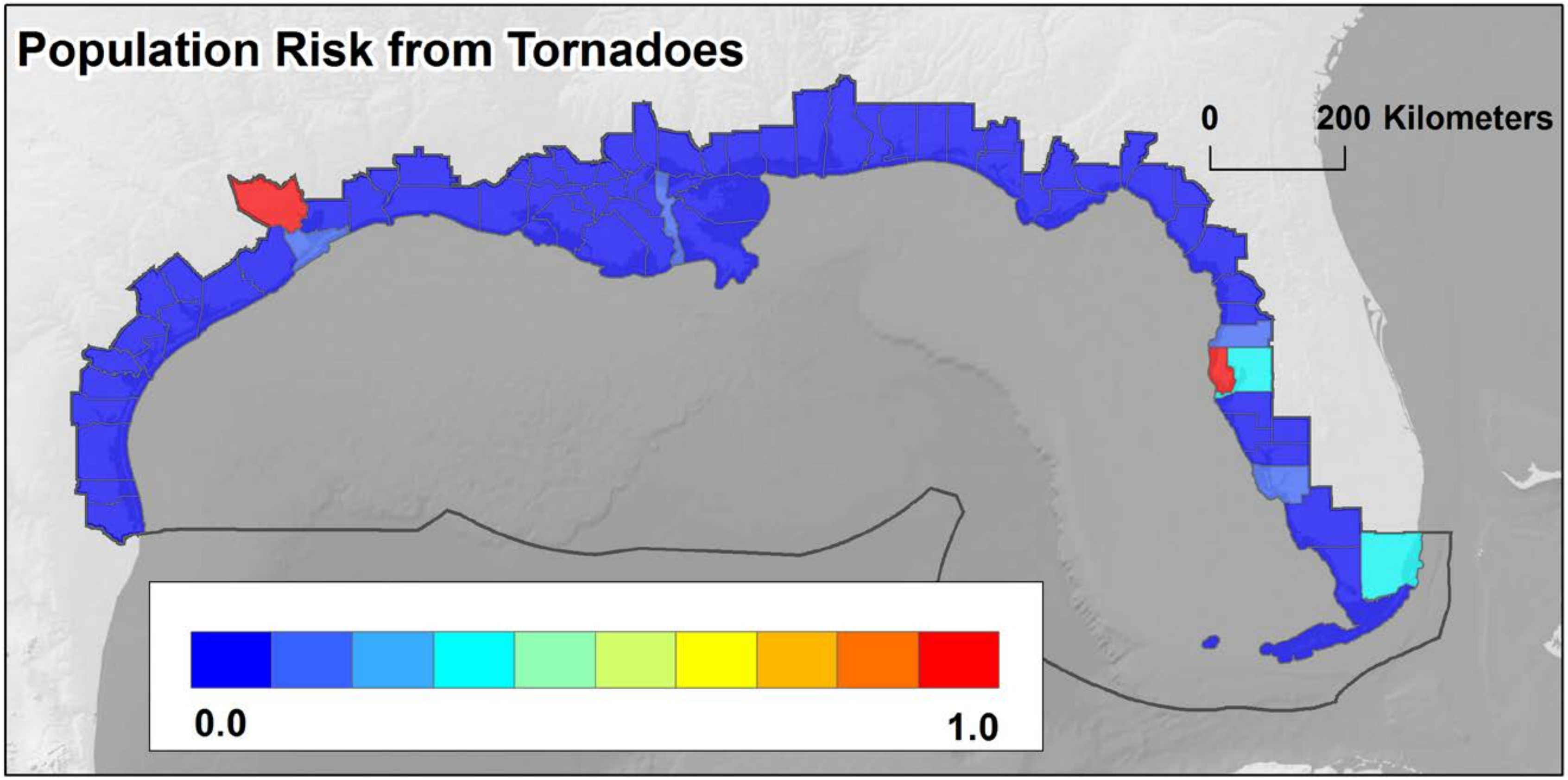


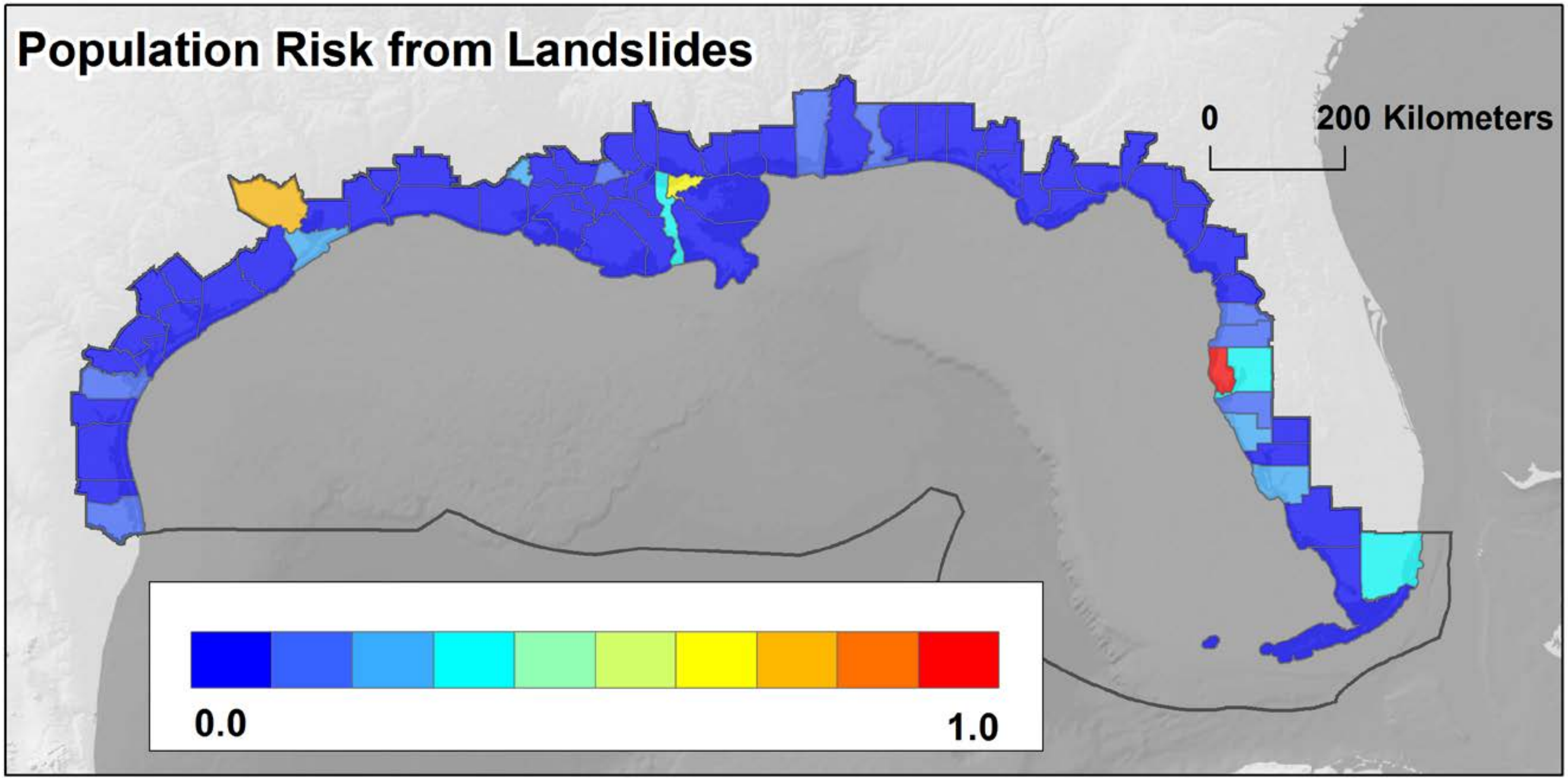
Population Risk from Flash Flooding
0
200 Kilometers
0.0
1.0

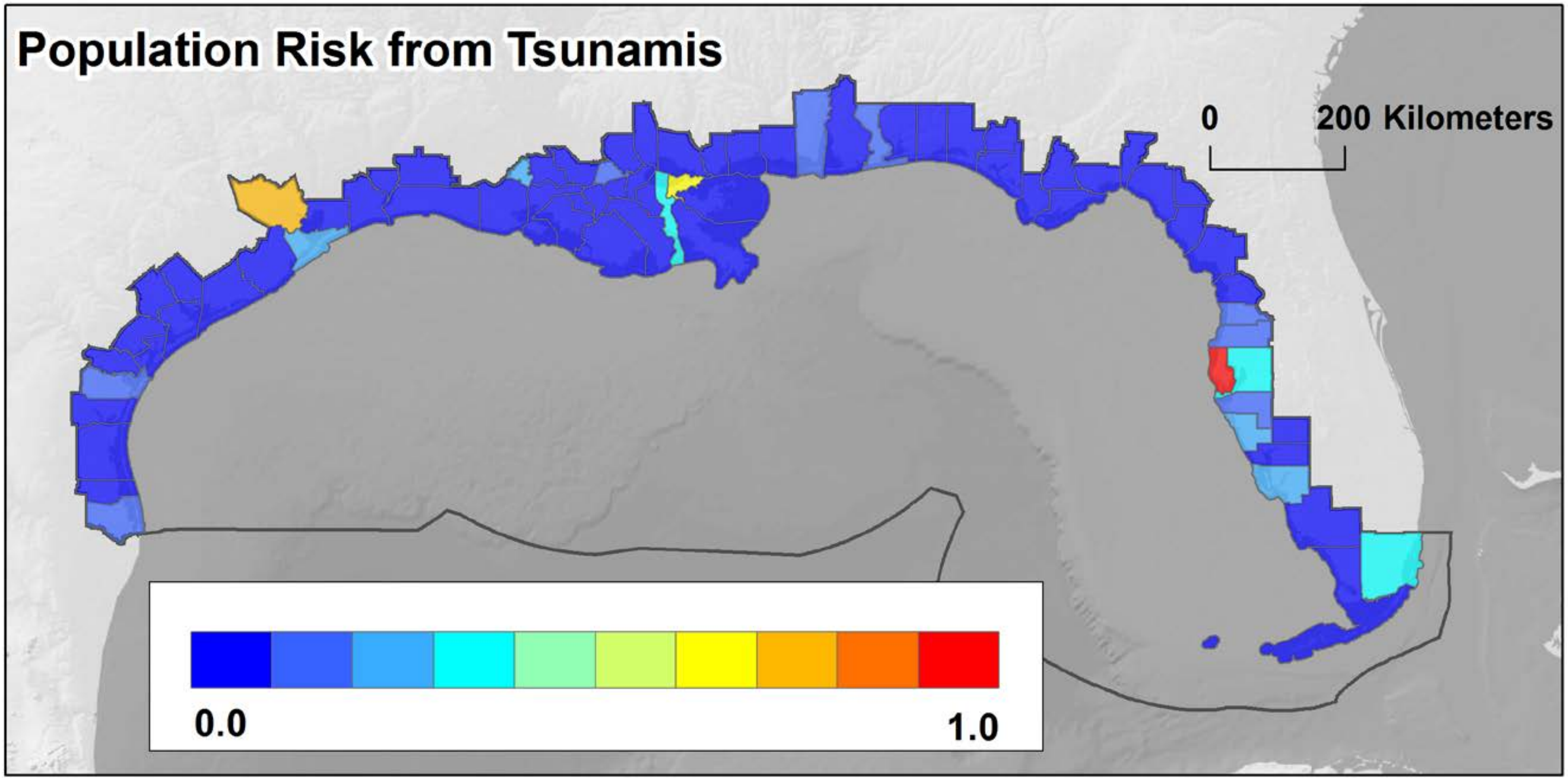

Population Risk from Riverine Flooding
0
200 Kilometers
0.0
1.0

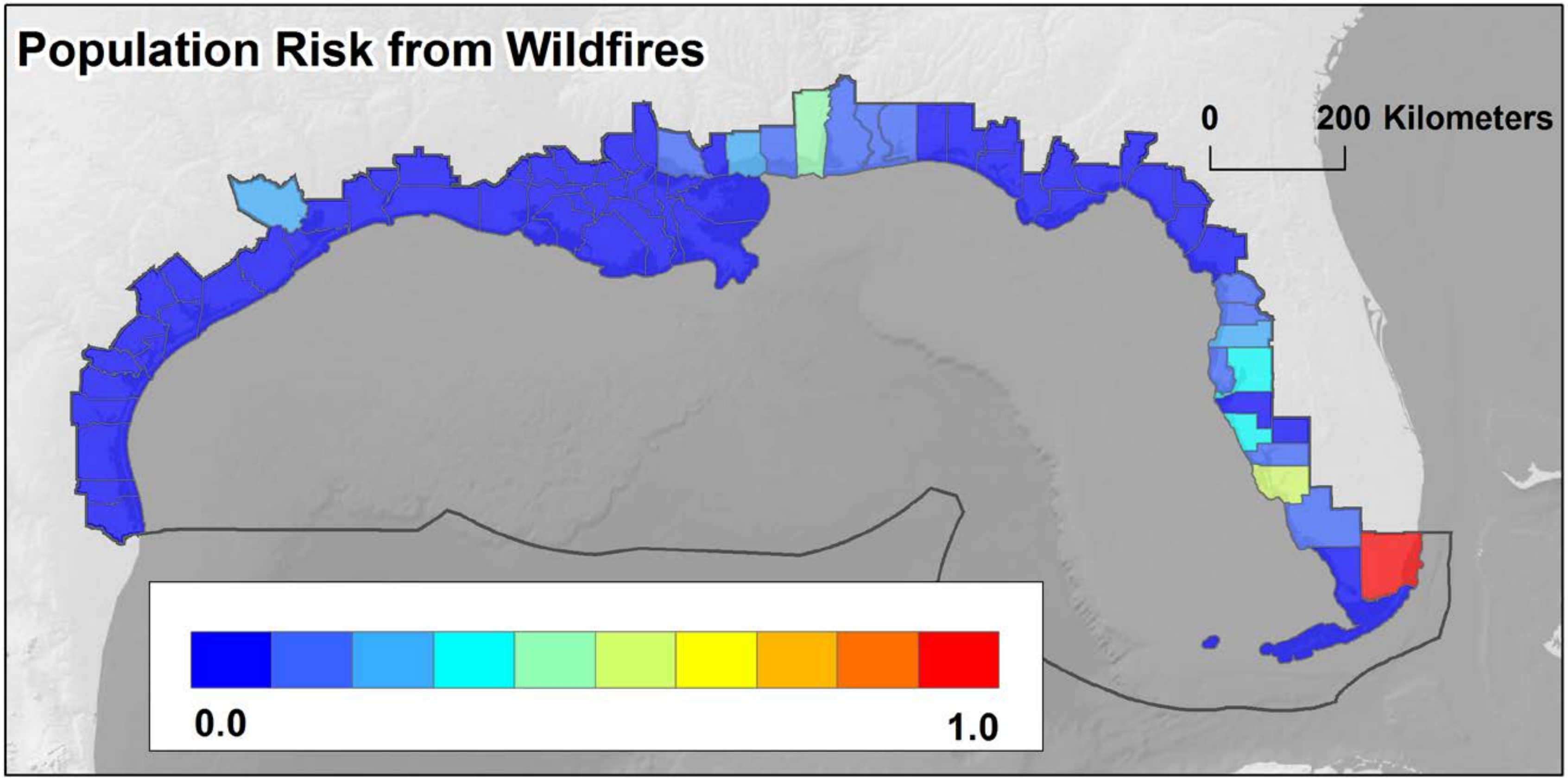

Population Risk from Earthquakes
0
200 Kilometers
0.0
1.0

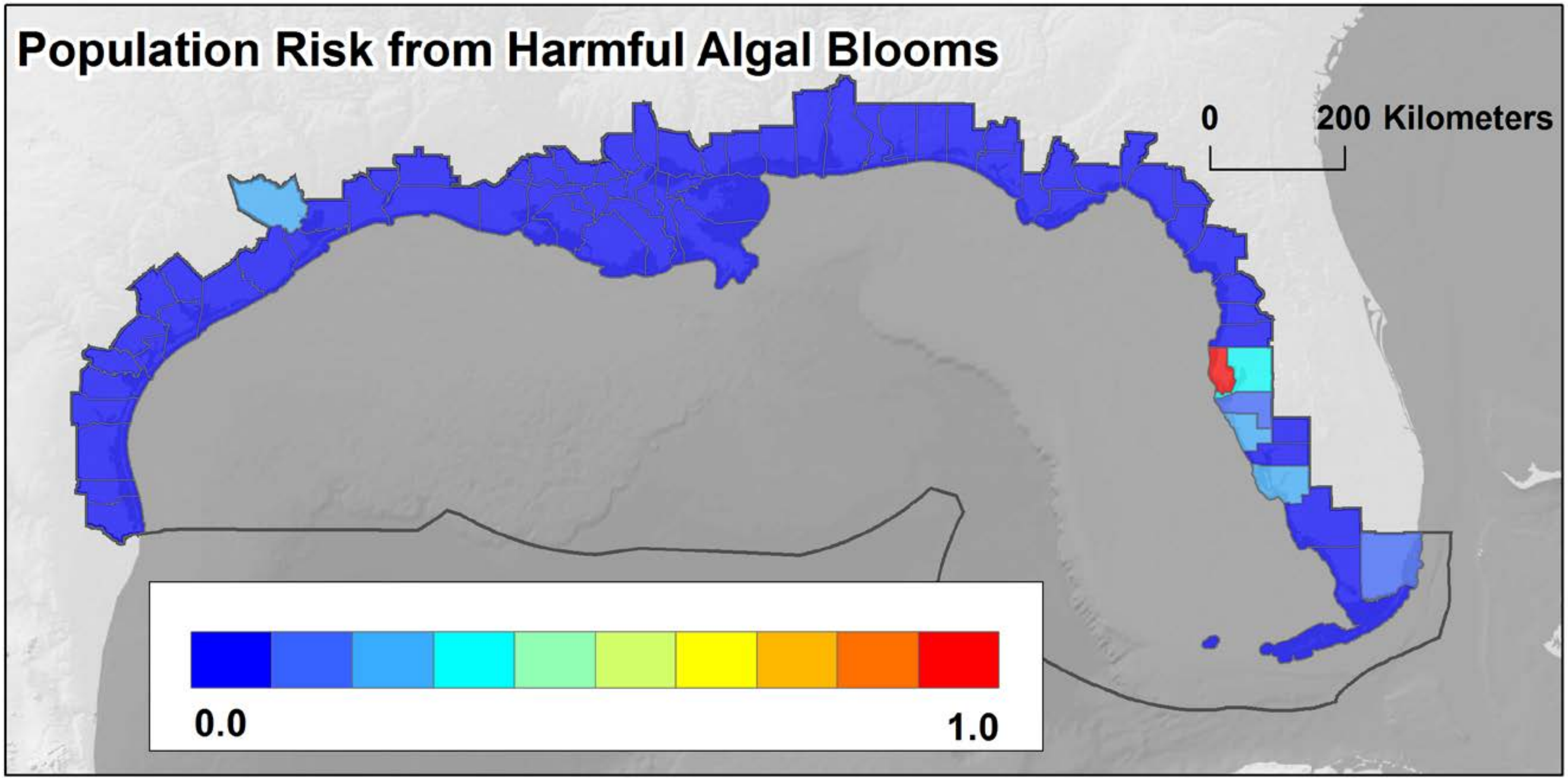

Population Risk from Volcanic Ash
0
200 Kilometers
0.0
1.0


Population Risk from Tornadoes
0
200 Kilometers
0.0
1.0


Population Risk from Landslides
0
200 Kilometers
0.0
1.0


Population Risk from Tsunamis
0
200 Kilometers
0.0
1.0


Population Risk from Wildfires
0
200 Kilometers
0.0
1.0

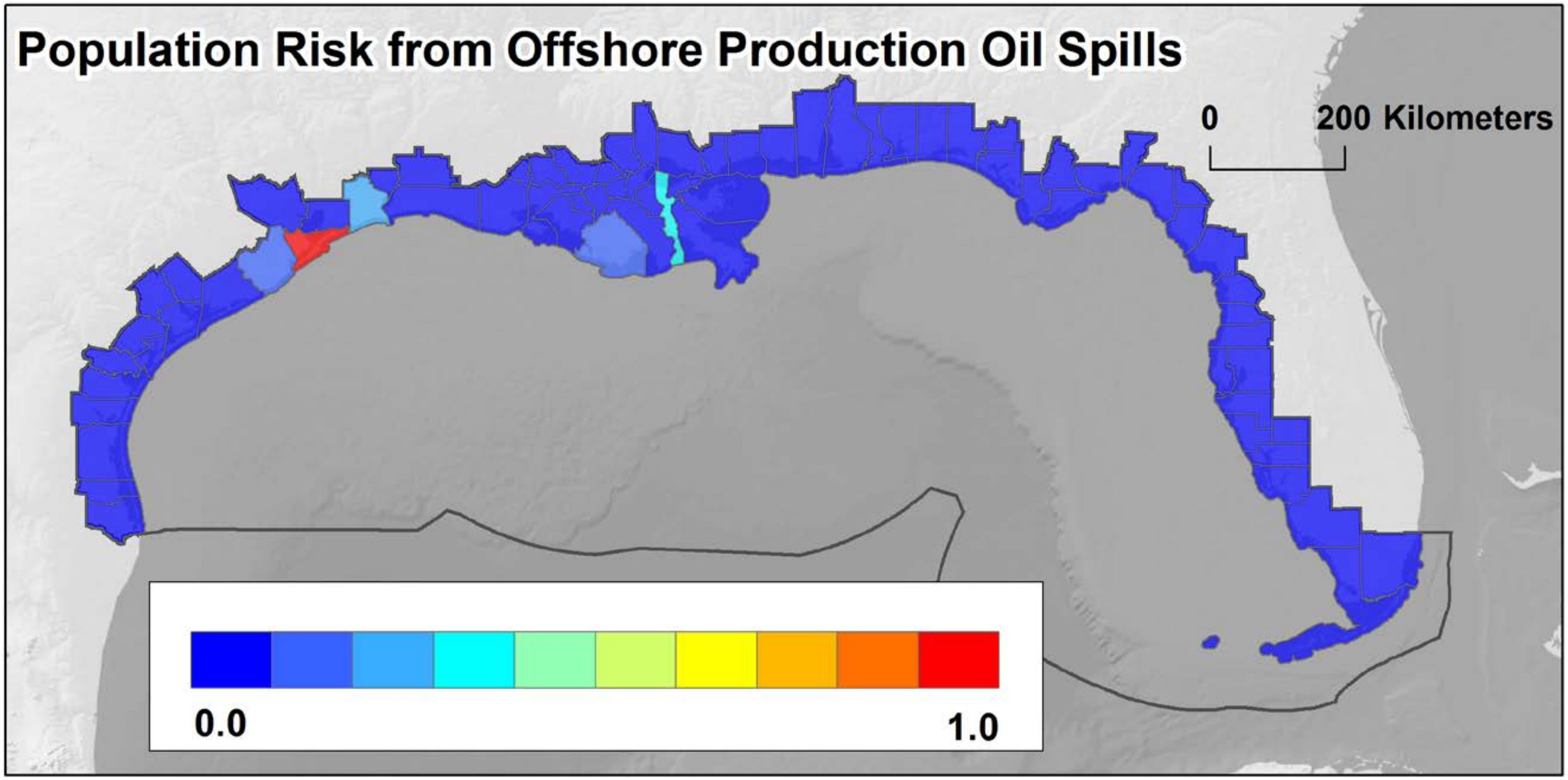


Population Risk from Harmful Algal Blooms
0
200 Kilometers
0.0
1.0

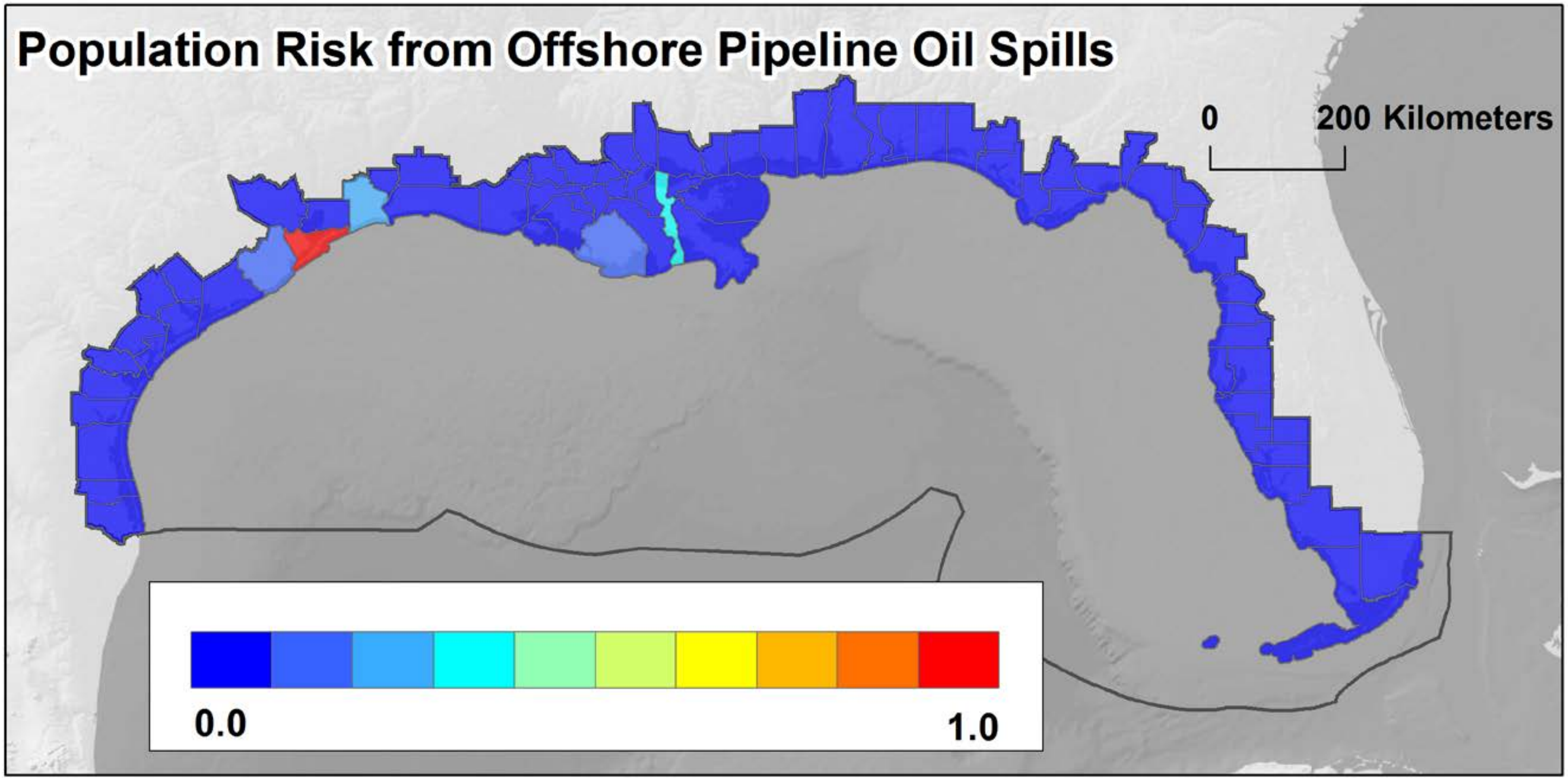
APPENDIX F

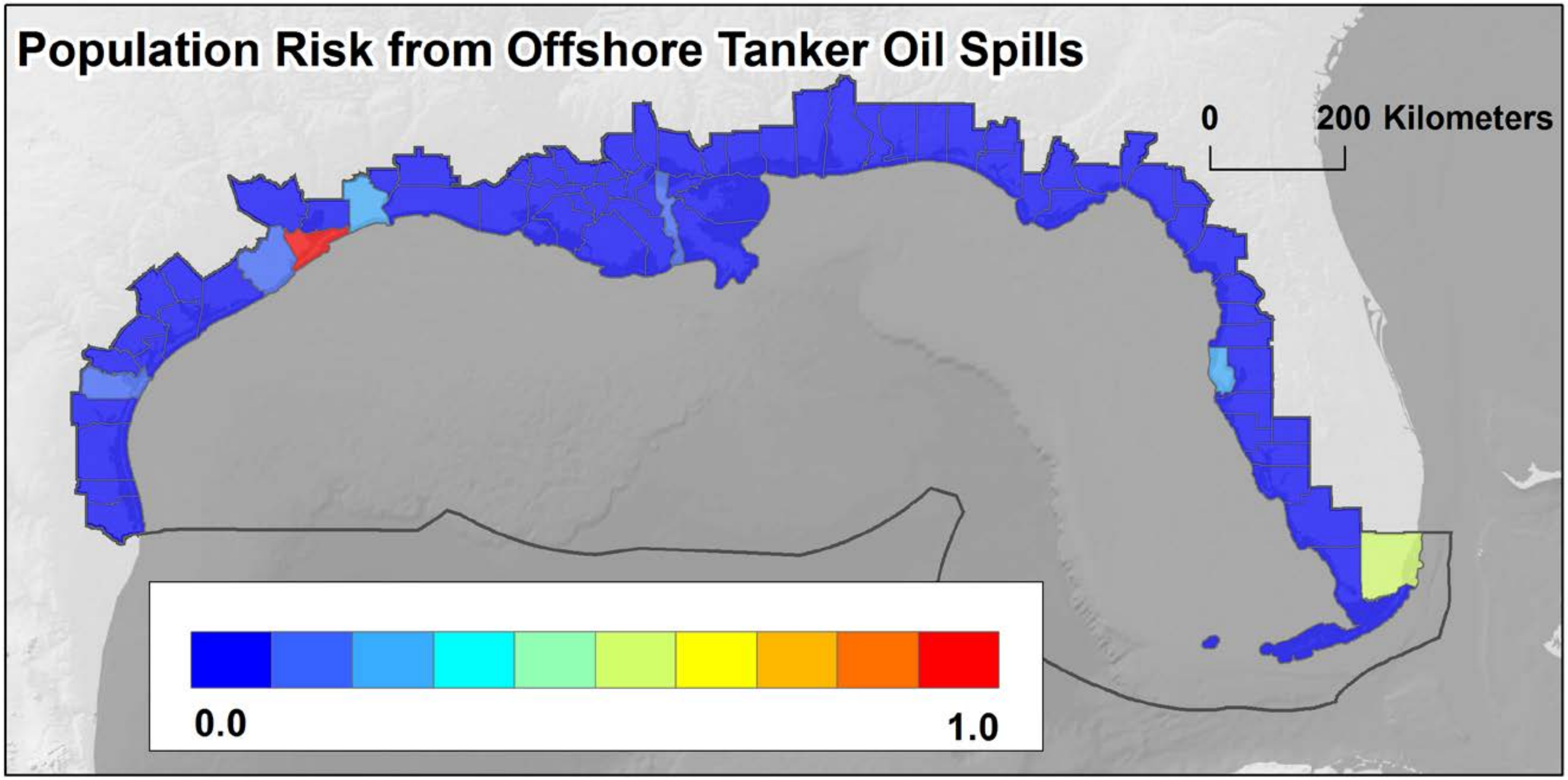
Risk to Human Population from Anthropogenic Hazards

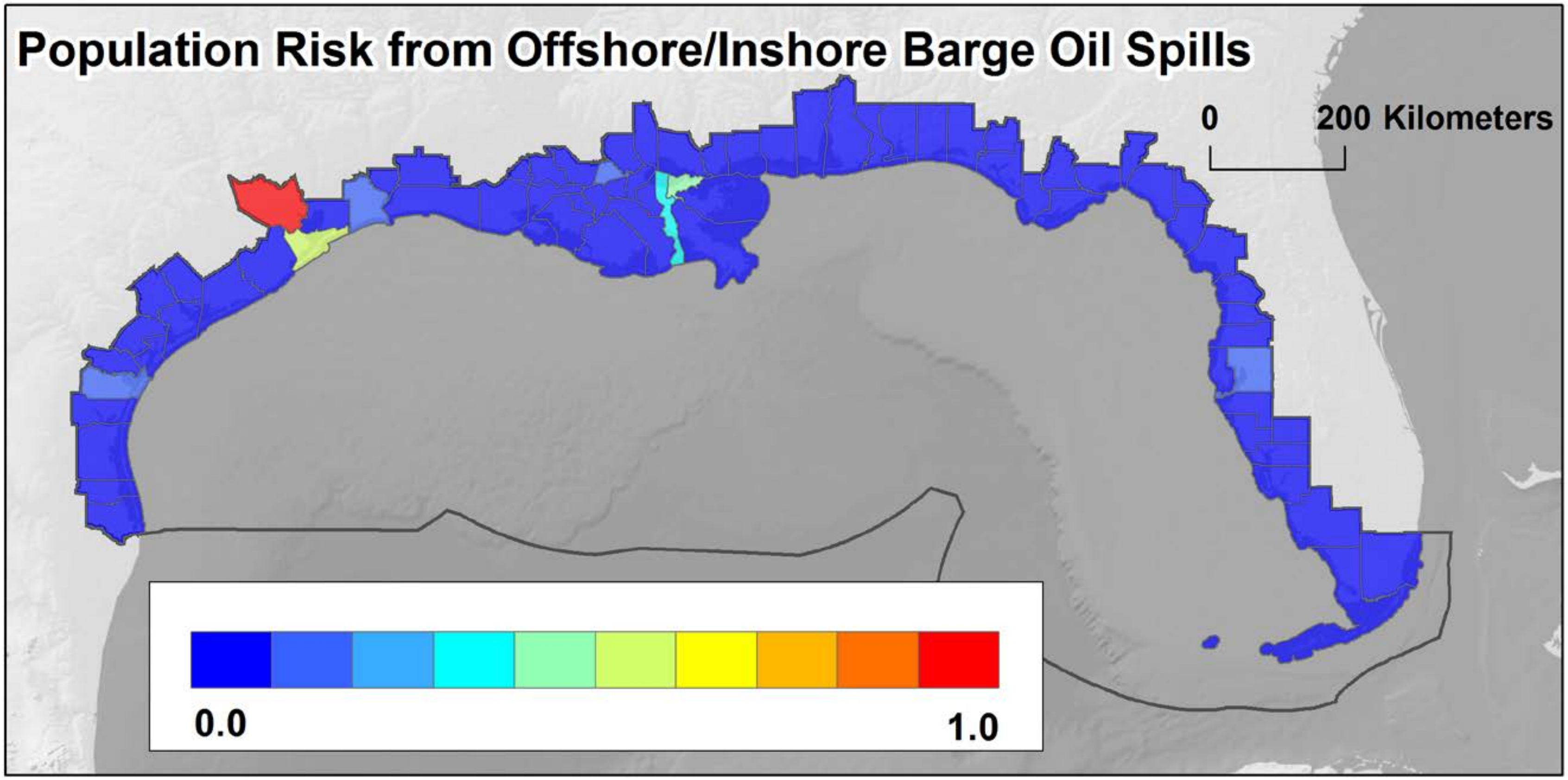
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 32 and display ranked risk index values to human population by county or parish for all anthropogenic hazards.

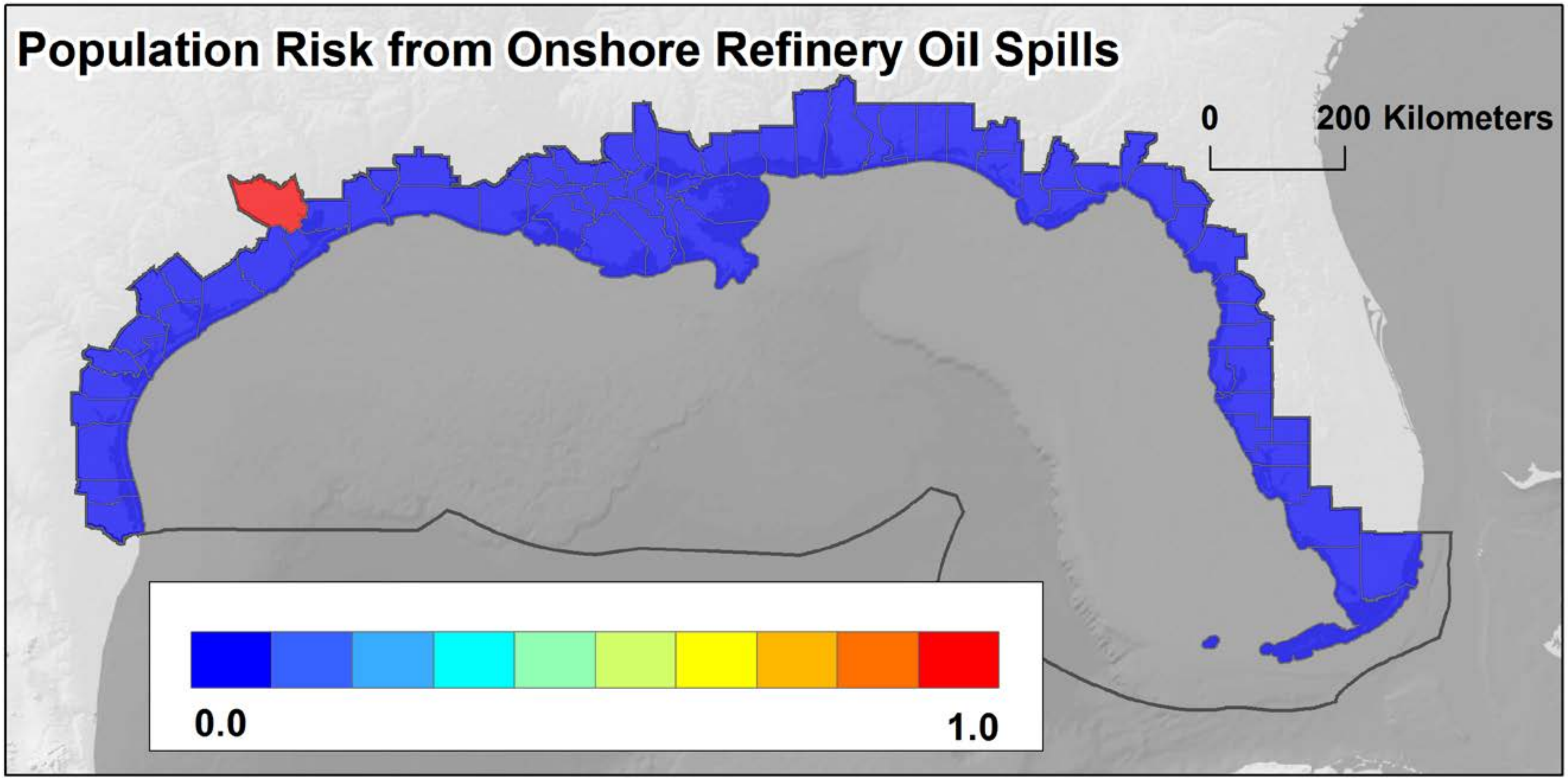


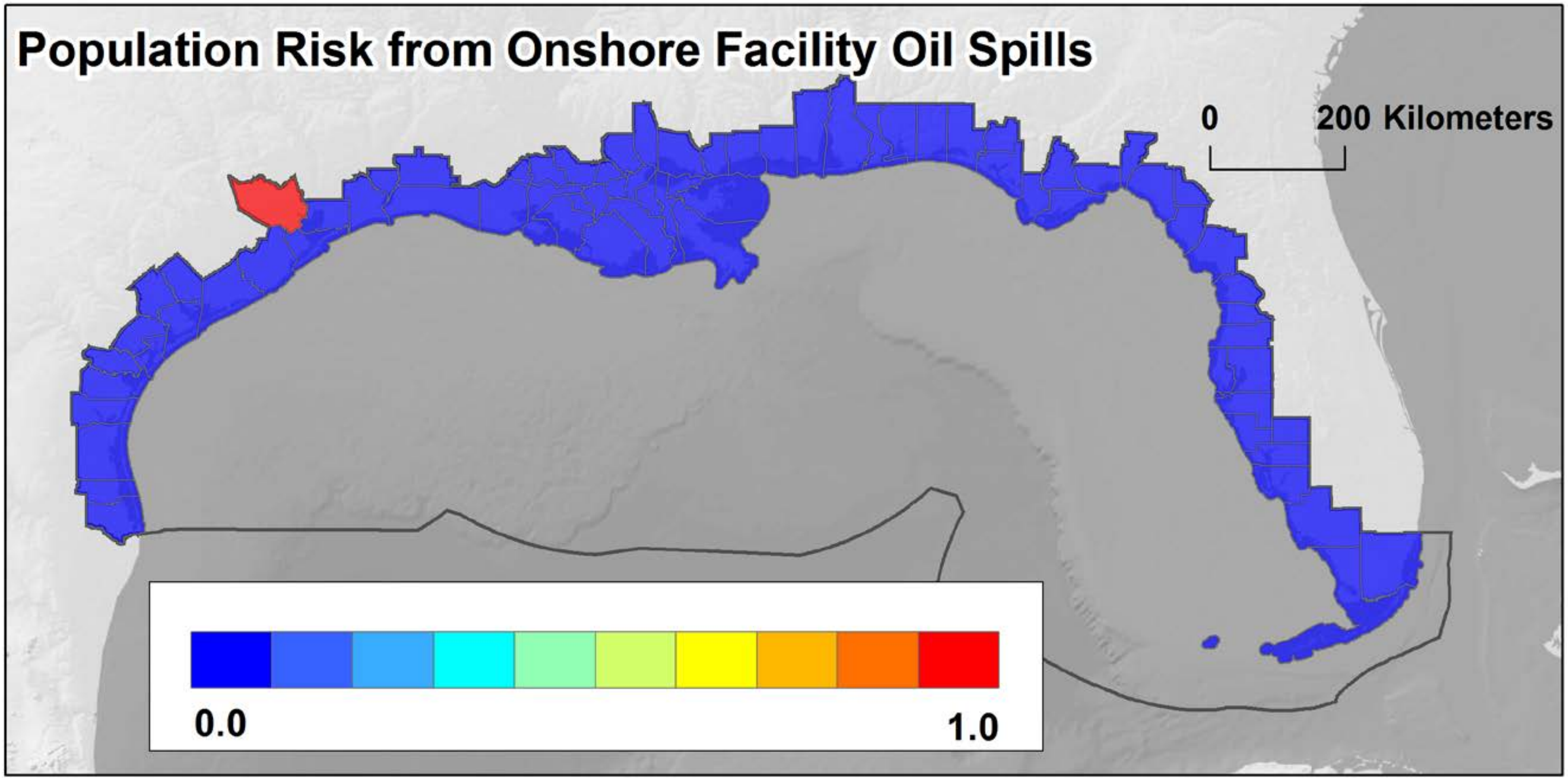
Population Risk from Offshore Production Oil Spills
0
200 Kilometers
0.0
1.0

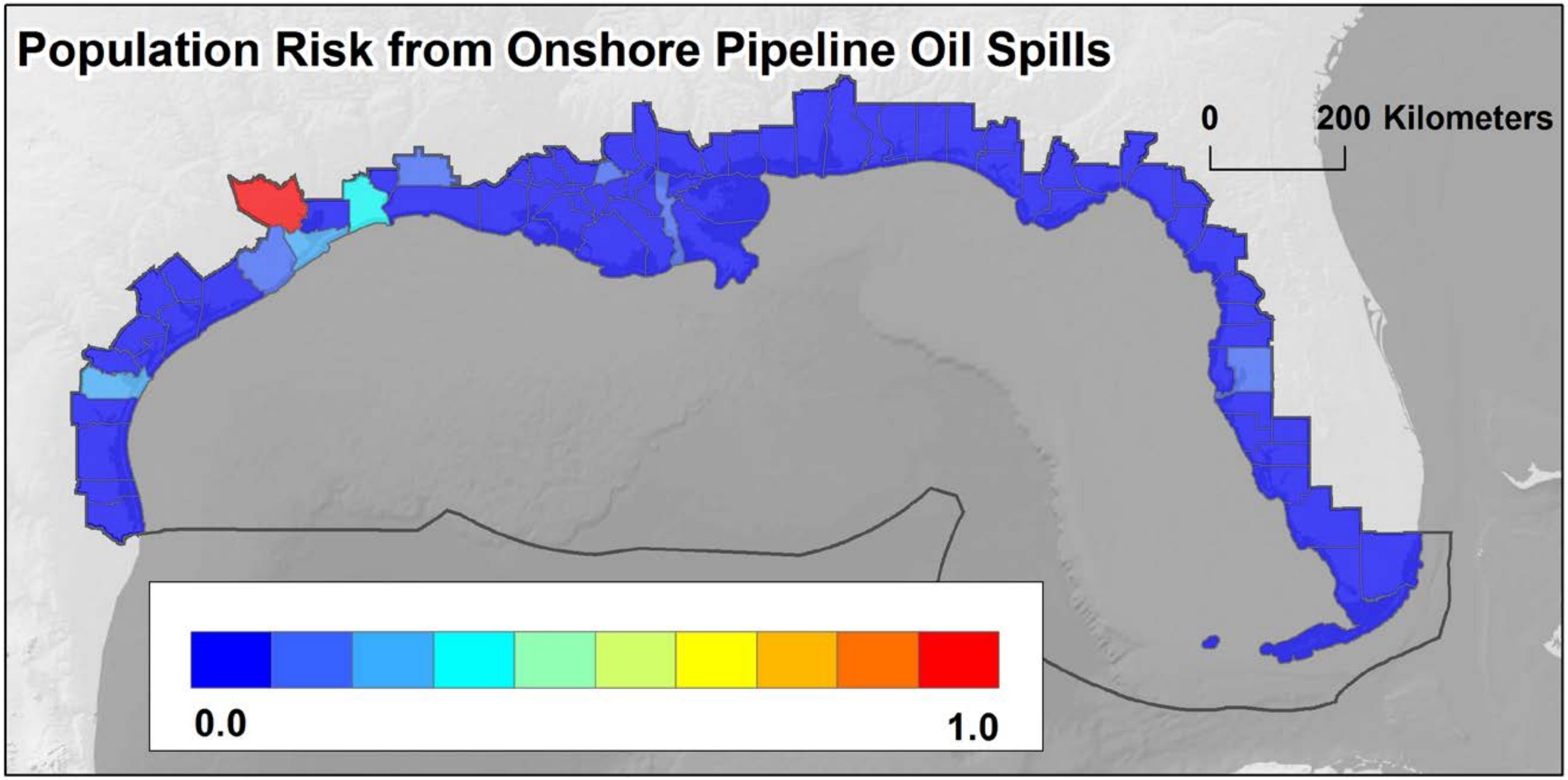

Population Risk from Offshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

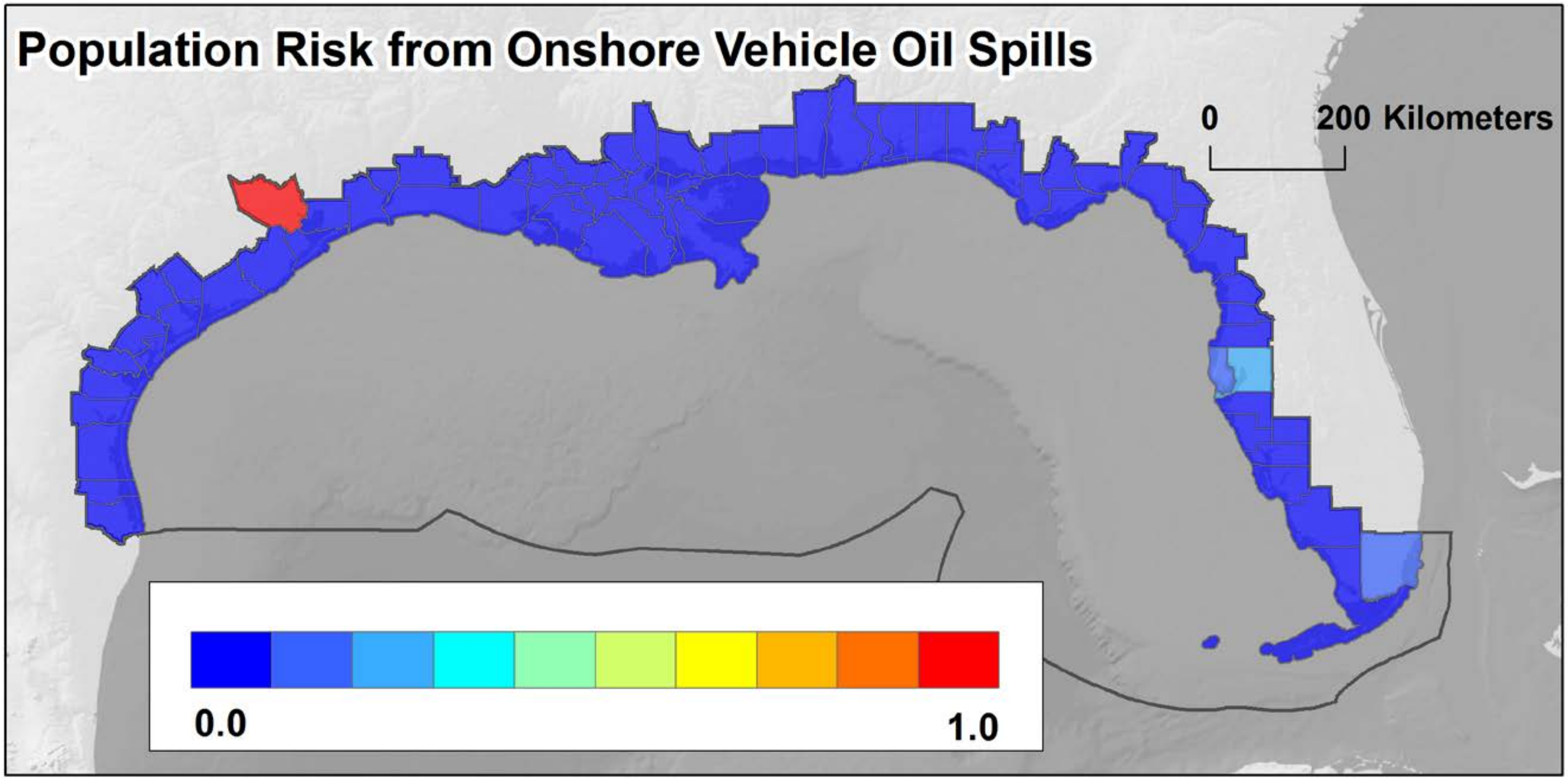

Population Risk from Offshore Tanker Oil Spills
0
200 Kilometers
0.0
1.0


Population Risk from Offshore/Inshore Barge Oil Spills
0
200 Kilometers
0.0
1.0

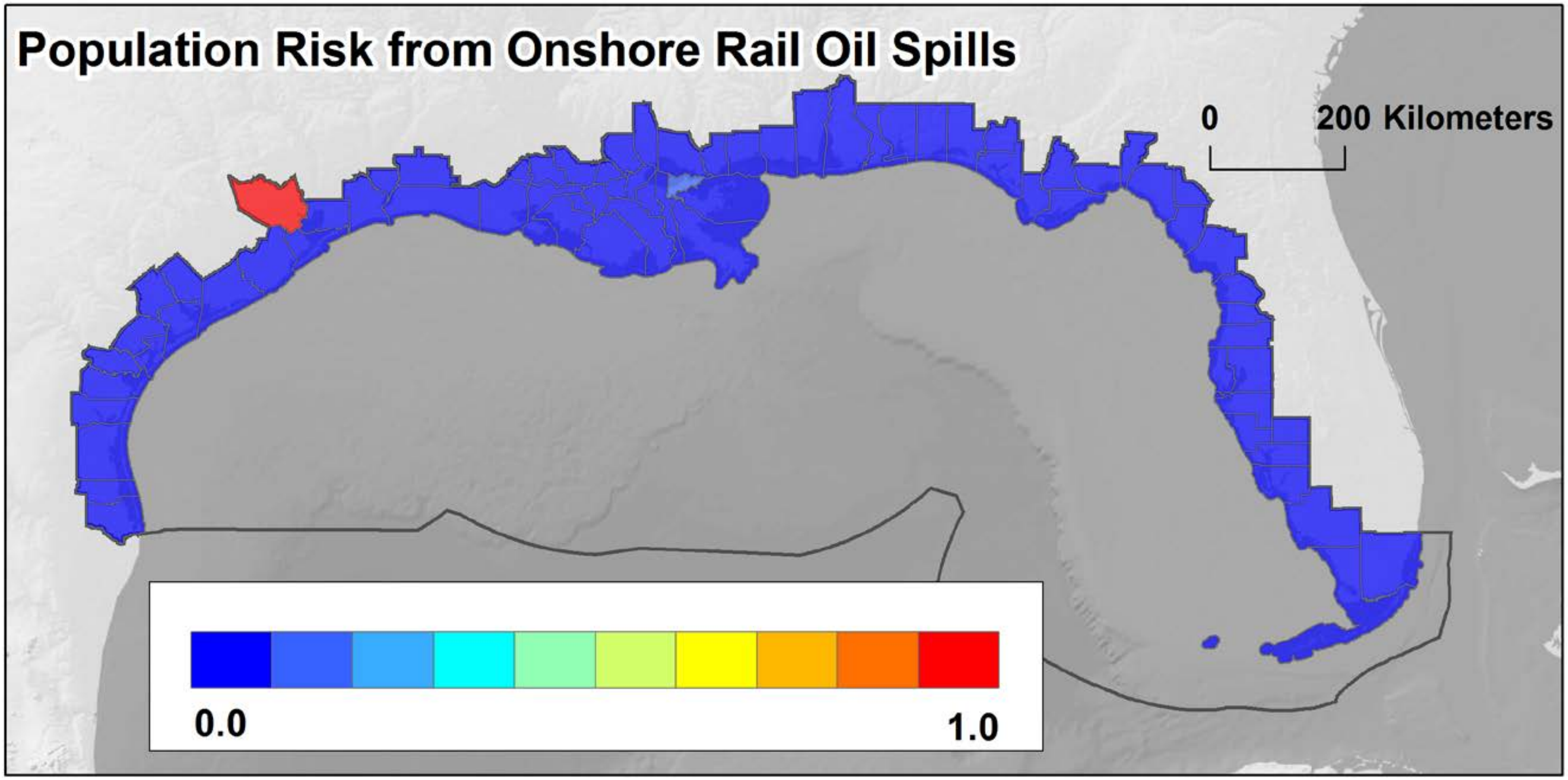

Population Risk from Onshore Refinery Oil Spills
0
200 Kilometers
0.0
1.0

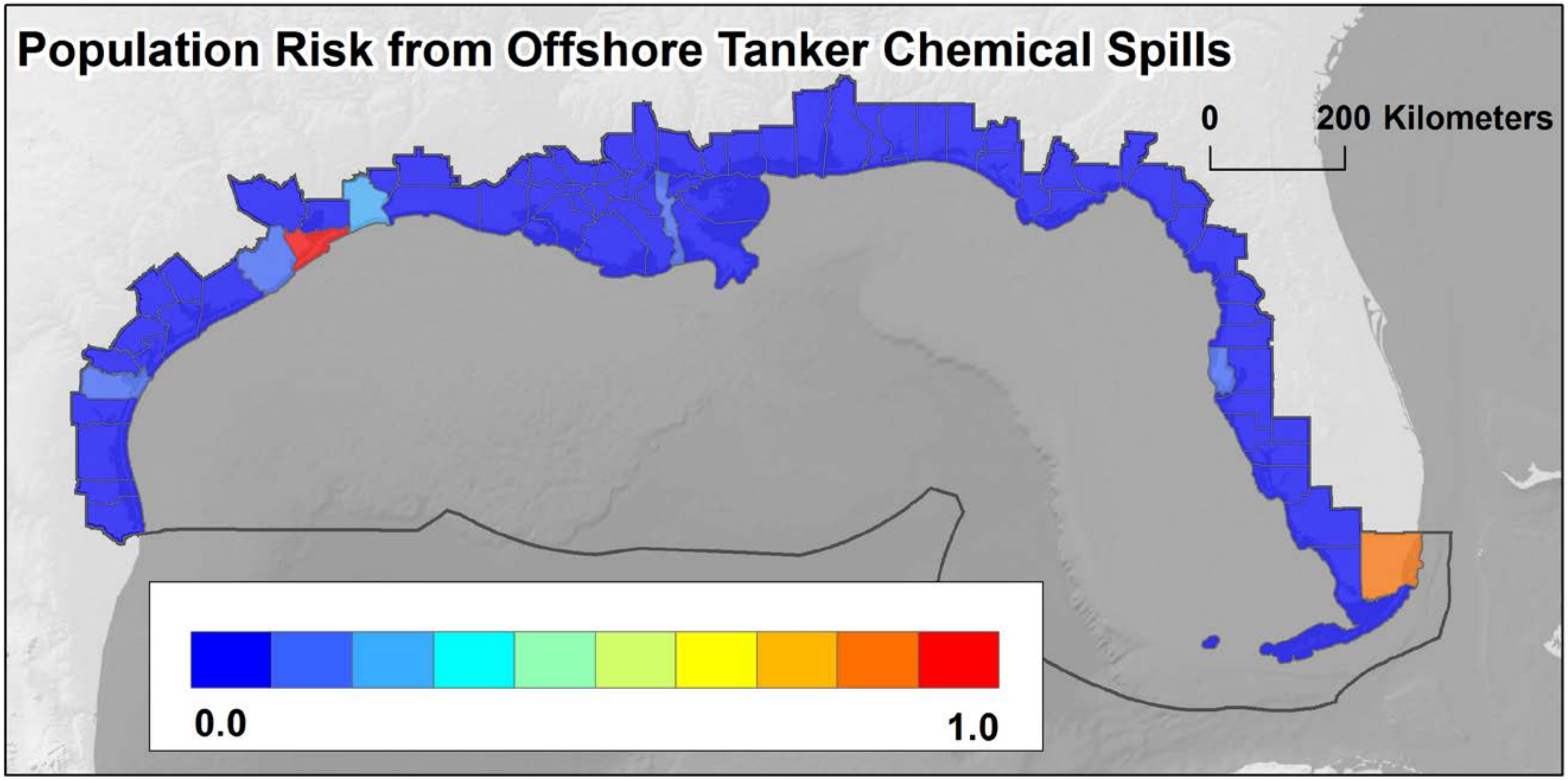

Population Risk from Onshore Facility Oil Spills
0
200 Kilometers
0.0
1.0


Population Risk from Onshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

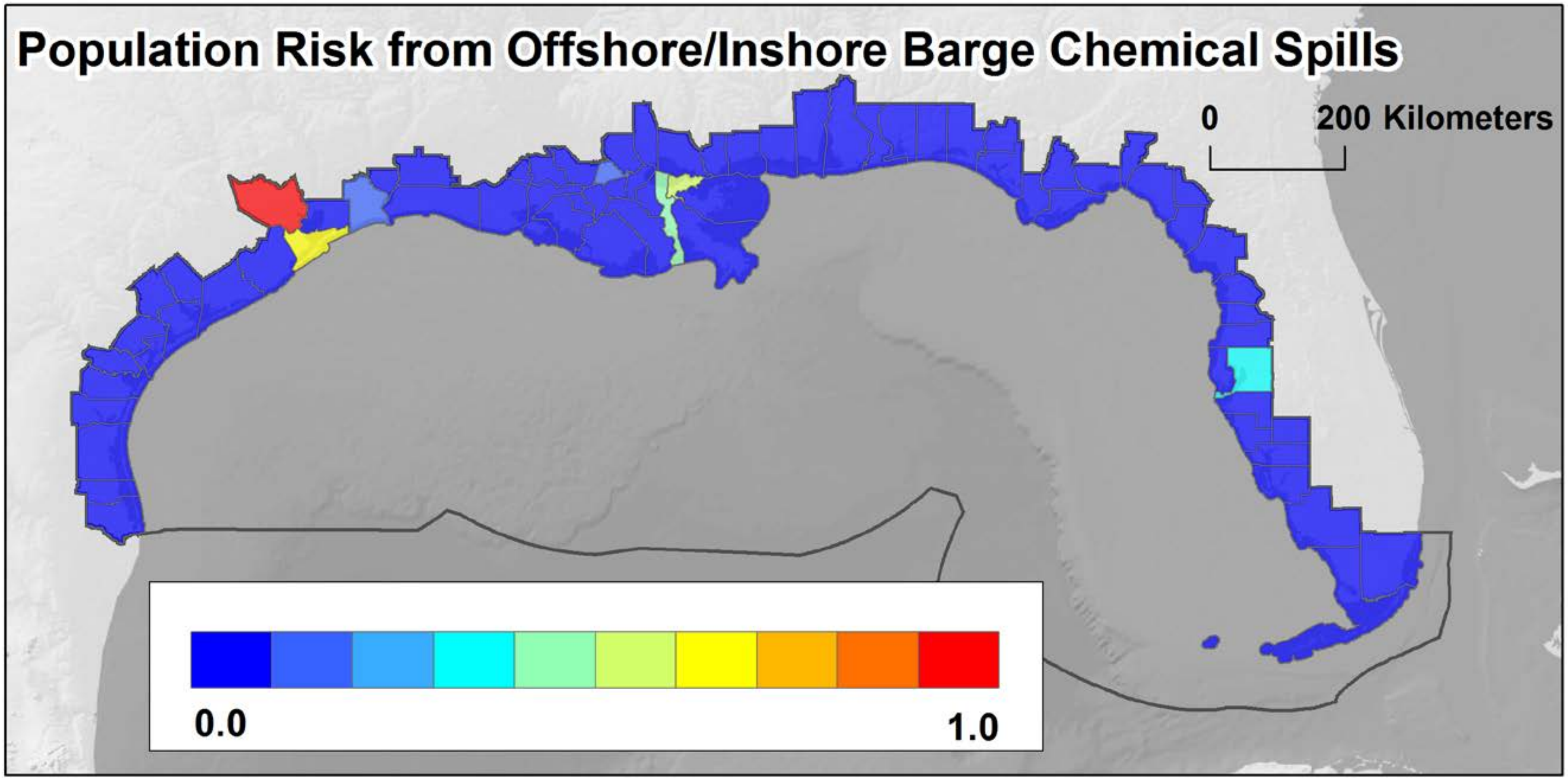


Population Risk from Onshore Vehicle Oil Spills
0
200 Kilometers
0.0
1.0

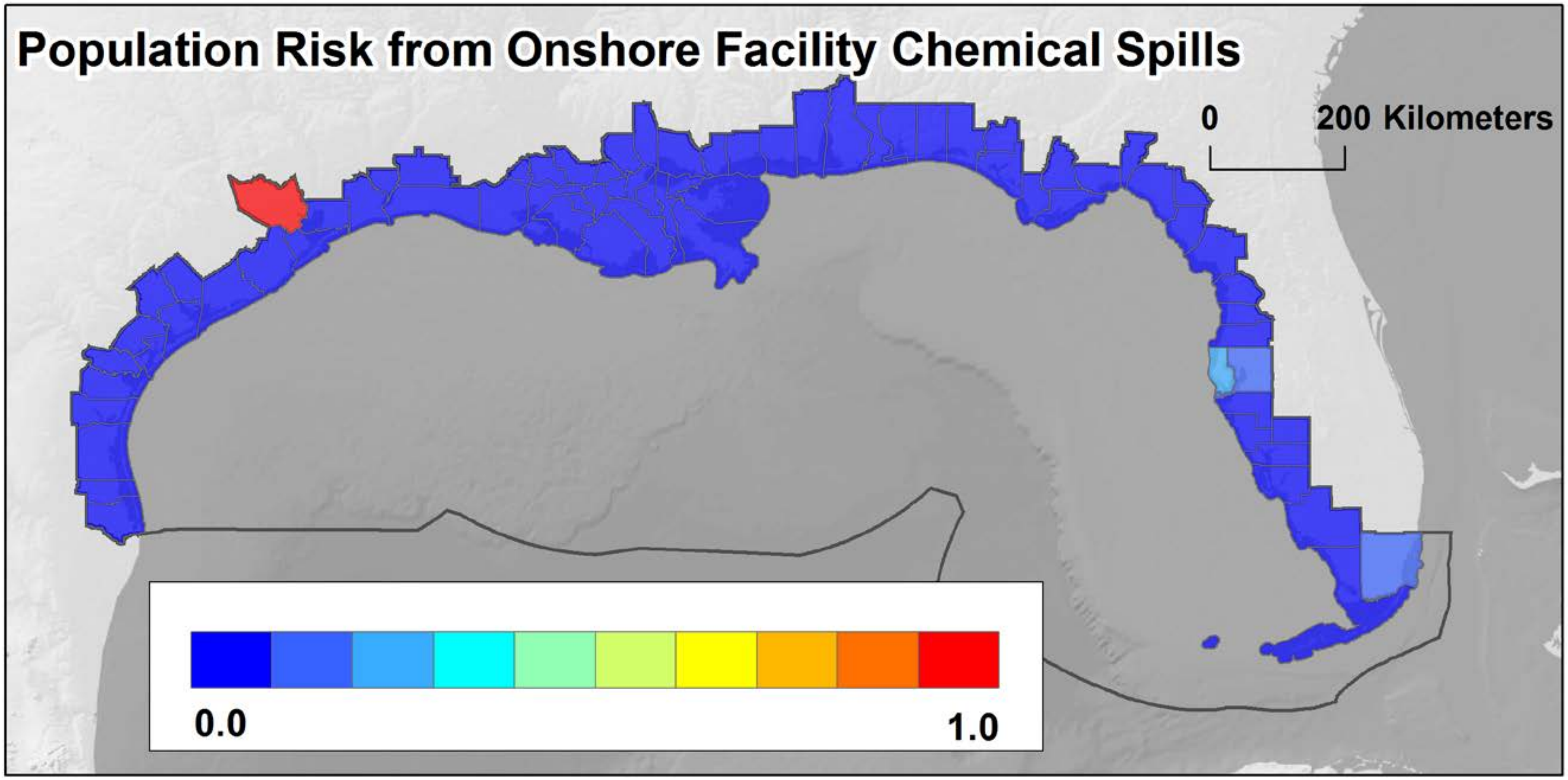

Population Risk from Onshore Rail Oil Spills
0
200 Kilometers
0.0
1.0

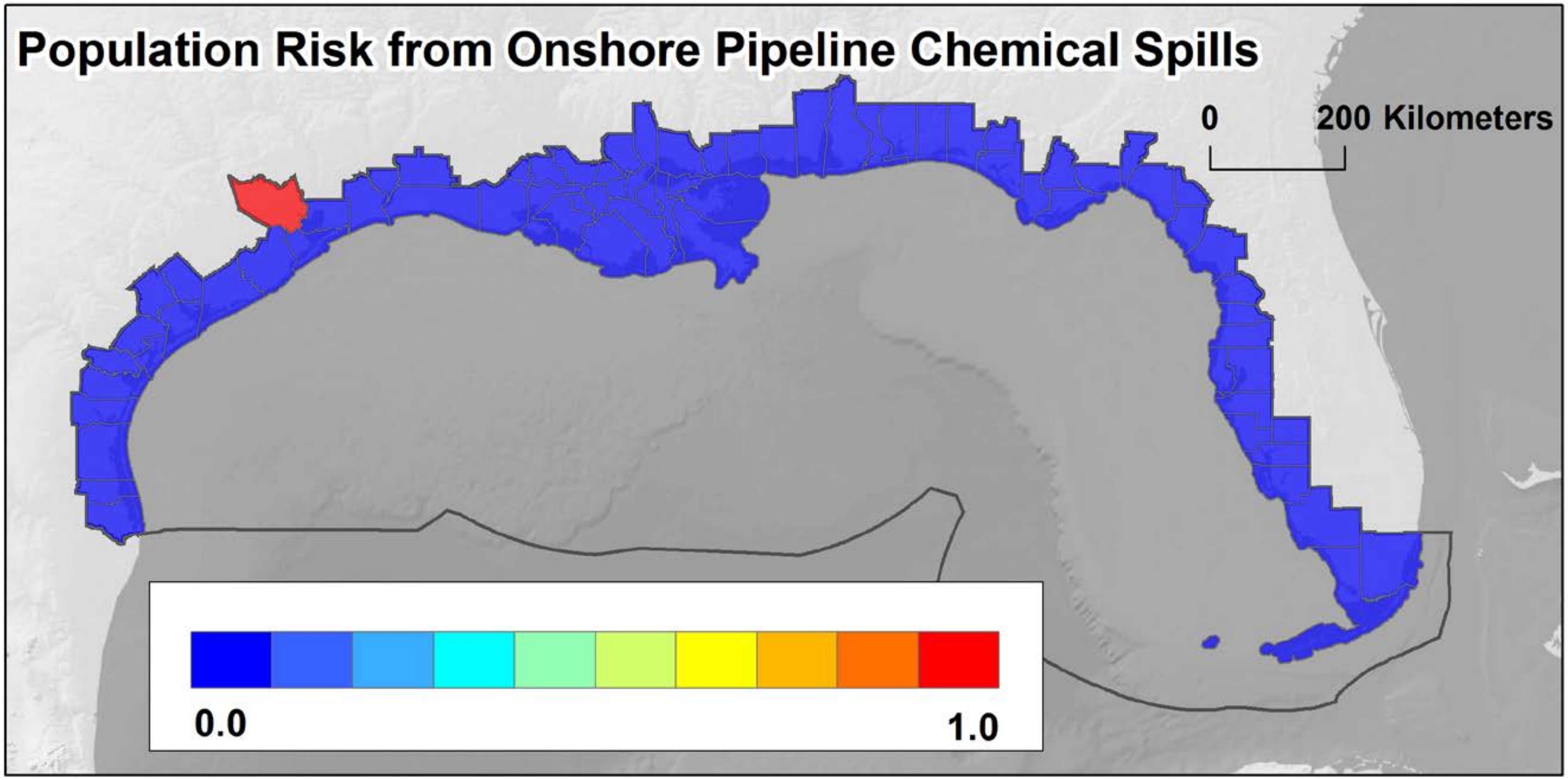


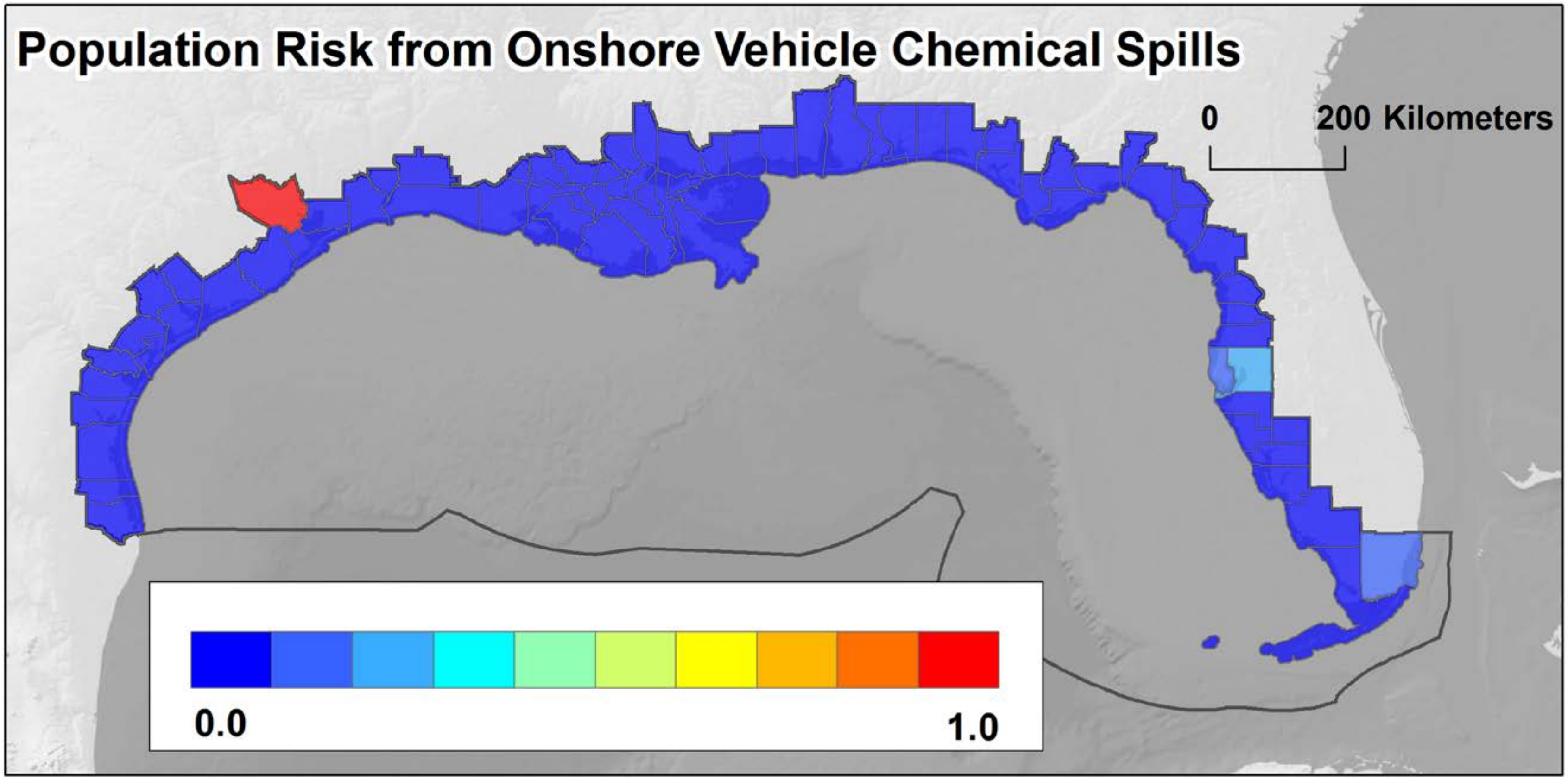
Population Risk from Offshore Tanker Chemical Spills
0
200 Kilometers
0.0
1.0



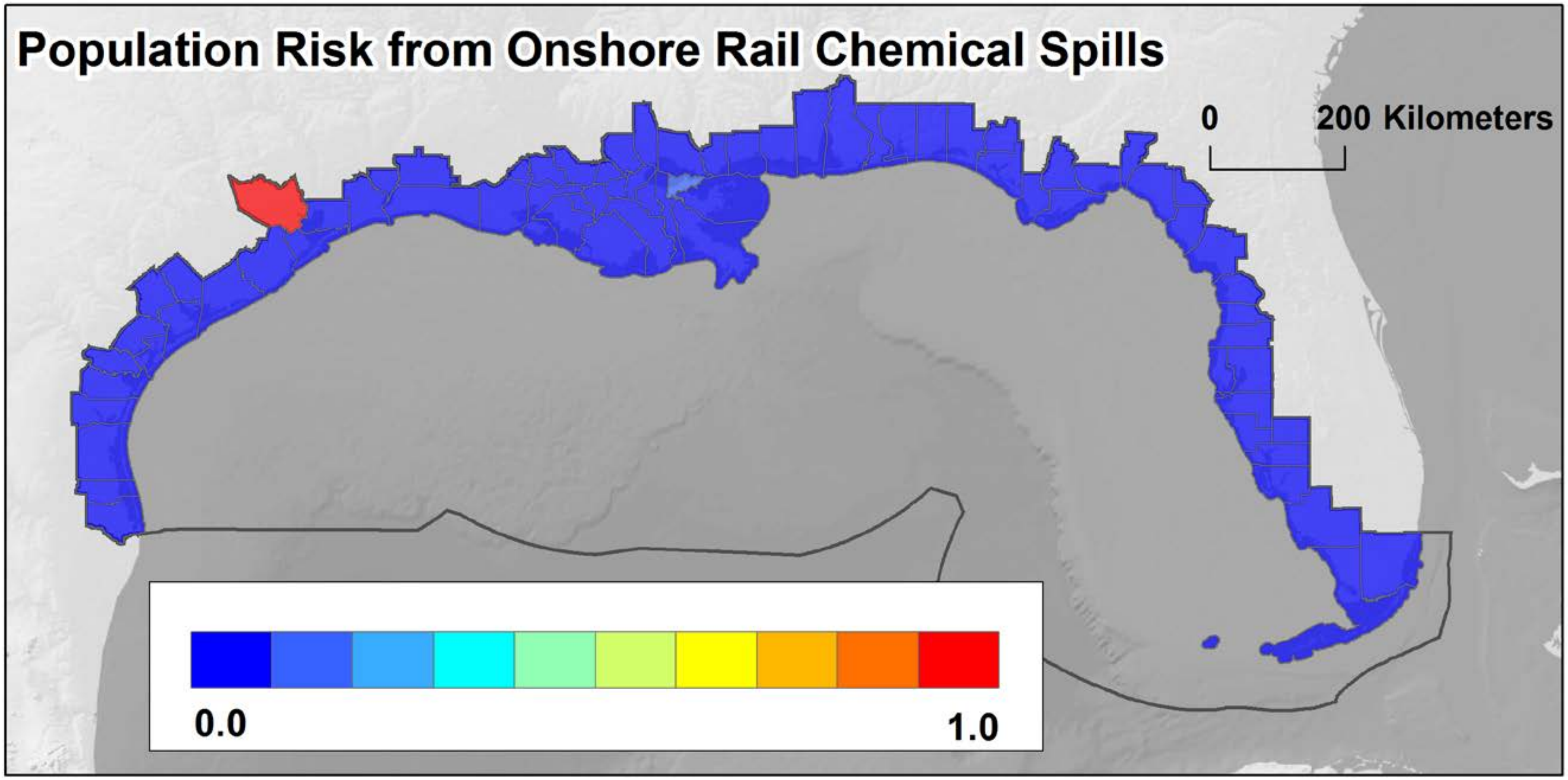
Population Risk from Offshore/Inshore Barge Chemical Spills
0
200 Kilometers
0.0
1.0

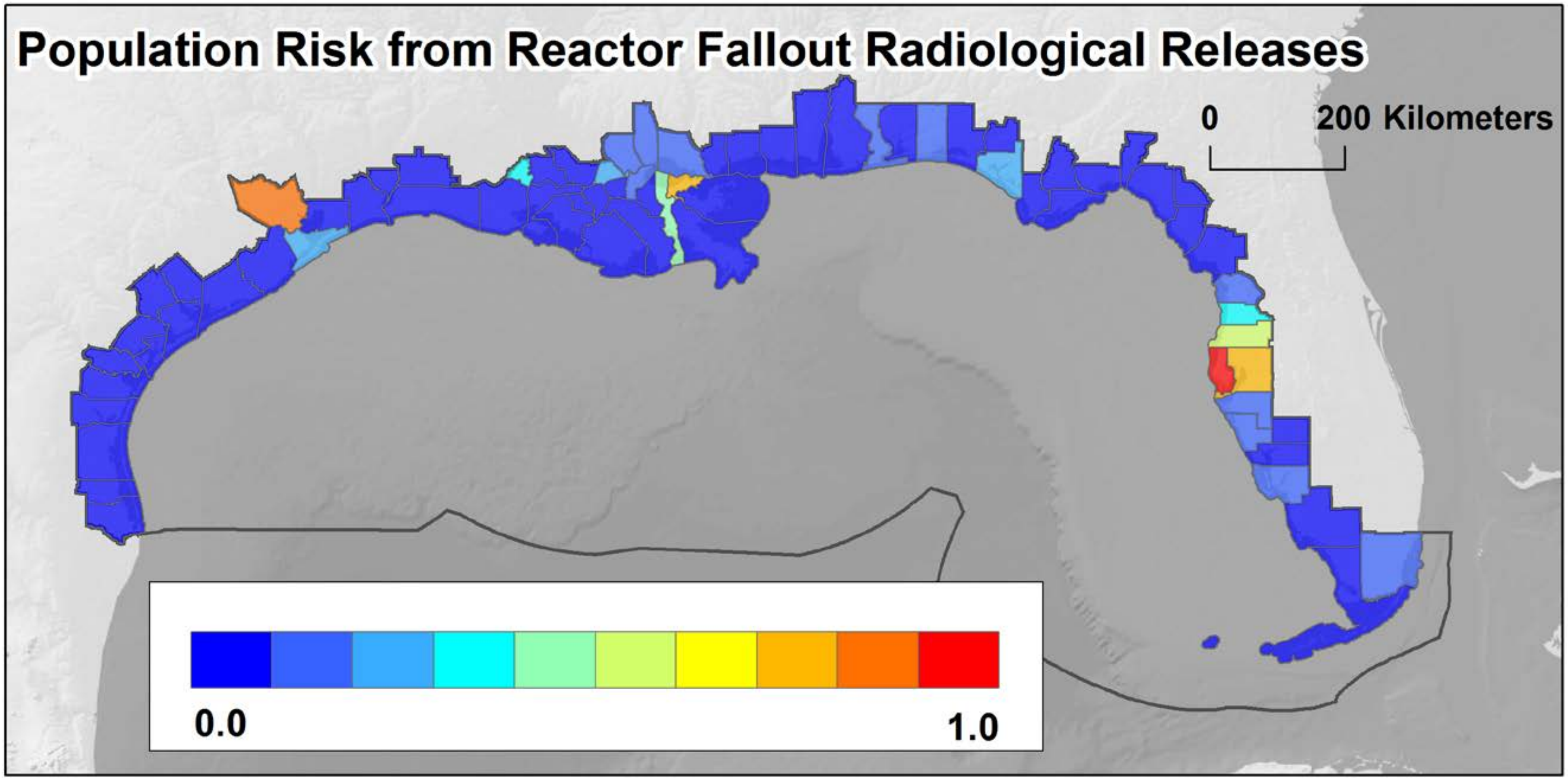

Population Risk from Onshore Facility Chemical Spills
0
200 Kilometers
0.0
1.0

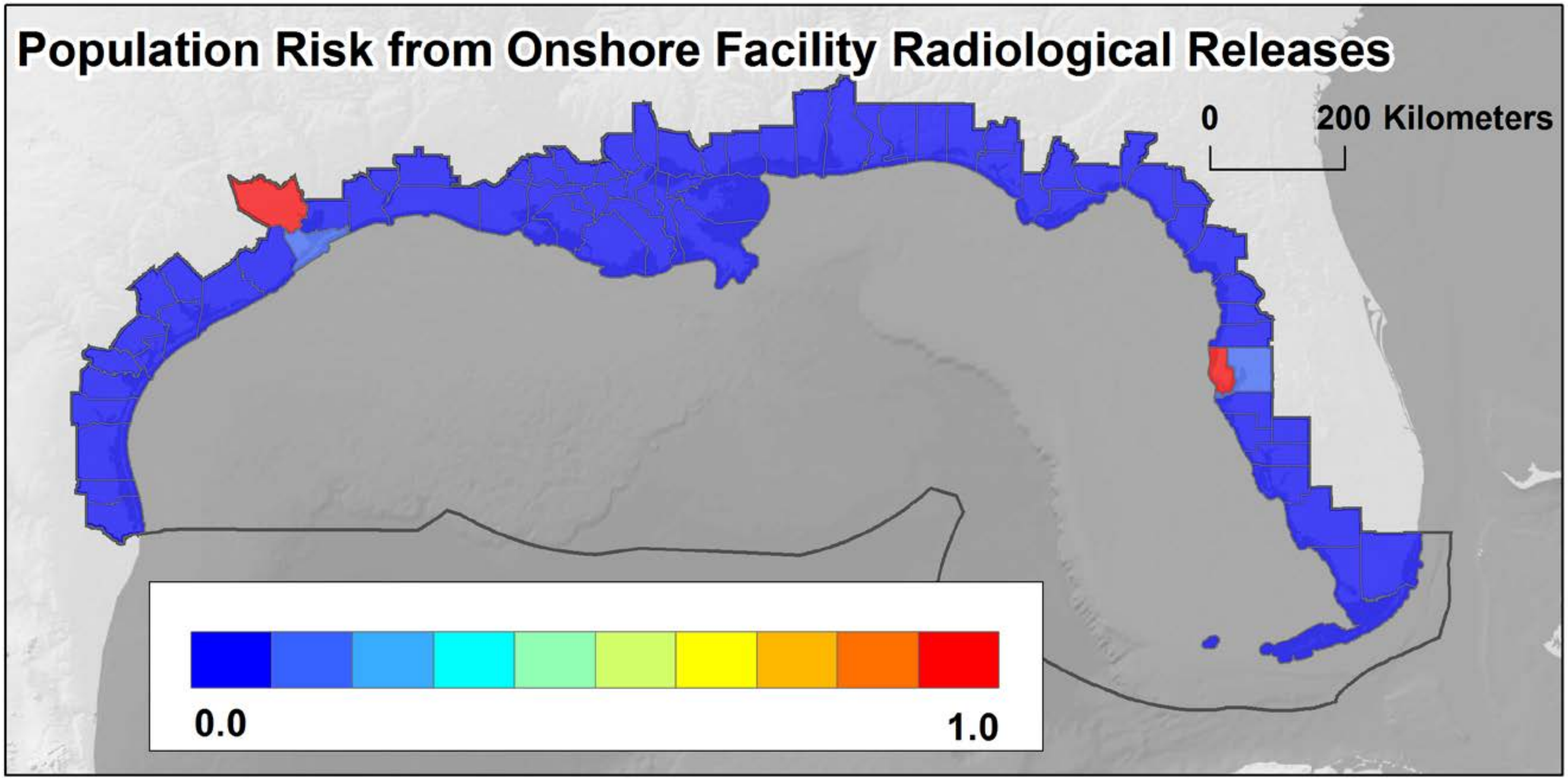

Population Risk from Onshore Pipeline Chemical Spills
0
200 Kilometers
0.0
1.0

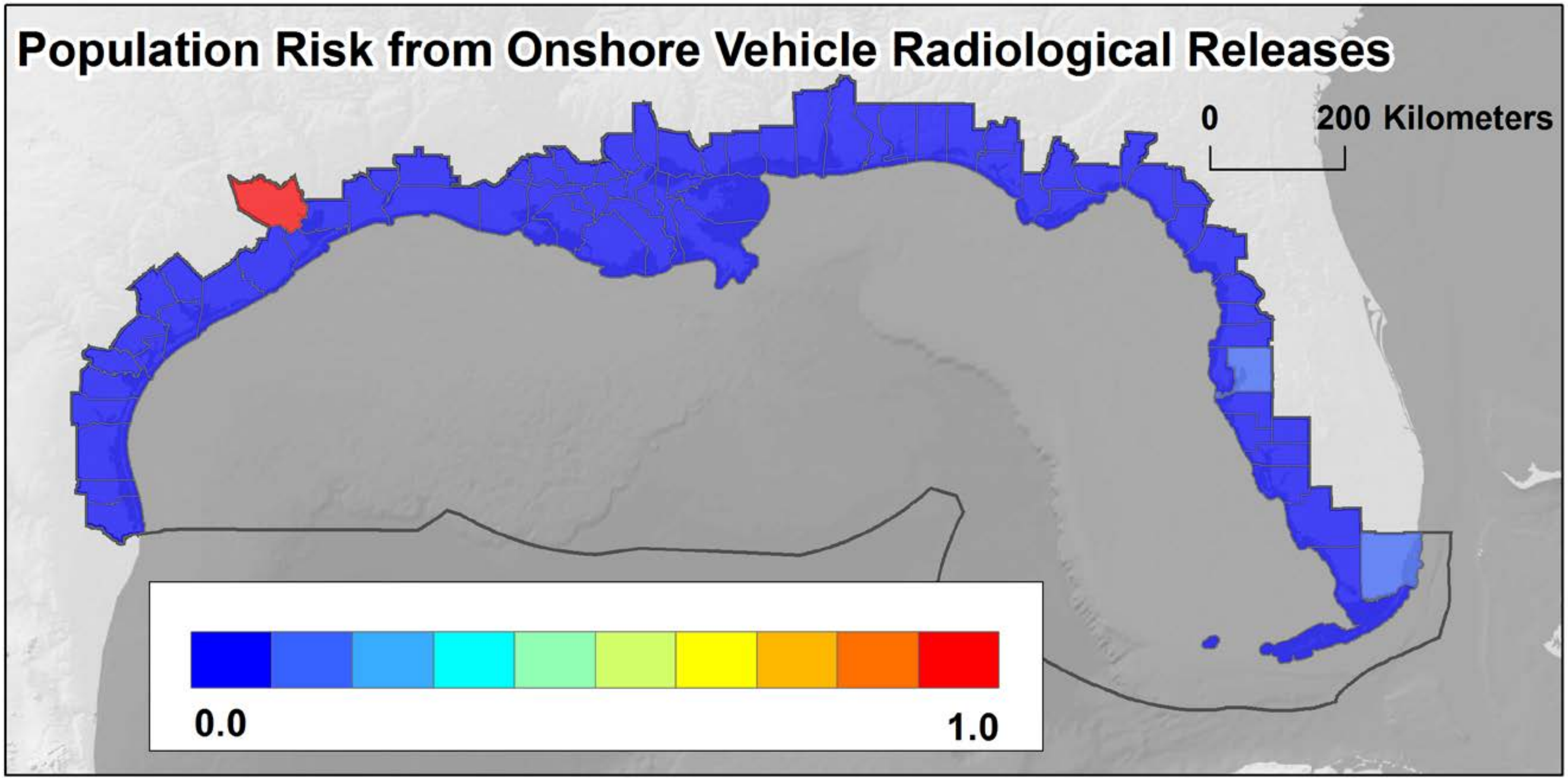


Population Risk from Onshore Vehicle Chemical Spills
0
200 Kilometers
0.0
1.0

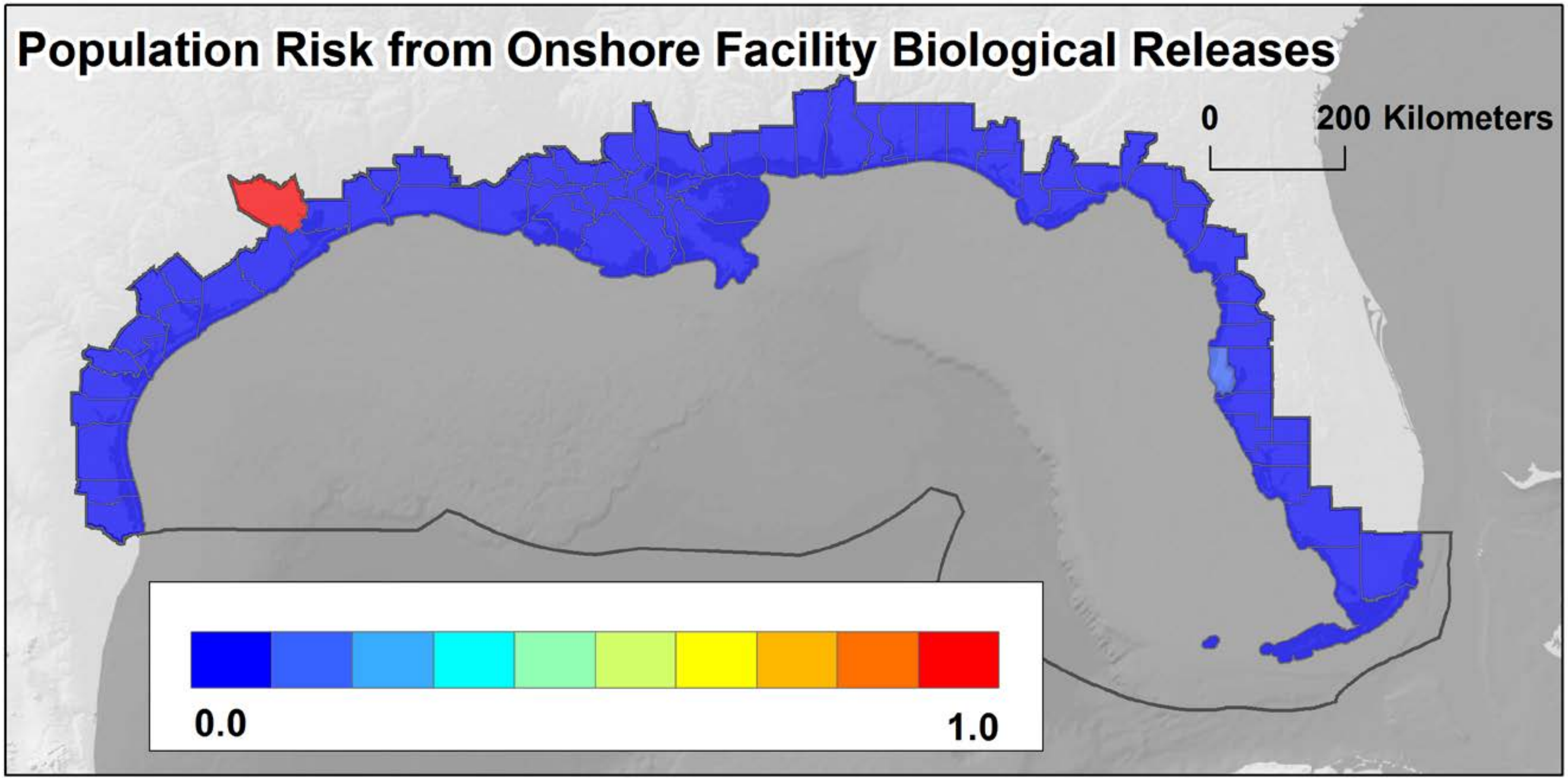

Population Risk from Onshore Rail Chemical Spills
0
200 Kilometers
0.0
1.0


Population Risk from Reactor Fallout Radiological Releases
0
200 Kilometers
0.0
1.0


Population Risk from Onshore Facility Radiological Releases
0
200 Kilometers
0.0
1.0



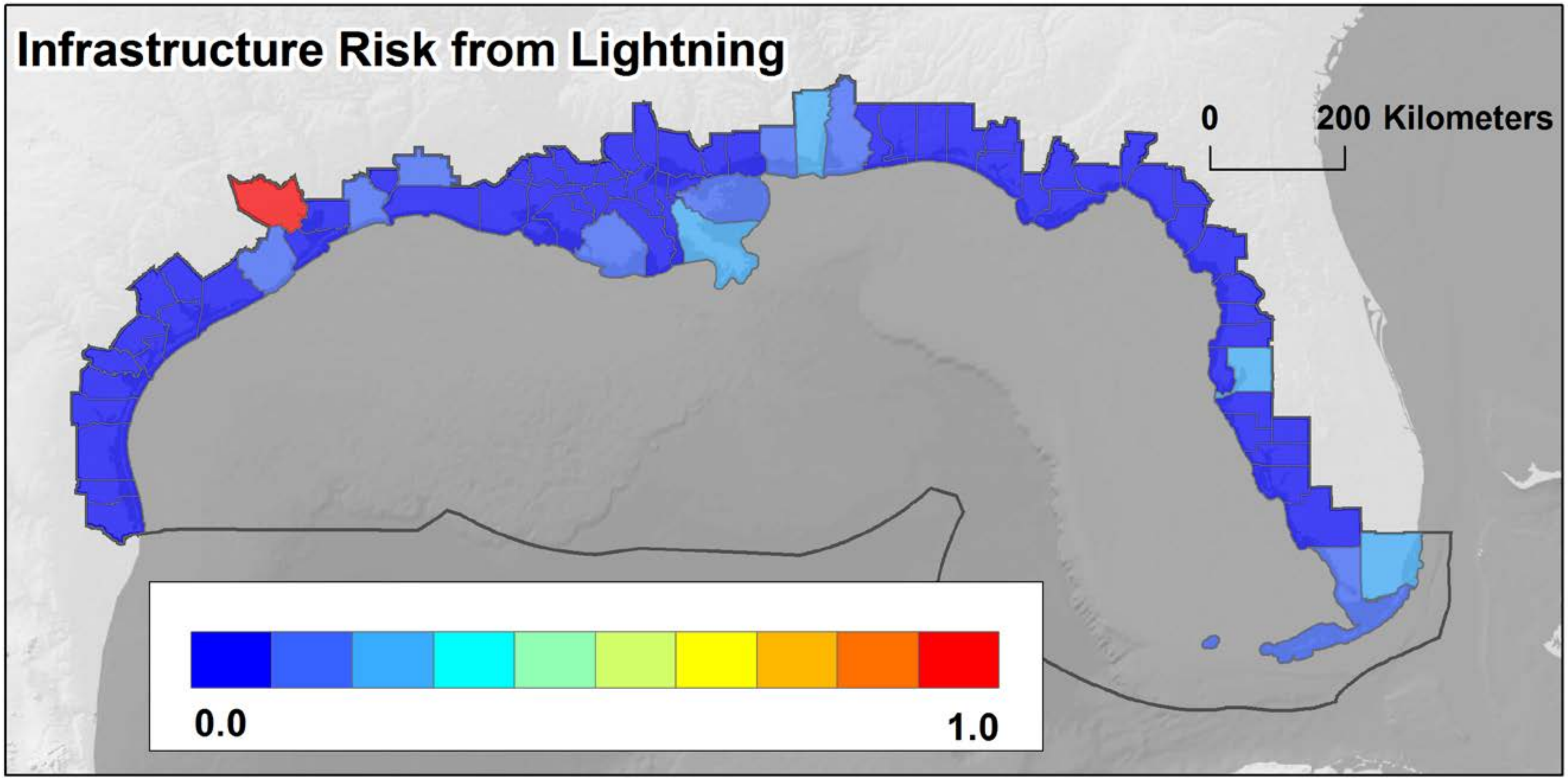
Population Risk from Onshore Vehicle Radiological Releases
0
200 Kilometers
0.0
1.0

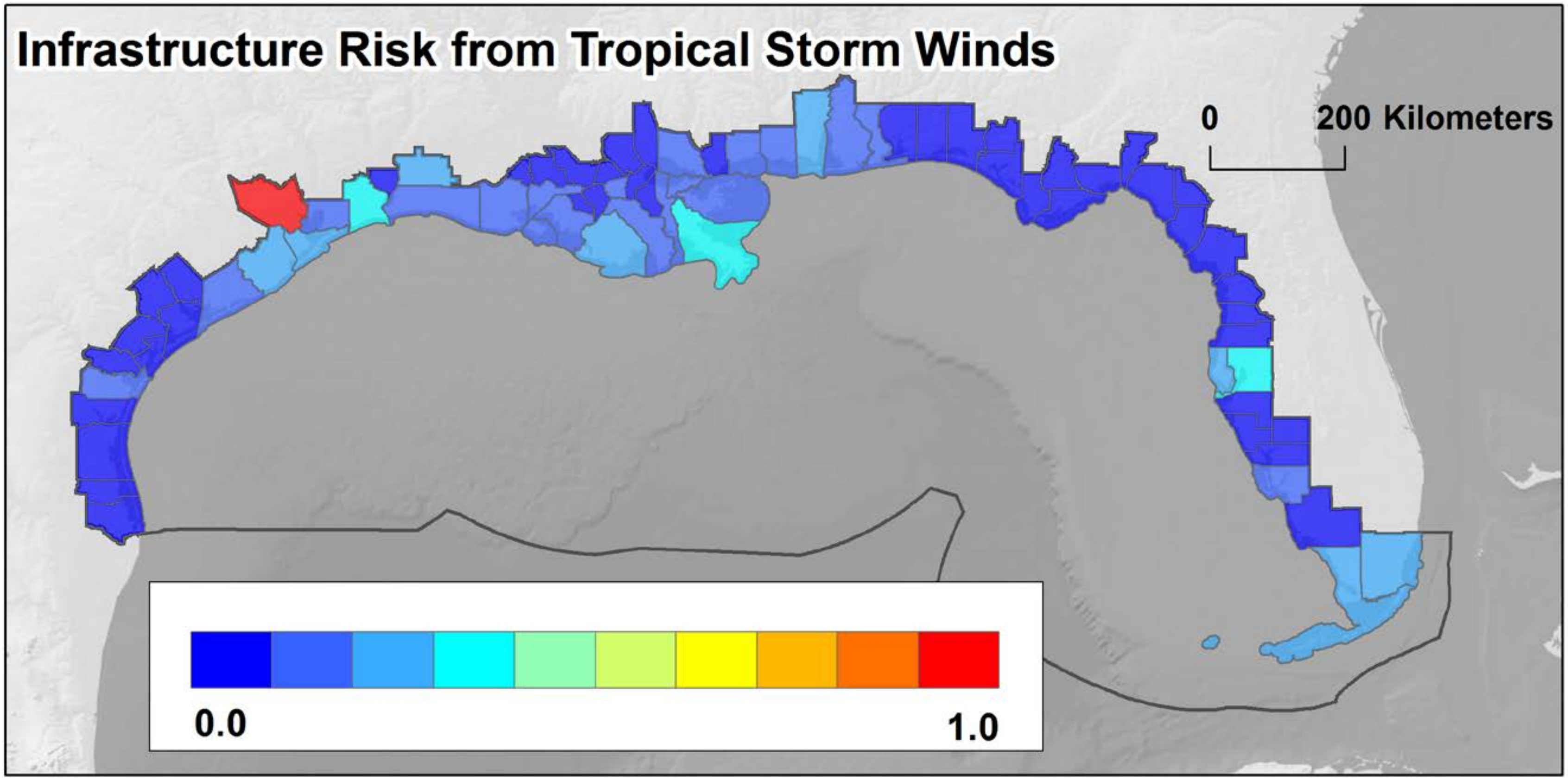

Population Risk from Onshore Facility Biological Releases
0
200 Kilometers
0.0
1.0

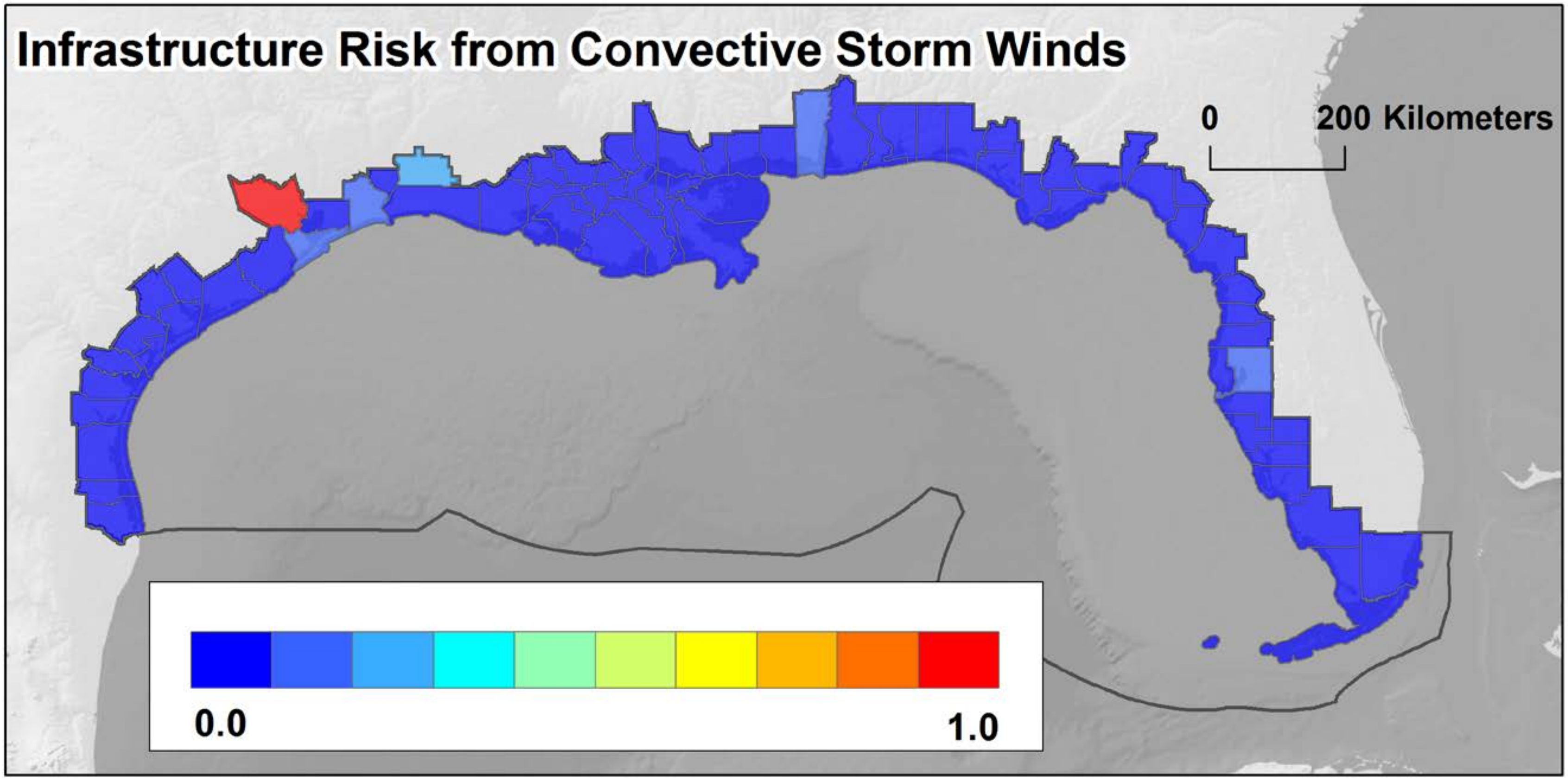
APPENDIX G

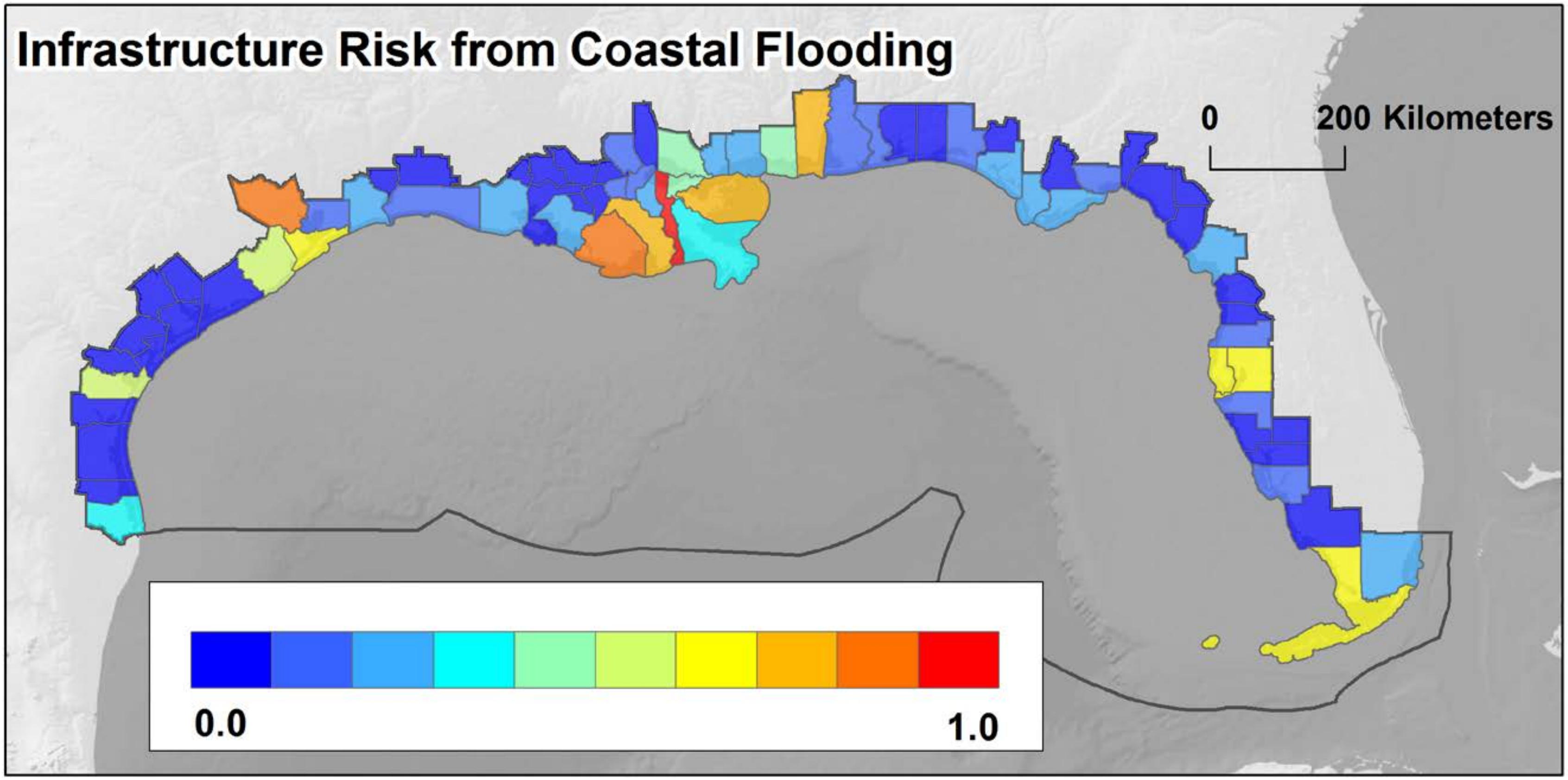
Risk to Infrastructure from Natural Hazards

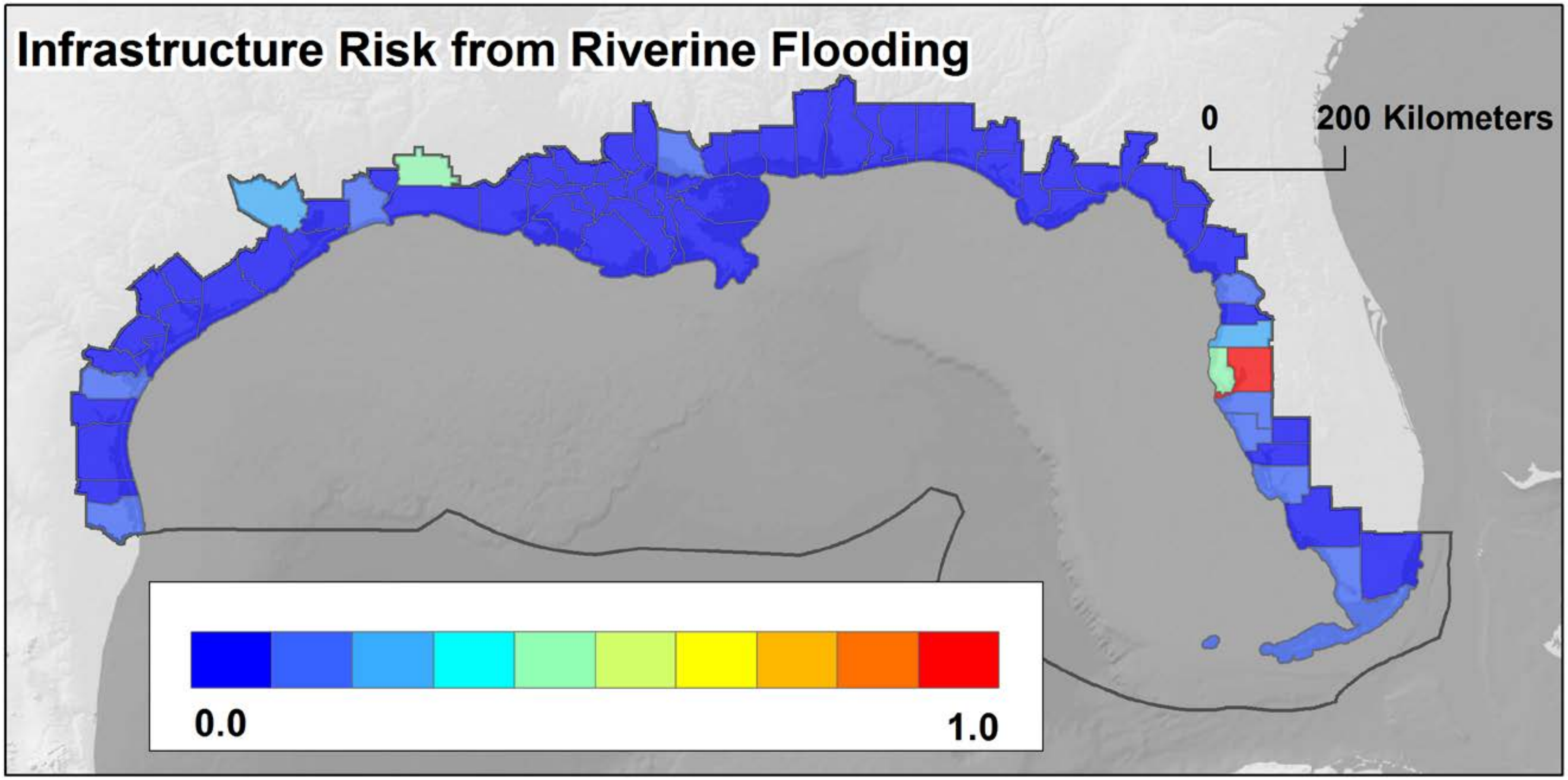
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 33 and display ranked risk index values to infrastructure by county or parish for all natural hazards.


Infrastructure Risk from Lightning
0
200 Kilometers
0.0
1.0

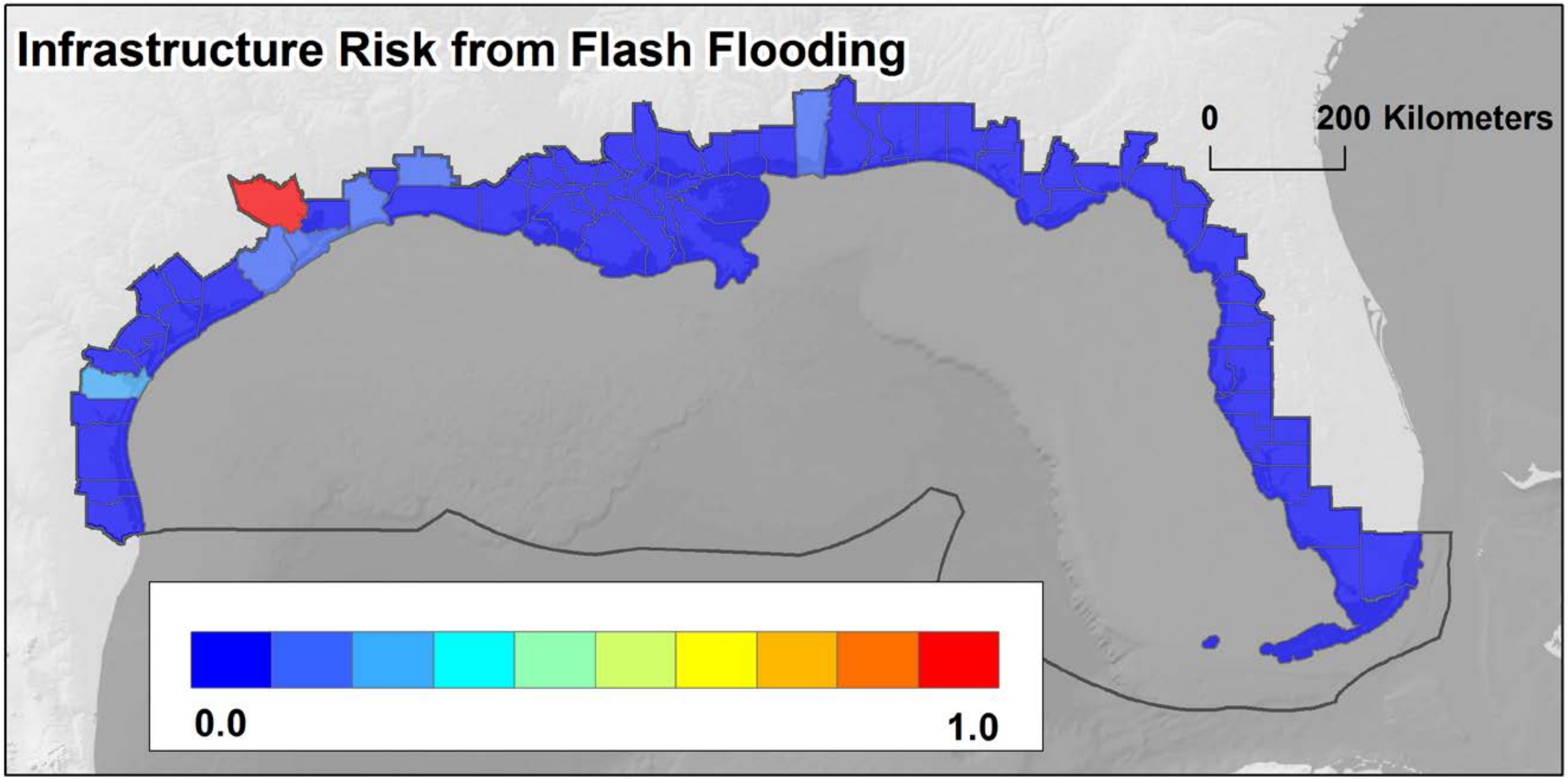

Infrastructure Risk from Tropical Storm Winds
0
200 Kilometers
0.0
1.0

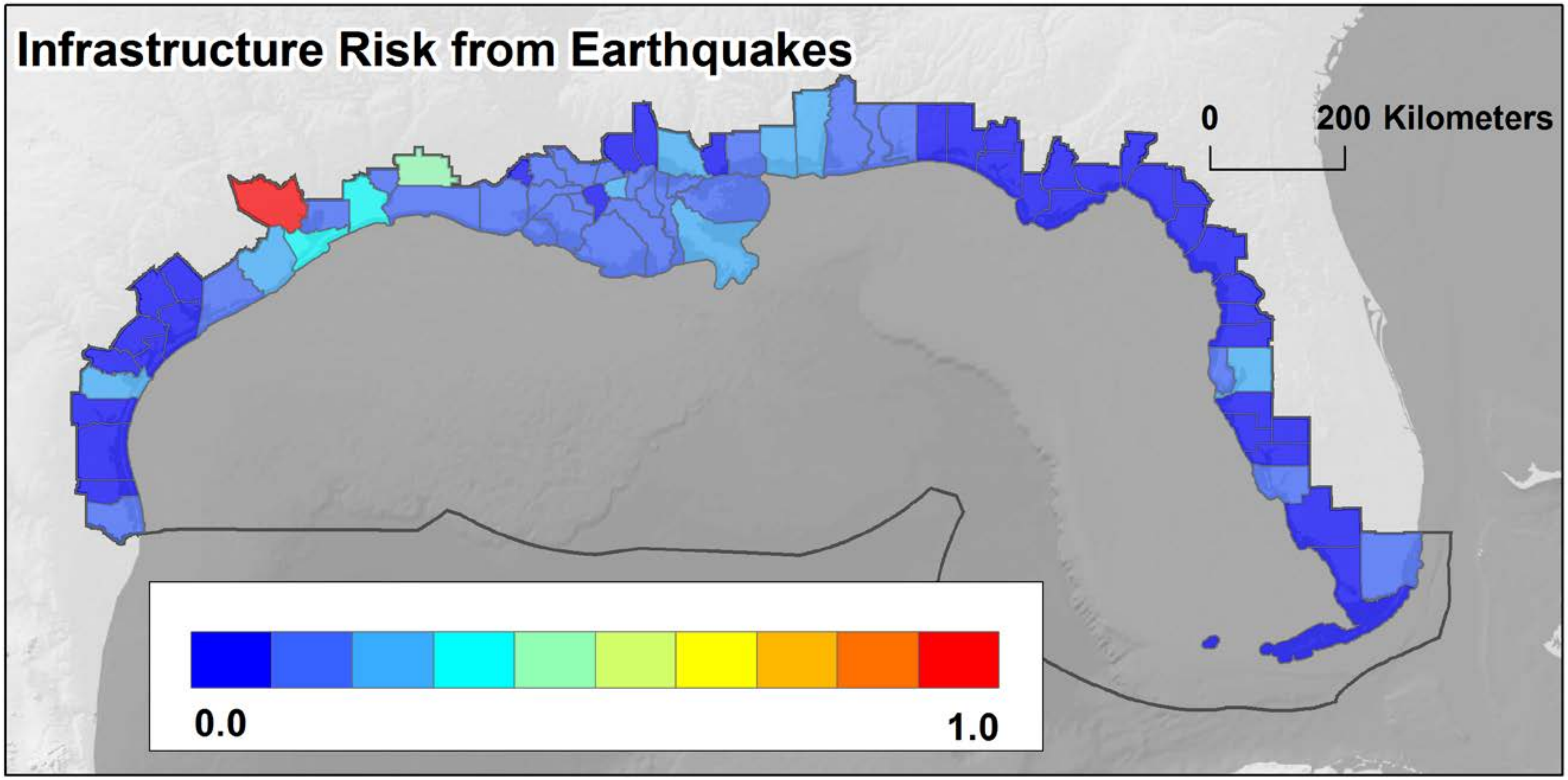

Infrastructure Risk from Convective Storm Winds
0
200 Kilometers
0.0
1.0

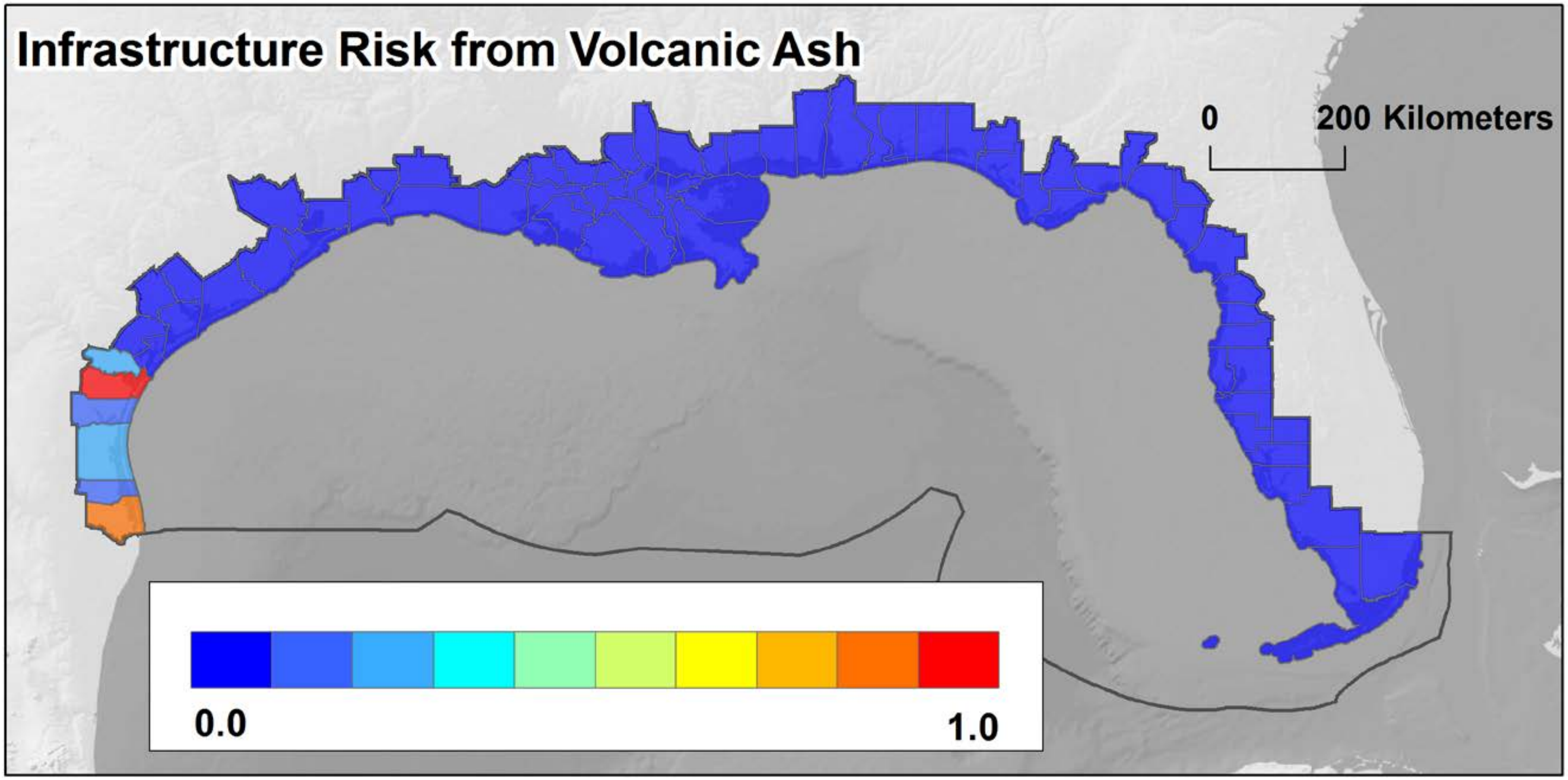

Infrastructure Risk from Coastal Flooding
0
200 Kilometers
0.0
1.0

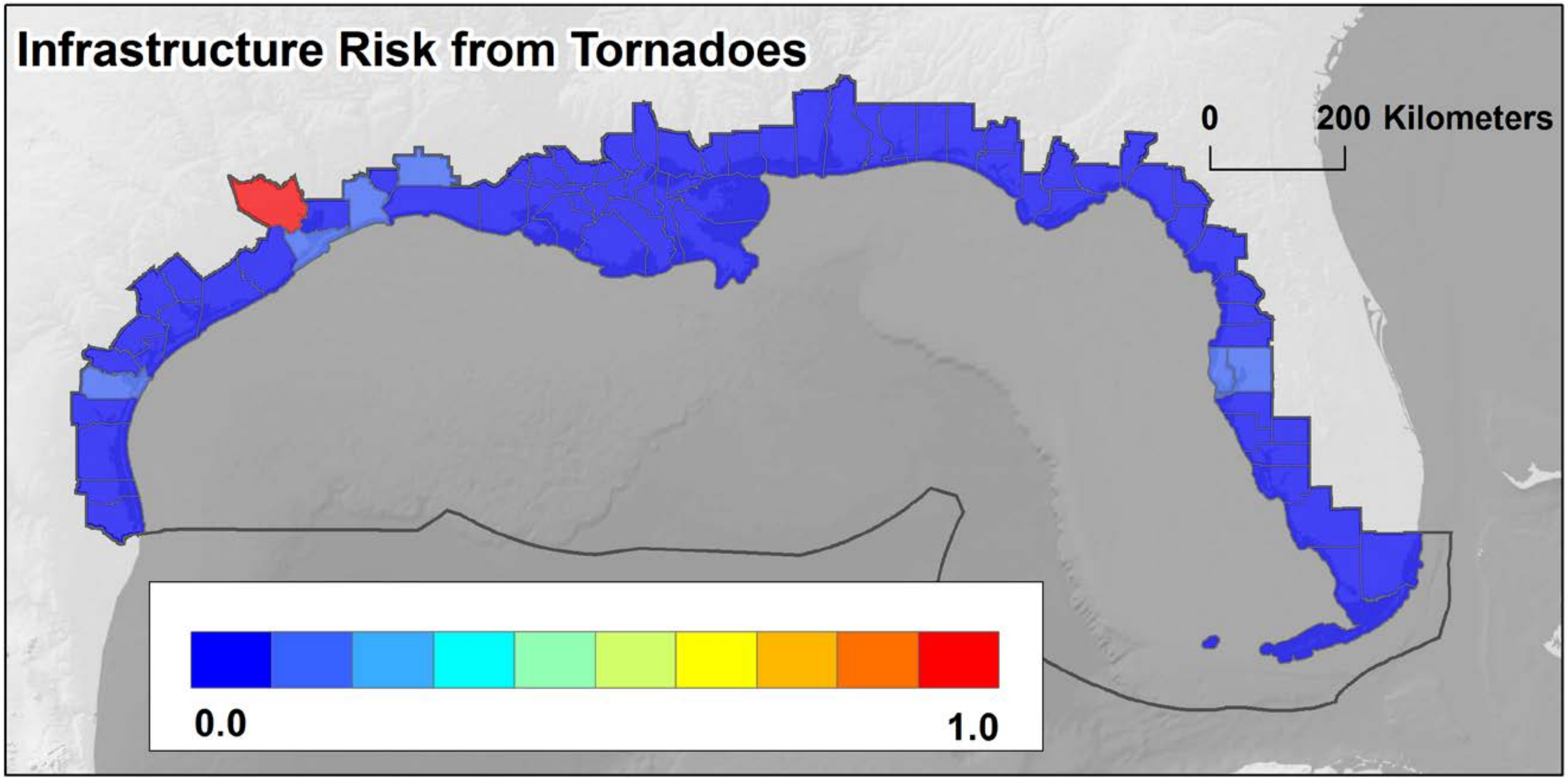


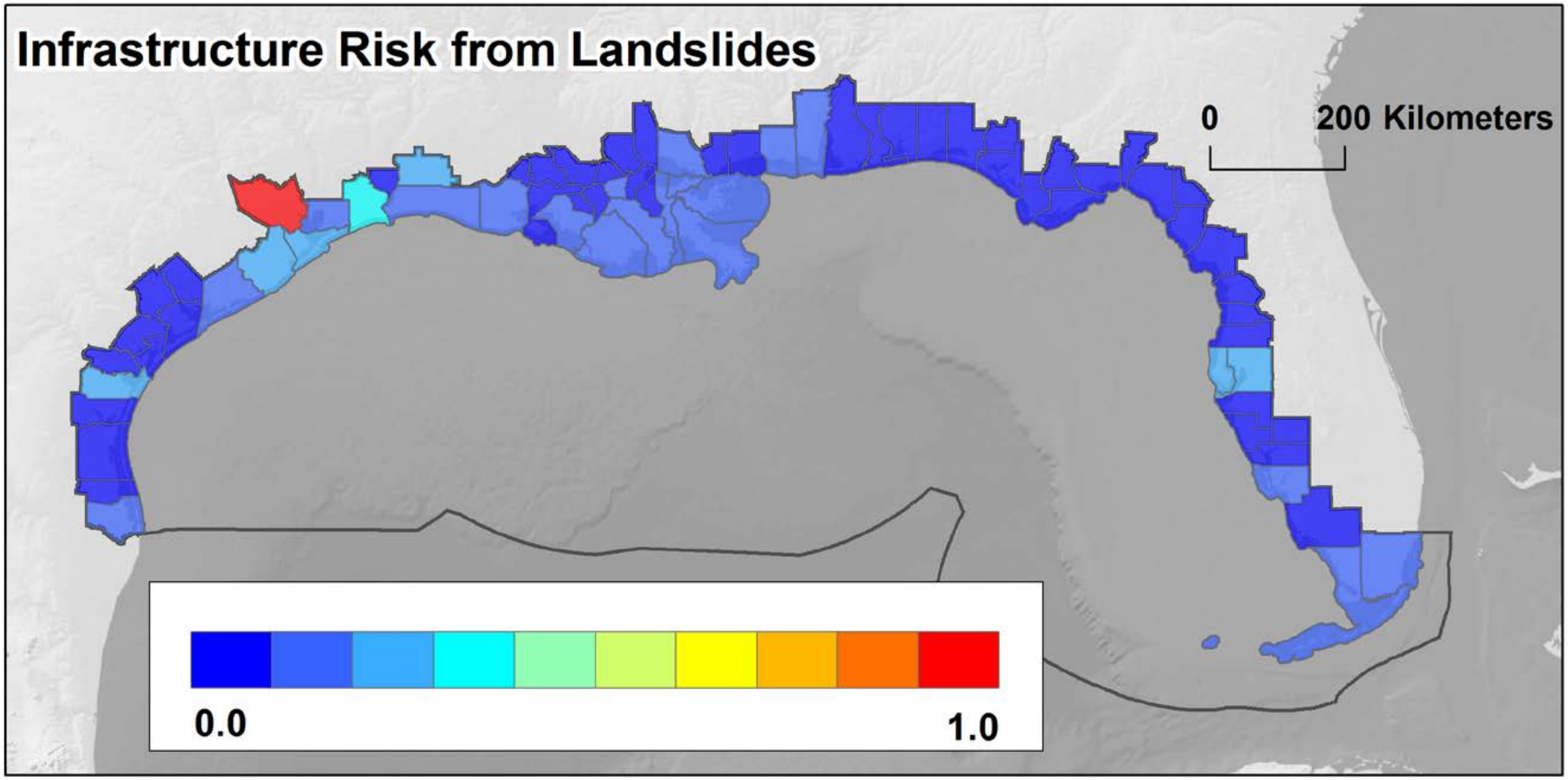
Infrastructure Risk from Riverine Flooding
0
200 Kilometers
0.0
1.0

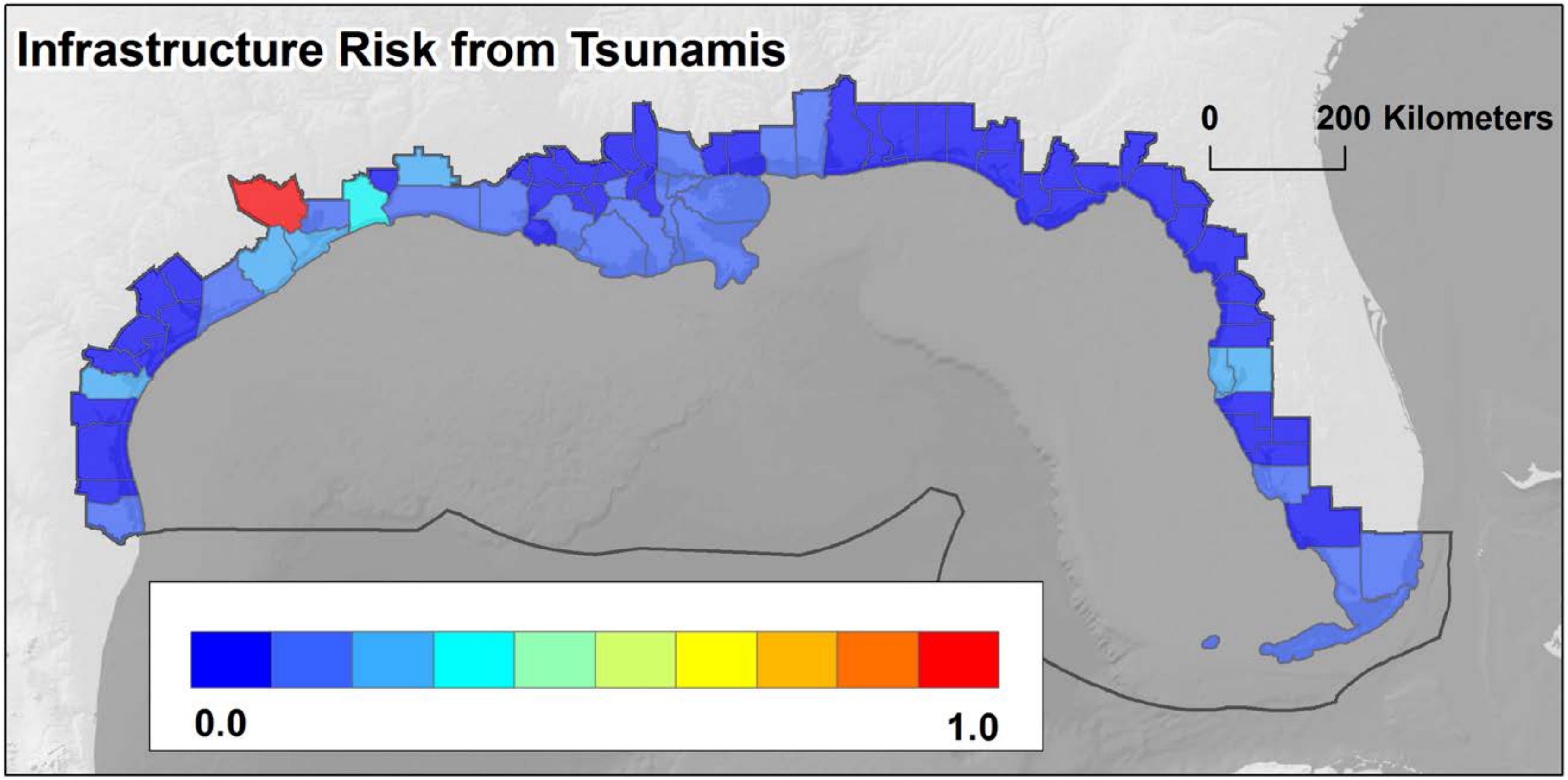

Infrastructure Risk from Flash Flooding
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Earthquakes
0
200 Kilometers
0.0
1.0

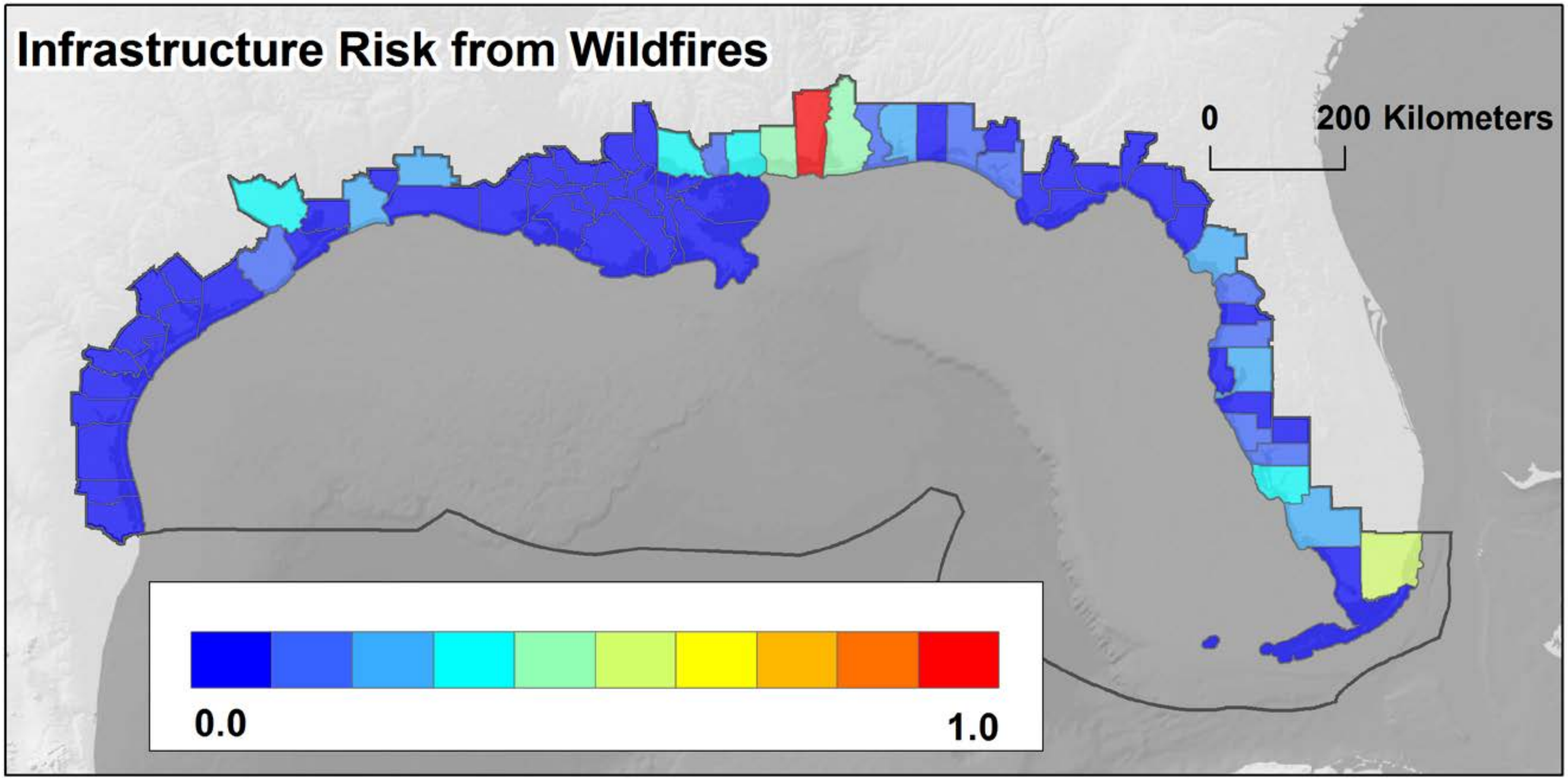

Infrastructure Risk from Volcanic Ash
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Tornadoes
0
200 Kilometers
0.0
1.0

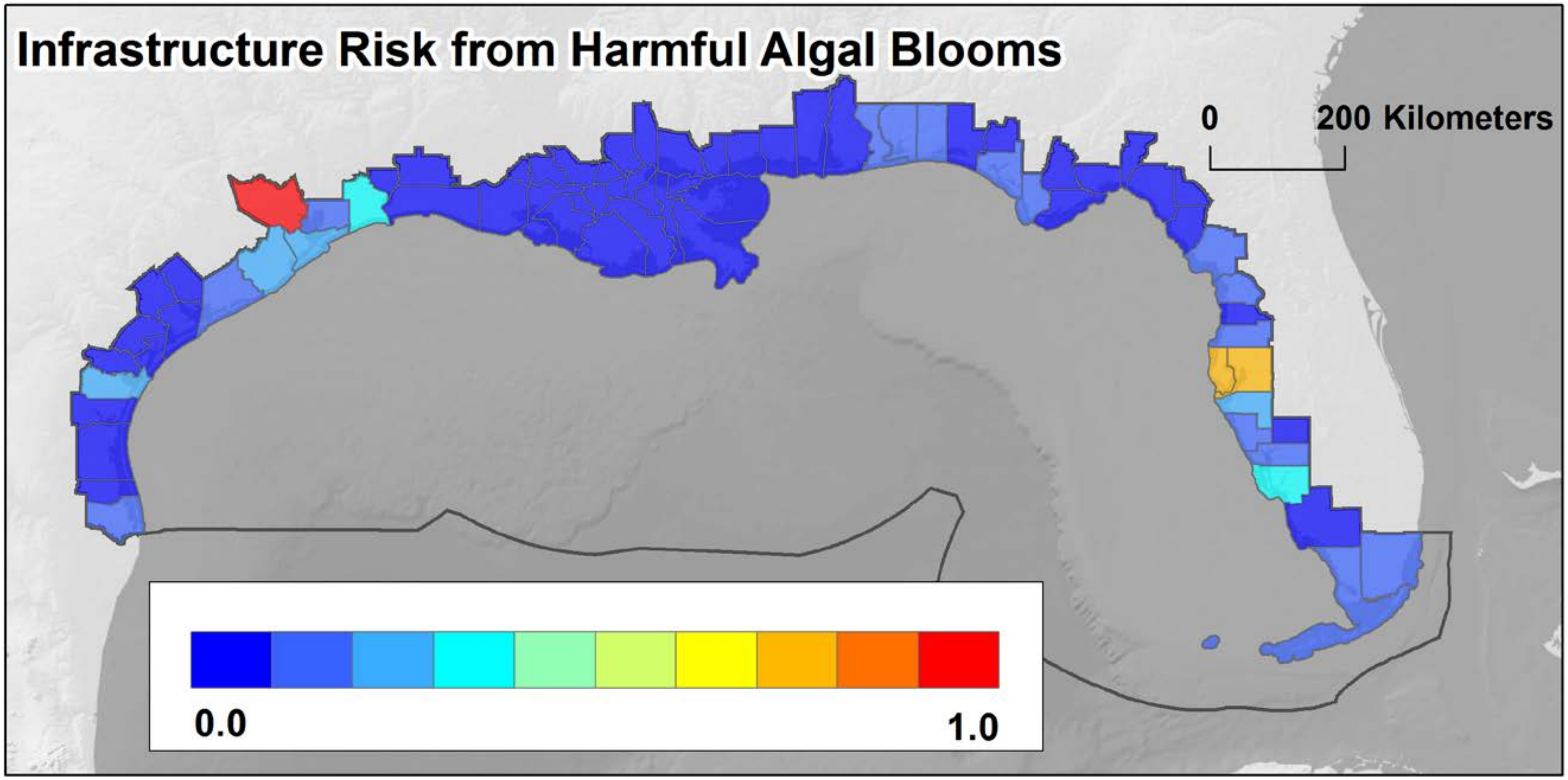

Infrastructure Risk from Landslides
0
200 Kilometers
0.0
1.0



Infrastructure Risk from Tsunamis
0
200 Kilometers
0.0
1.0



Infrastructure Risk from Wildfires
0
200 Kilometers
0.0
1.0

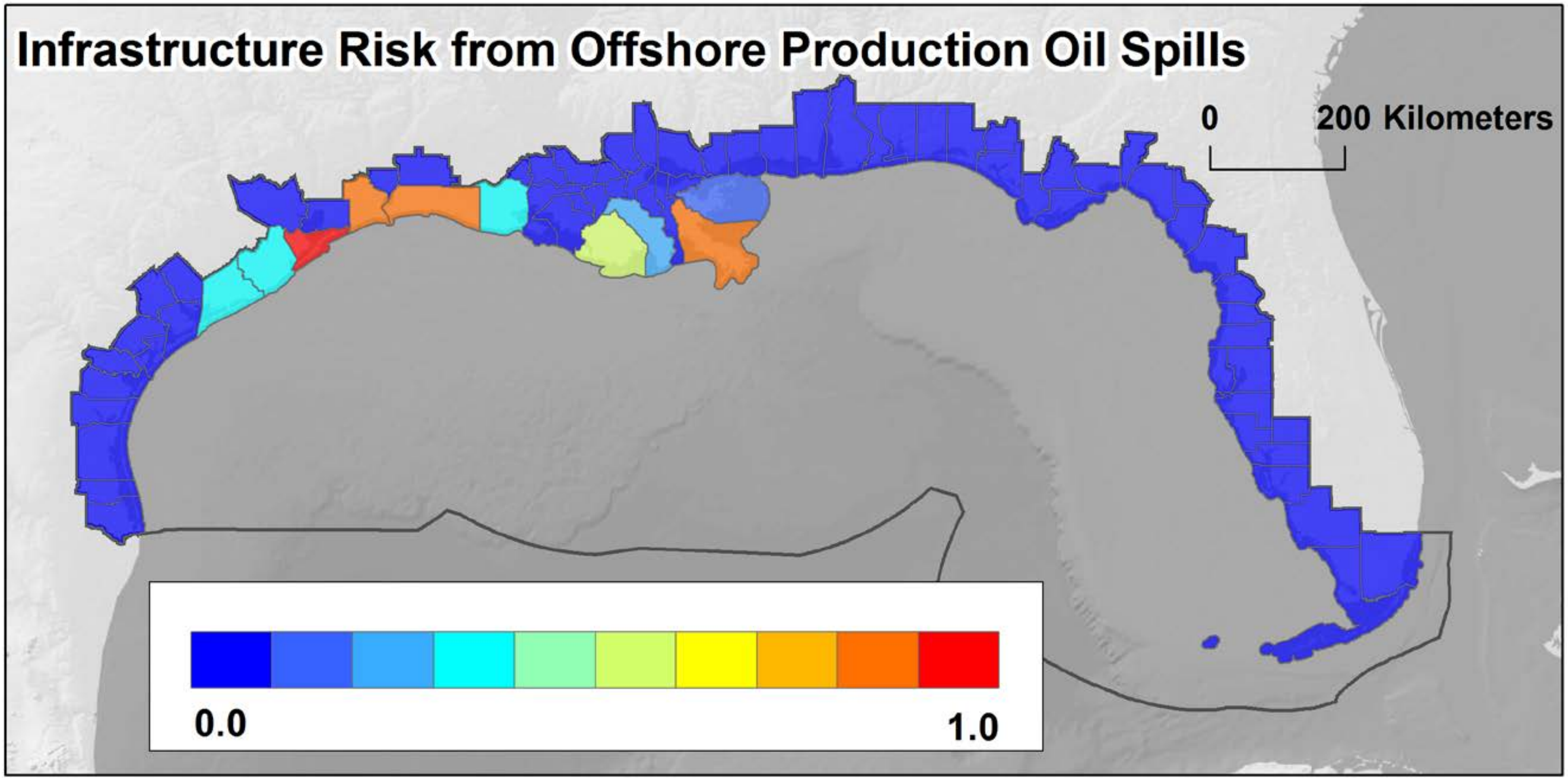


Infrastructure Risk from Harmful Algal Blooms
0
200 Kilometers
0.0
1.0

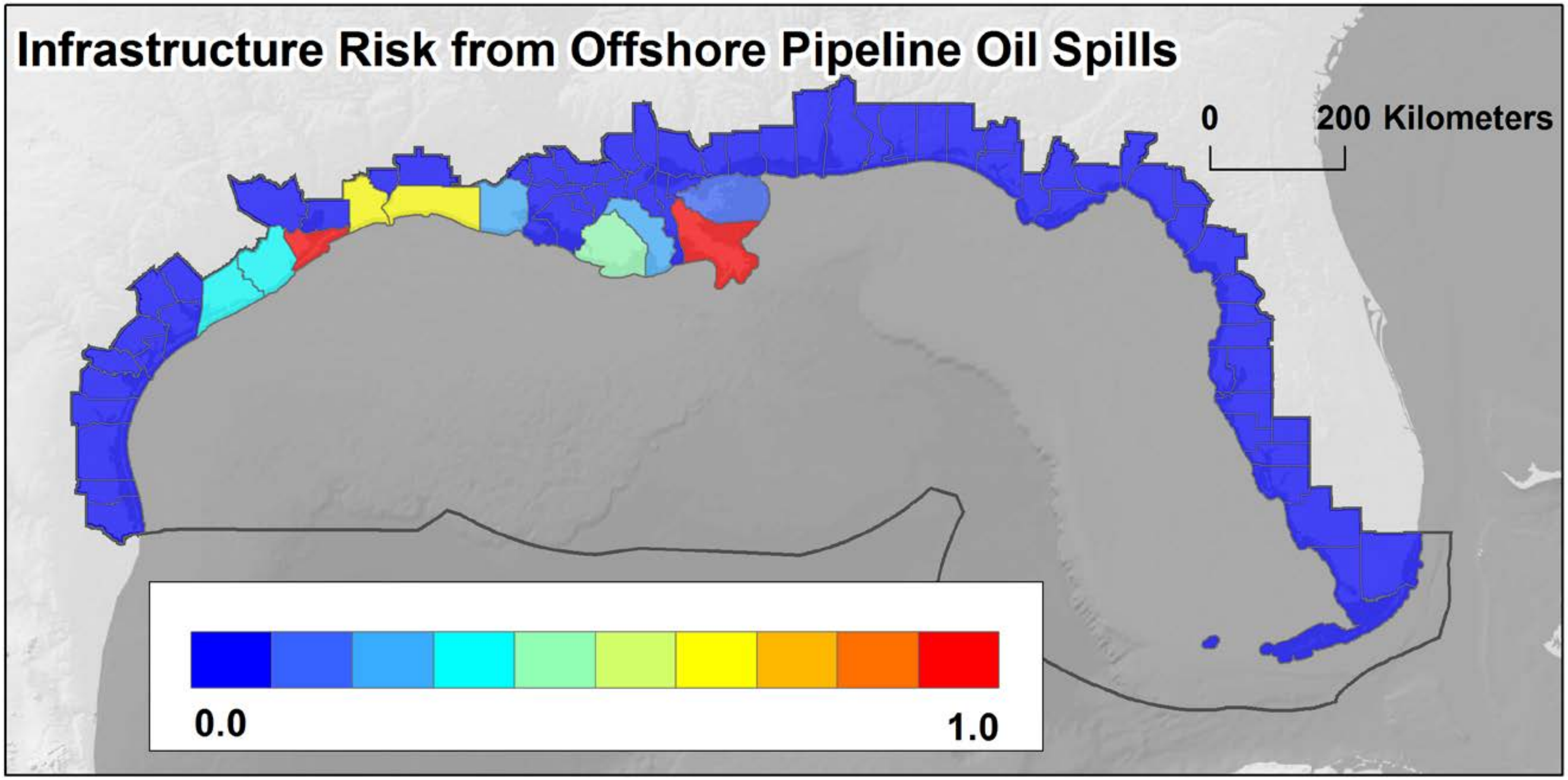
APPENDIX H

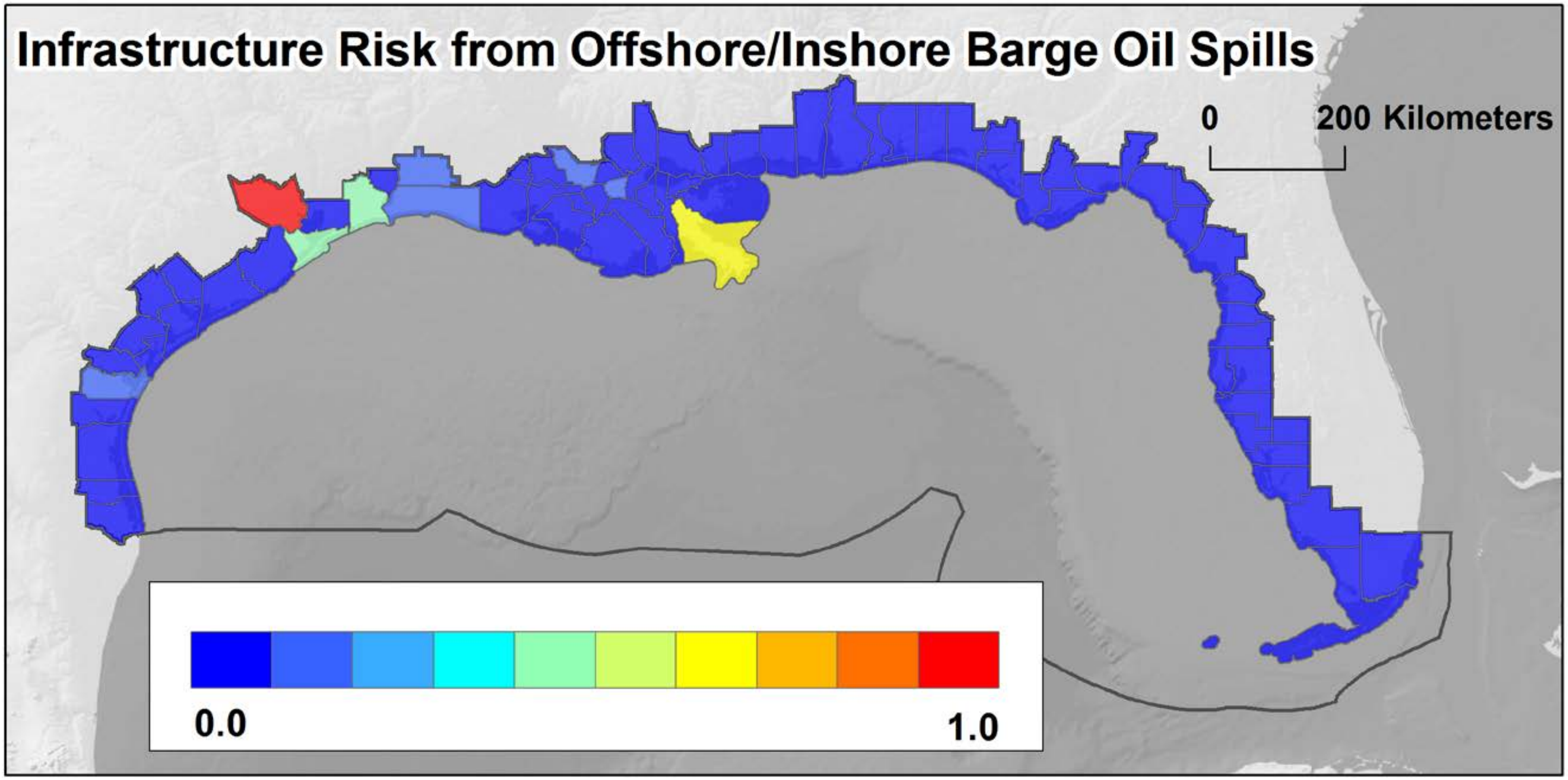
Risk to Infrastructure from Anthropogenic Hazards

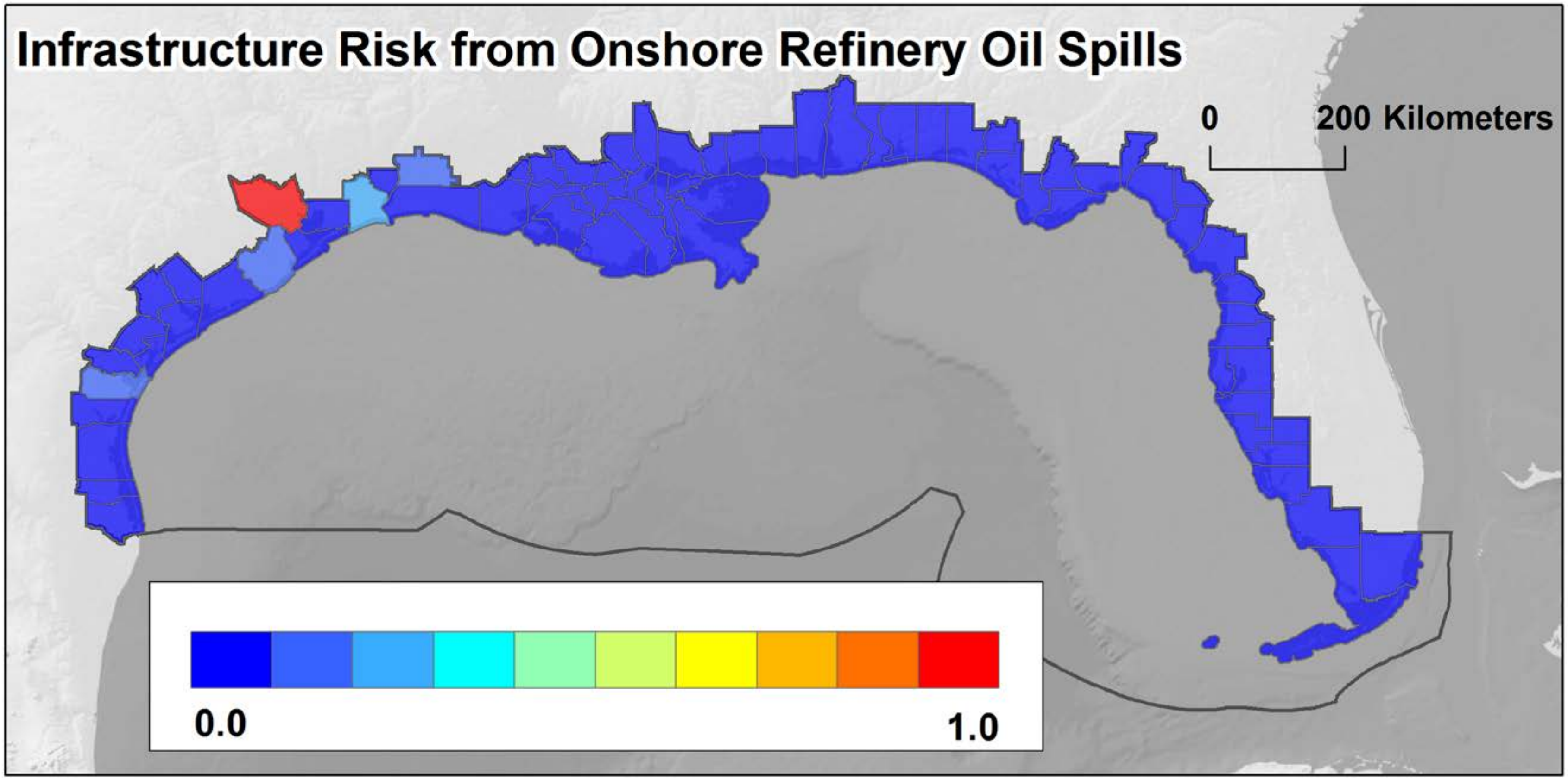
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 34 and display ranked risk index values to infrastructure by county or parish for all anthropogenic hazards.

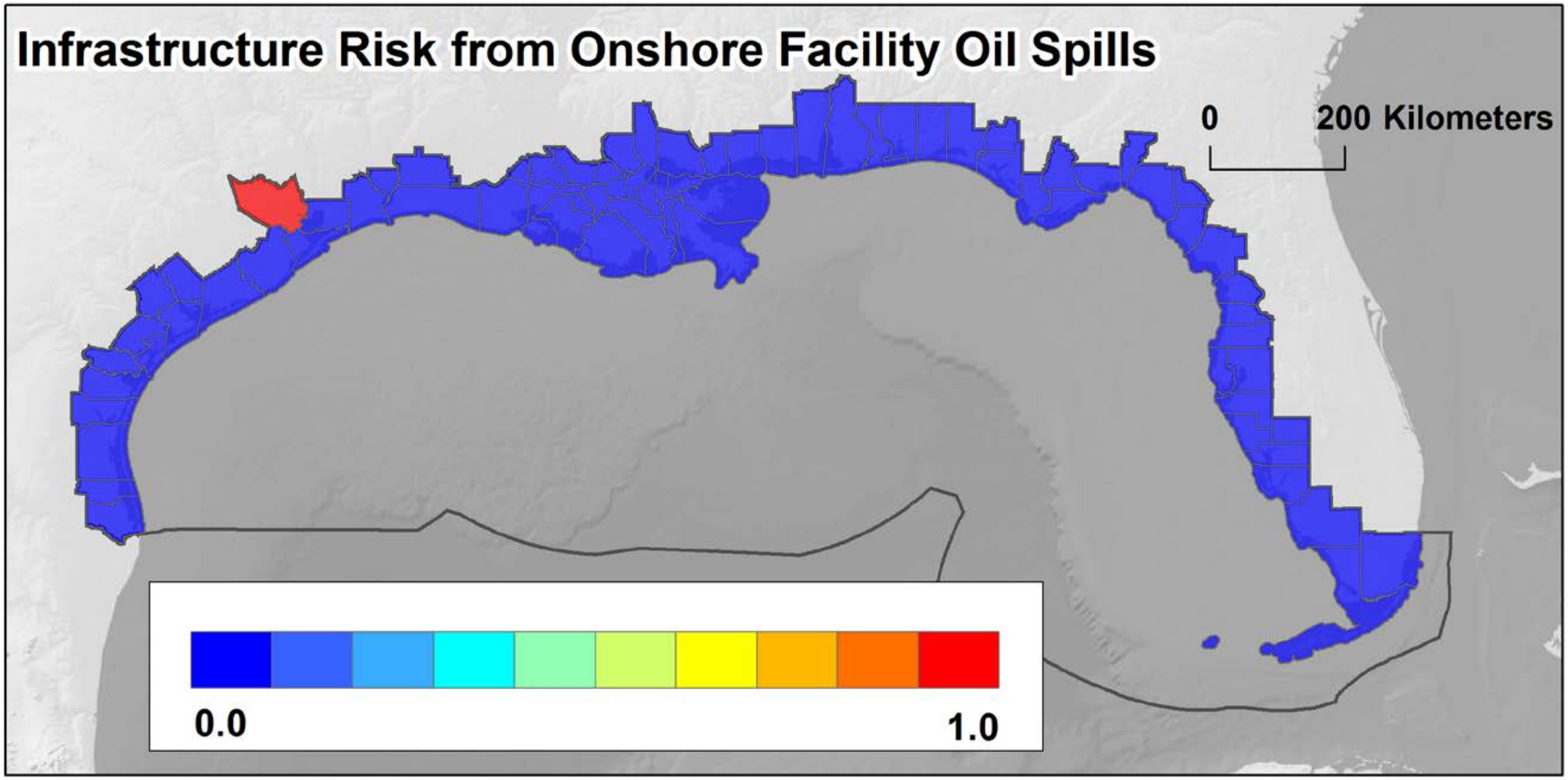


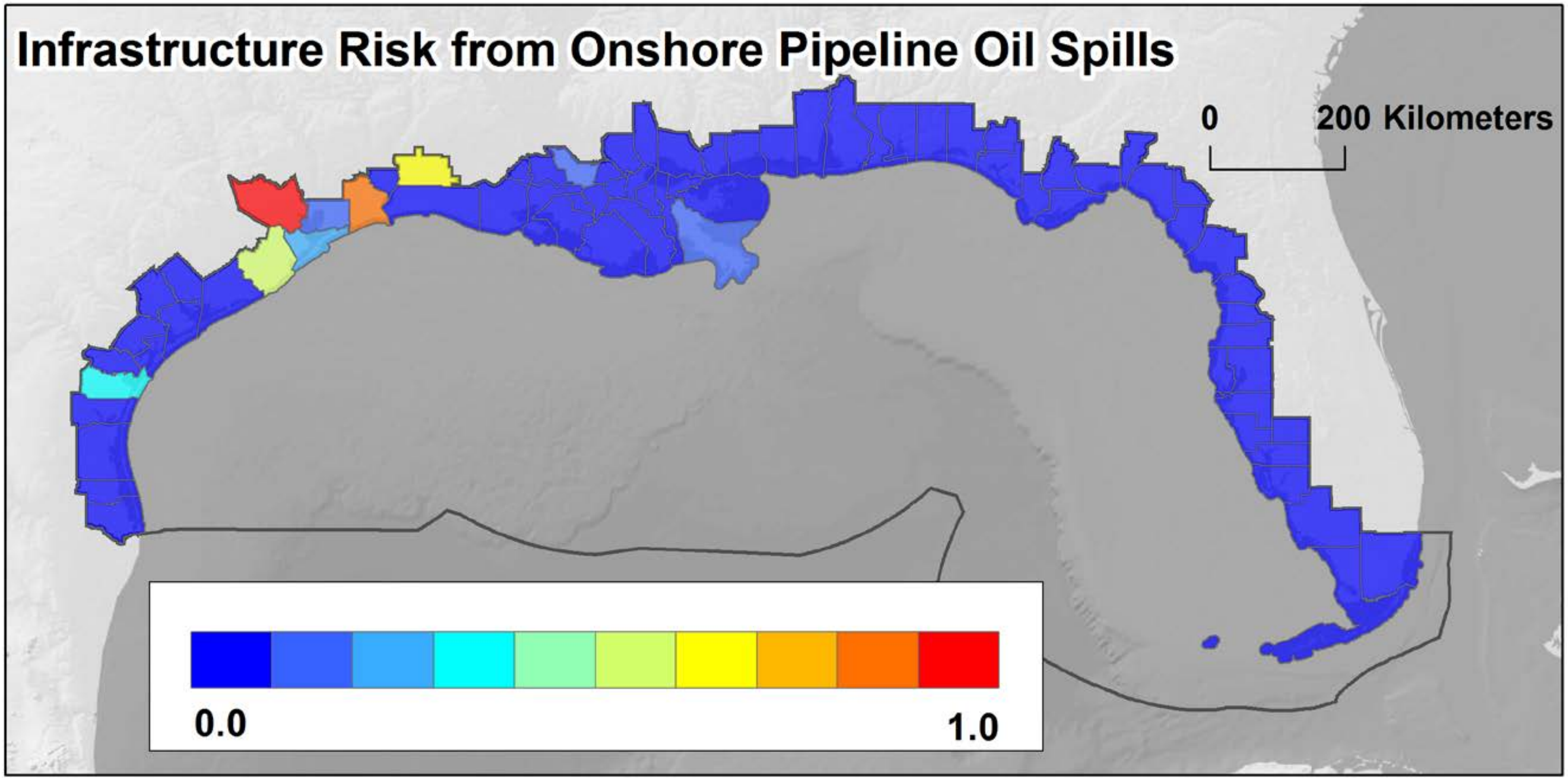
Infrastructure Risk from Offshore Production Oil Spills
0
200 Kilometers
0.0
1.0

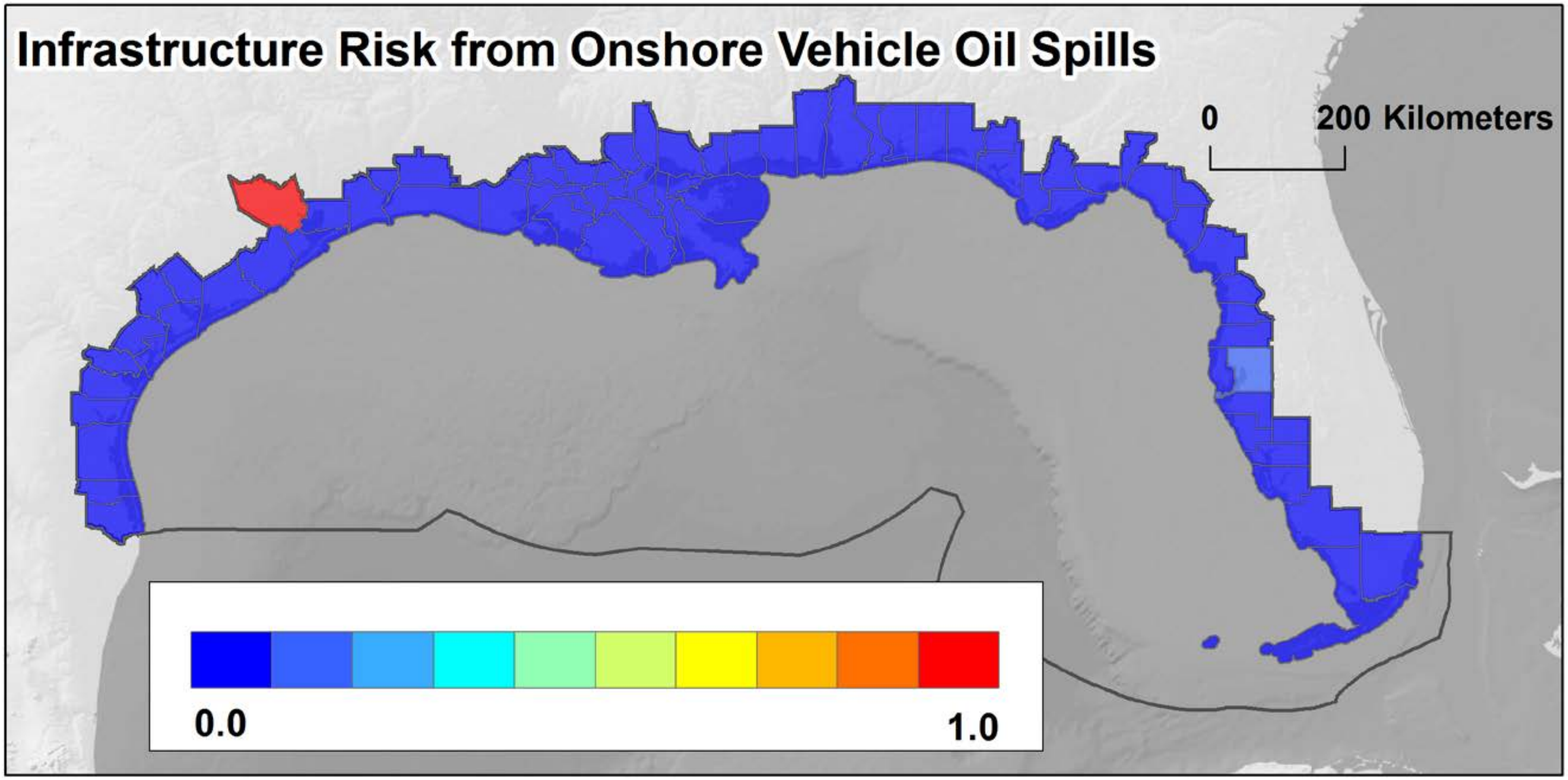

Infrastructure Risk from Offshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Offshore/Inshore Barge Oil Spills
0
200 Kilometers
0.0
1.0

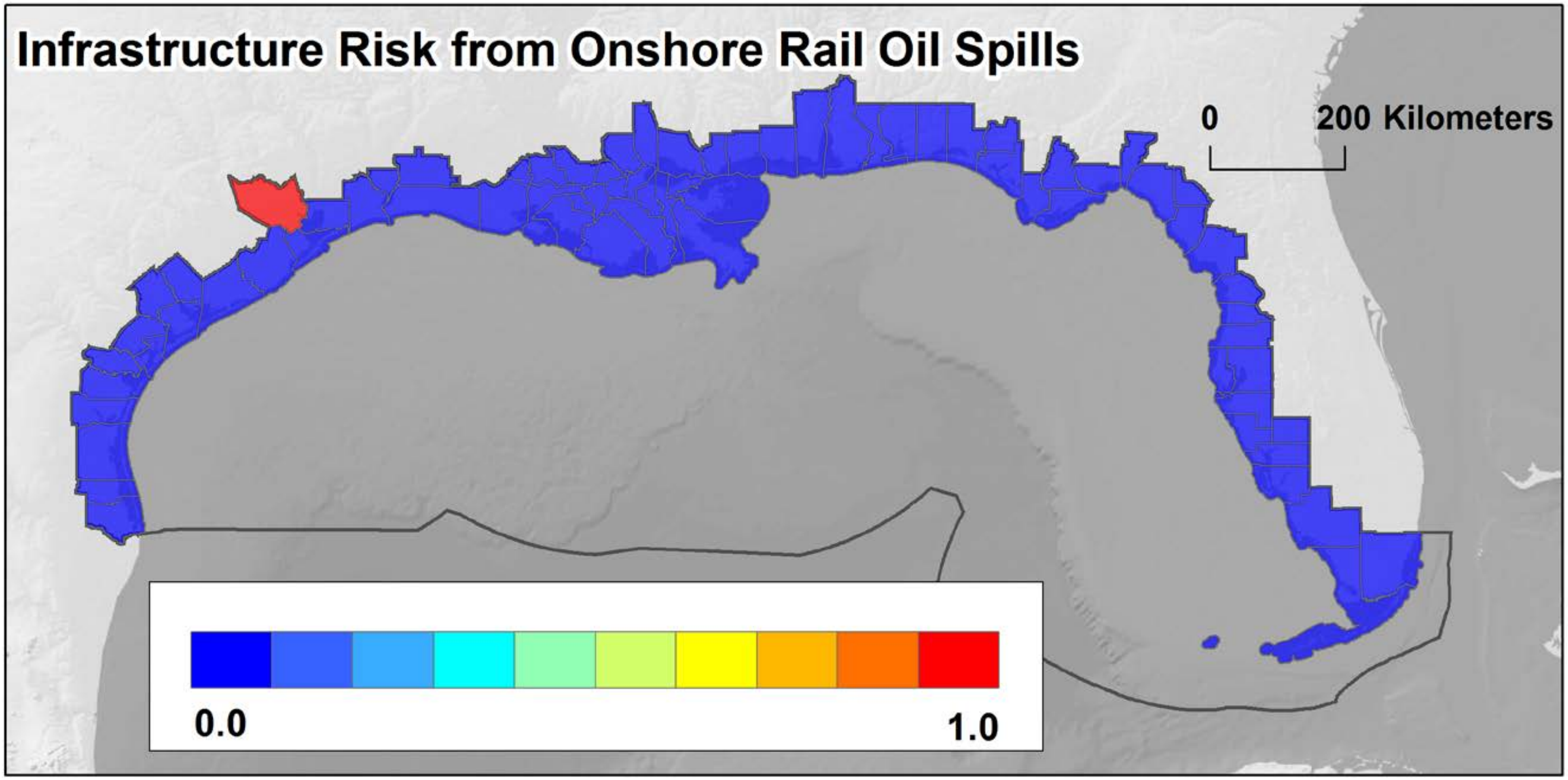

Infrastructure Risk from Onshore Refinery Oil Spills
0
200 Kilometers
0.0
1.0

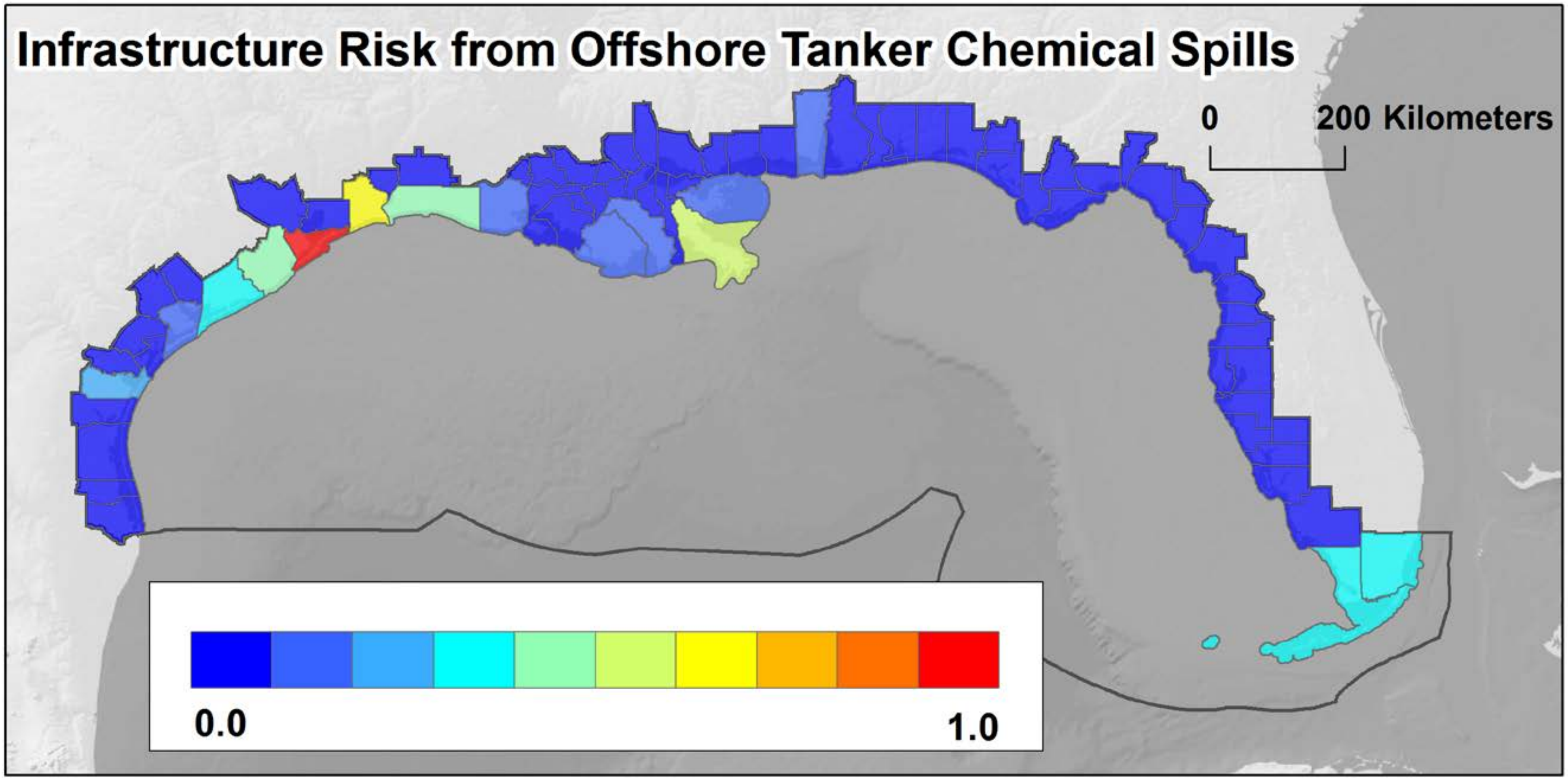

Infrastructure Risk from Onshore Facility Oil Spills
0
200 Kilometers
0.0
1.0

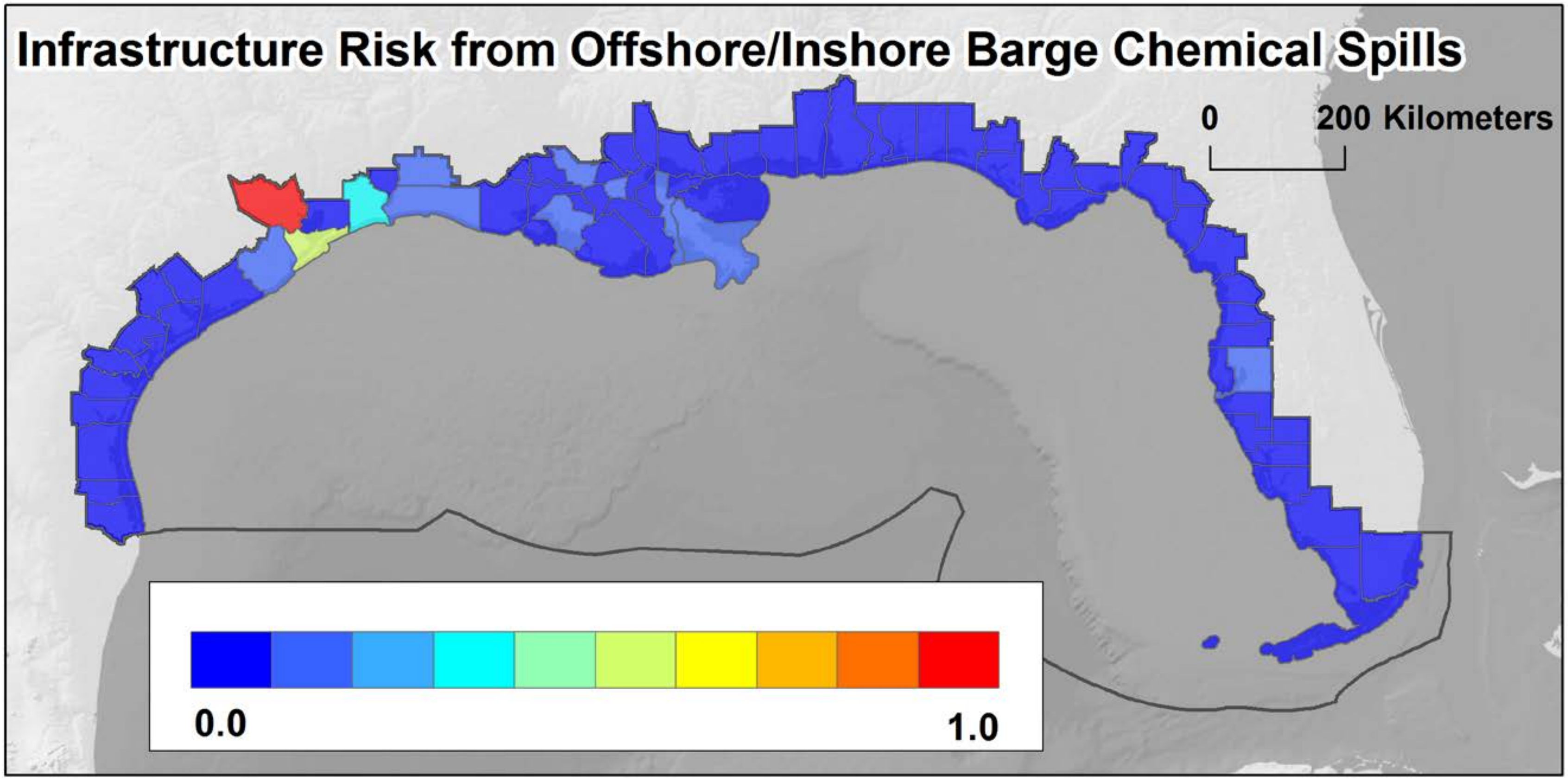

Infrastructure Risk from Onshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

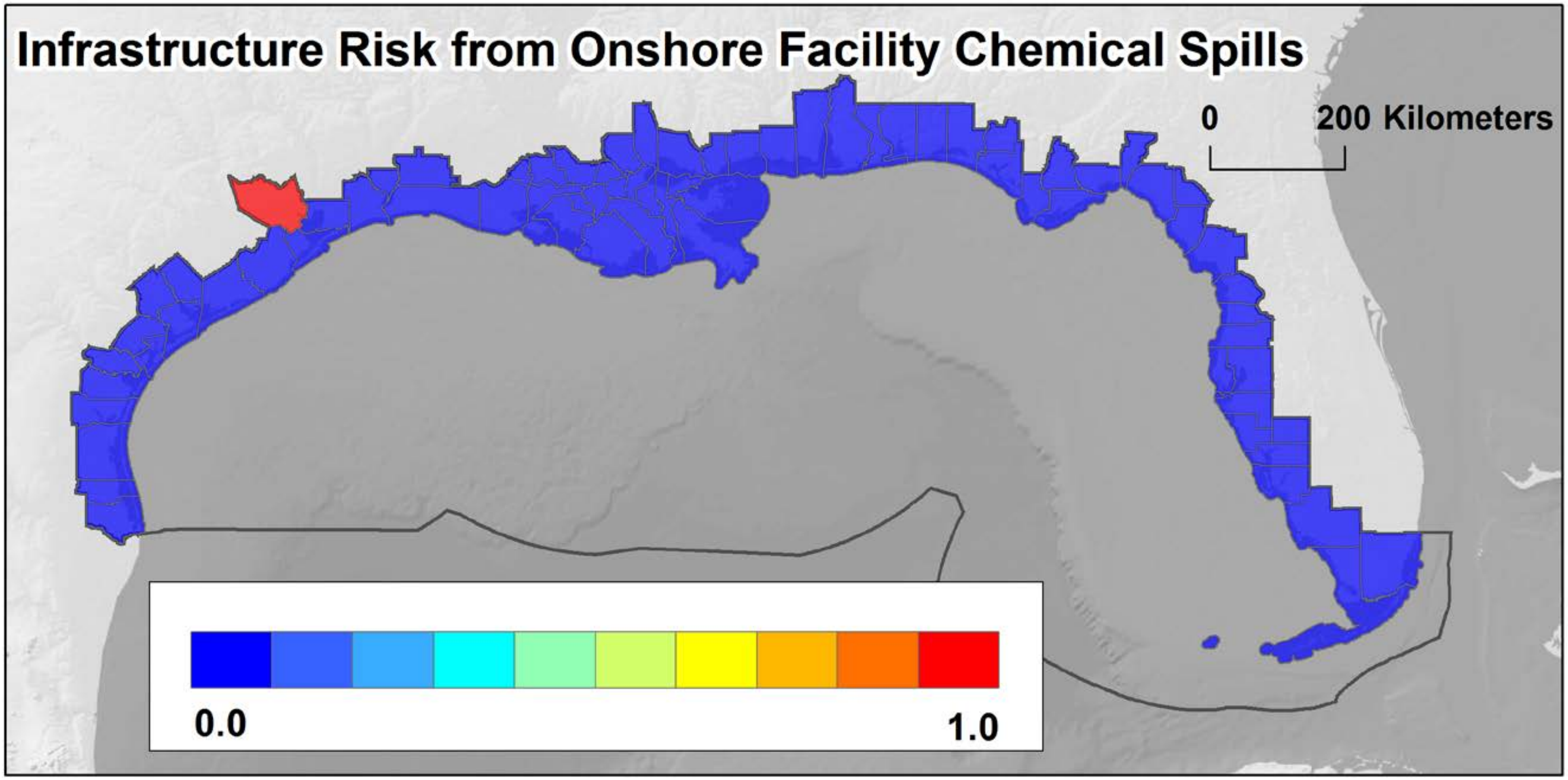


Infrastructure Risk from Onshore Vehicle Oil Spills
0
200 Kilometers
0.0
1.0

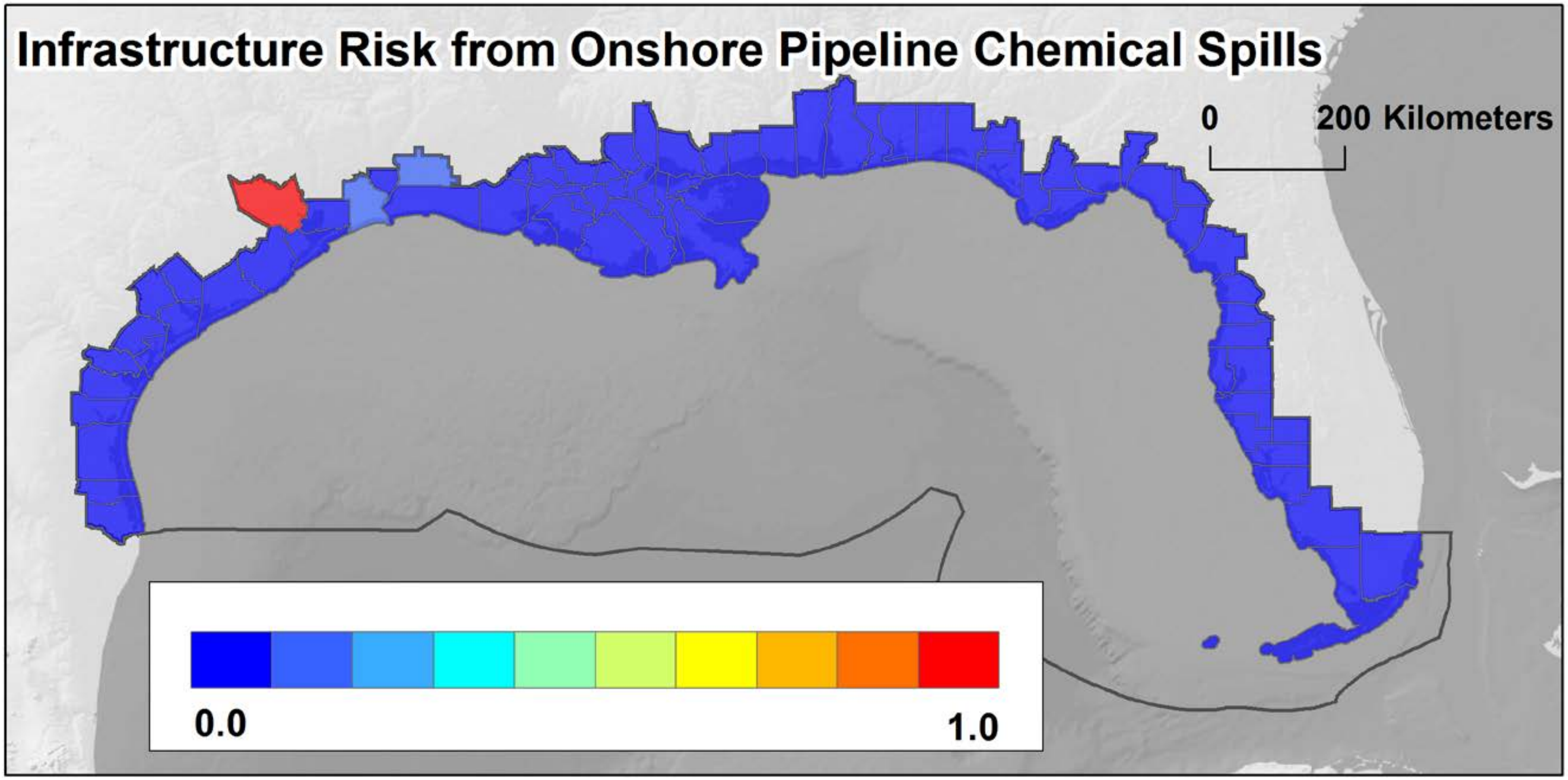

Infrastructure Risk from Onshore Rail Oil Spills
0
200 Kilometers
0.0
1.0

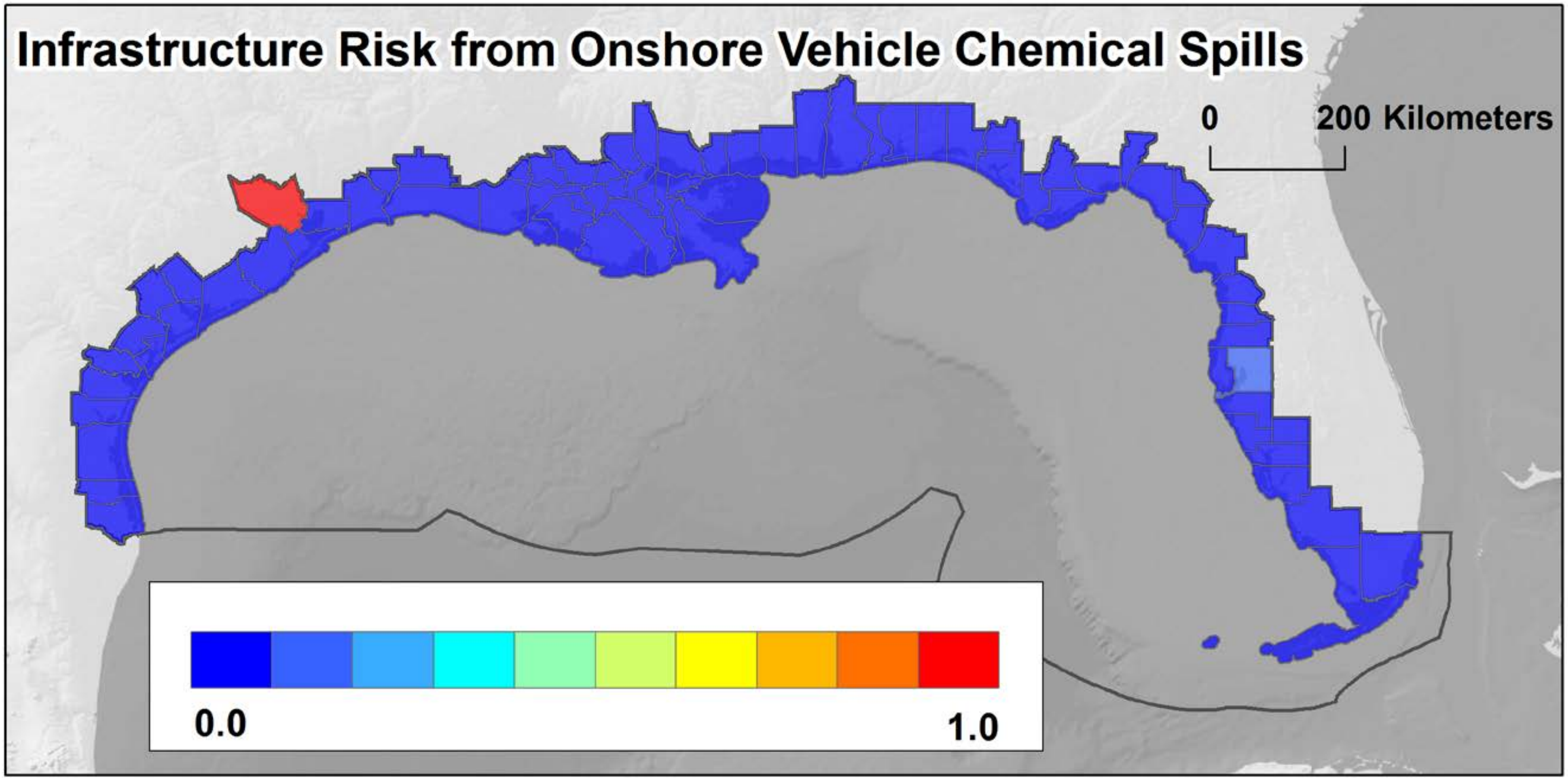

Infrastructure Risk from Offshore Tanker Chemical Spills
0
200 Kilometers
0.0
1.0

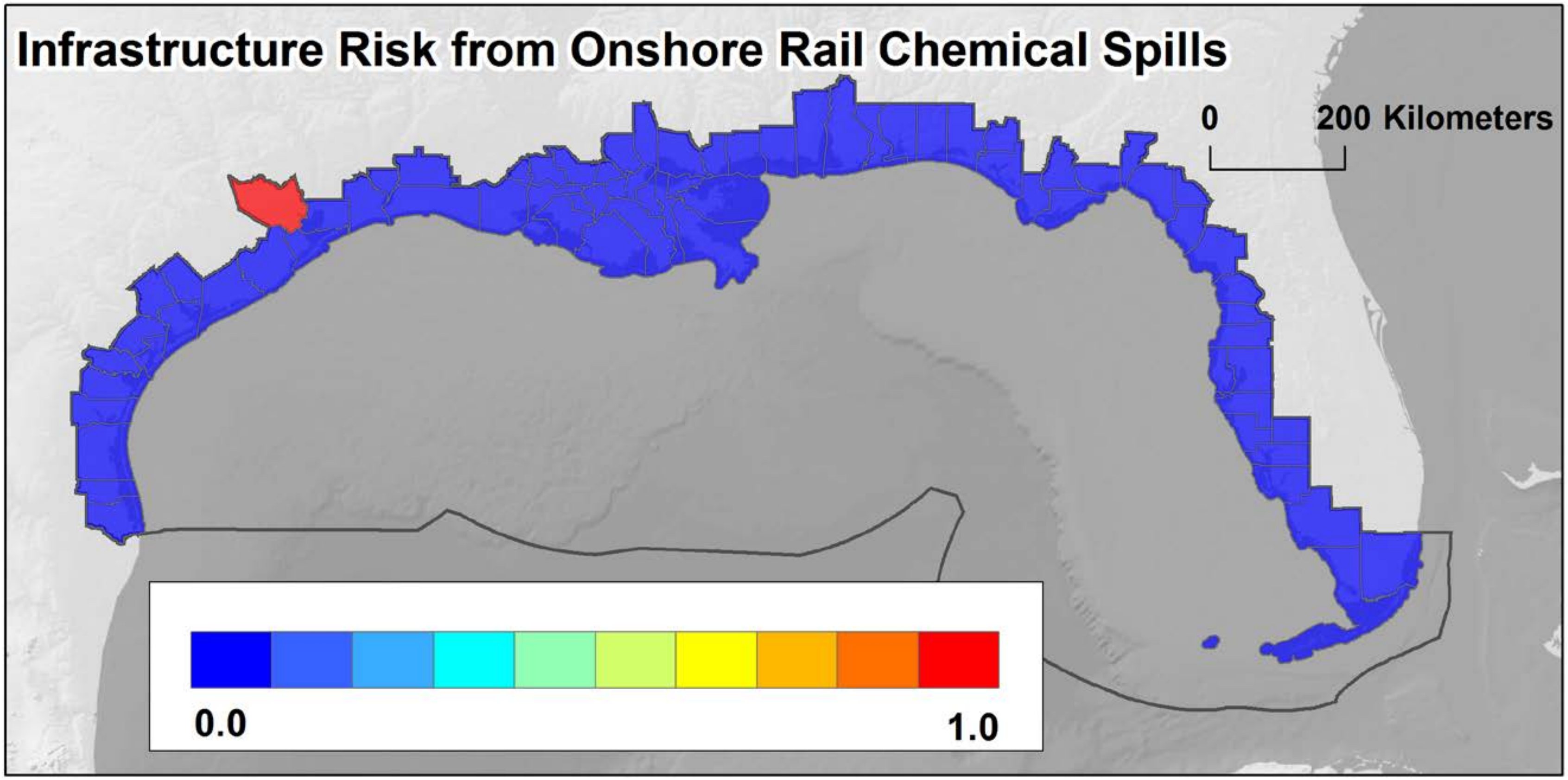

Infrastructure Risk from Offshore/Inshore Barge Chemical Spills
0
200 Kilometers
0.0
1.0

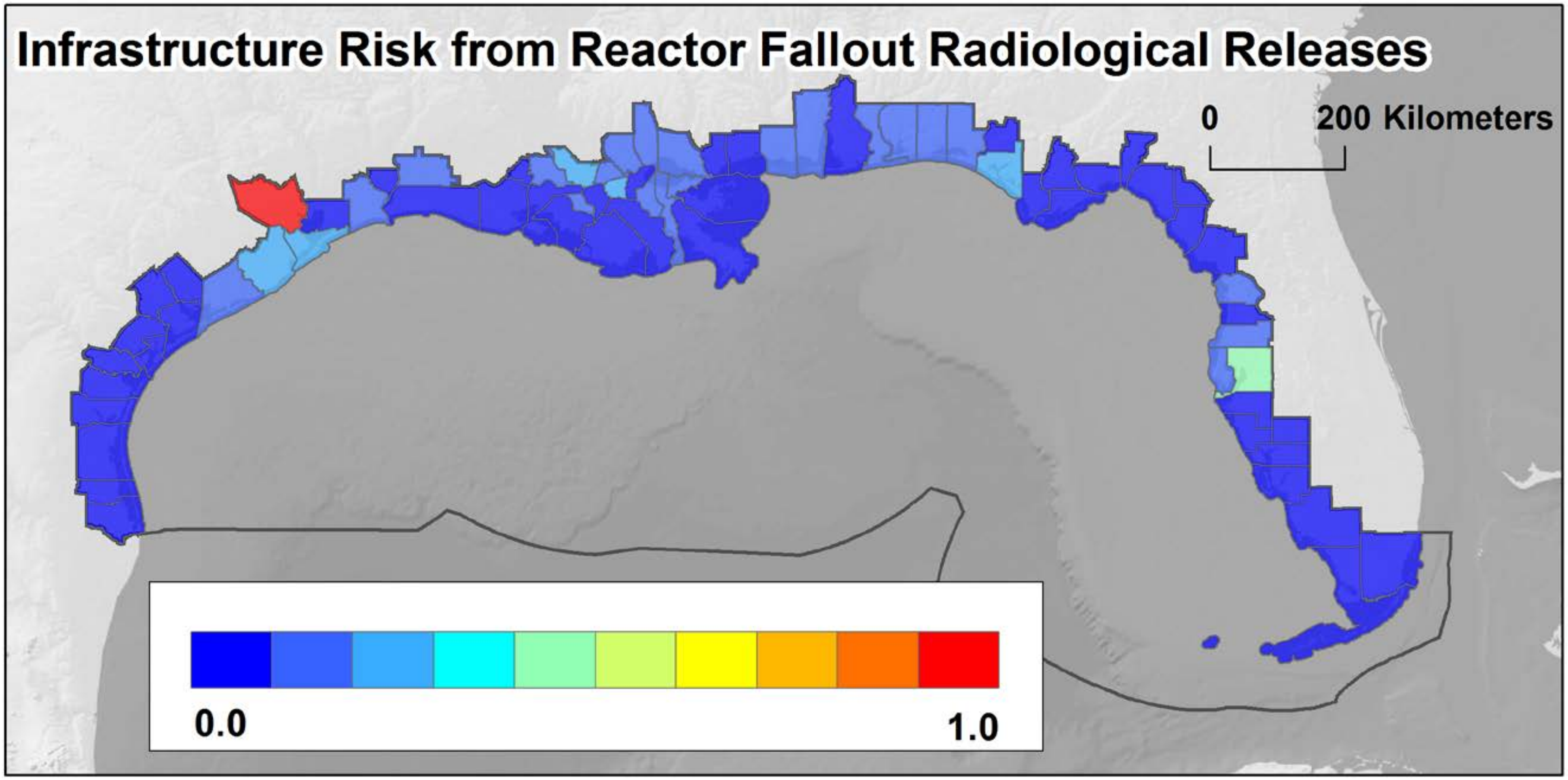


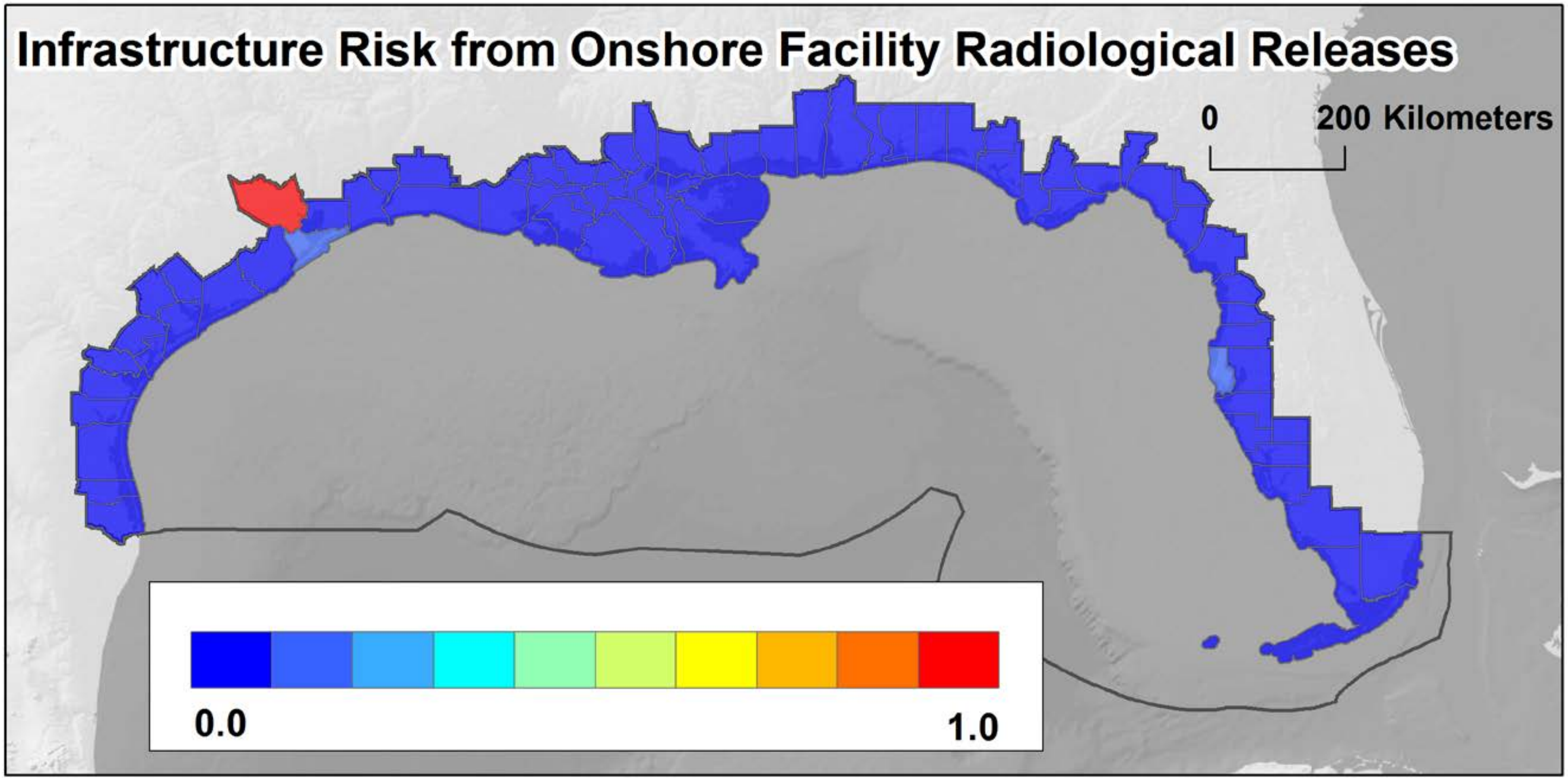
Infrastructure Risk from Onshore Facility Chemical Spills
0
200 Kilometers
0.0
1.0

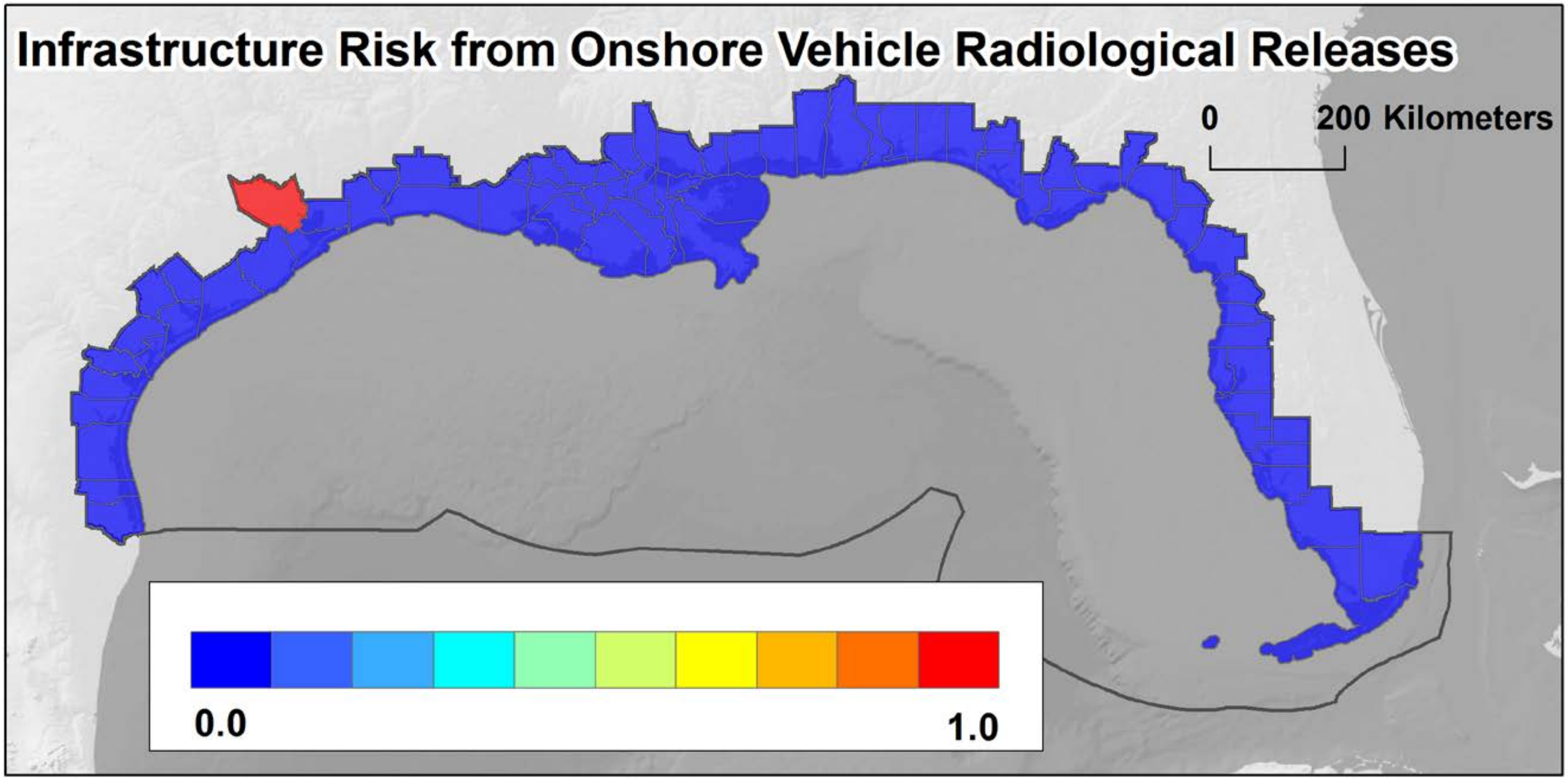

Infrastructure Risk from Onshore Pipeline Chemical Spills
0
200 Kilometers
0.0
1.0

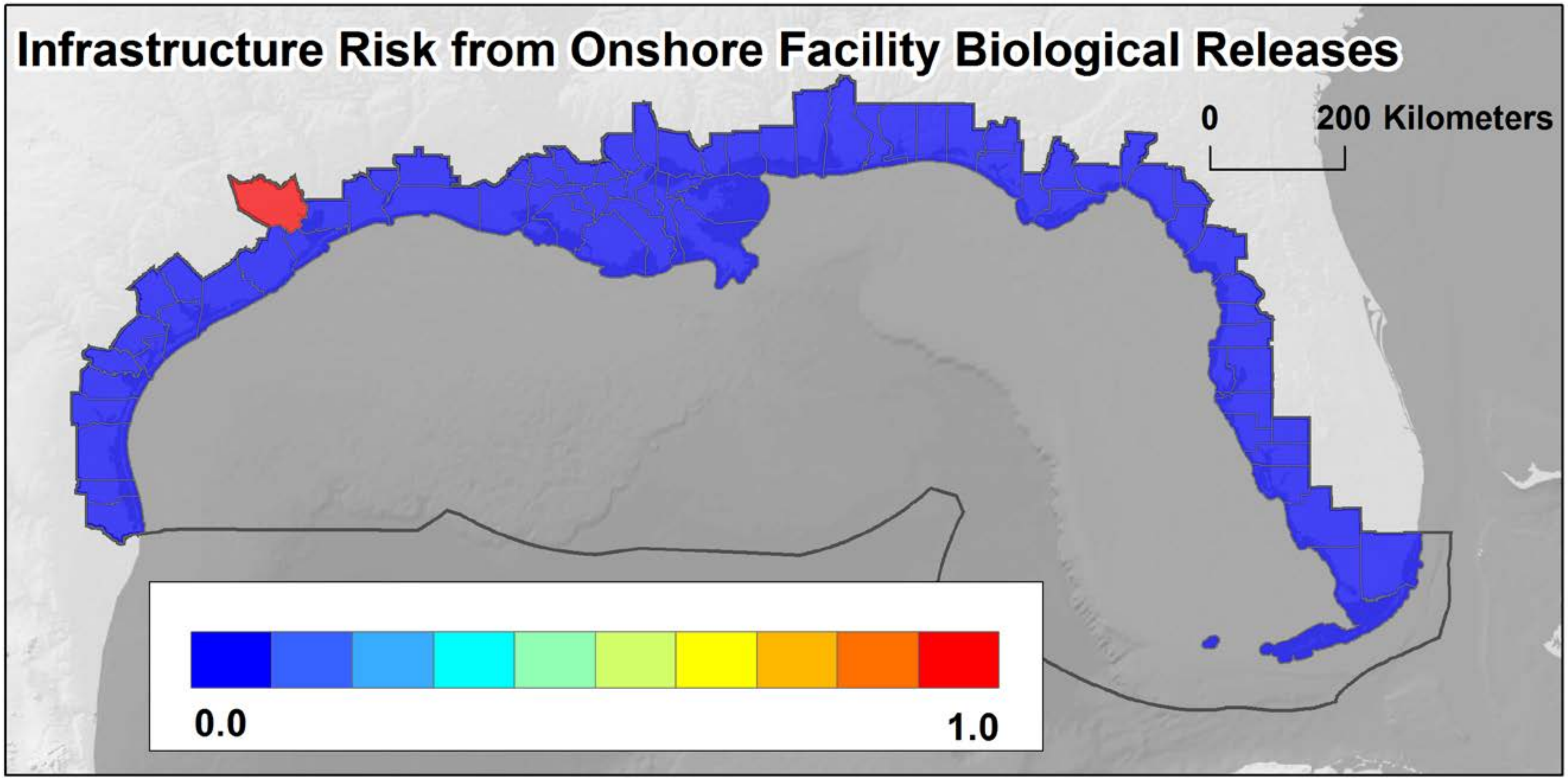

Infrastructure Risk from Onshore Vehicle Chemical Spills
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Onshore Rail Chemical Spills
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Reactor Fallout Radiological Releases
0
200 Kilometers
0.0
1.0


Infrastructure Risk from Onshore Facility Radiological Releases
0
200 Kilometers
0.0
1.0

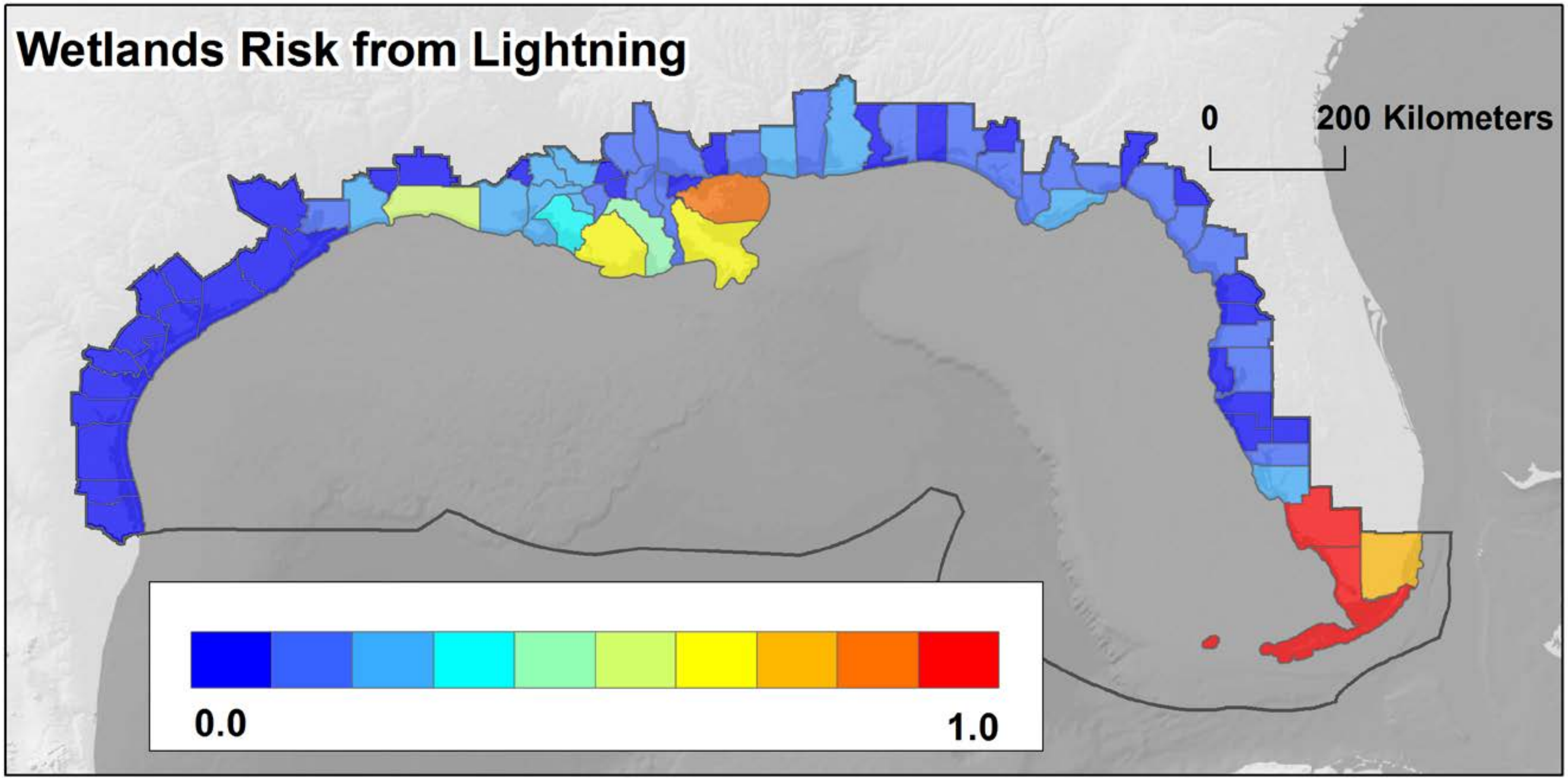

Infrastructure Risk from Onshore Vehicle Radiological Releases
0
200 Kilometers
0.0
1.0

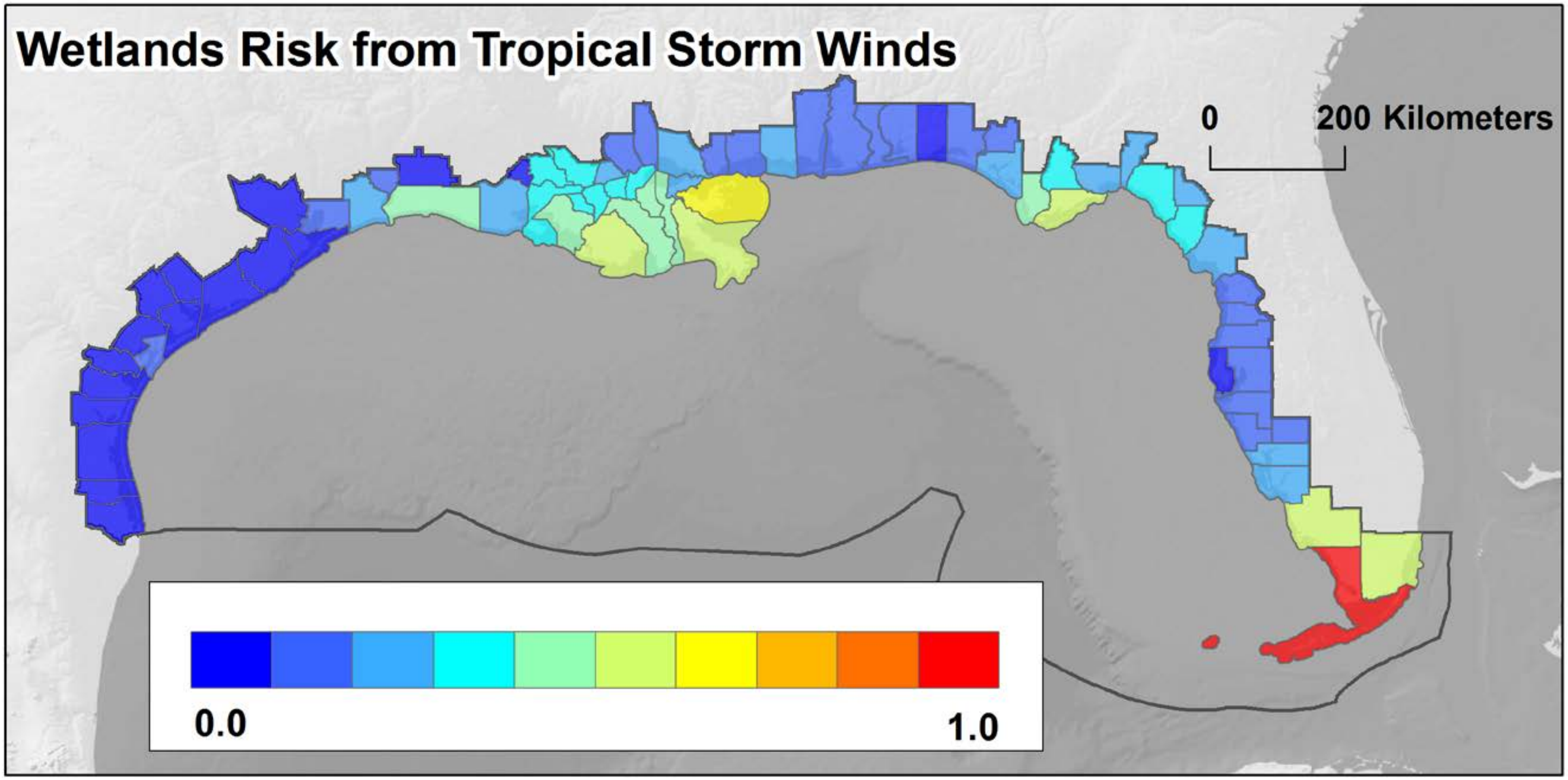

Infrastructure Risk from Onshore Facility Biological Releases
0
200 Kilometers
0.0
1.0

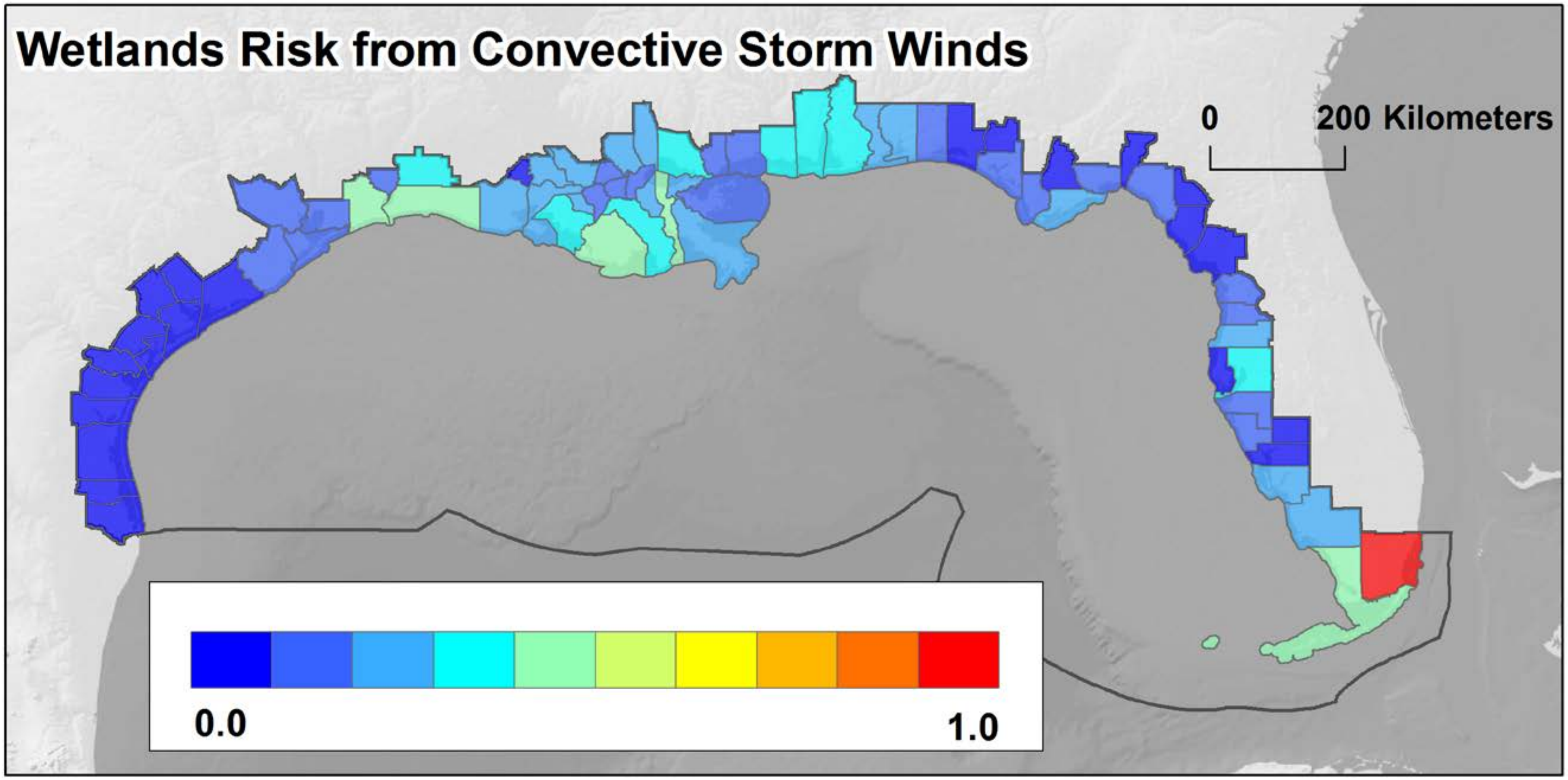
APPENDIX I

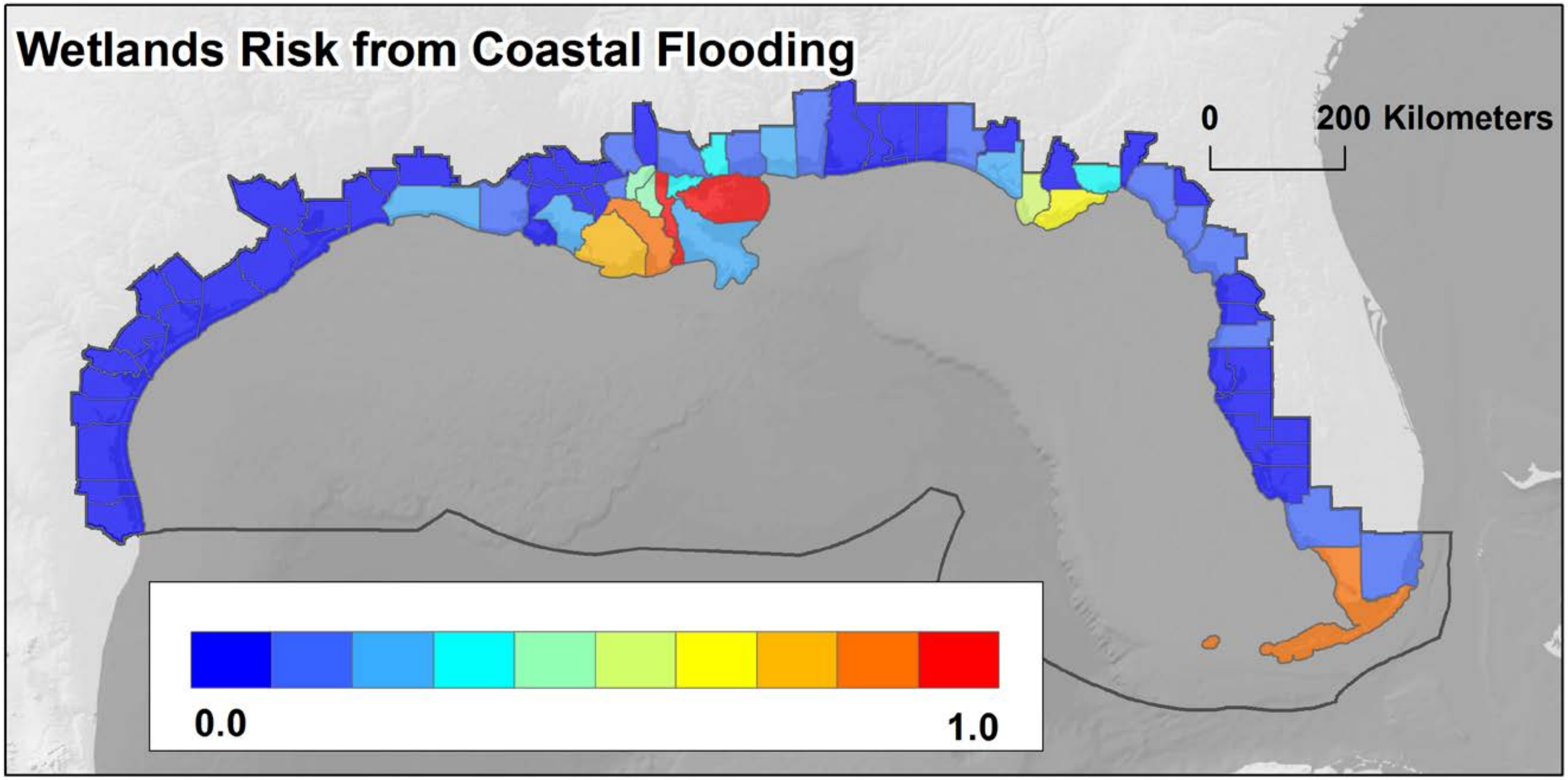
Risk to Sensitive Habitats from Natural Hazards

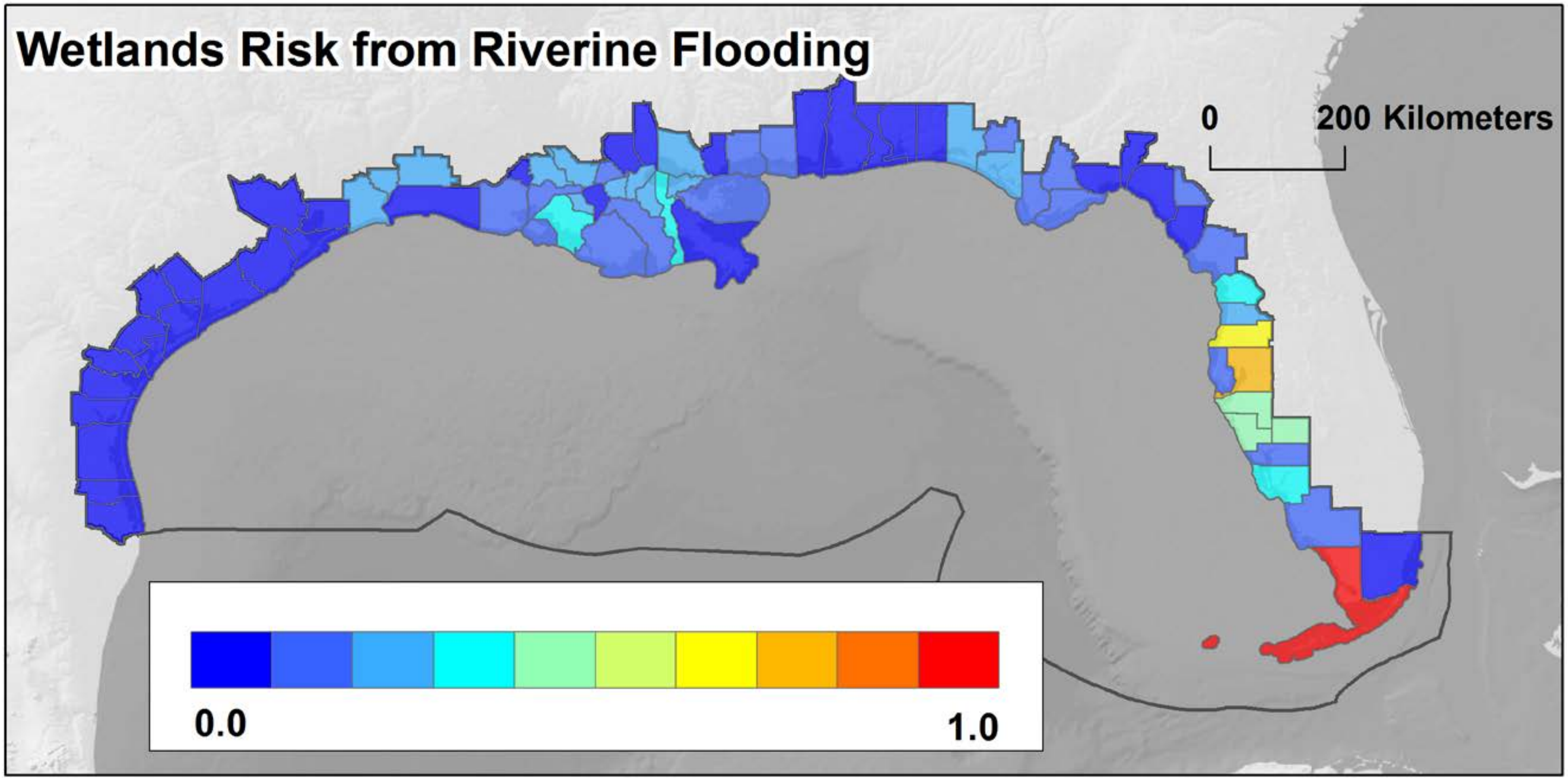
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 35 and display ranked risk index values to sensitive habitats (wetlands) by county or parish for all natural hazards.

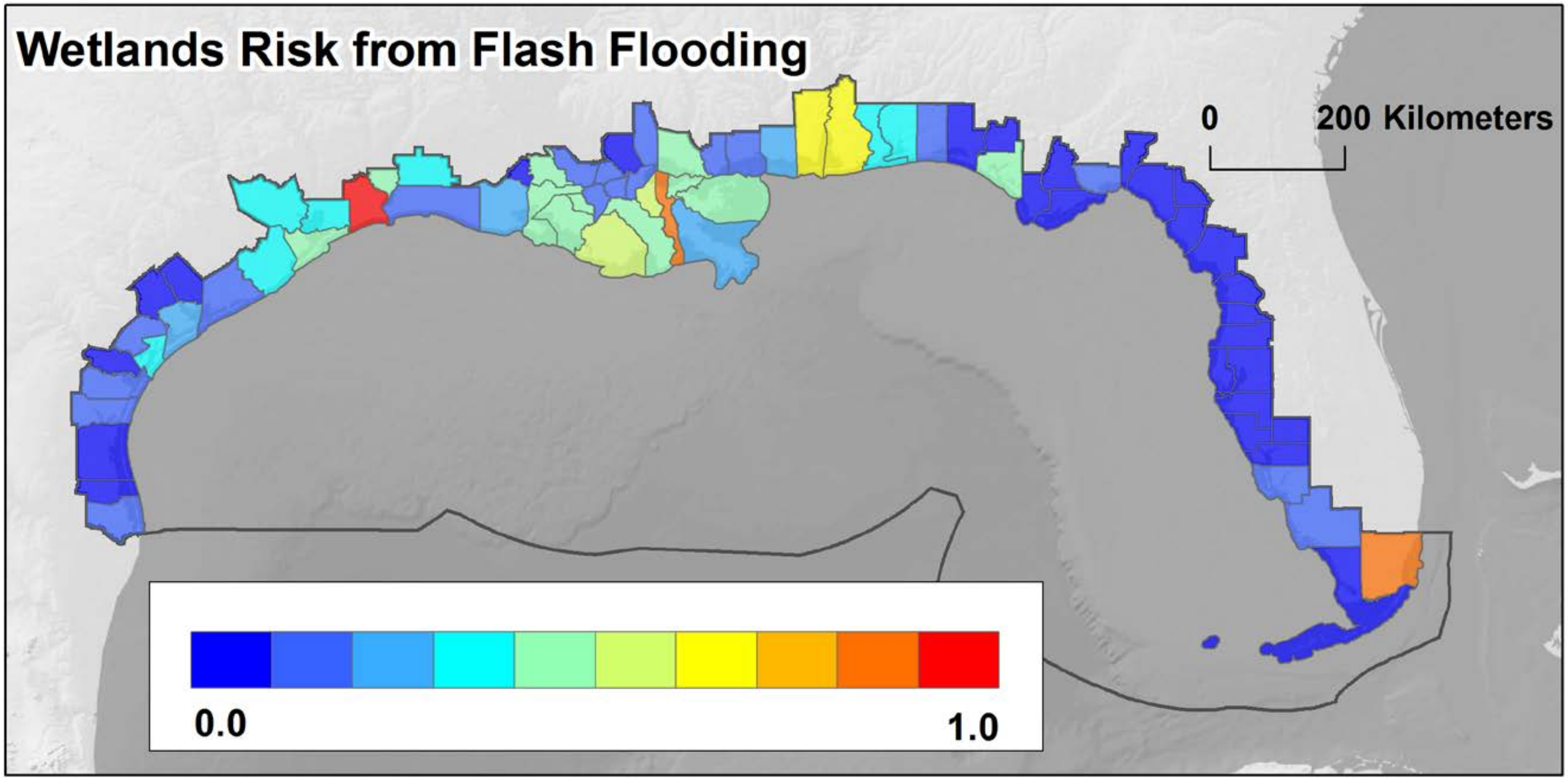

Wetlands Risk from Lightning
0
200 Kilometers
0.0
1.0

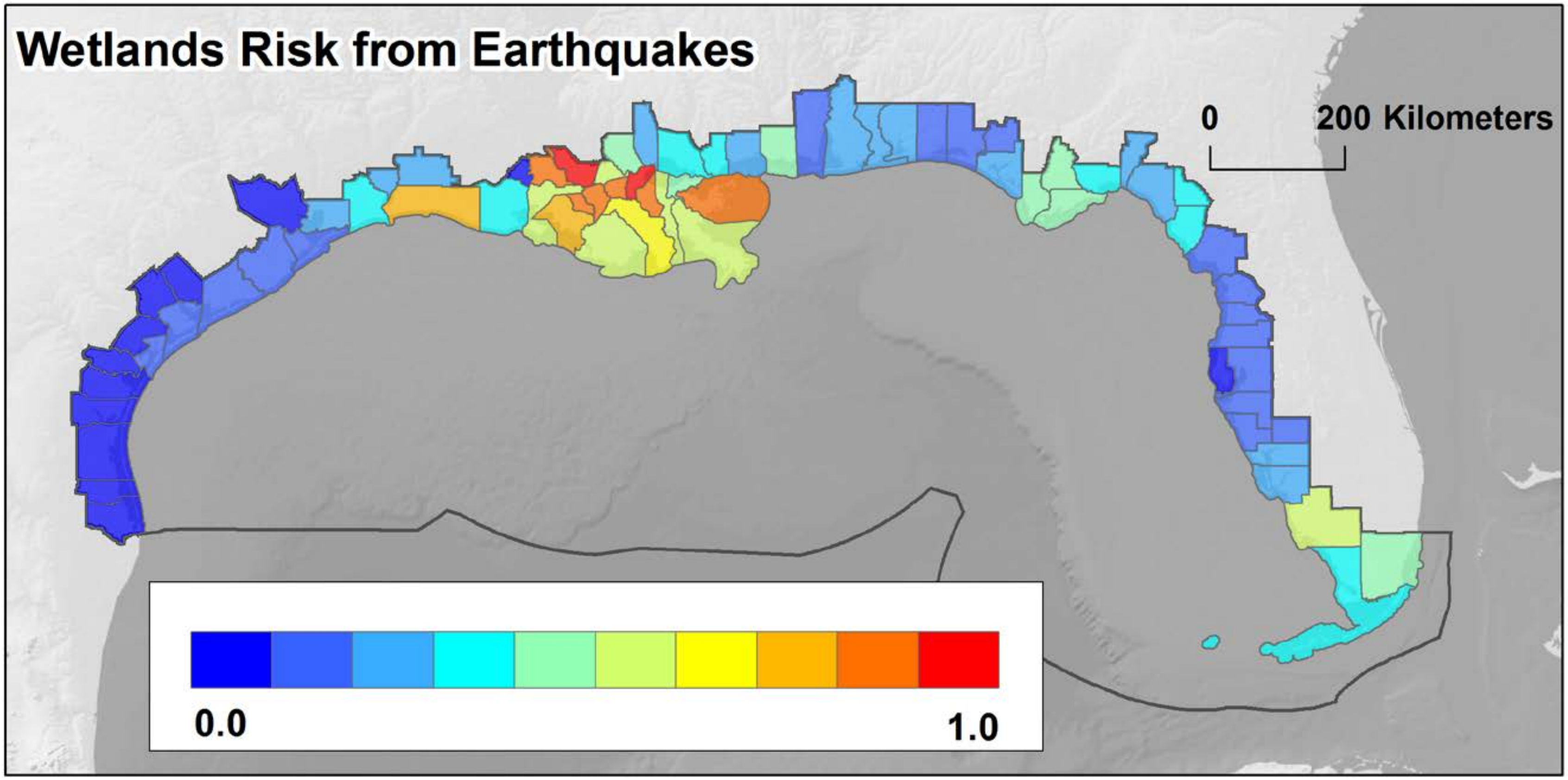

Wetlands Risk from Tropical Storm Winds
0
200 Kilometers
0.0
1.0

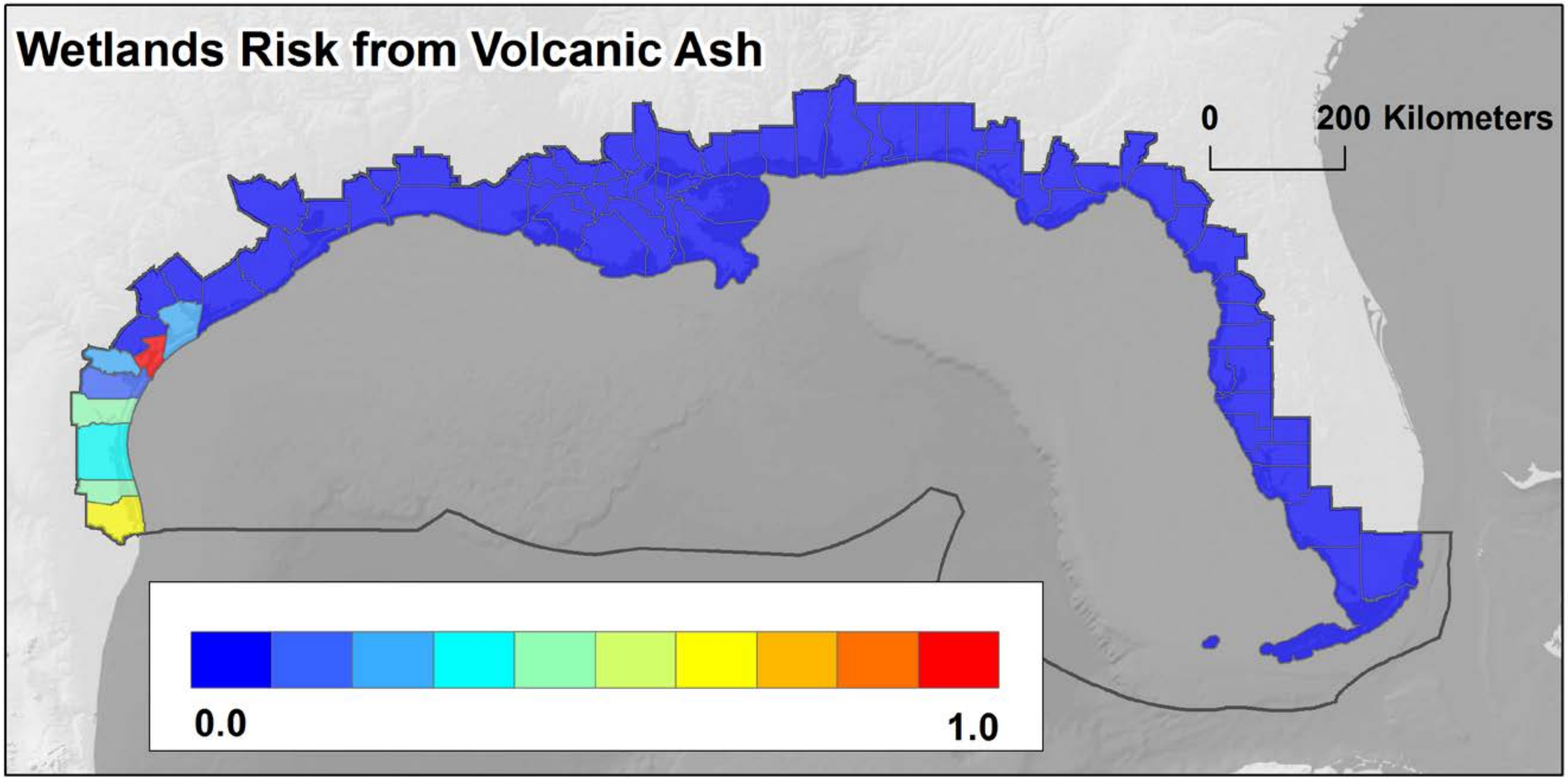

Wetlands Risk from Convective Storm Winds
0
200 Kilometers
0.0
1.0

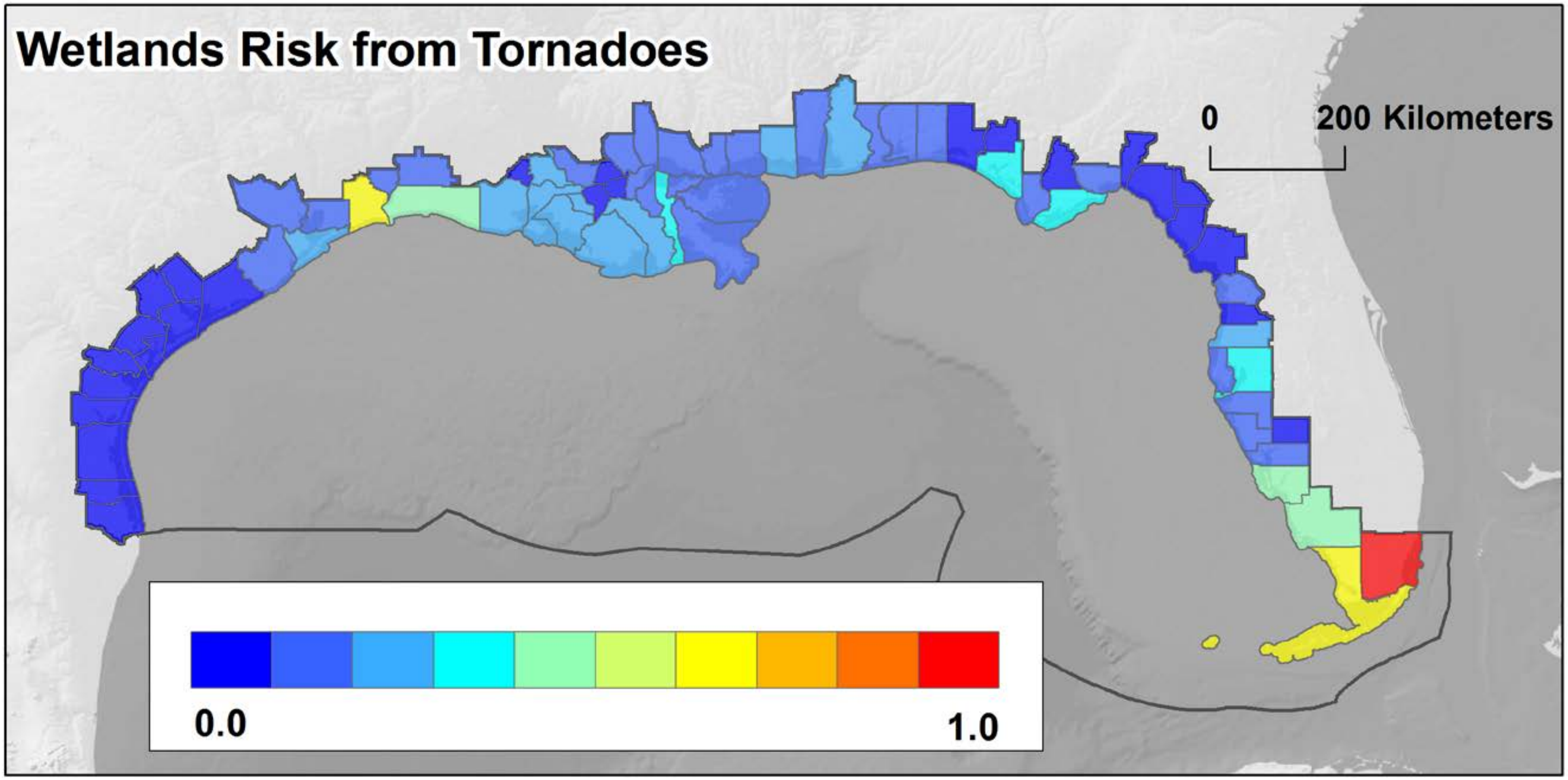

Wetlands Risk from Coastal Flooding
0
200 Kilometers
0.0
1.0


Wetlands Risk from Riverine Flooding
0
200 Kilometers
0.0
1.0

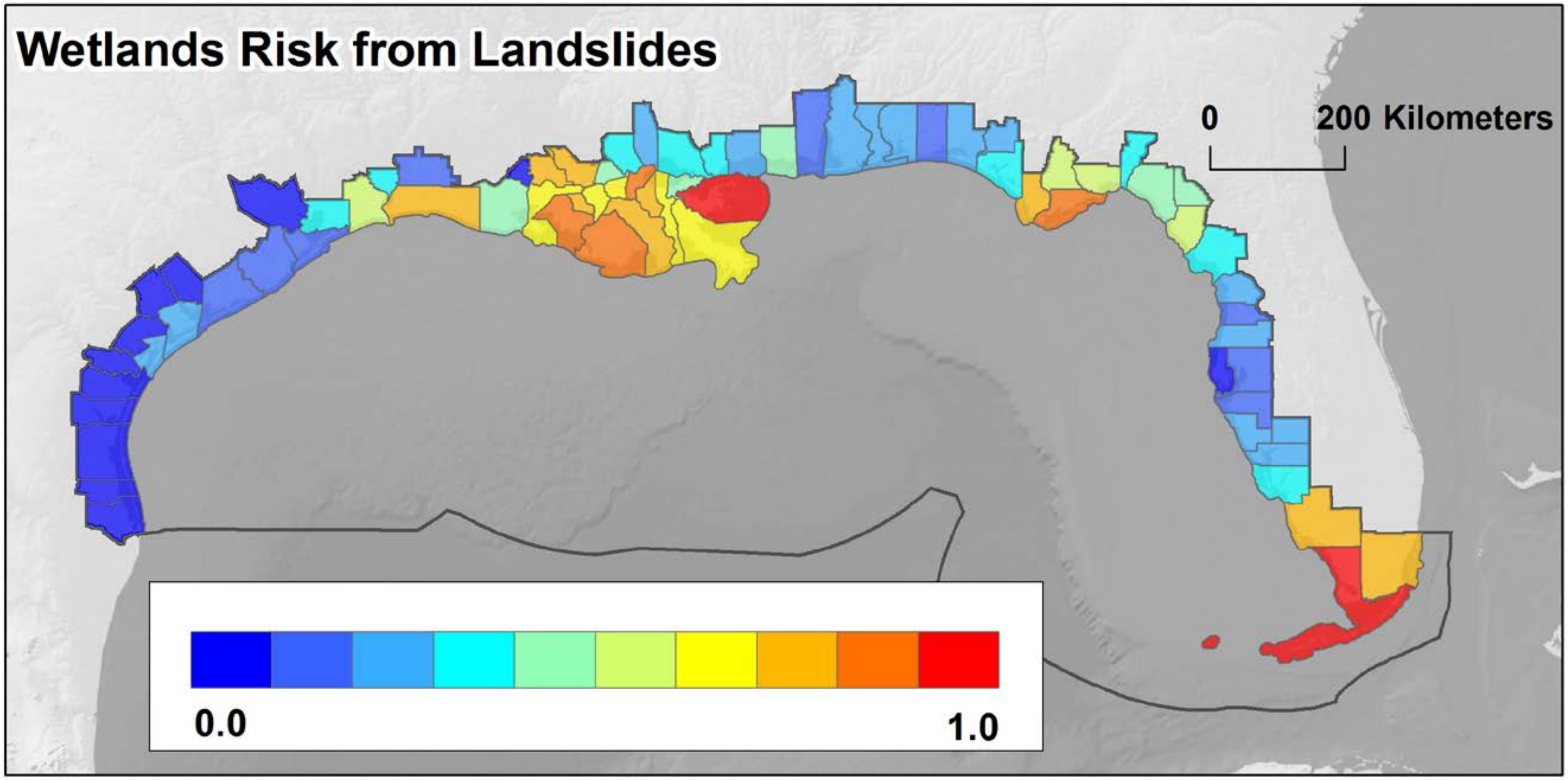

Wetlands Risk from Flash Flooding
0
200 Kilometers
0.0
1.0


Wetlands Risk from Earthquakes
0
200 Kilometers
0.0
1.0

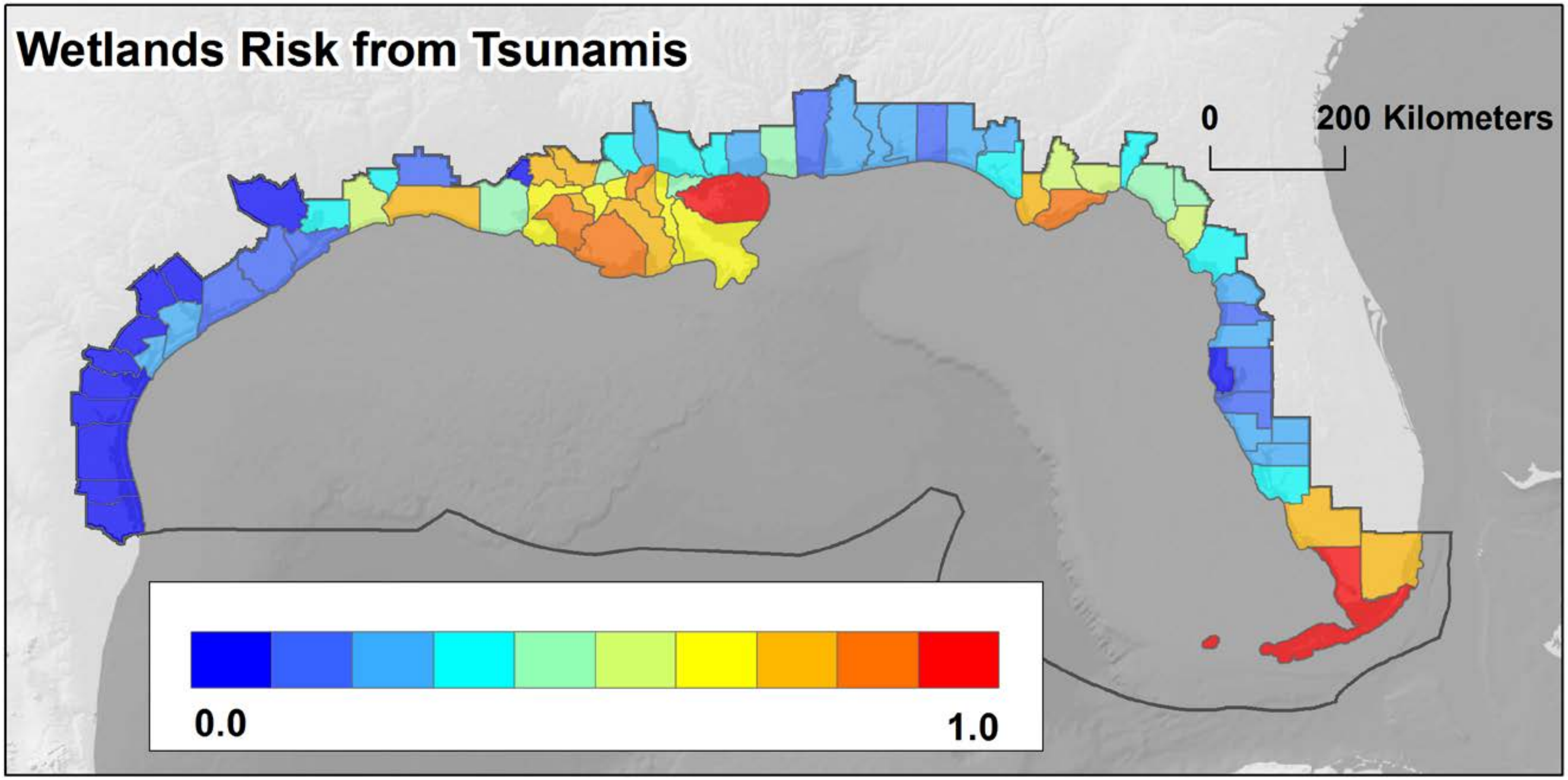

Wetlands Risk from Volcanic Ash
0
200 Kilometers
0.0
1.0

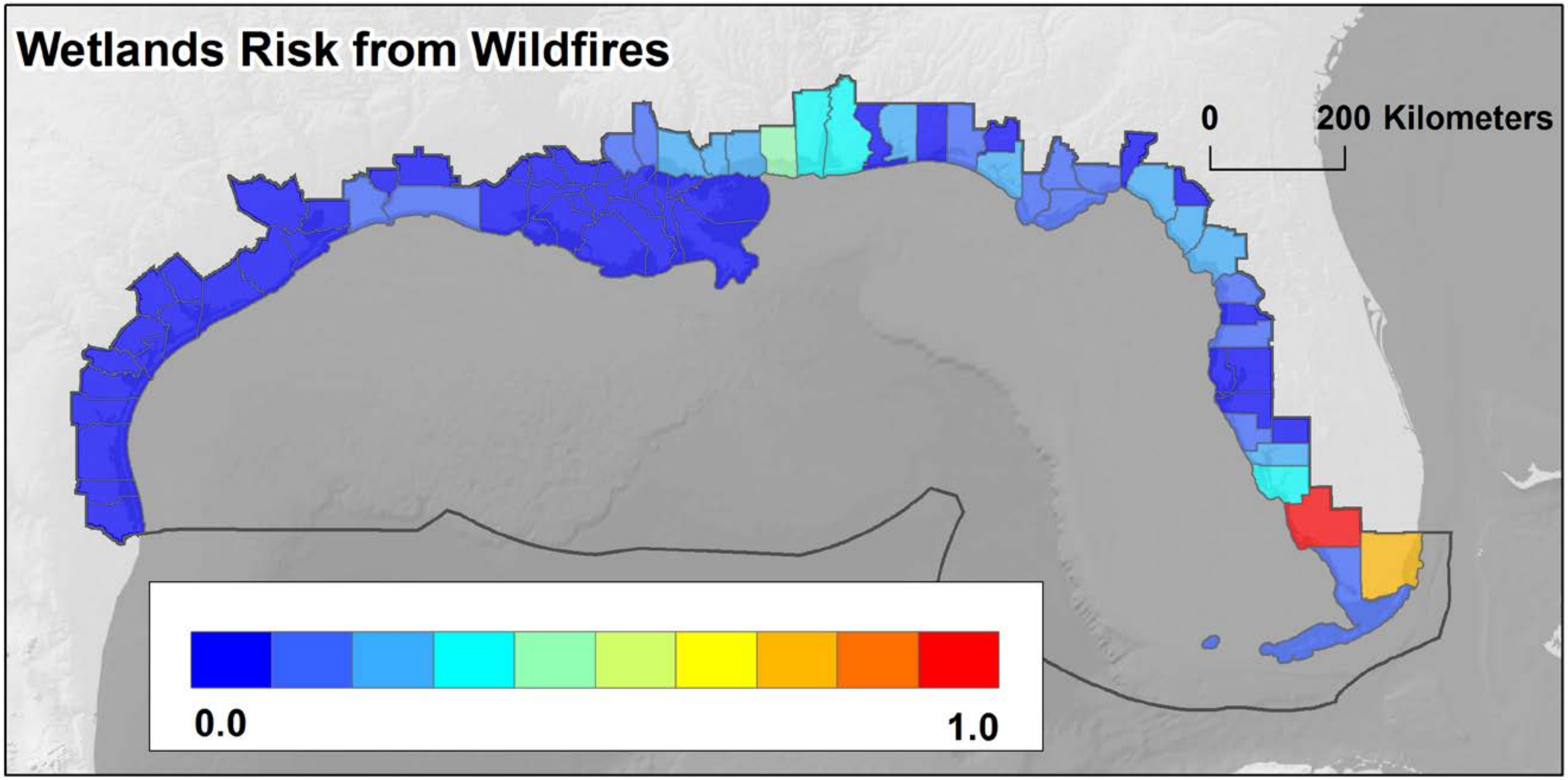


Wetlands Risk from Tornadoes
0
200 Kilometers
0.0
1.0

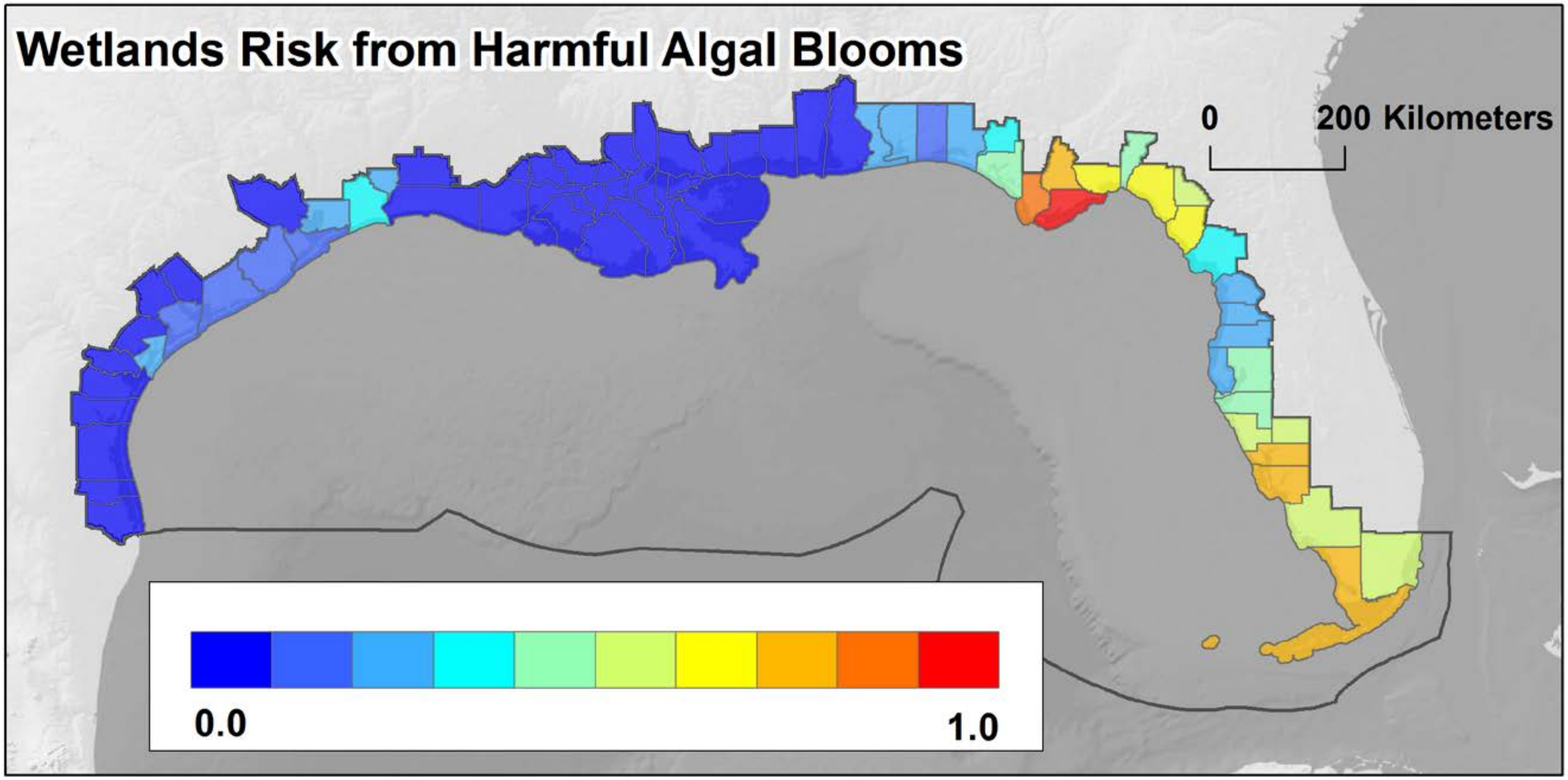


Wetlands Risk from Landslides
0
200 Kilometers
0.0
1.0


Wetlands Risk from Tsunamis
0
200 Kilometers
0.0
1.0



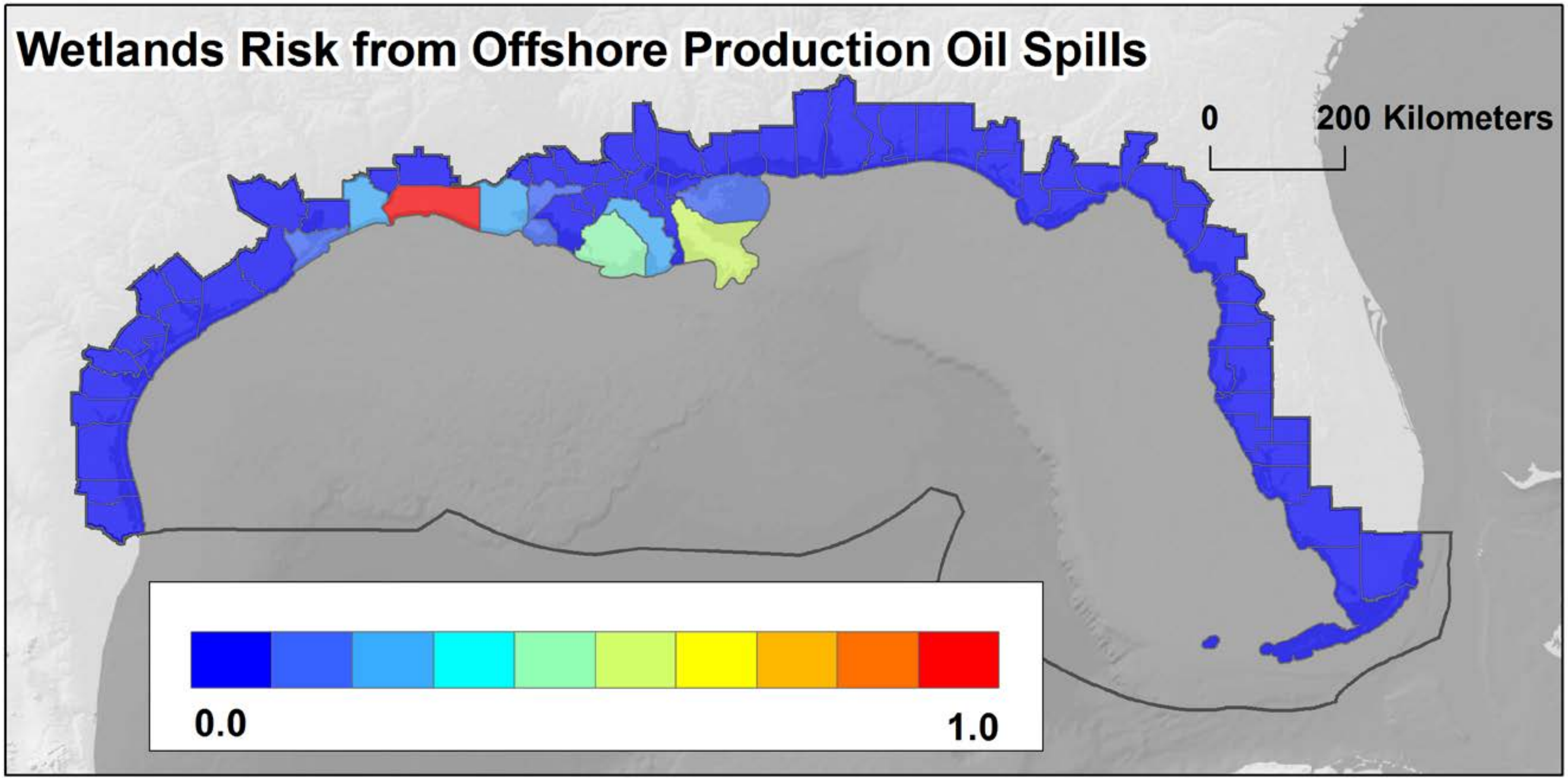
Wetlands Risk from Wildfires
0
200 Kilometers
0.0
1.0

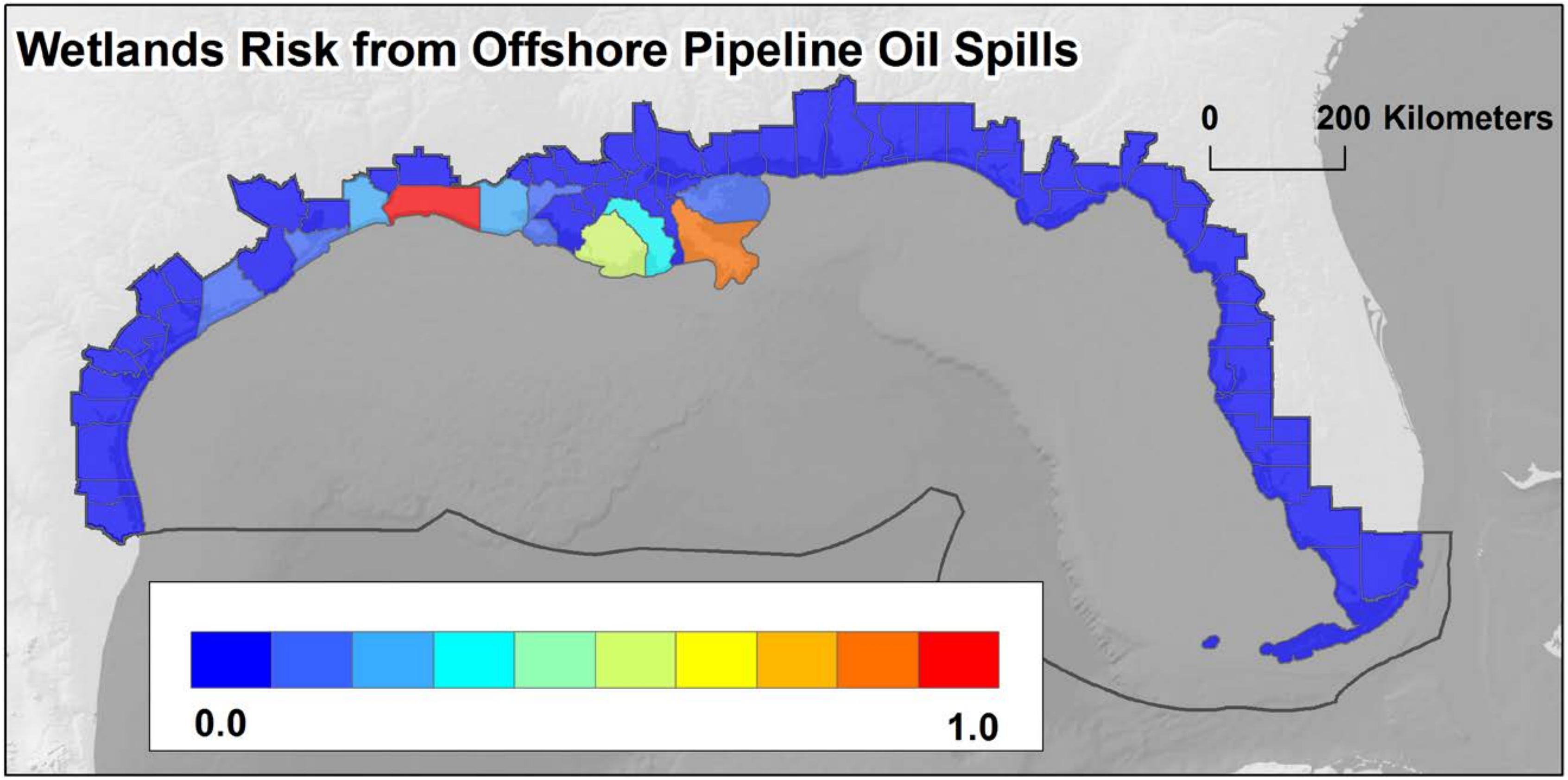

Wetlands Risk from Harmful Algal Blooms
0
200 Kilometers
0.0
1.0

APPENDIX J

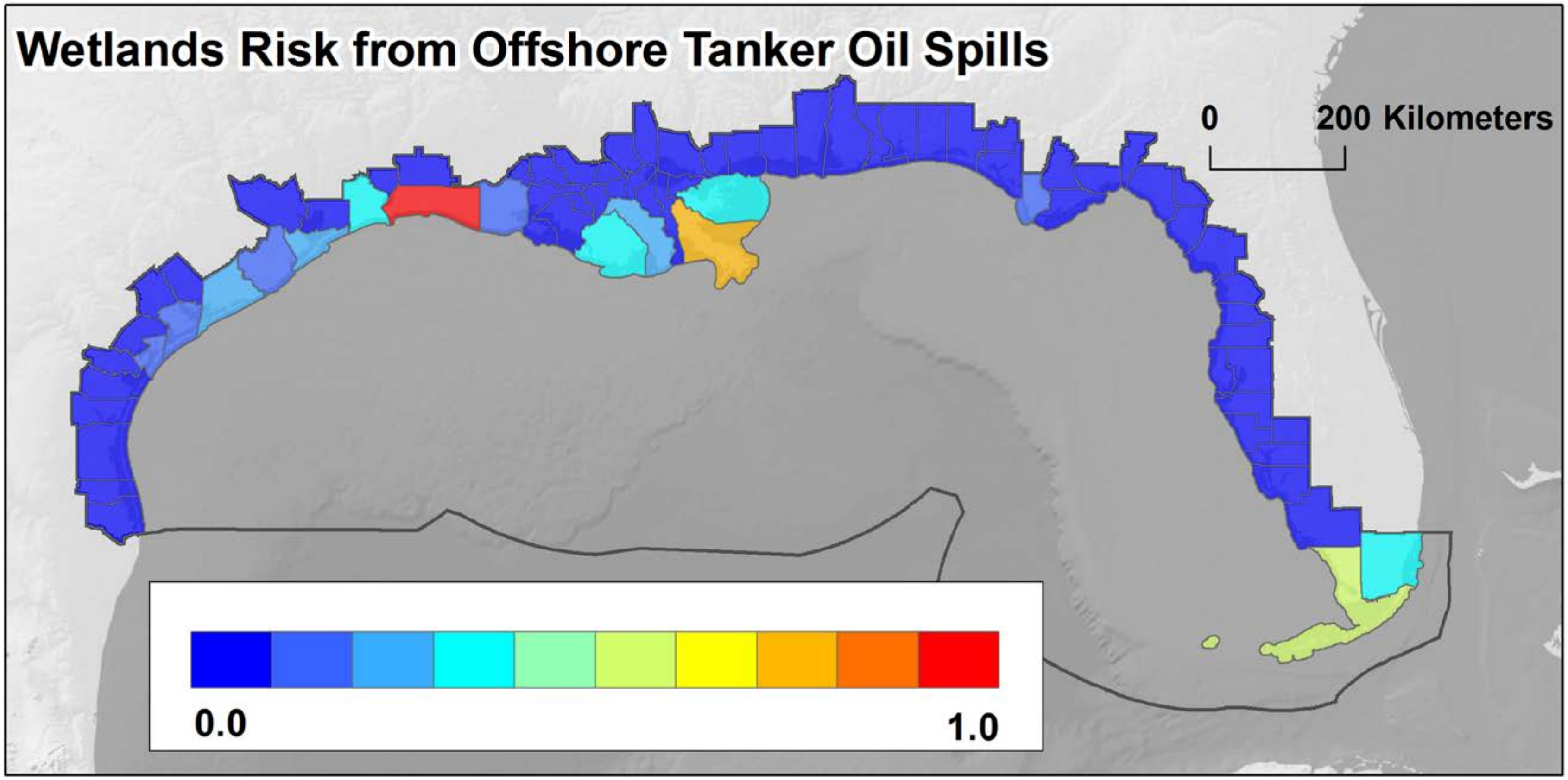
Risk to Sensitive Habitats from Anthropogenic Hazards

Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 36 and display ranked risk index values to sensitive habitats (wetlands) by county or parish for all anthropogenic hazards.

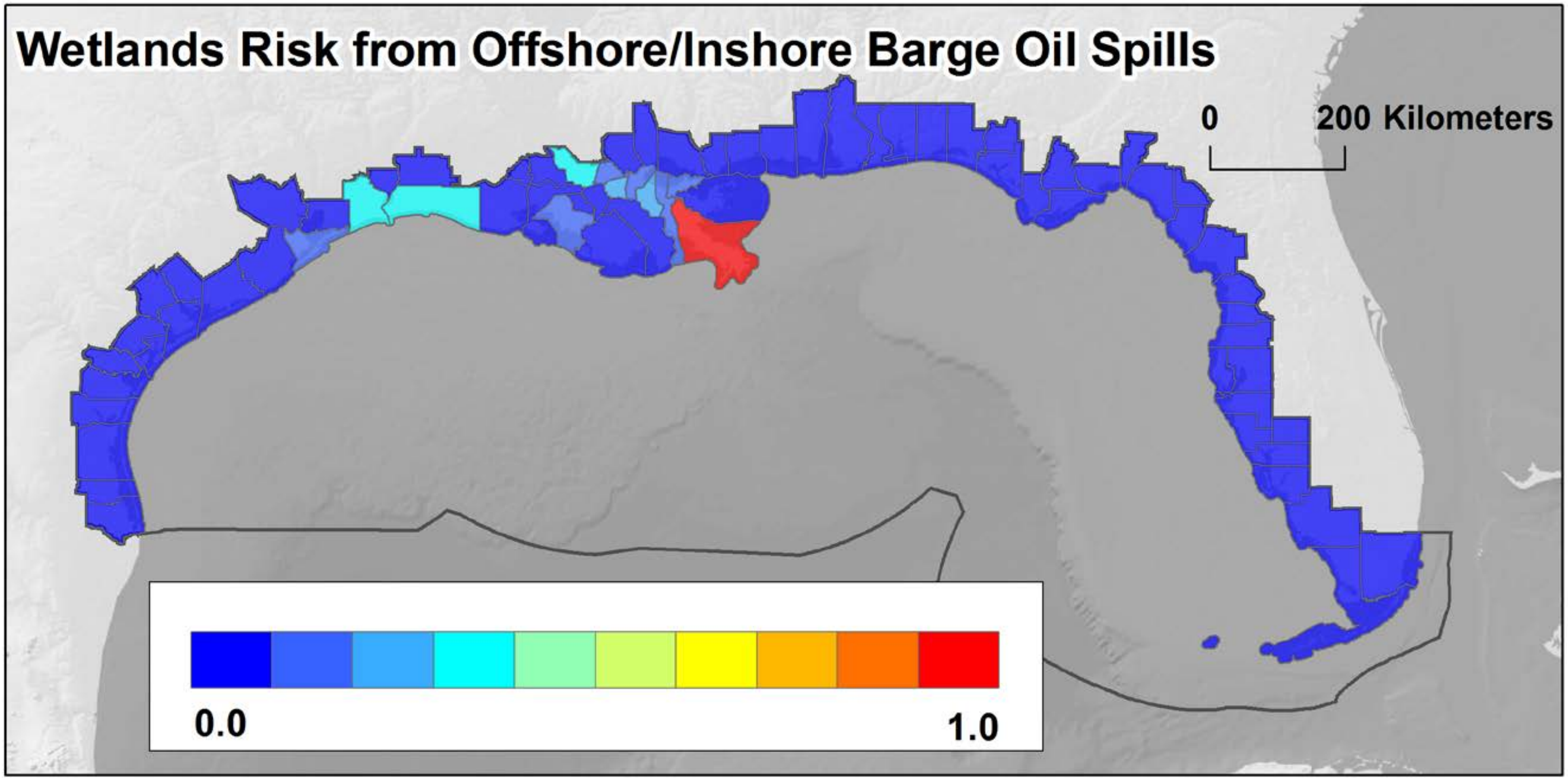

Wetlands Risk from Offshore Production Oil Spills
0
200 Kilometers
0.0
1.0

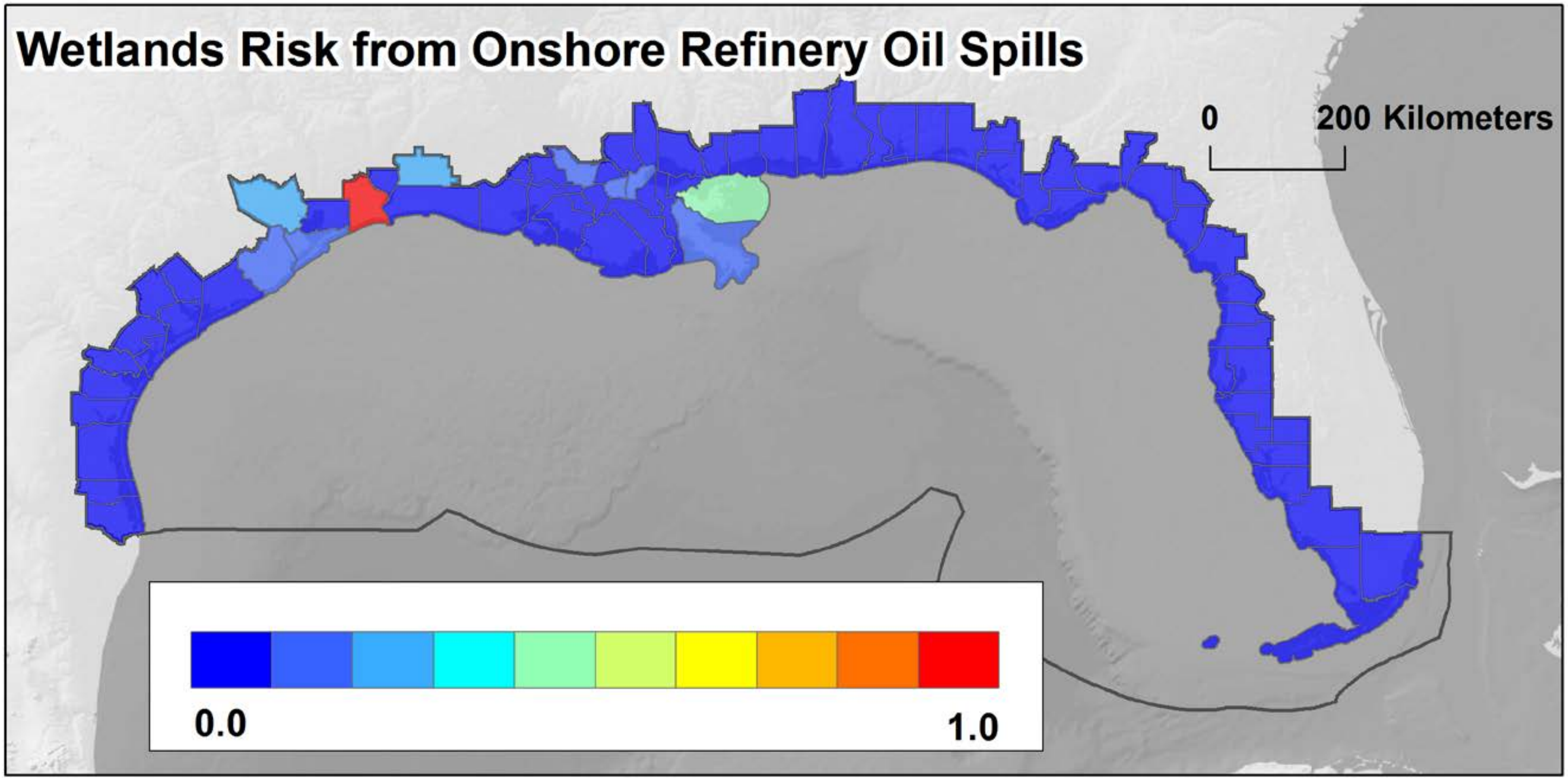


Wetlands Risk from Offshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

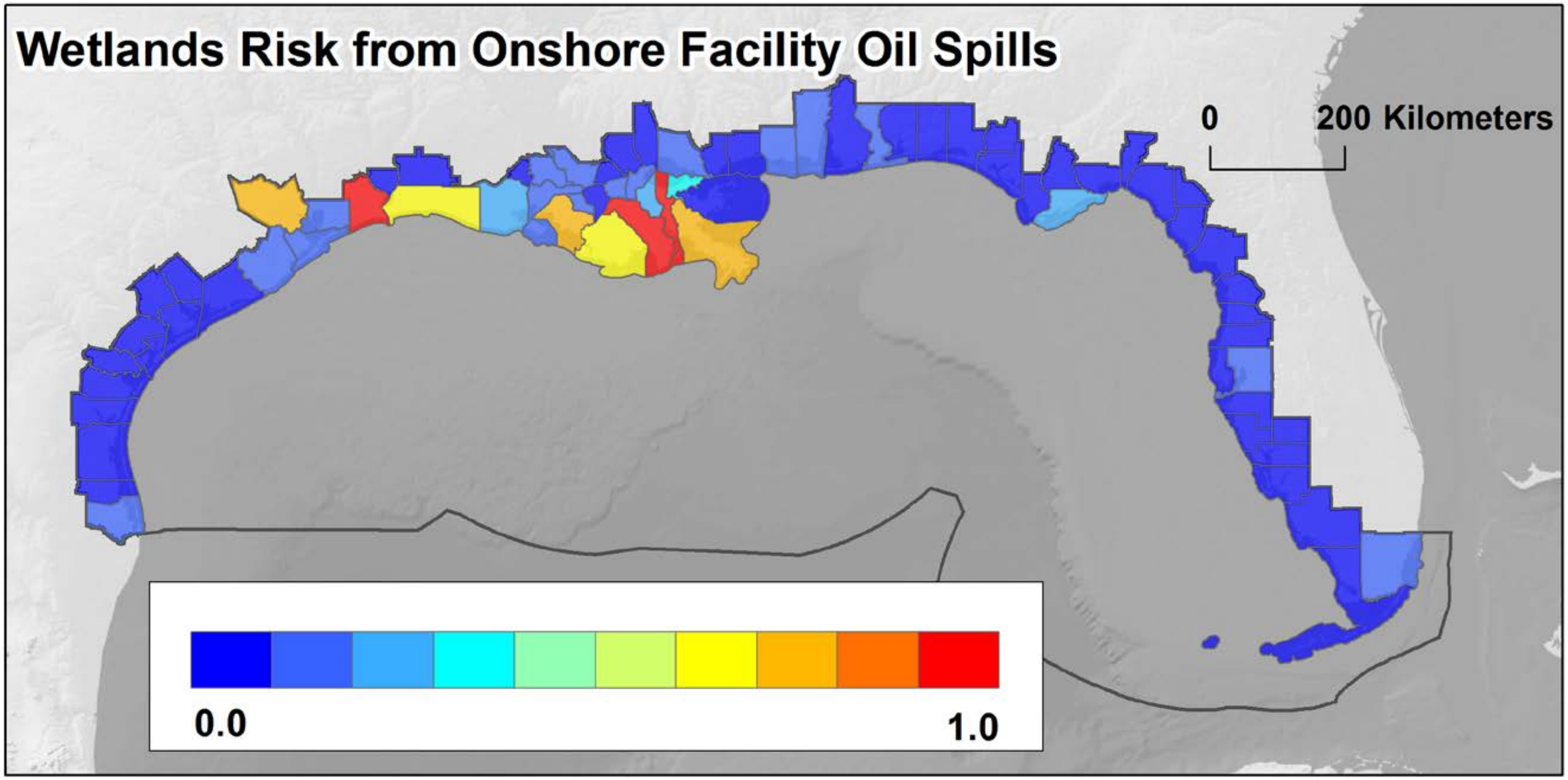


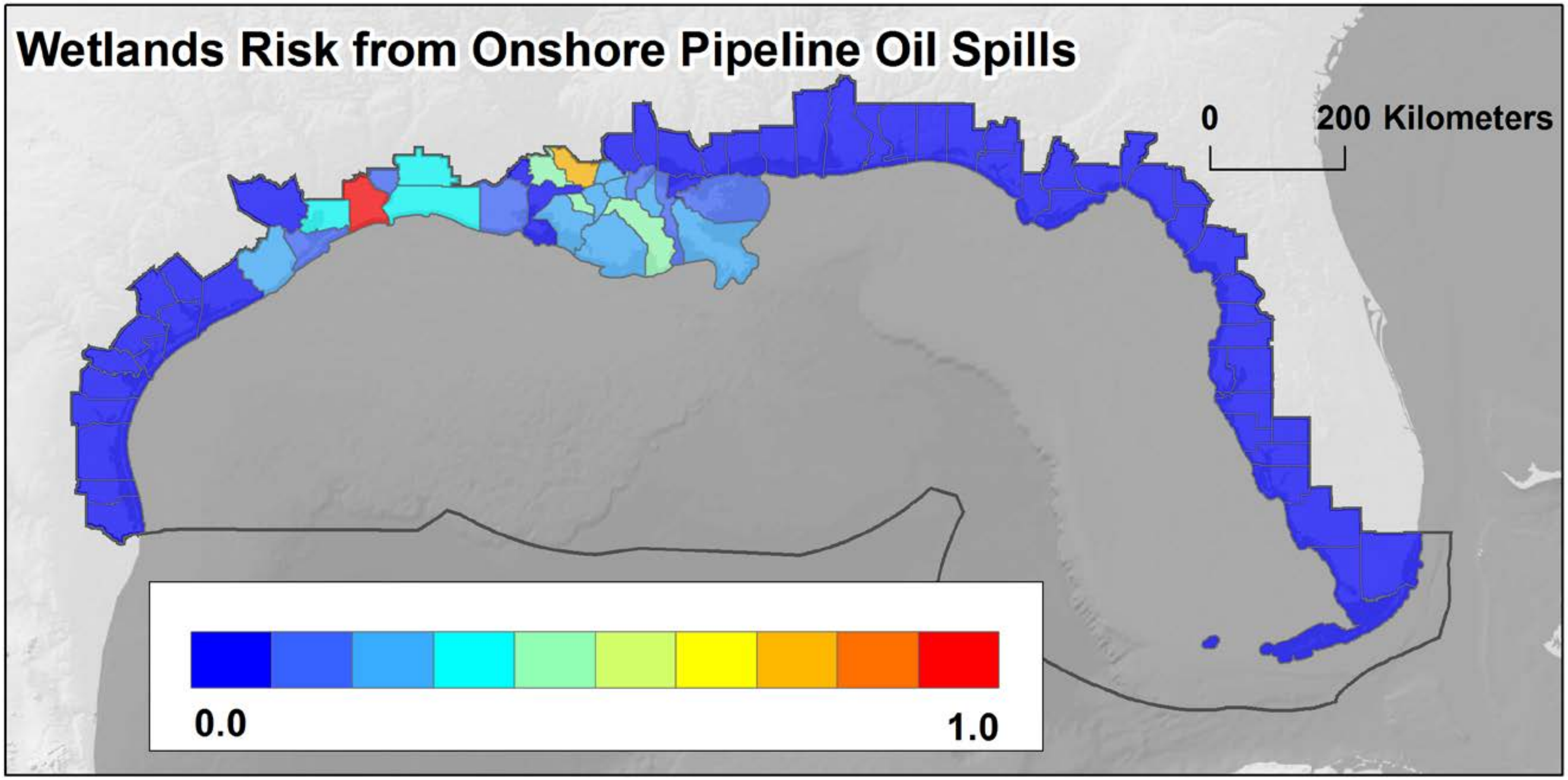
Wetlands Risk from Offshore Tanker Oil Spills
0
200 Kilometers
0.0
1.0


Wetlands Risk from Offshore/Inshore Barge Oil Spills
0
200 Kilometers
0.0
1.0

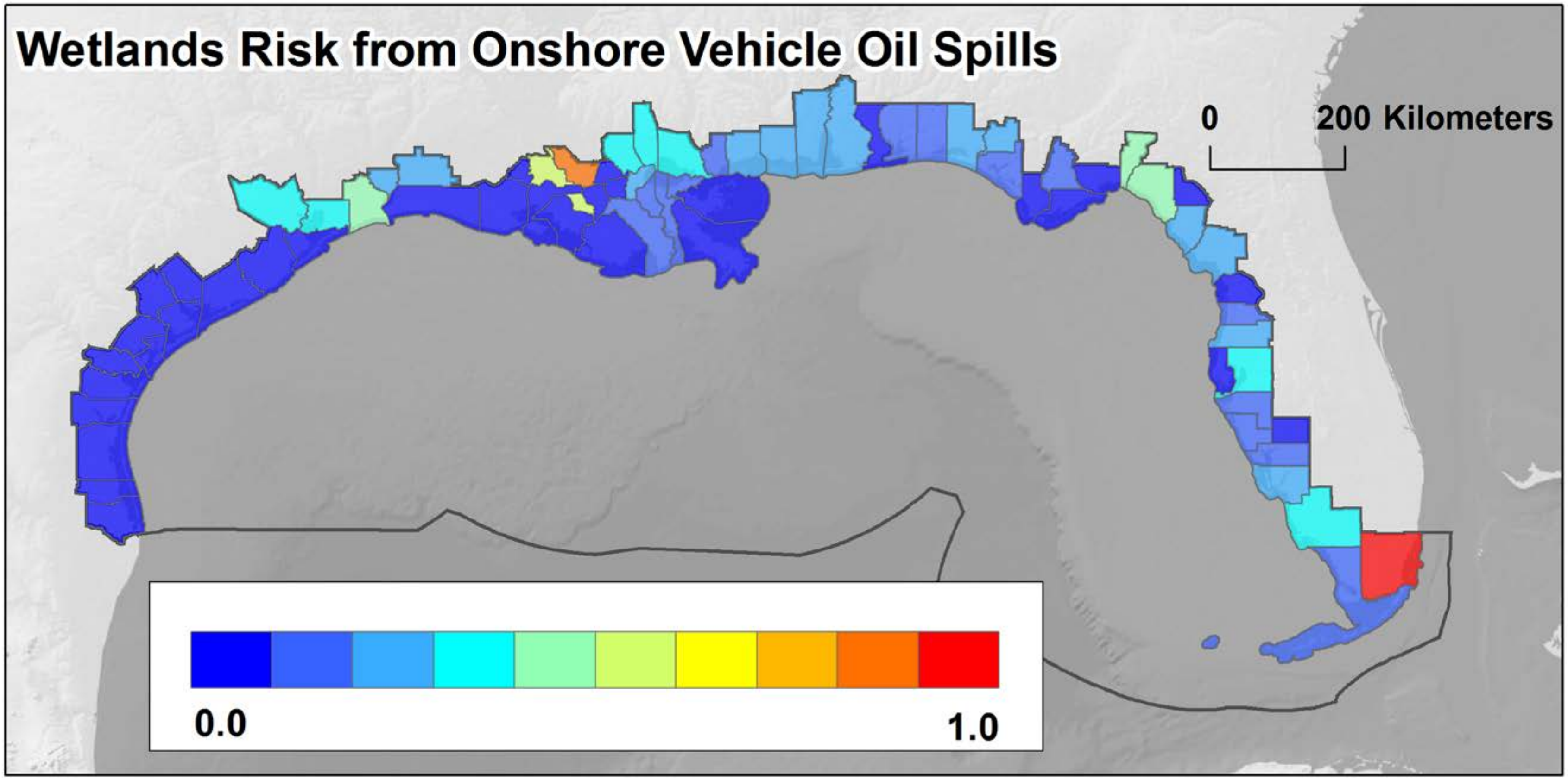


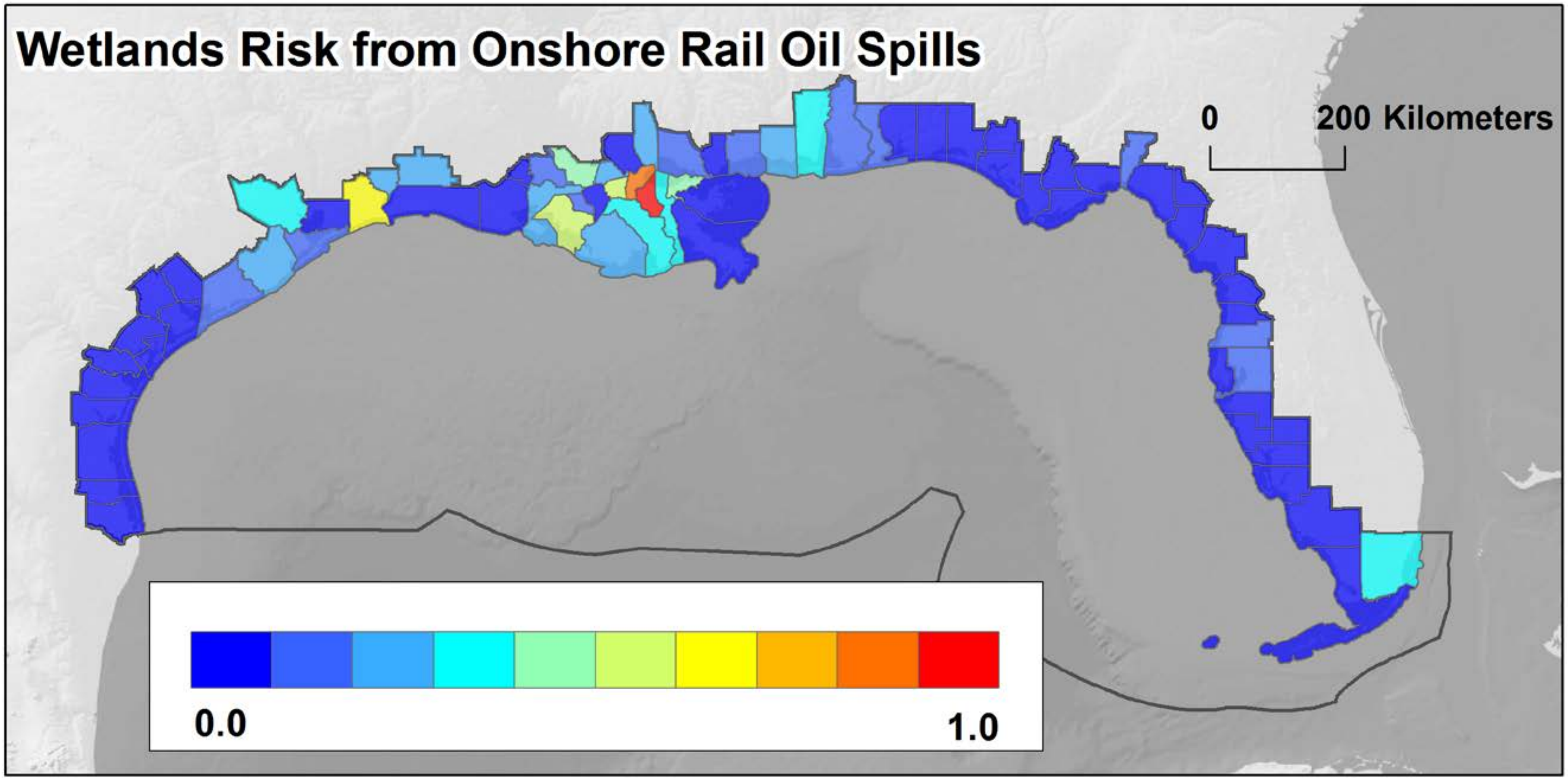
Wetlands Risk from Onshore Refinery Oil Spills
0
200 Kilometers
0.0
1.0

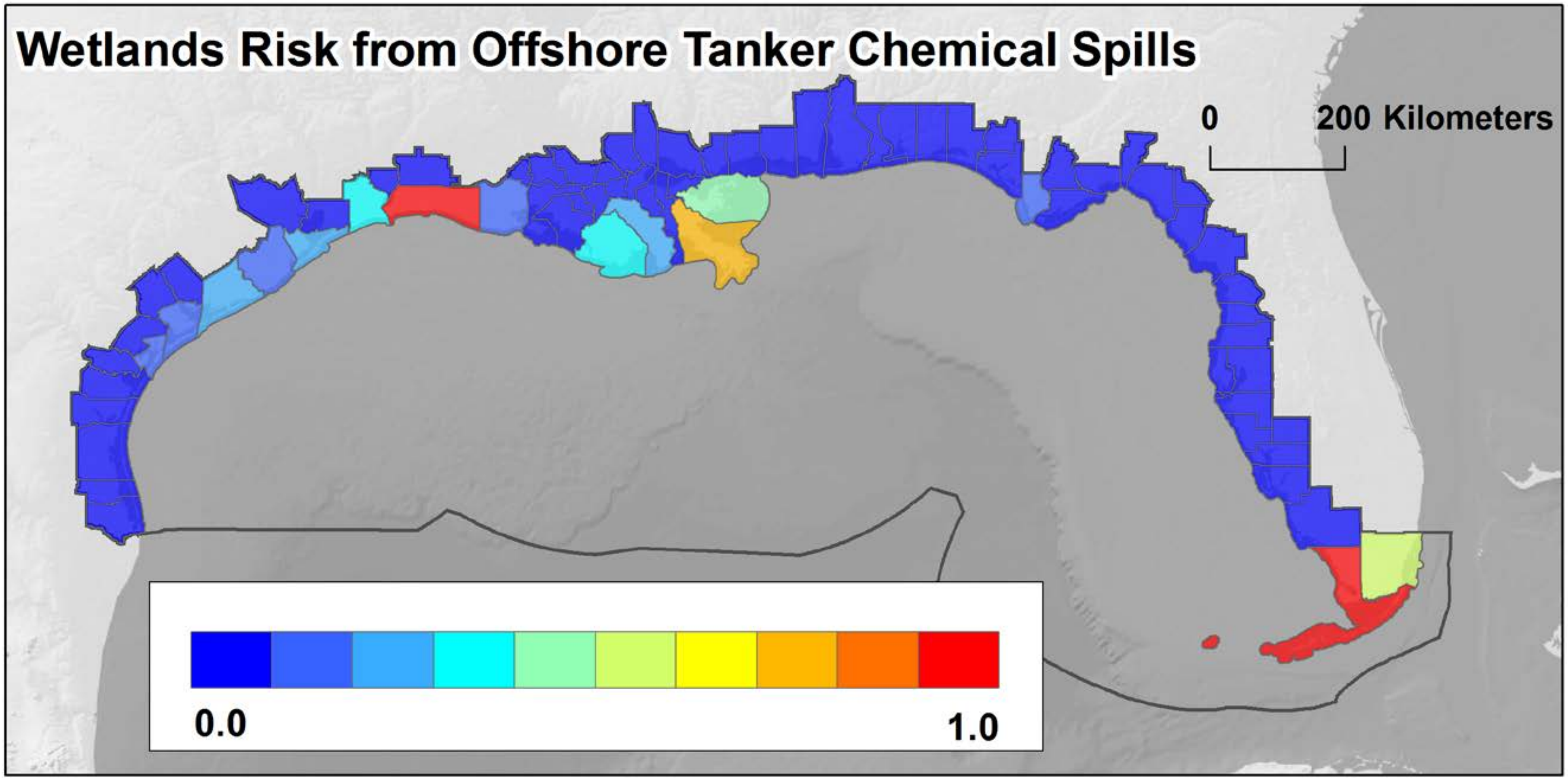

Wetlands Risk from Onshore Facility Oil Spills
0
200 Kilometers
0.0
1.0



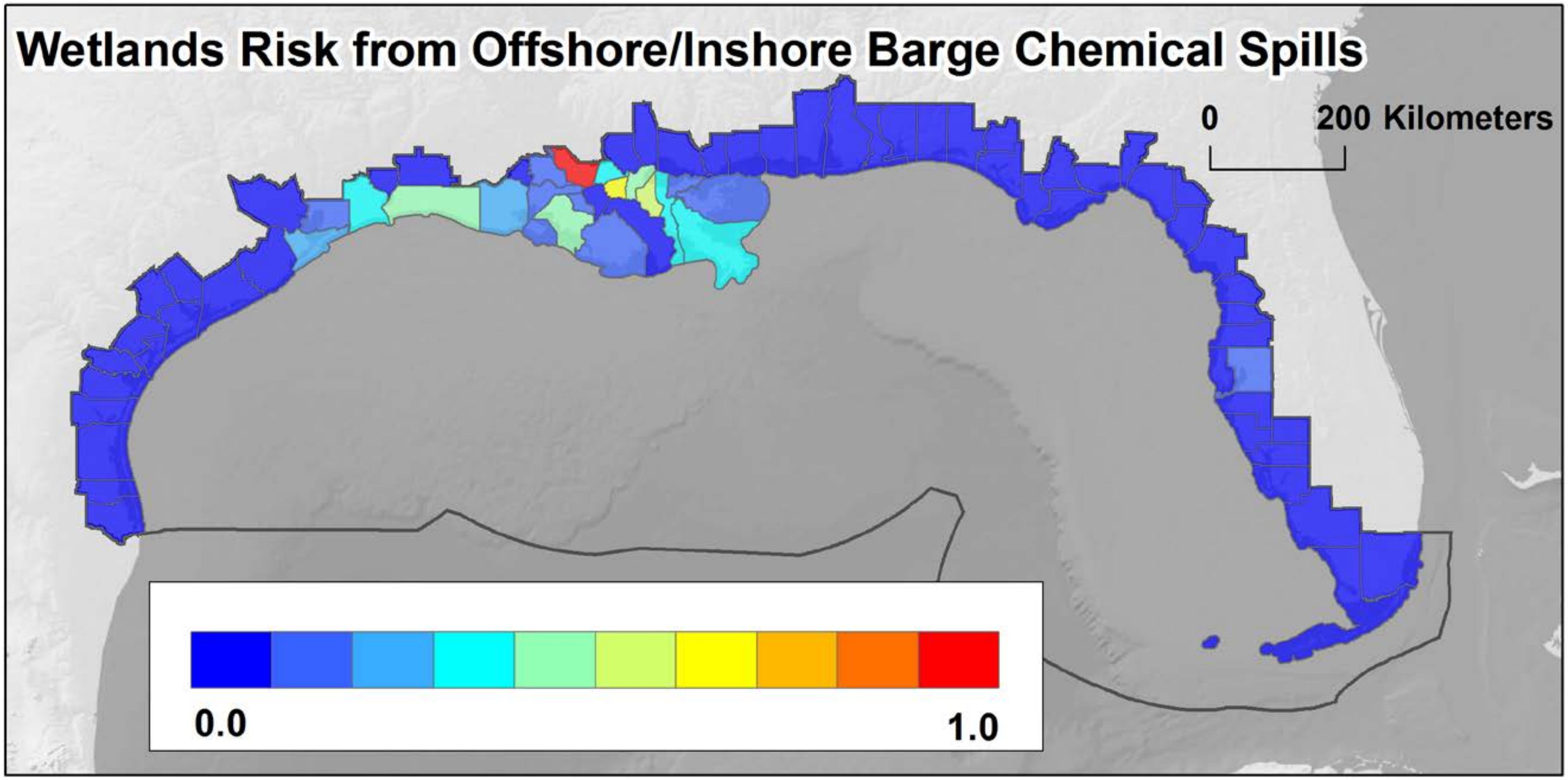
Wetlands Risk from Onshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

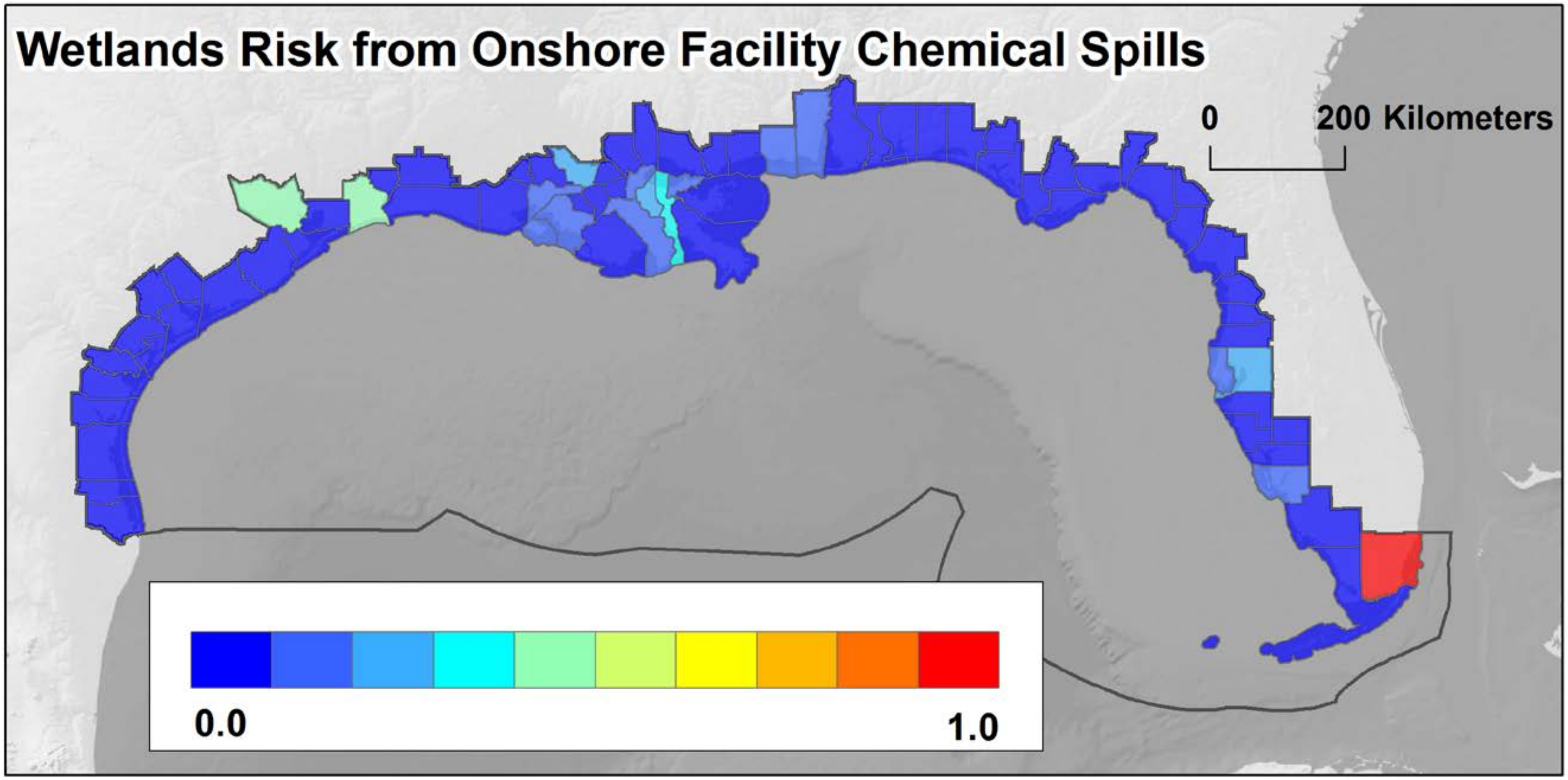

Wetlands Risk from Onshore Vehicle Oil Spills
0
200 Kilometers
0.0
1.0

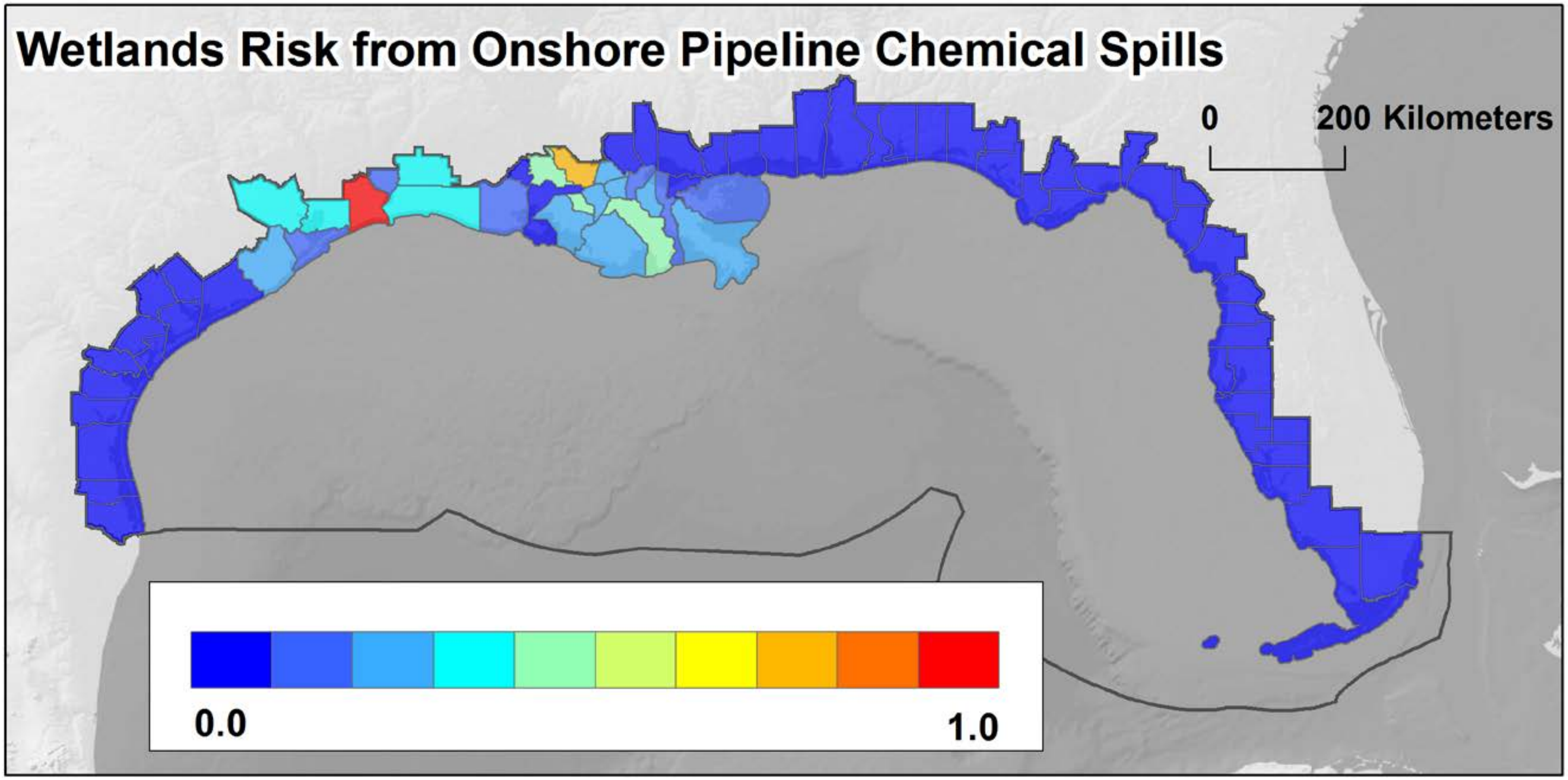

Wetlands Risk from Onshore Rail Oil Spills
0
200 Kilometers
0.0
1.0

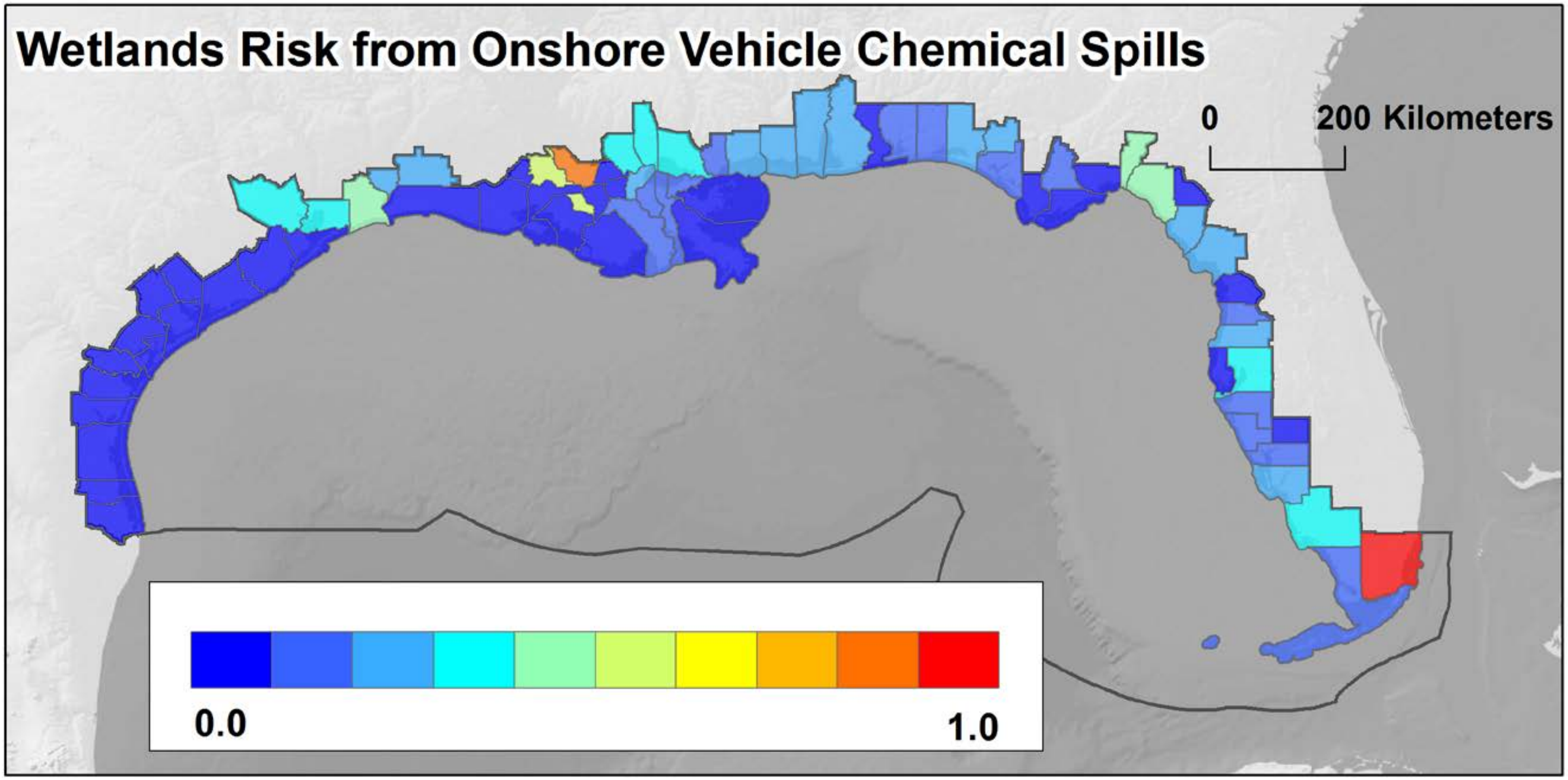


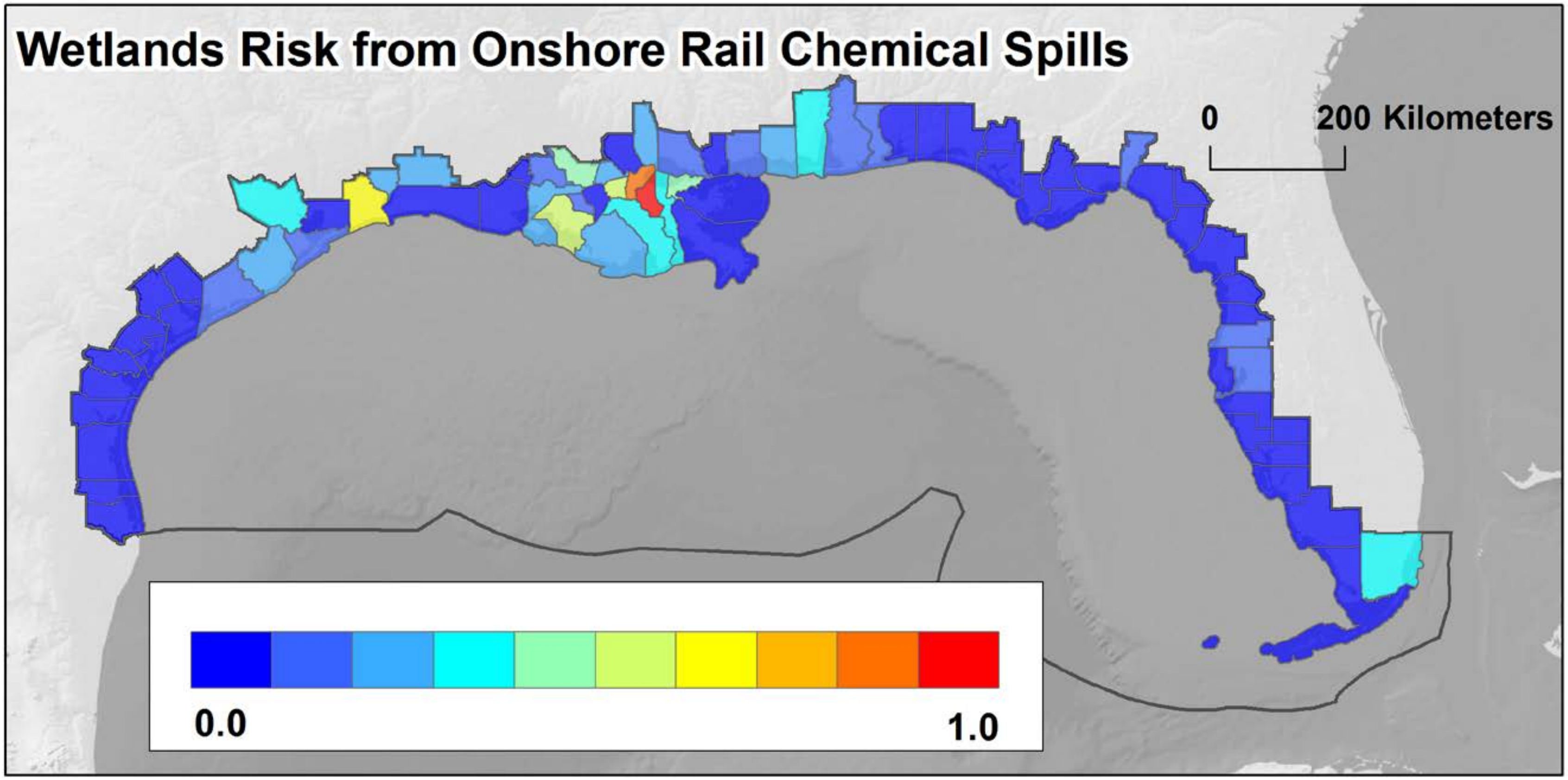
Wetlands Risk from Offshore Tanker Chemical Spills
0
200 Kilometers
0.0
1.0

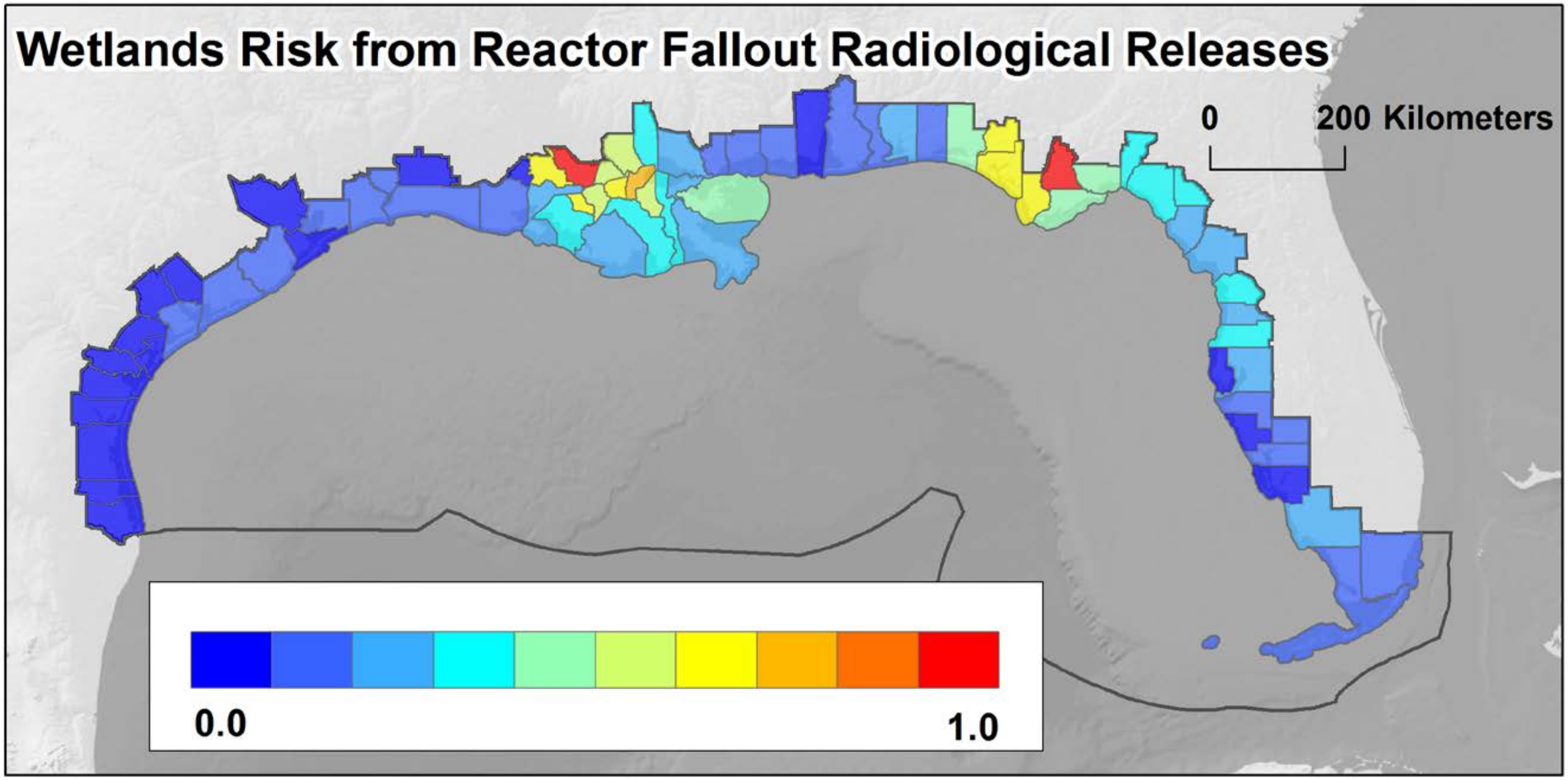

Wetlands Risk from Offshore/Inshore Barge Chemical Spills
0
200 Kilometers
0.0
1.0

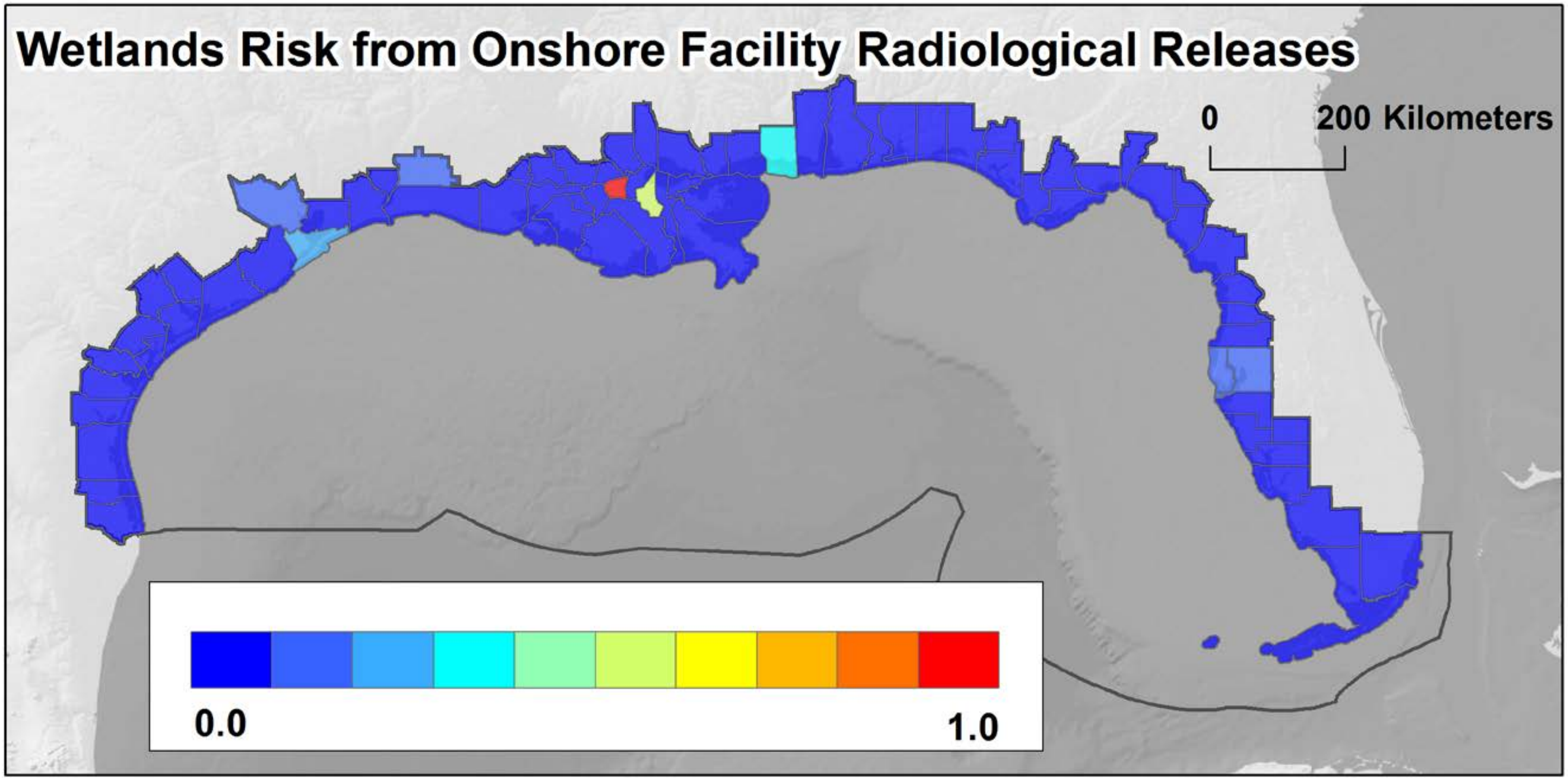

Wetlands Risk from Onshore Facility Chemical Spills
0
200 Kilometers
0.0
1.0

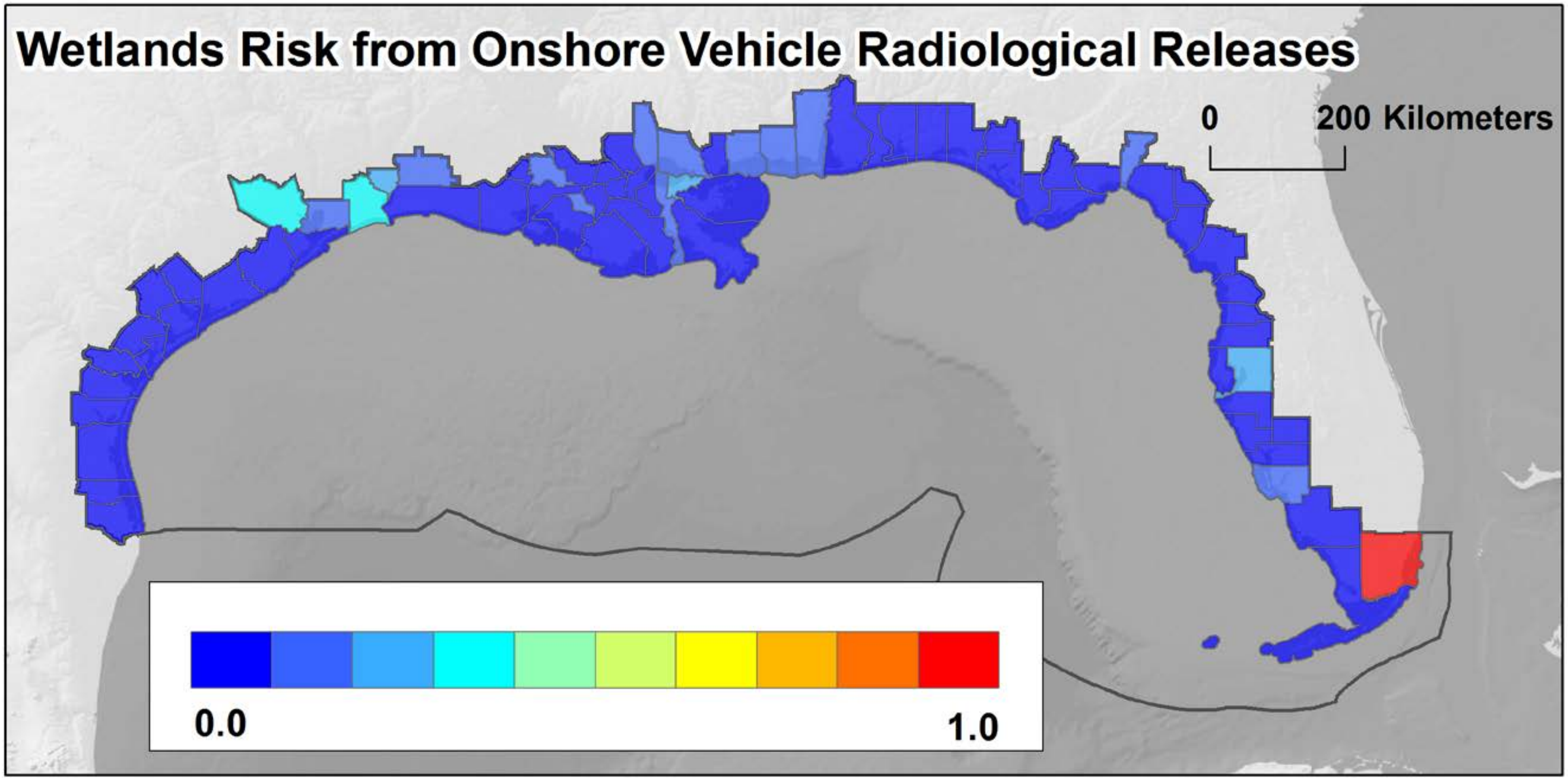

Wetlands Risk from Onshore Pipeline Chemical Spills
0
200 Kilometers
0.0
1.0

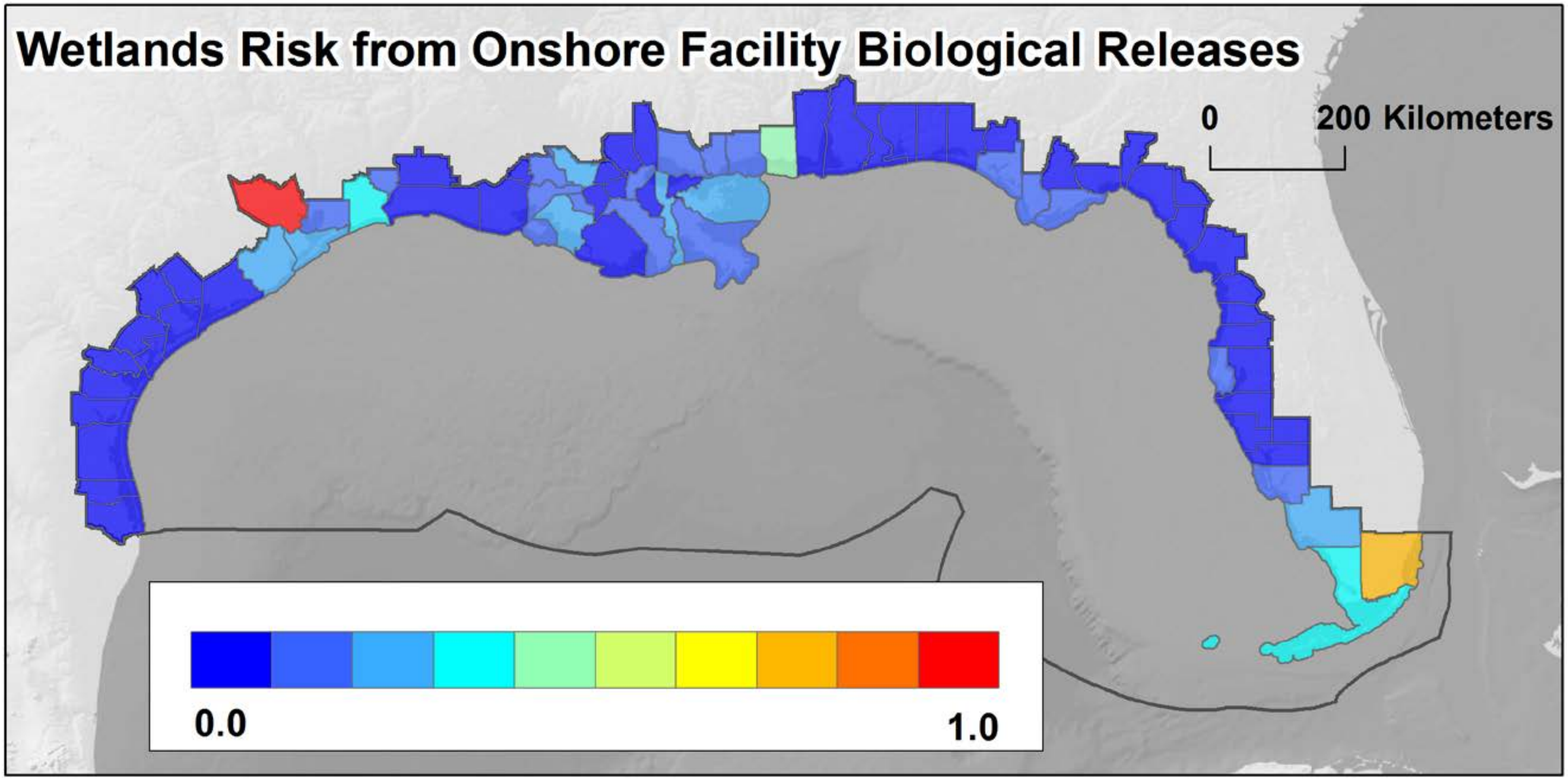

Wetlands Risk from Onshore Vehicle Chemical Spills
0
200 Kilometers
0.0
1.0


Wetlands Risk from Onshore Rail Chemical Spills
0
200 Kilometers
0.0
1.0


Wetlands Risk from Reactor Fallout Radiological Releases
0
200 Kilometers
0.0
1.0


Wetlands Risk from Onshore Facility Radiological Releases
0
200 Kilometers
0.0
1.0

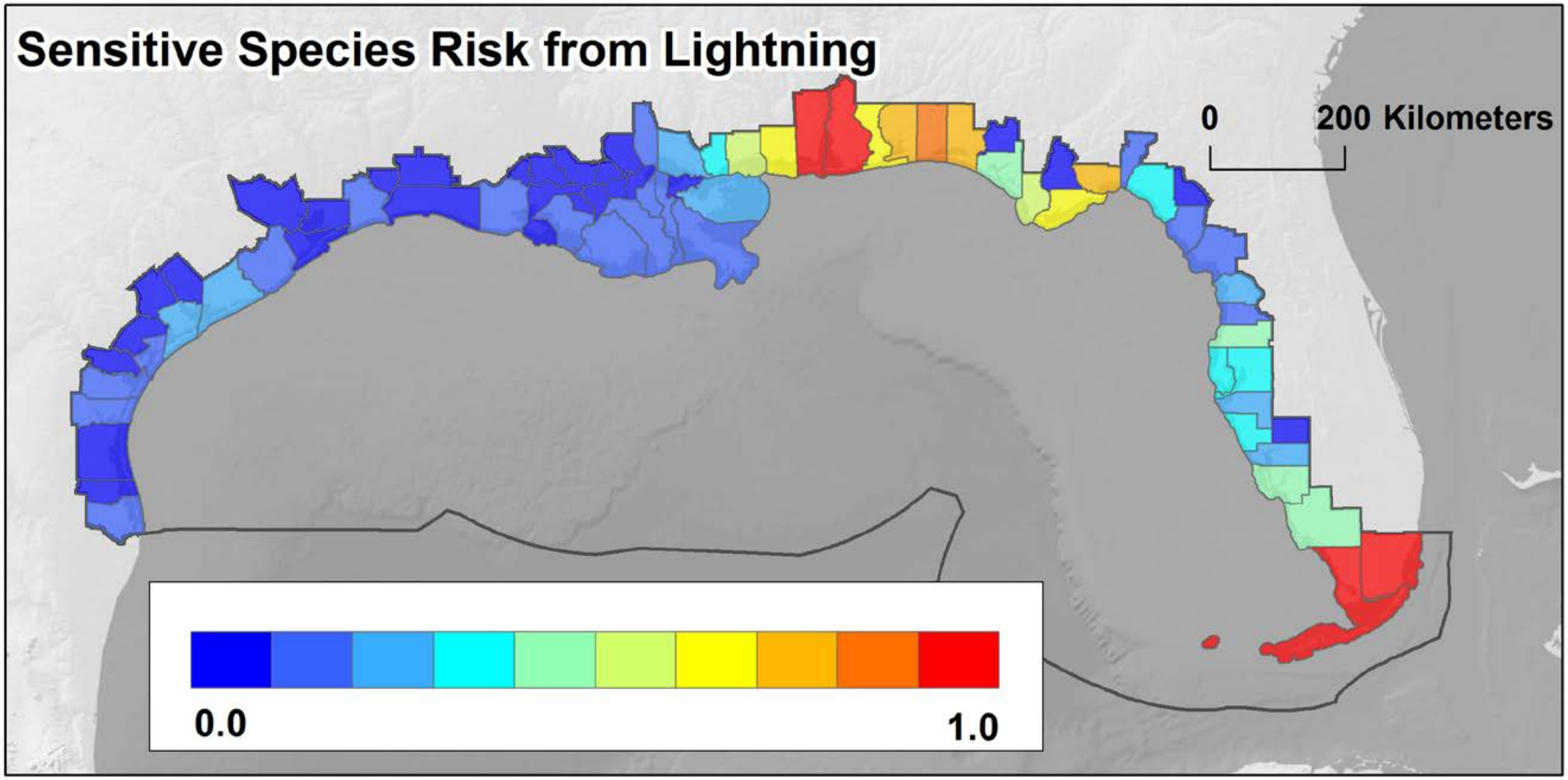

Wetlands Risk from Onshore Vehicle Radiological Releases
0
200 Kilometers
0.0
1.0

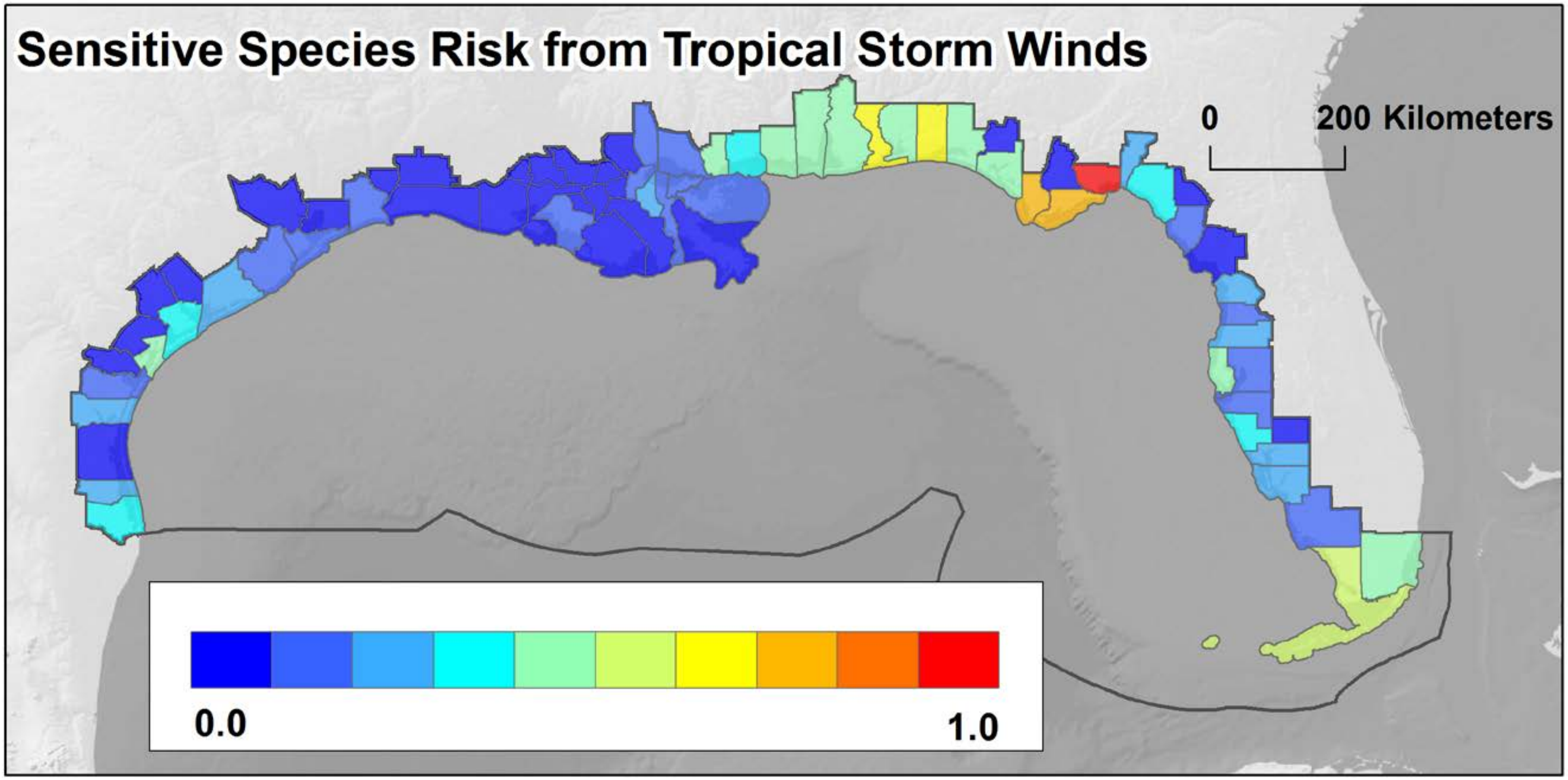

Wetlands Risk from Onshore Facility Biological Releases
0
200 Kilometers
0.0
1.0

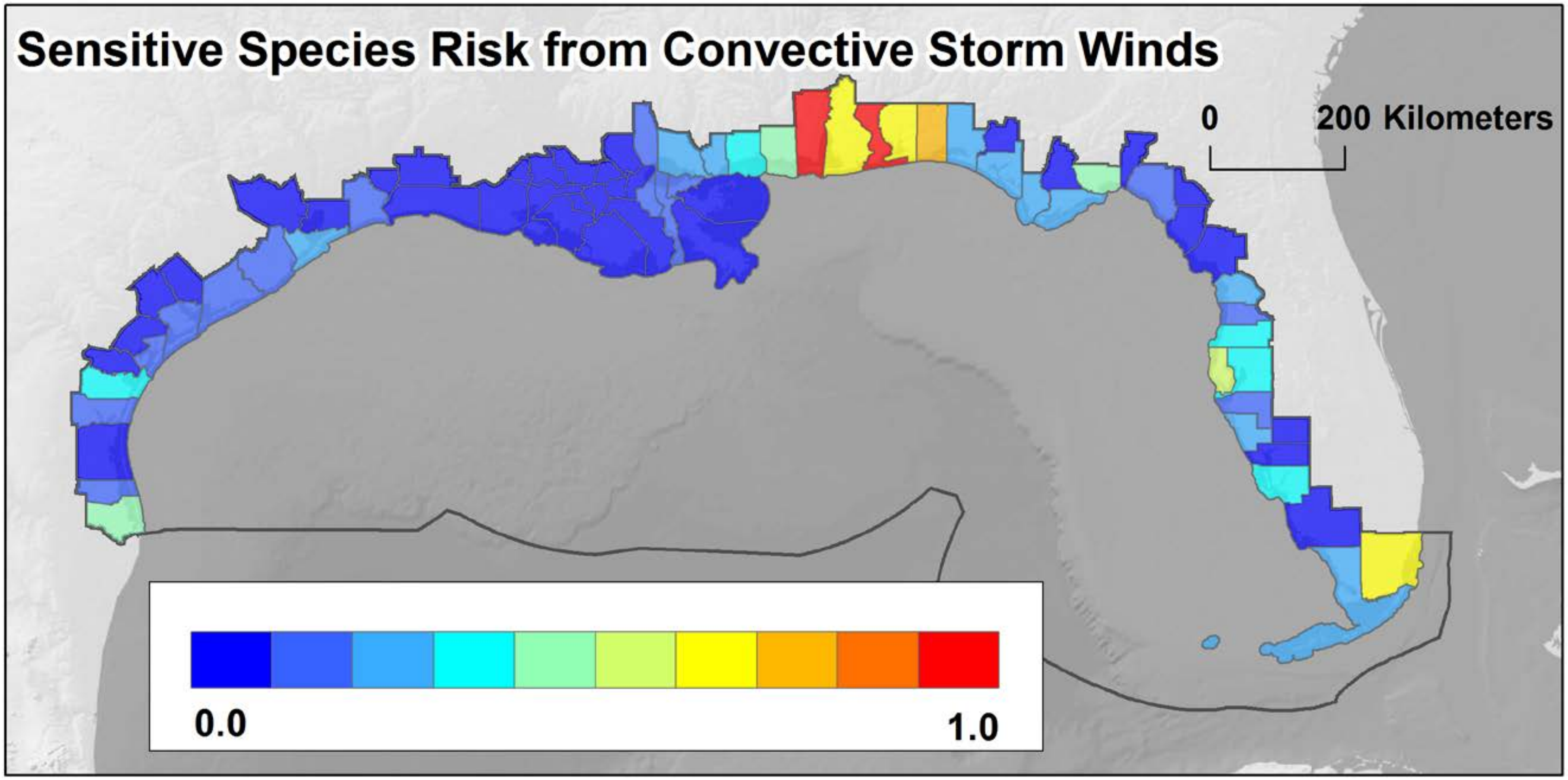
APPENDIX K

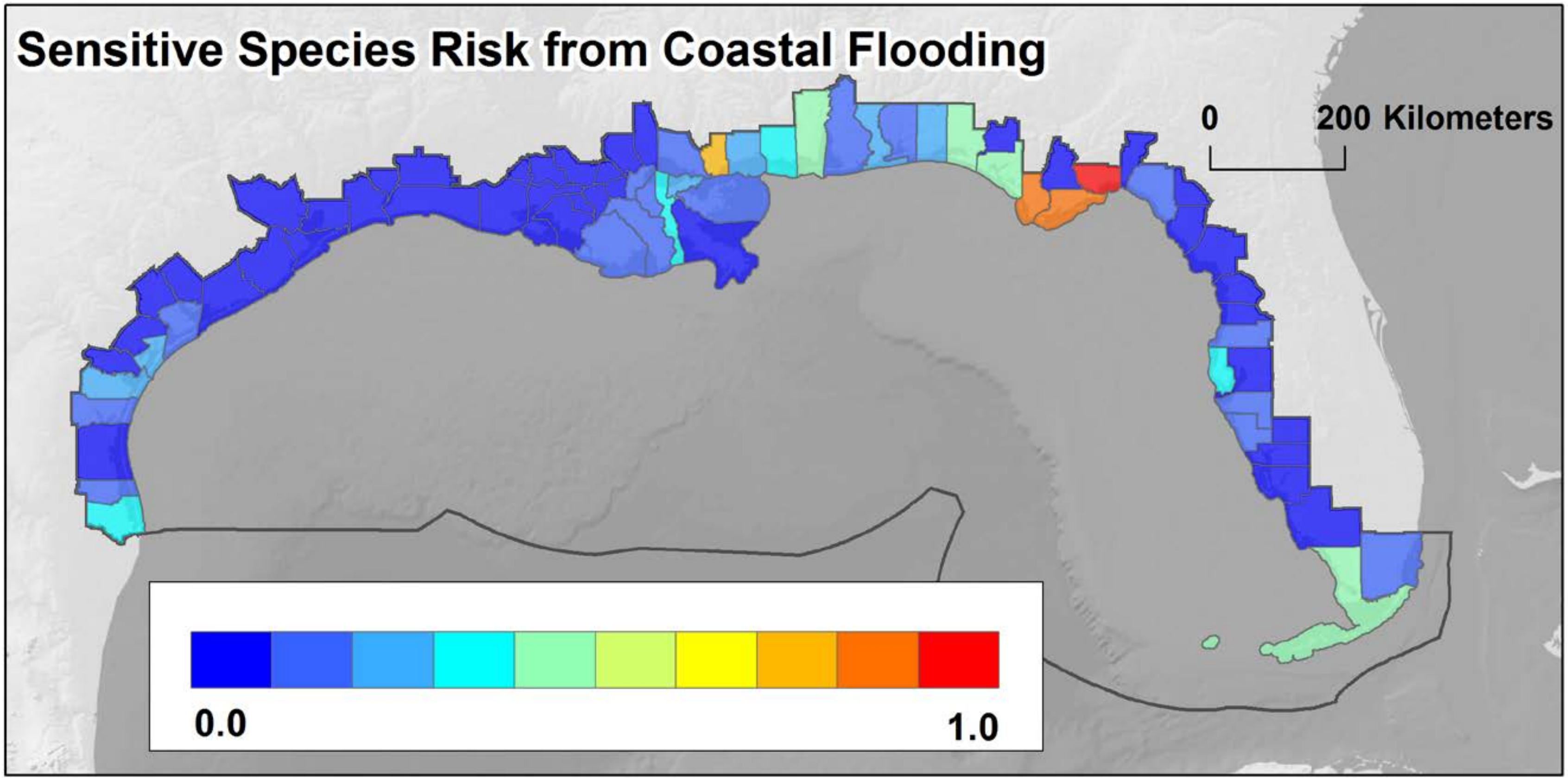
Risk to Sensitive Species from Natural Hazards

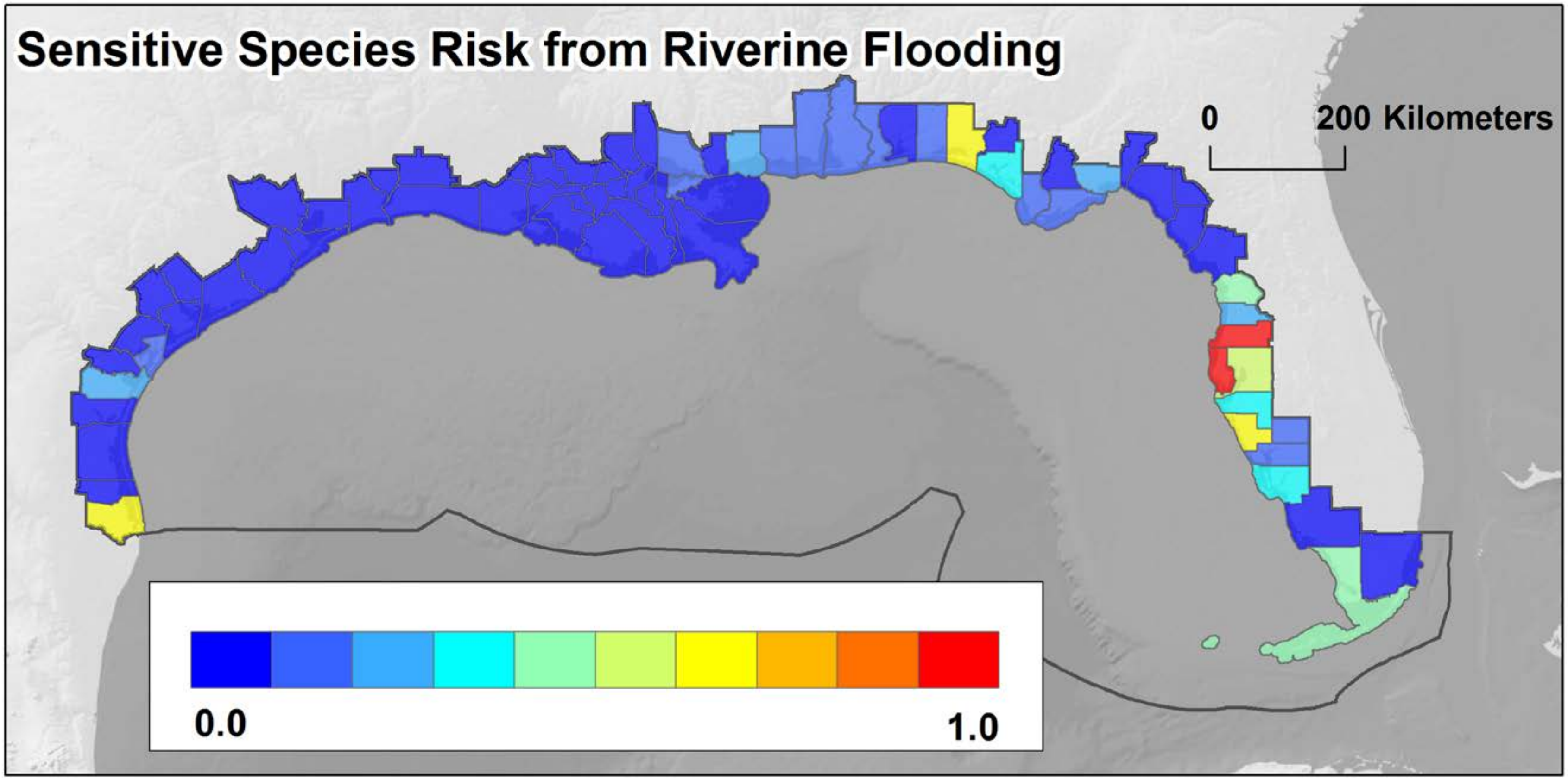
Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 37 and display ranked risk index values to sensitive species by county or parish for all natural hazards.

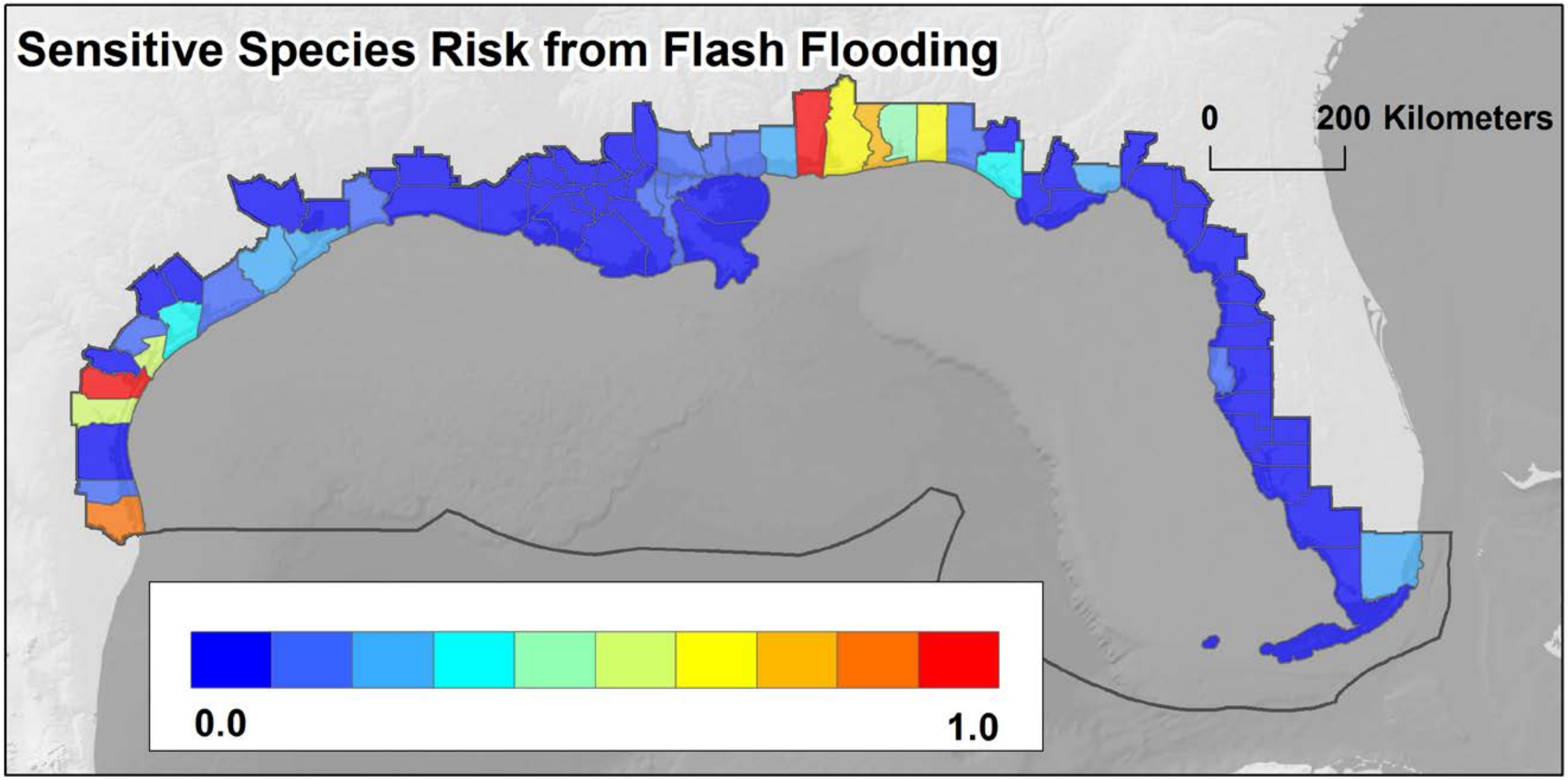

Sensitive Species Risk from Lightning
0
200 Kilometers
0.0
1.0

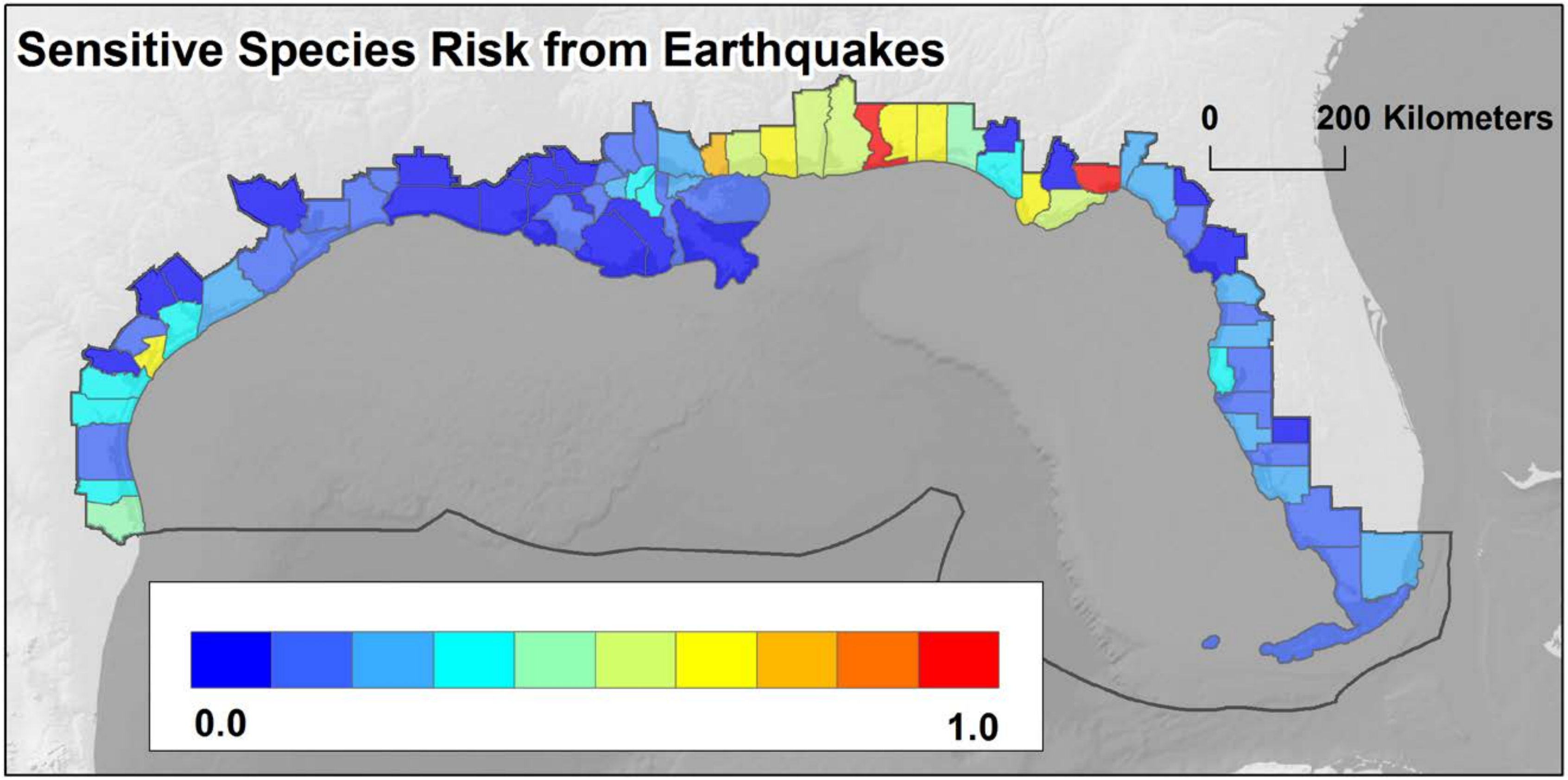

Sensitive Species Risk from Tropical Storm Winds
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Convective Storm Winds
0
200 Kilometers
0.0
1.0

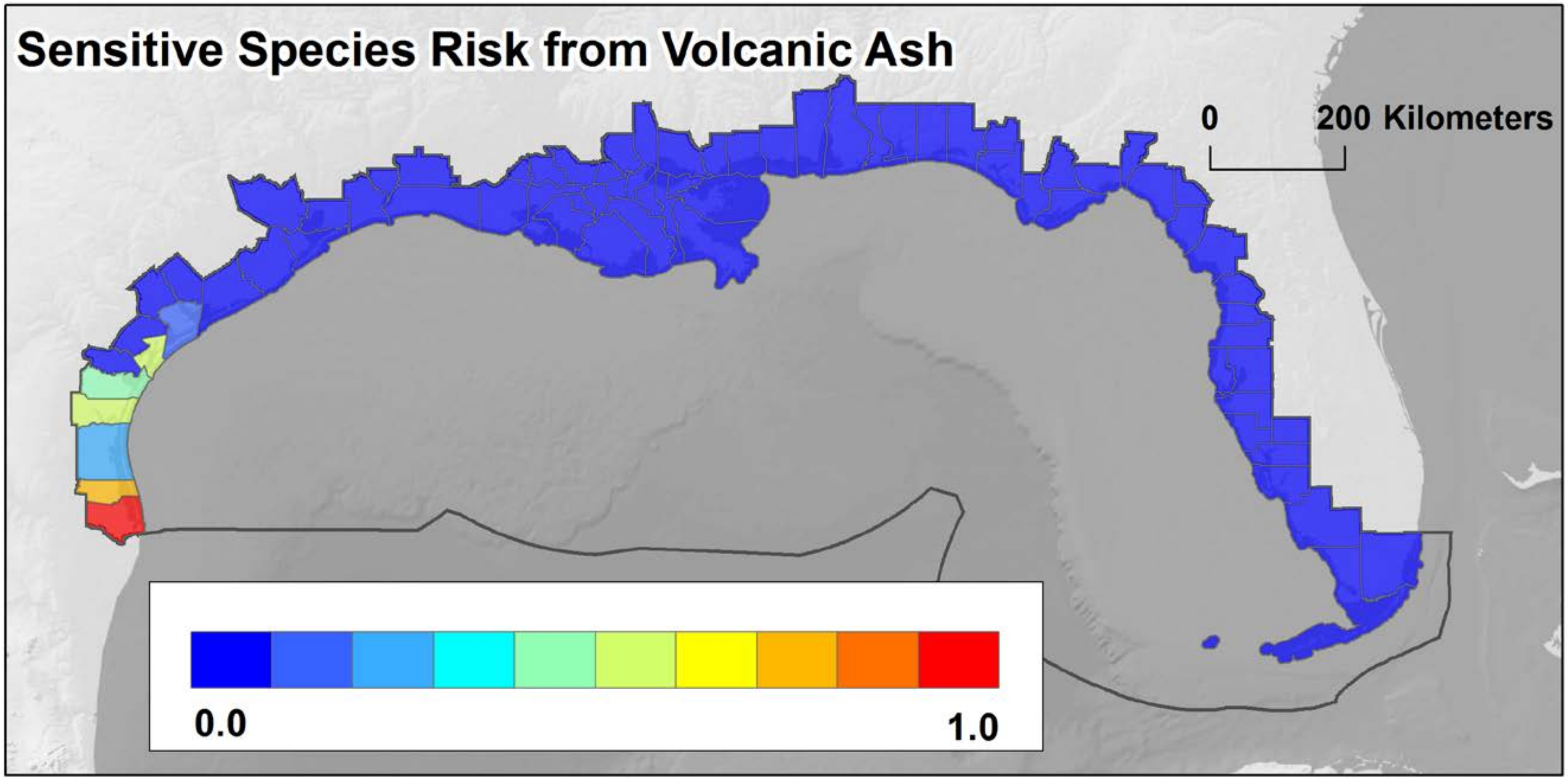

Sensitive Species Risk from Coastal Flooding
0
200 Kilometers
0.0
1.0

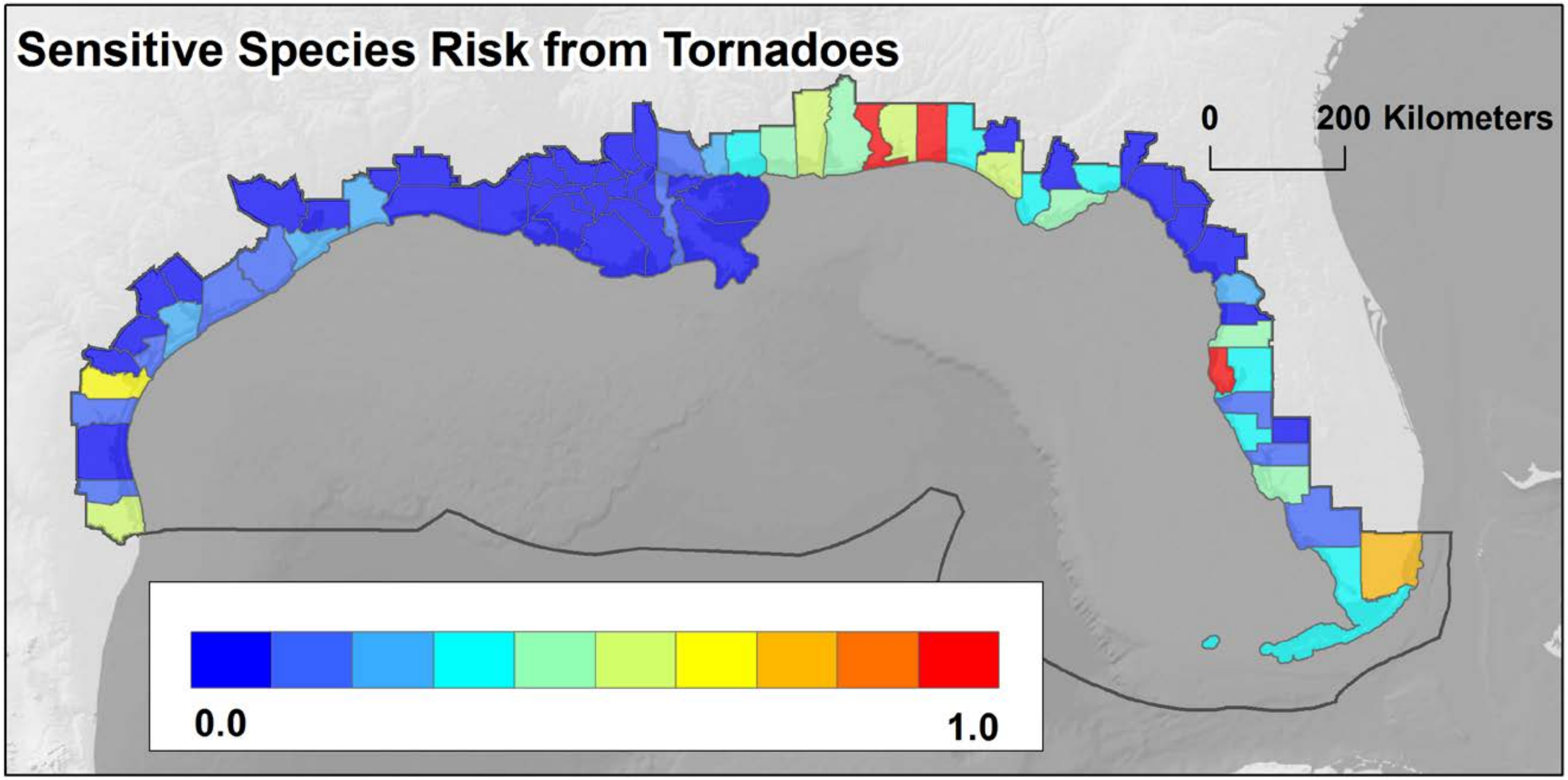

Sensitive Species Risk from Riverine Flooding
0
200 Kilometers
0.0
1.0

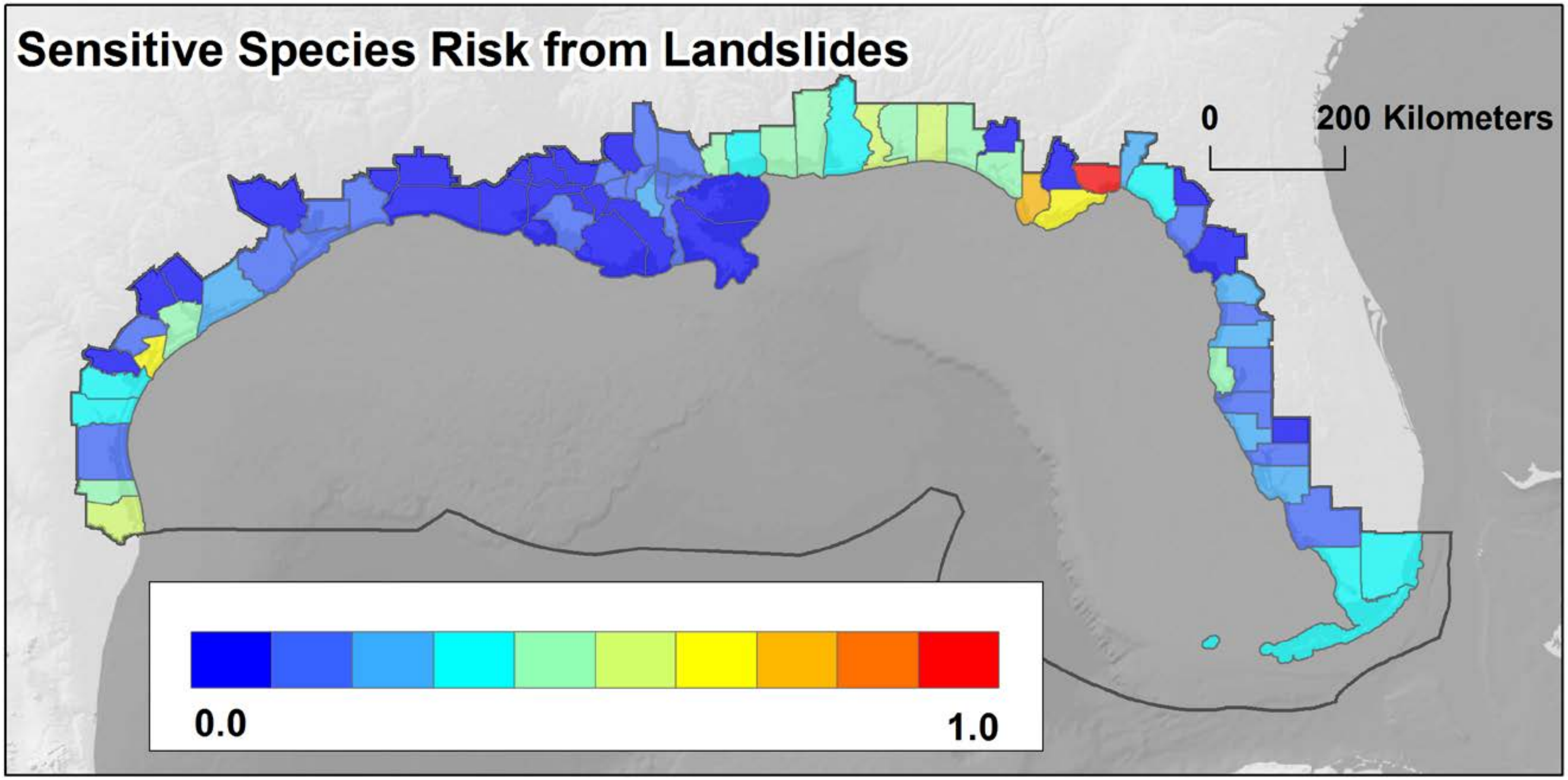

Sensitive Species Risk from Flash Flooding
0
200 Kilometers
0.0
1.0



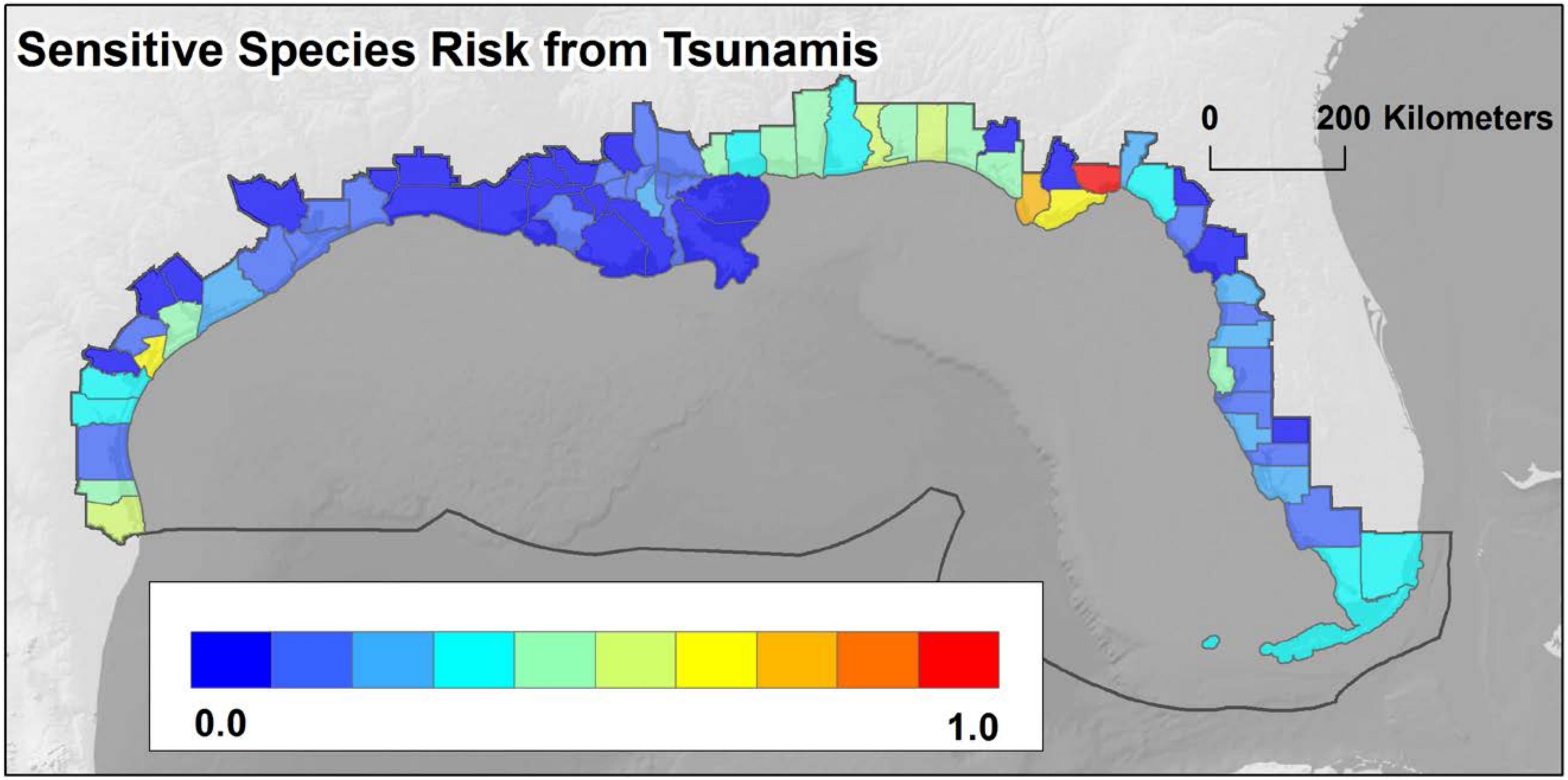
Sensitive Species Risk from Earthquakes
0
200 Kilometers
0.0
1.0

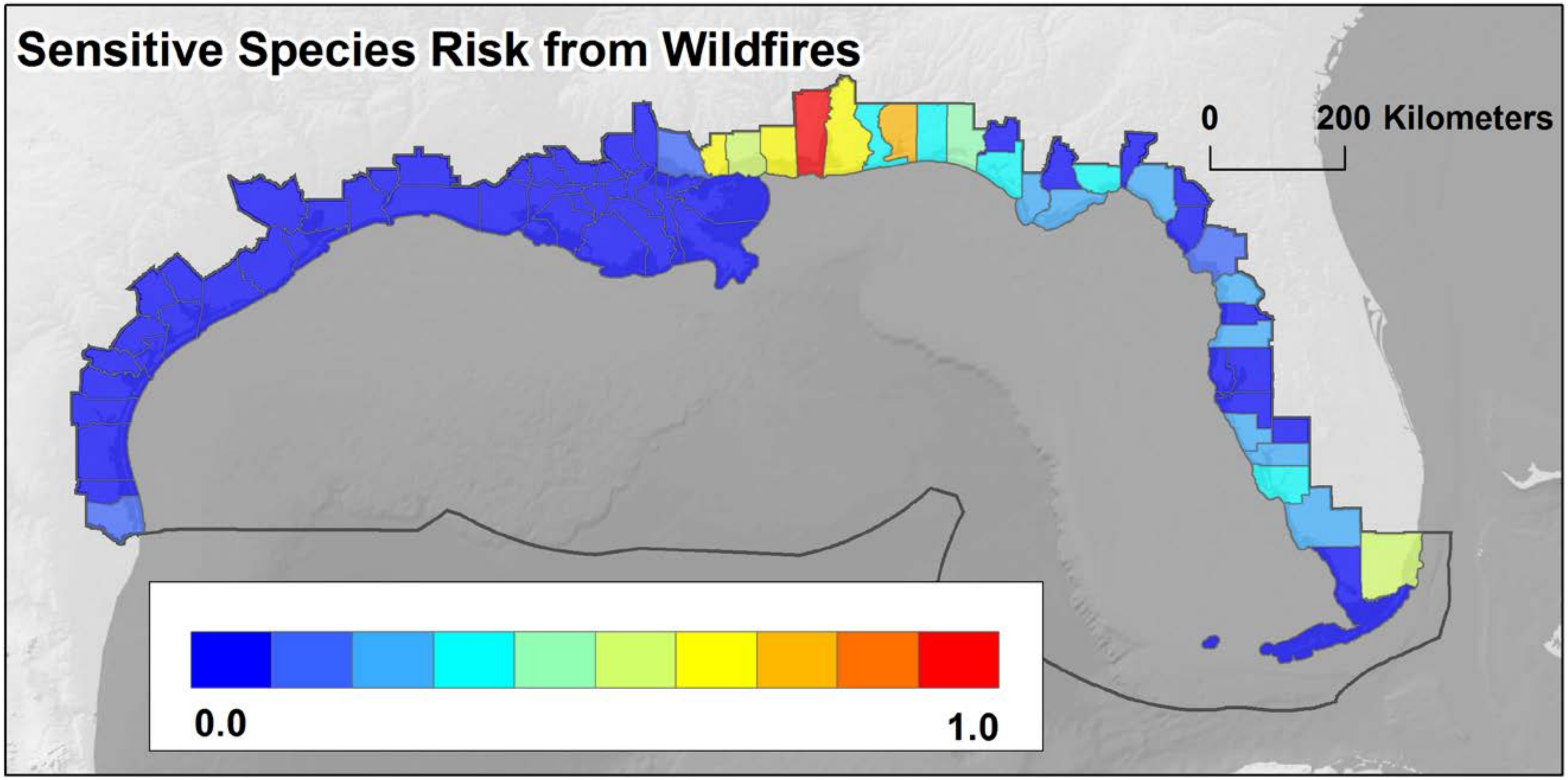

Sensitive Species Risk from Volcanic Ash
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Tornadoes
0
200 Kilometers
0.0
1.0

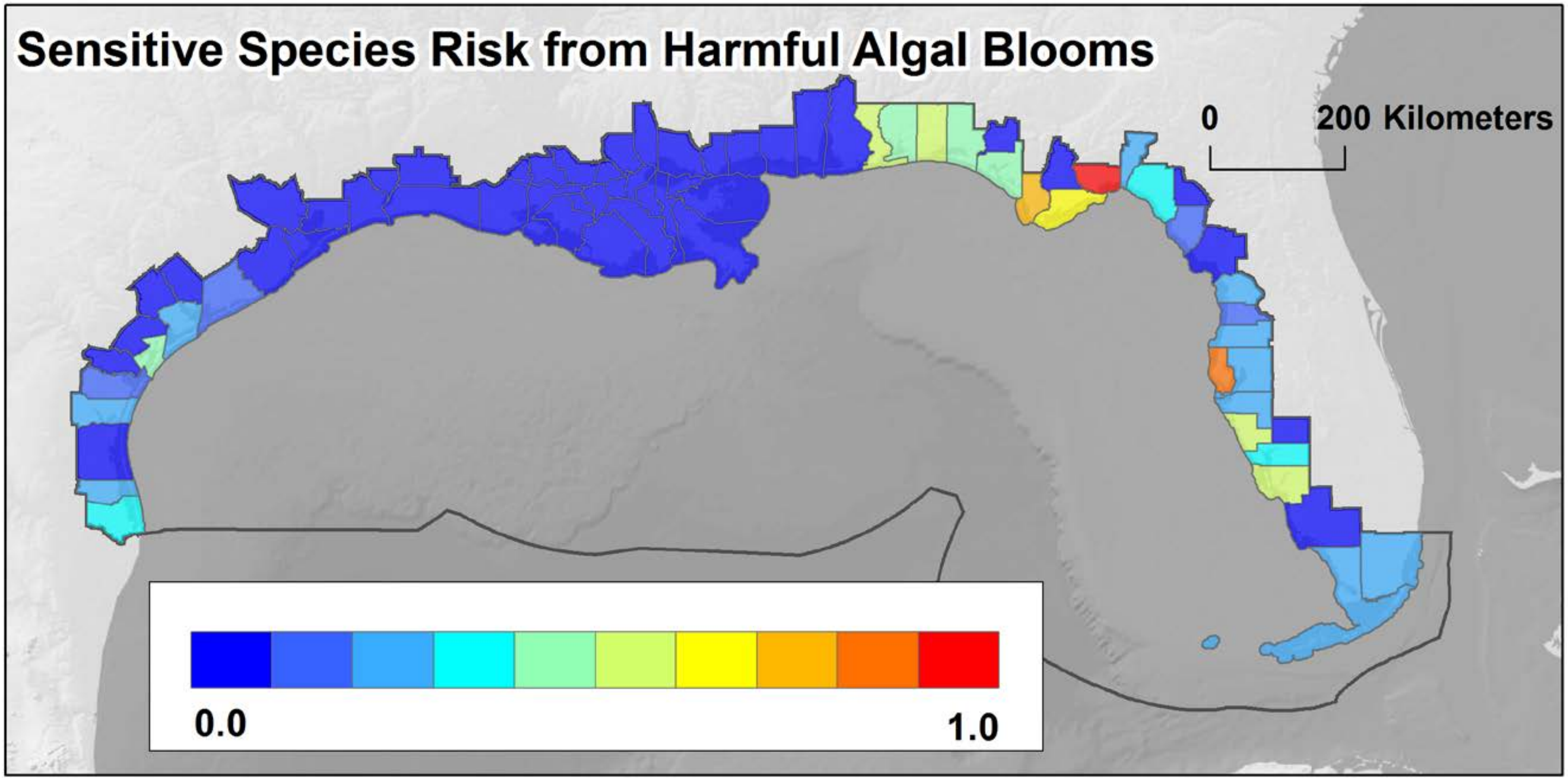


Sensitive Species Risk from Landslides
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Tsunamis
0
200 Kilometers
0.0
1.0



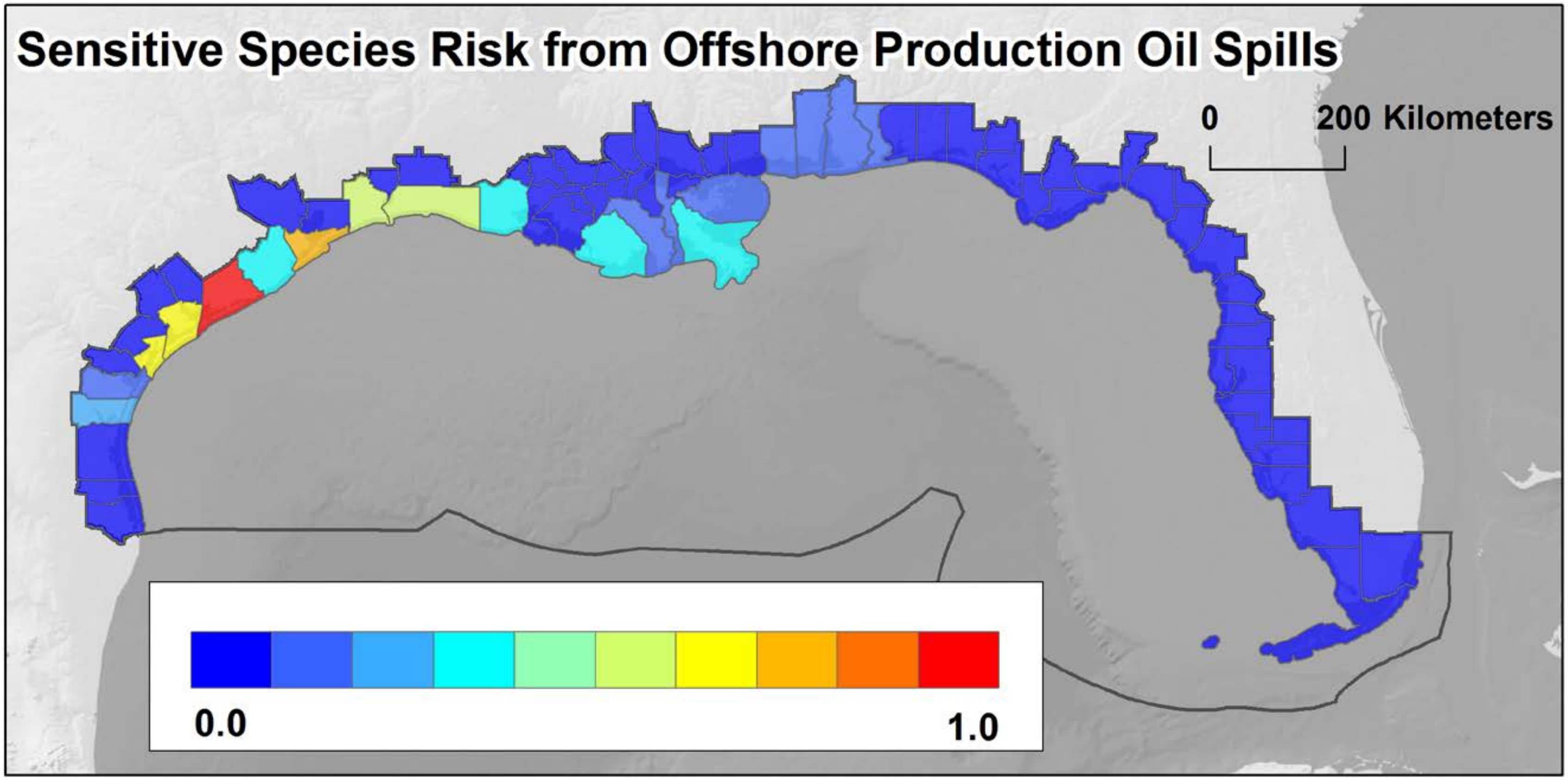
Sensitive Species Risk from Wildfires
0
200 Kilometers
0.0
1.0

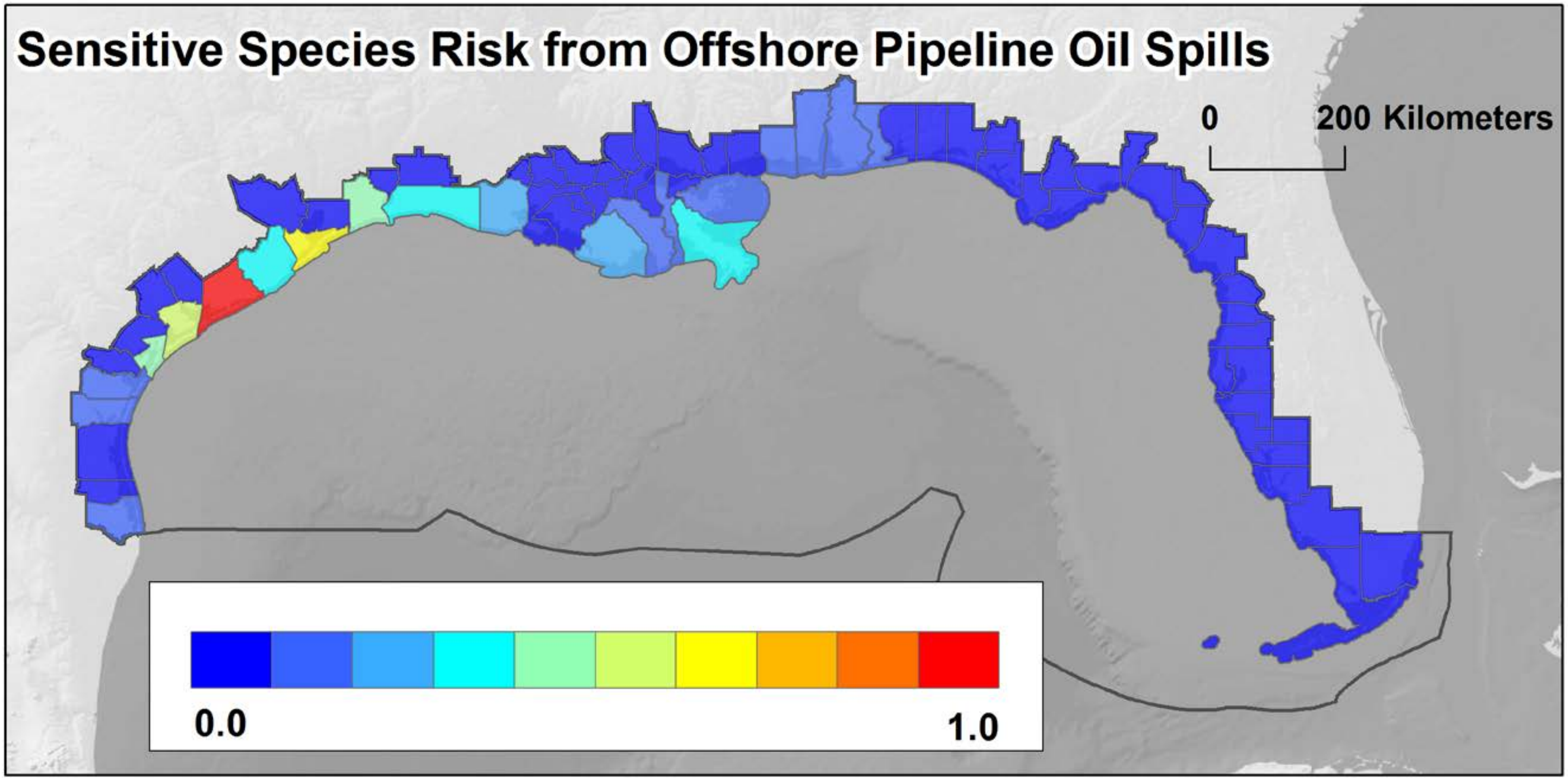

Sensitive Species Risk from Harmful Algal Blooms
0
200 Kilometers
0.0
1.0

APPENDIX L

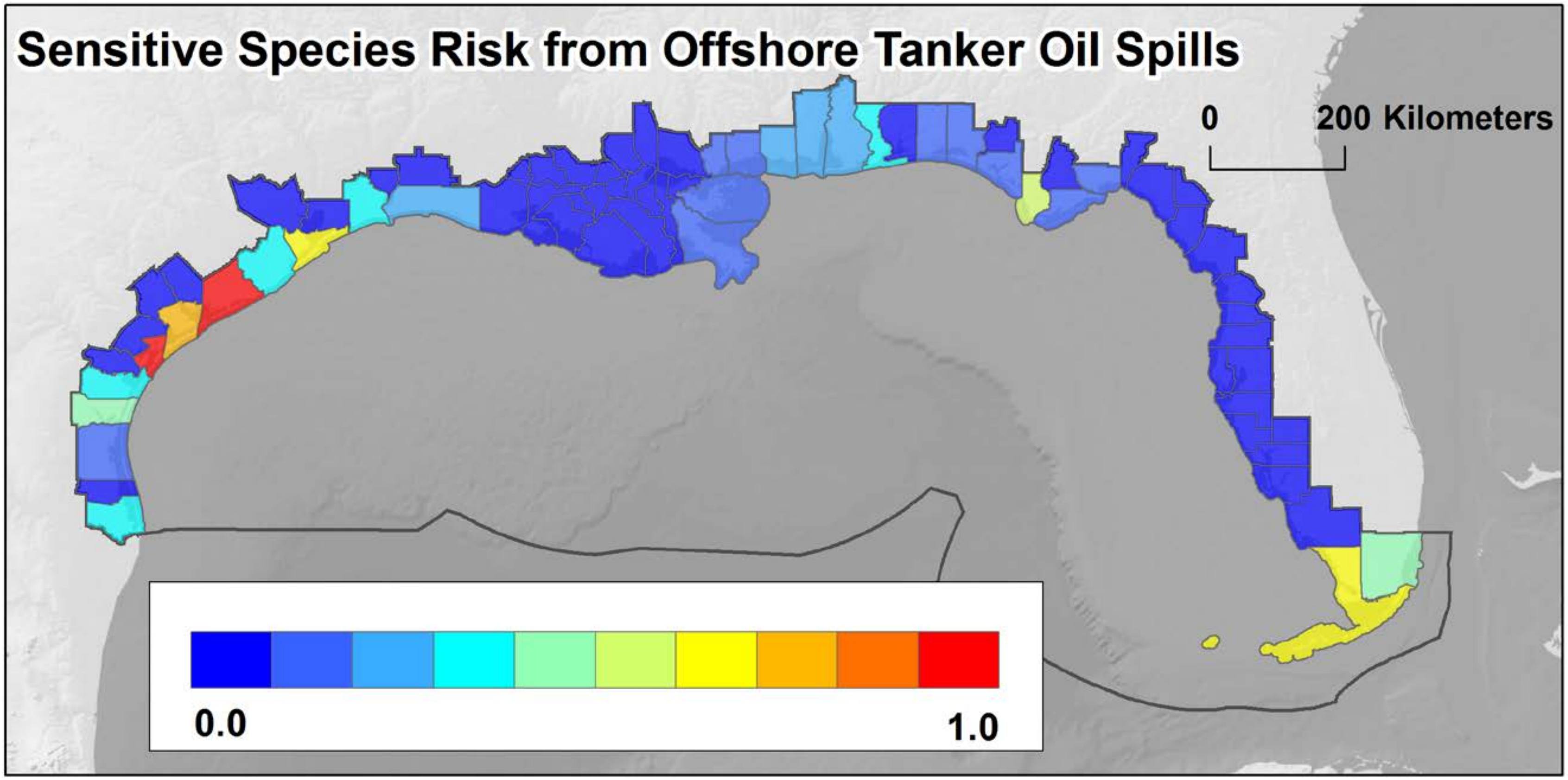
Risk to Sensitive Species from Anthropogenic Hazards

Maps within this appendix represent a higher resolution image for each of the maps presented in Figure 38 and display ranked risk index values to sensitive species by county or parish for all anthropogenic hazards.

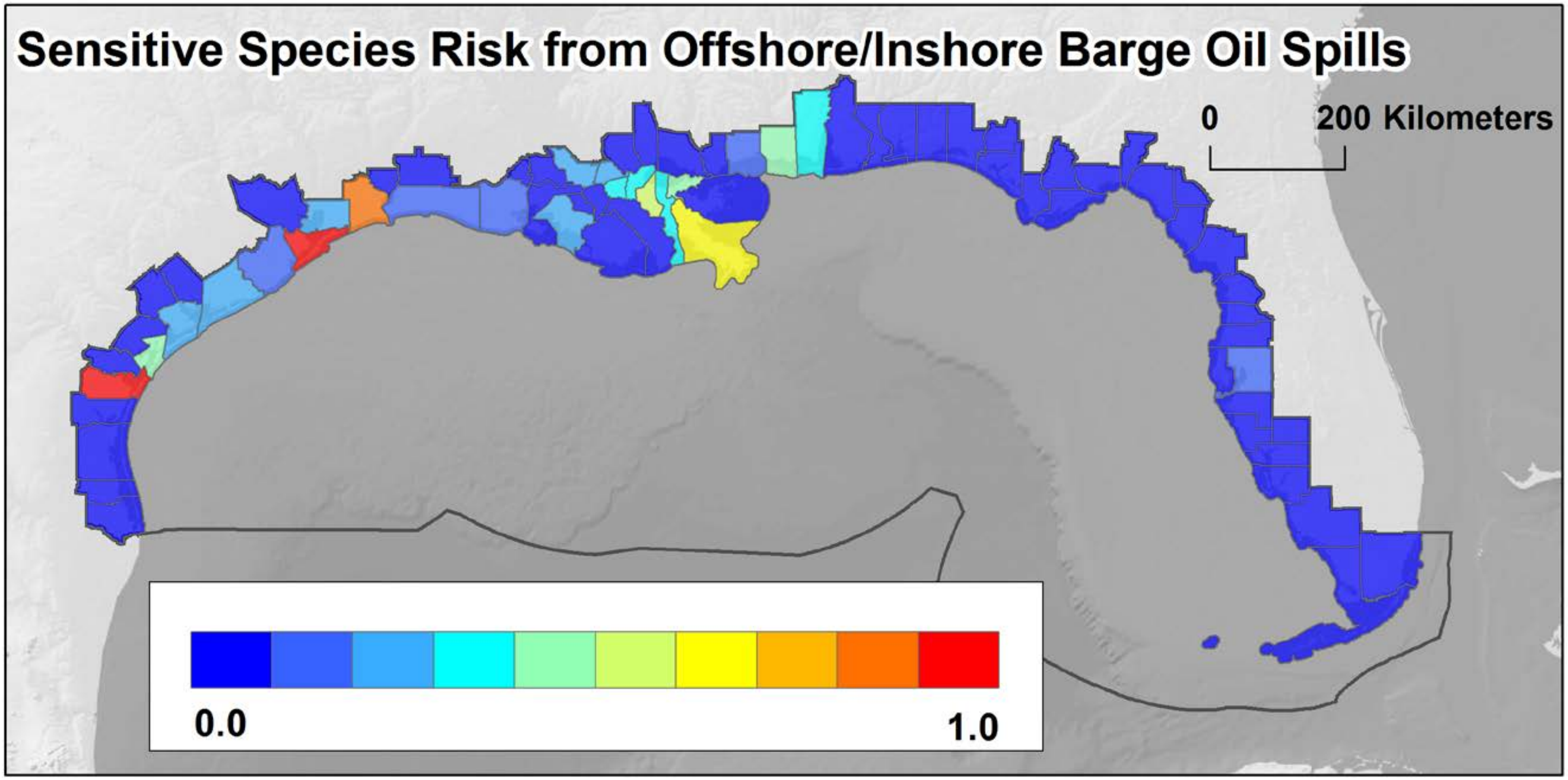

Sensitive Species Risk from Offshore Production Oil Spills
0
200 Kilometers
0.0
1.0



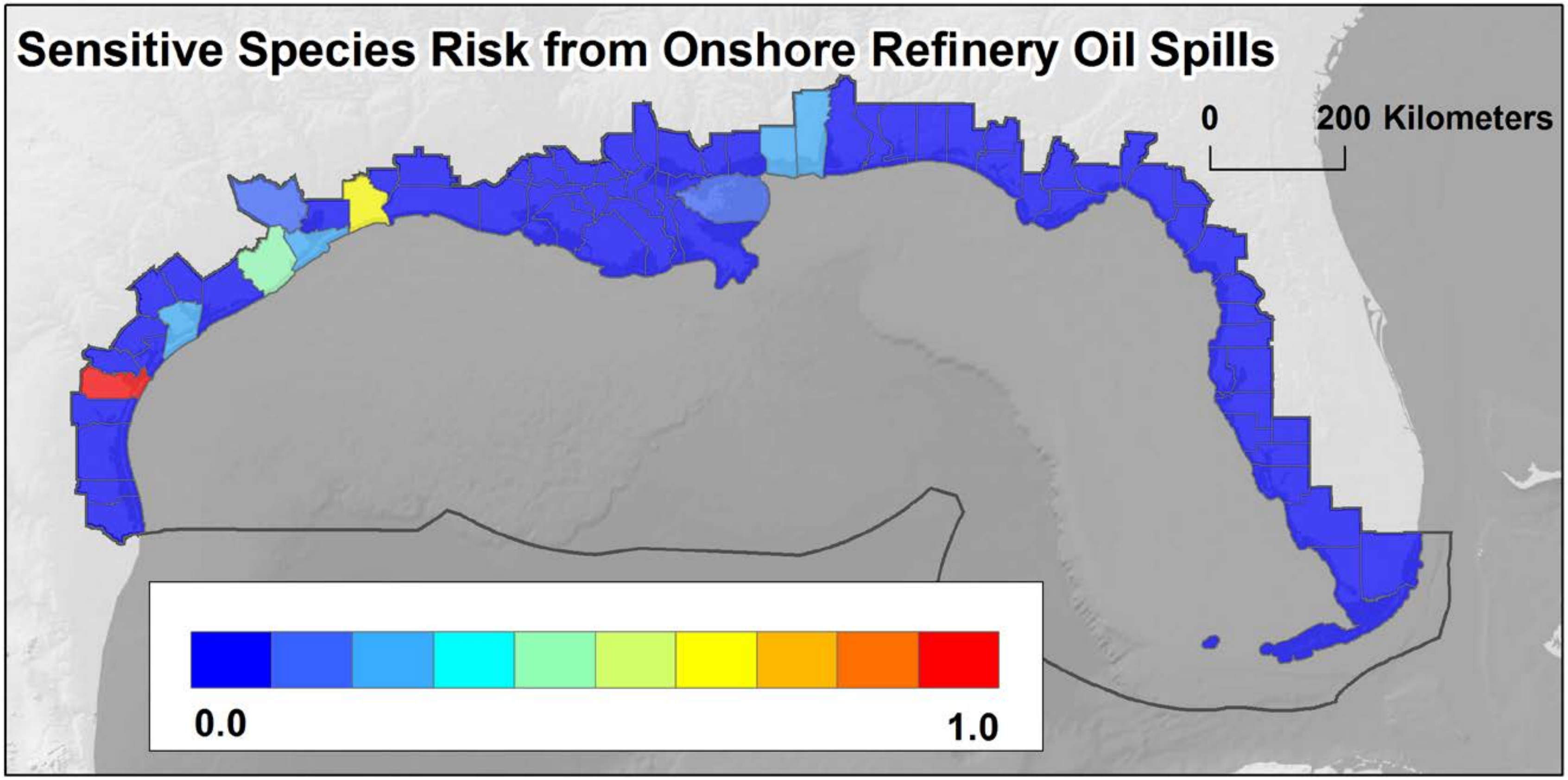
Sensitive Species Risk from Offshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

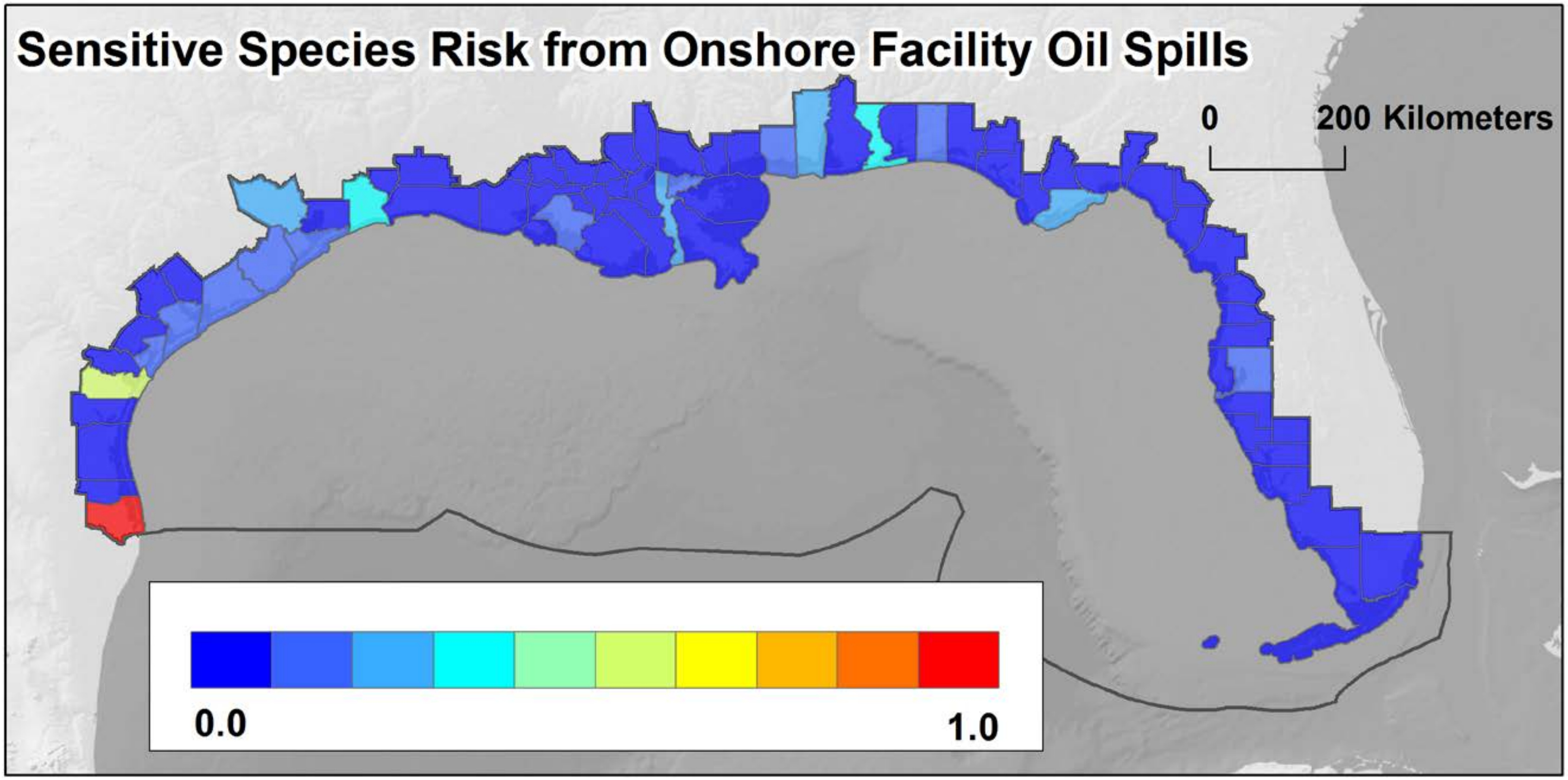


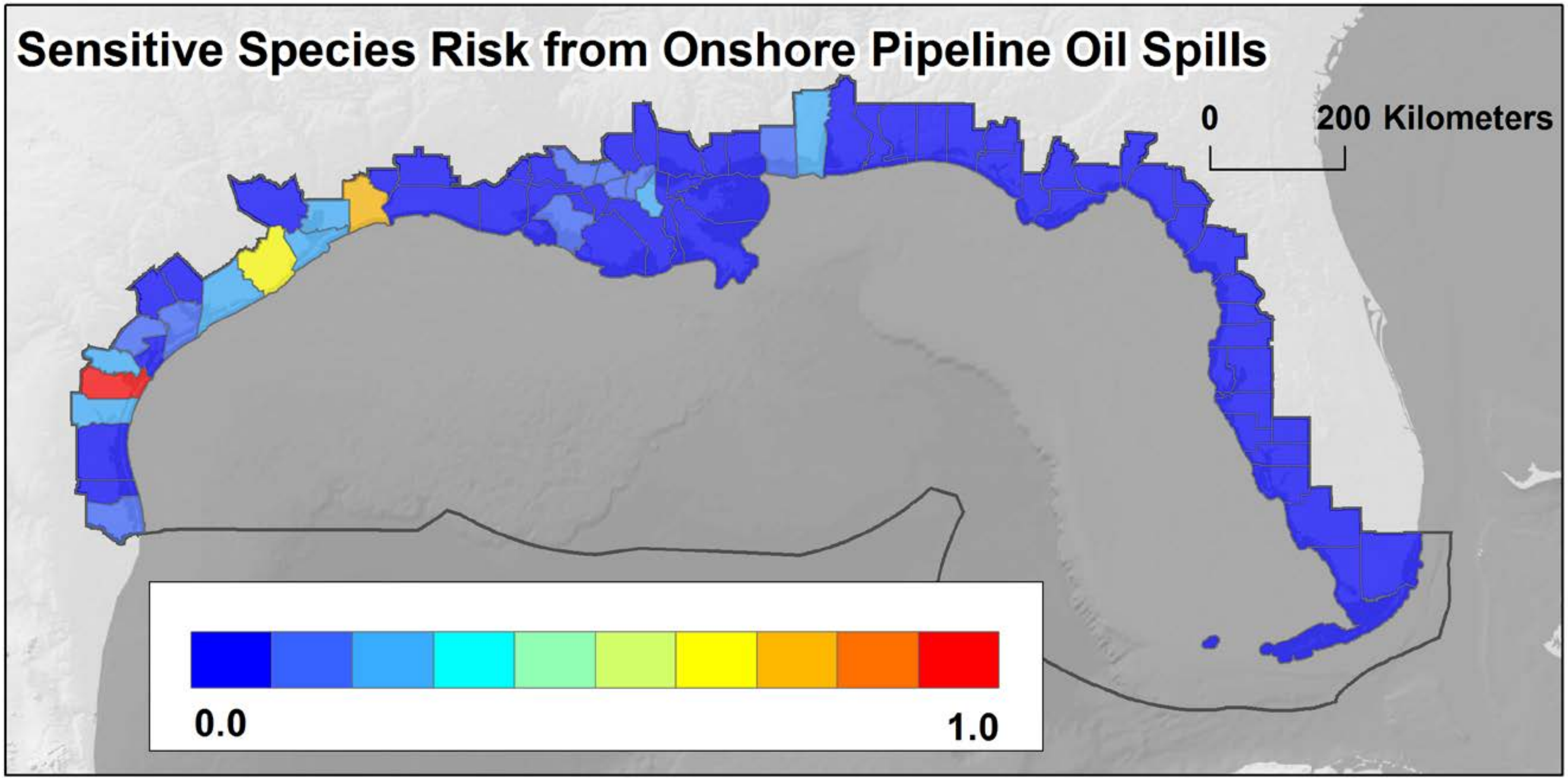
Sensitive Species Risk from Offshore Tanker Oil Spills
0
200 Kilometers
0.0
1.0

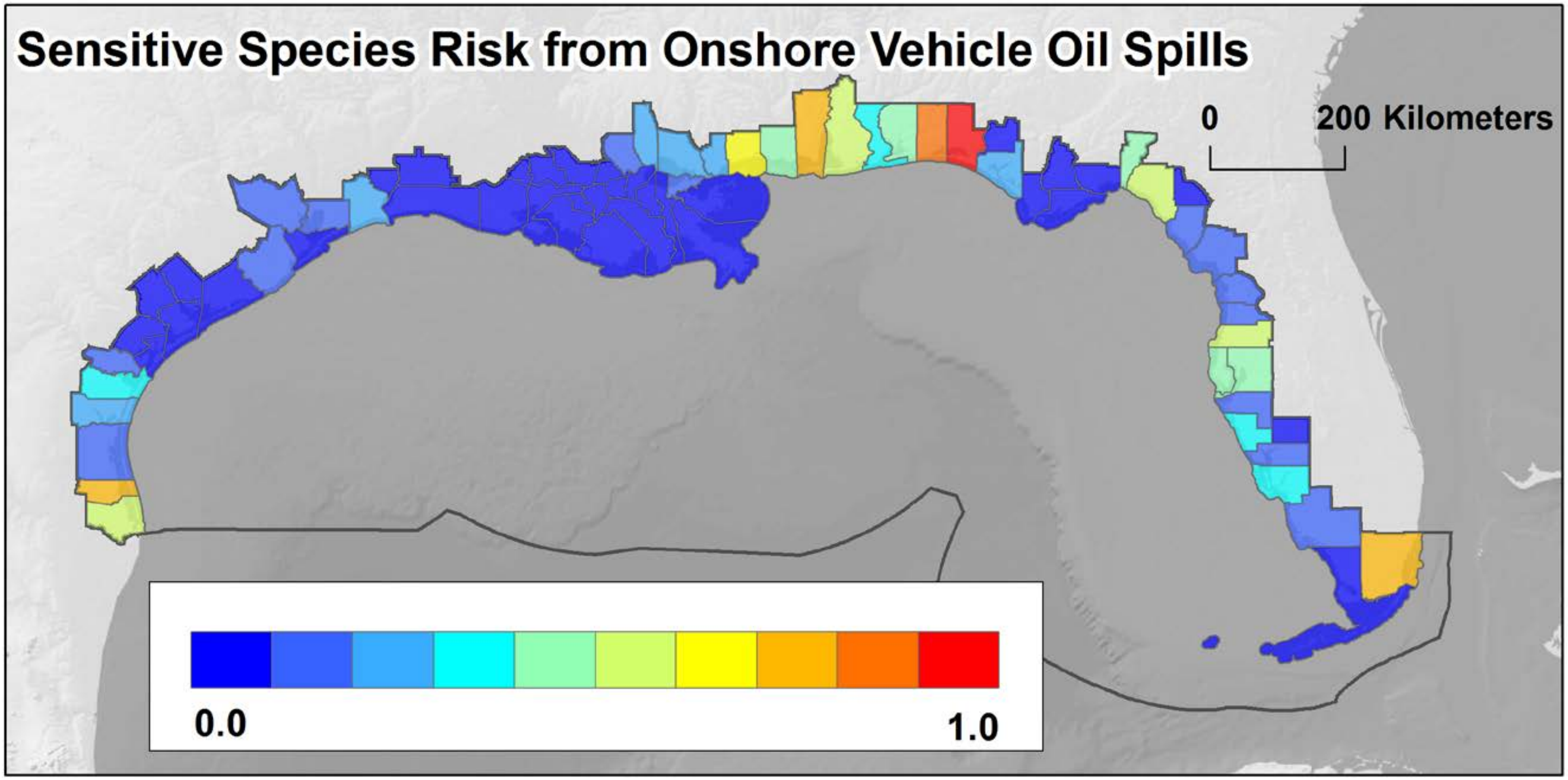


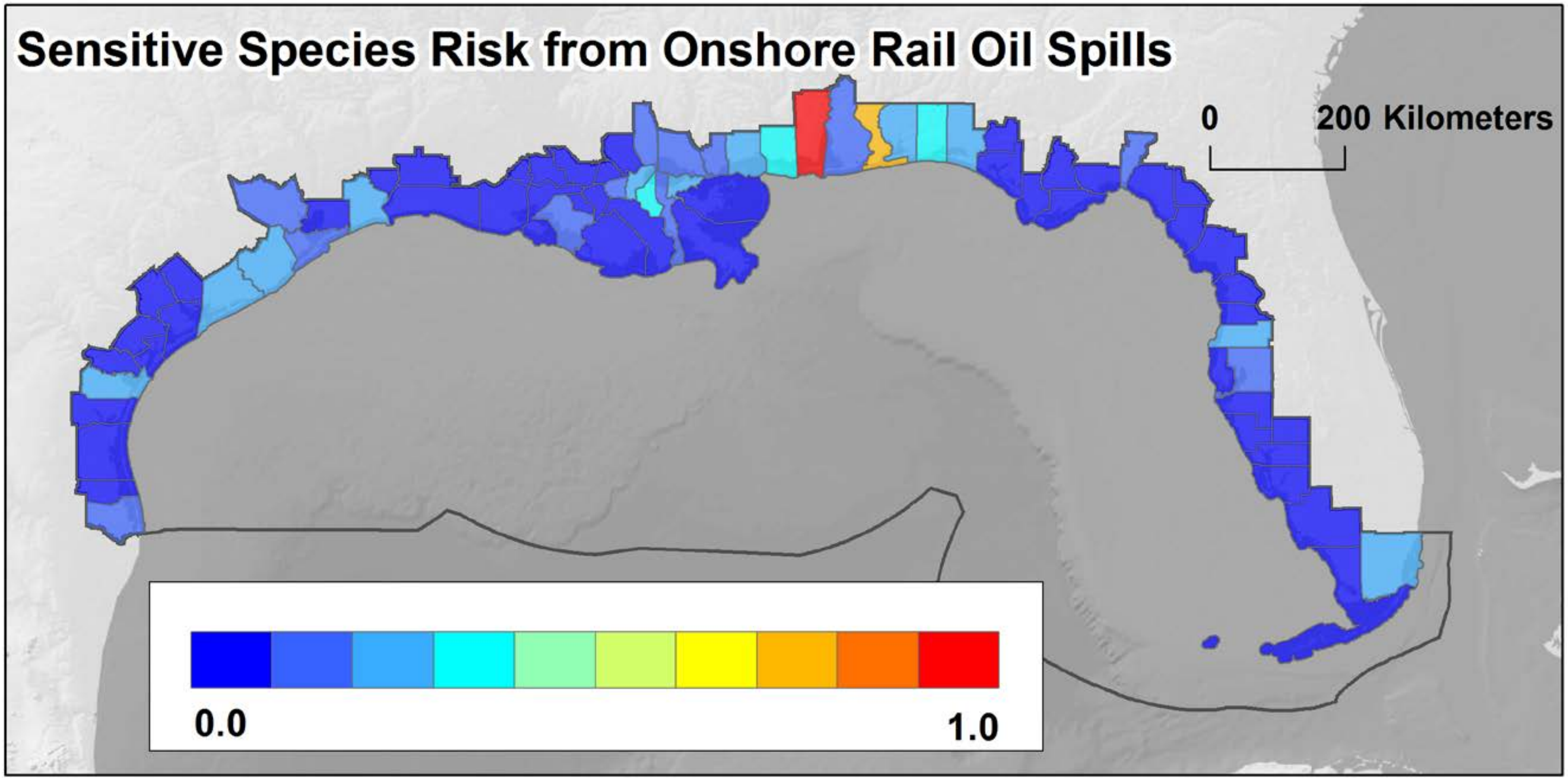
Sensitive Species Risk from Offshore/Inshore Barge Oil Spills
0
200 Kilometers
0.0
1.0

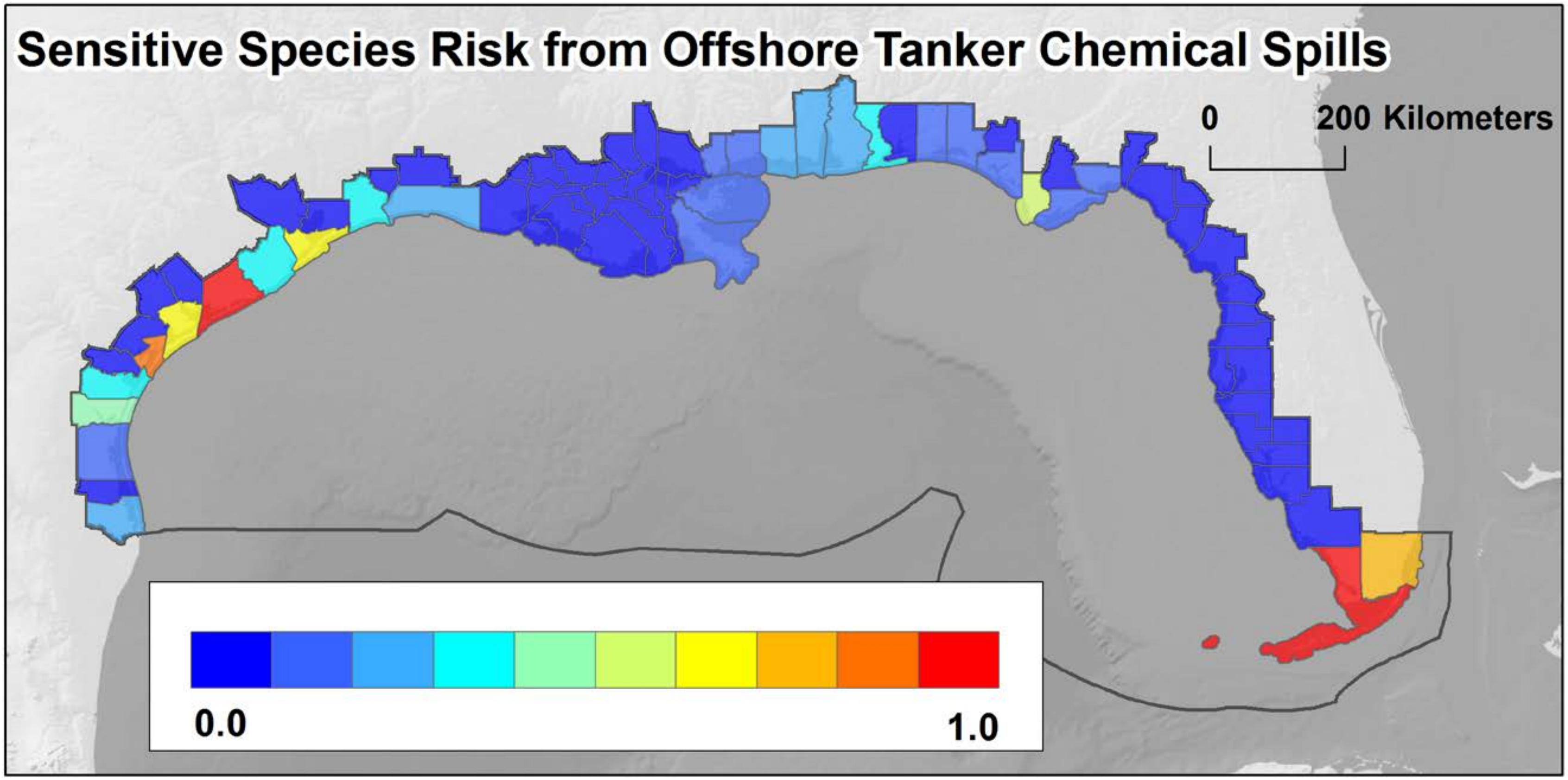

Sensitive Species Risk from Onshore Refinery Oil Spills
0
200 Kilometers
0.0
1.0

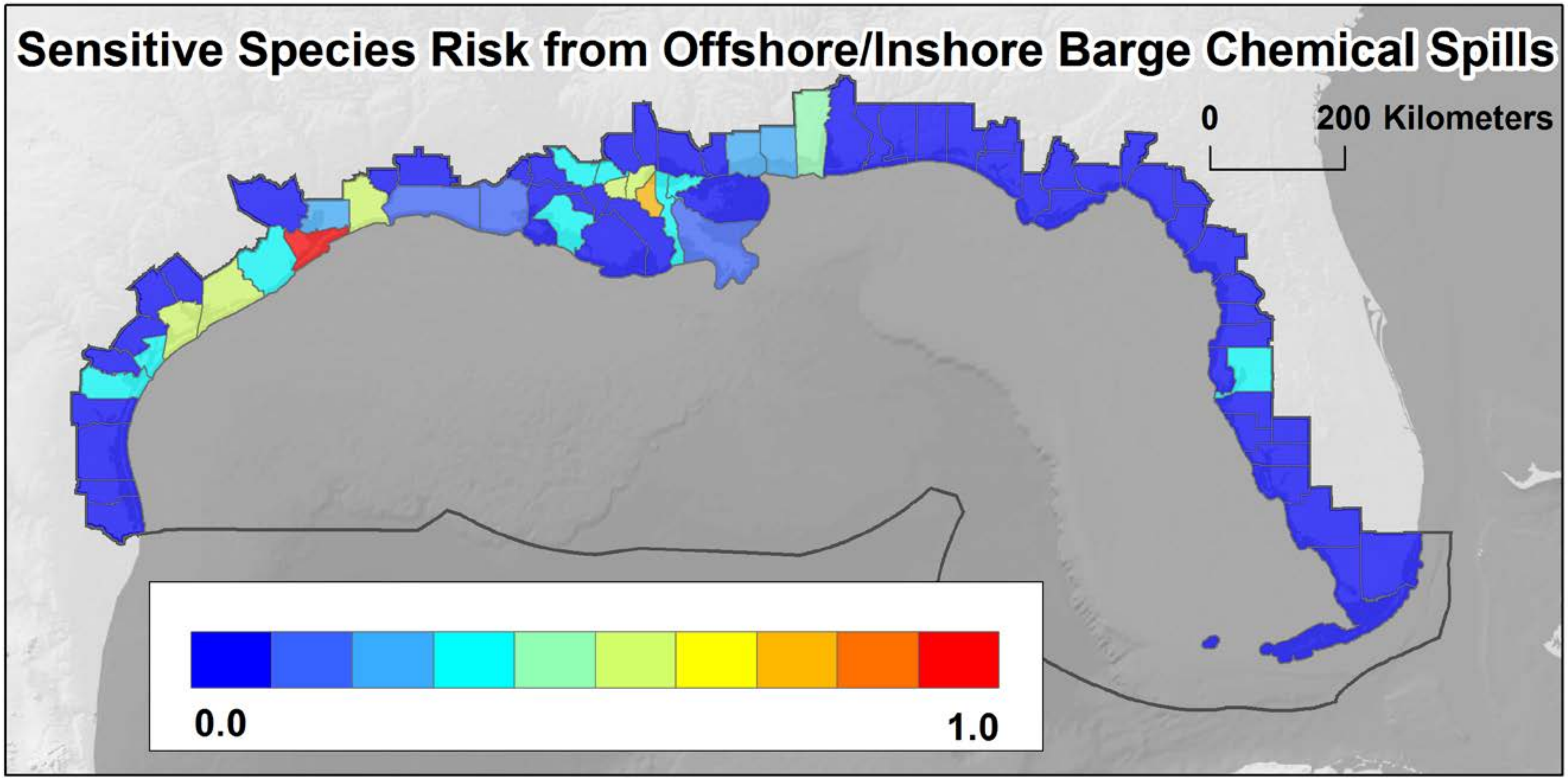

Sensitive Species Risk from Onshore Facility Oil Spills
0
200 Kilometers
0.0
1.0

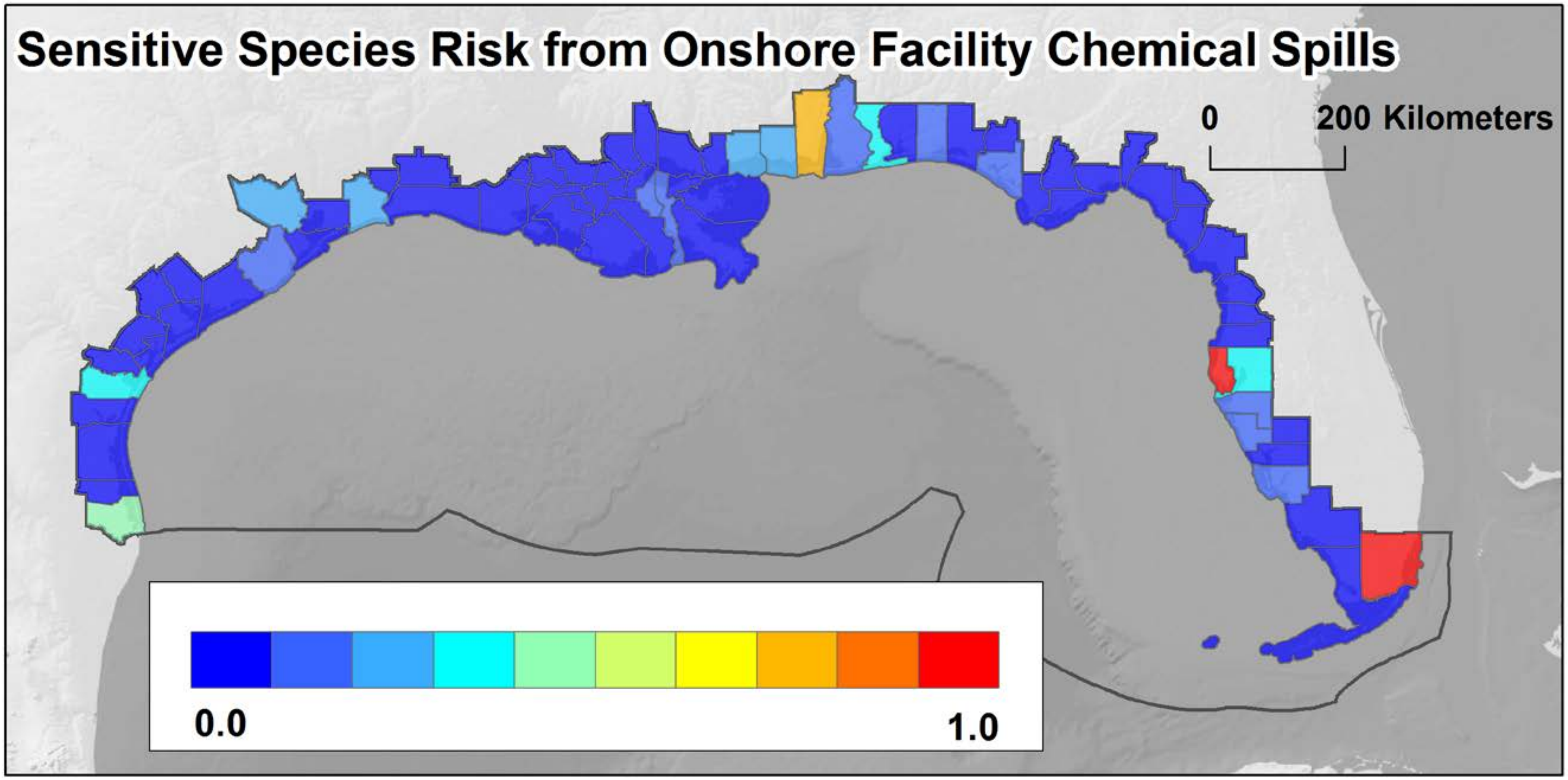

Sensitive Species Risk from Onshore Pipeline Oil Spills
0
200 Kilometers
0.0
1.0

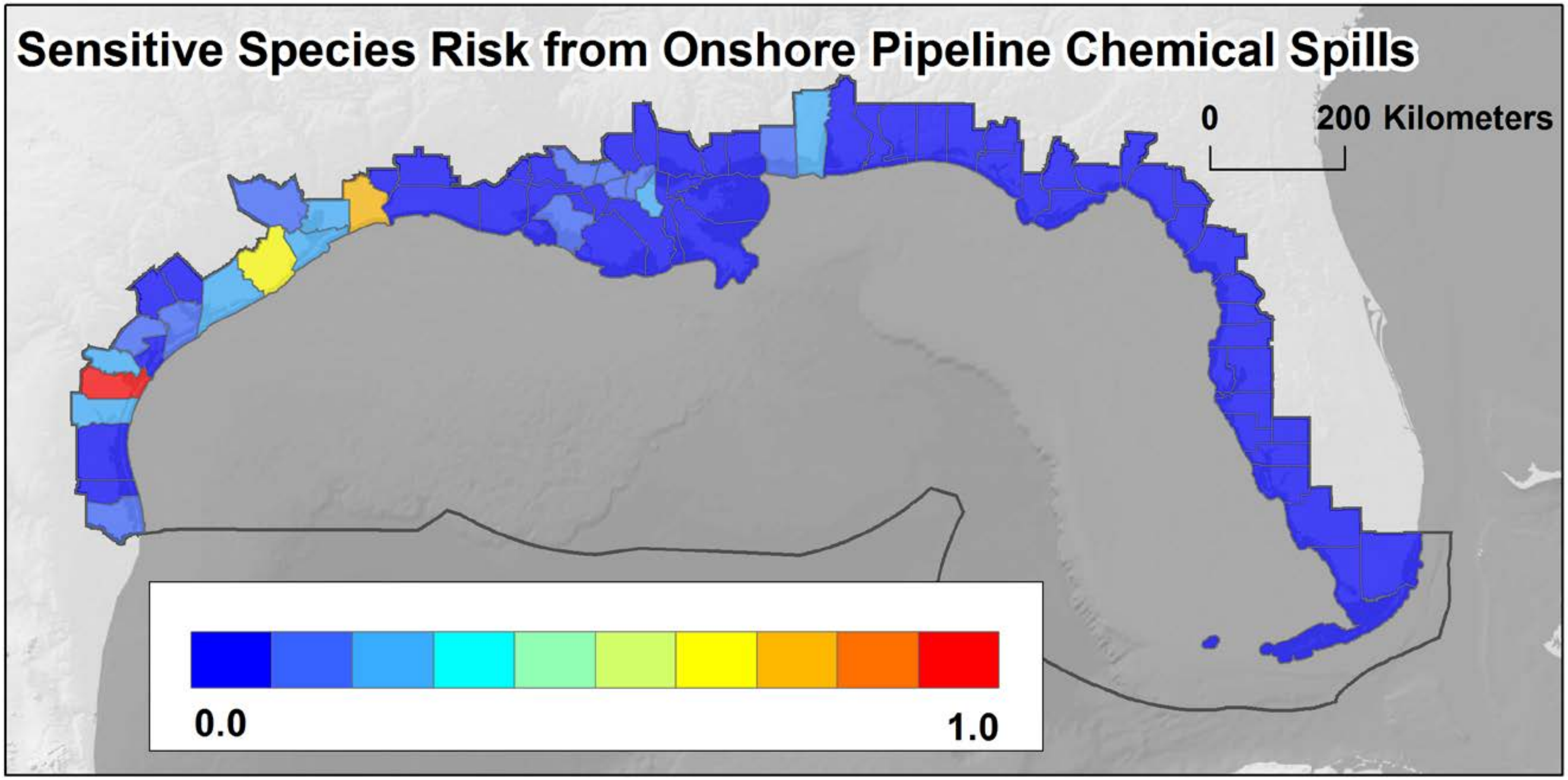

Sensitive Species Risk from Onshore Vehicle Oil Spills
0
200 Kilometers
0.0
1.0

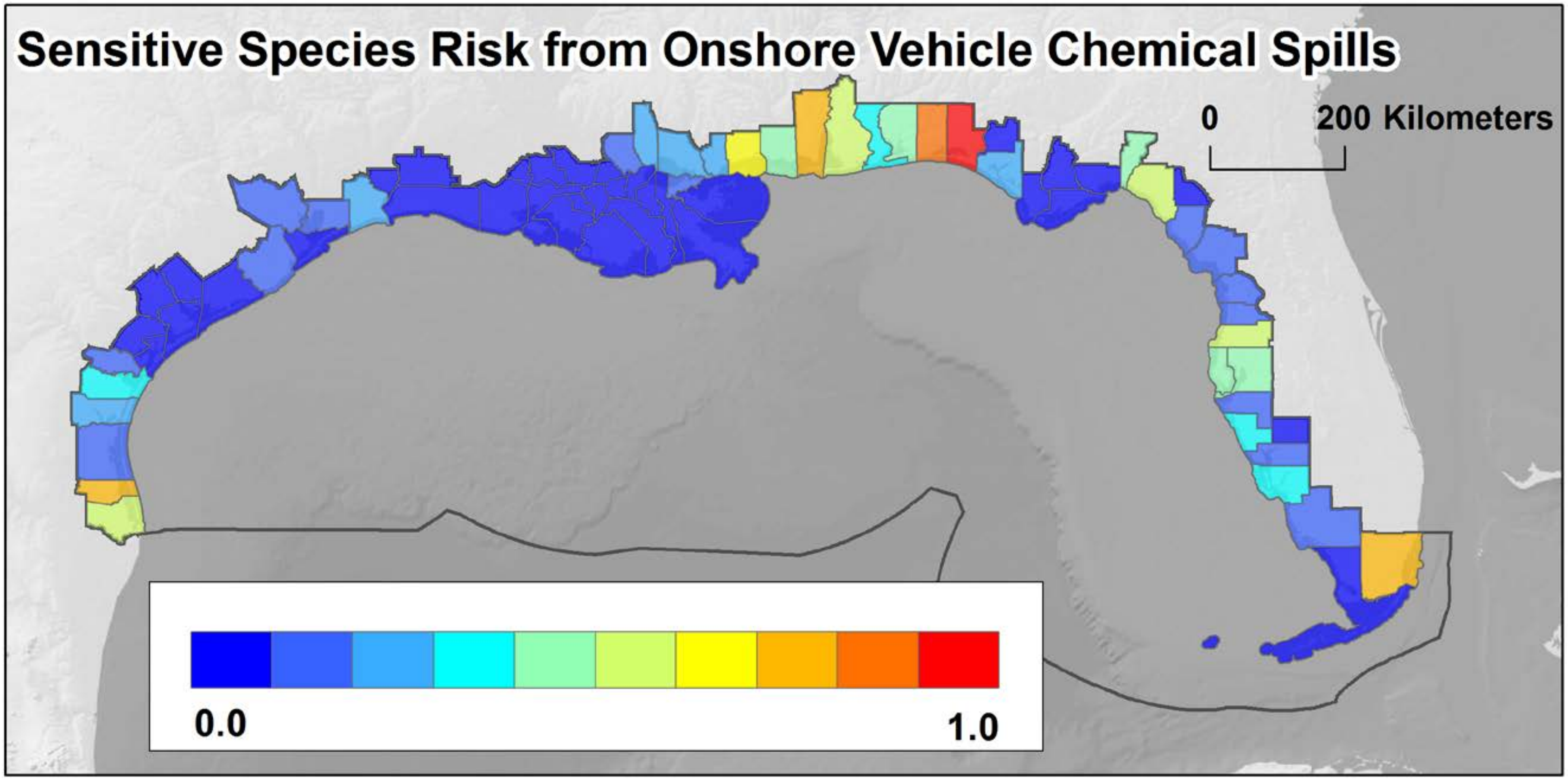

Sensitive Species Risk from Onshore Rail Oil Spills
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Offshore Tanker Chemical Spills
0
200 Kilometers
0.0
1.0

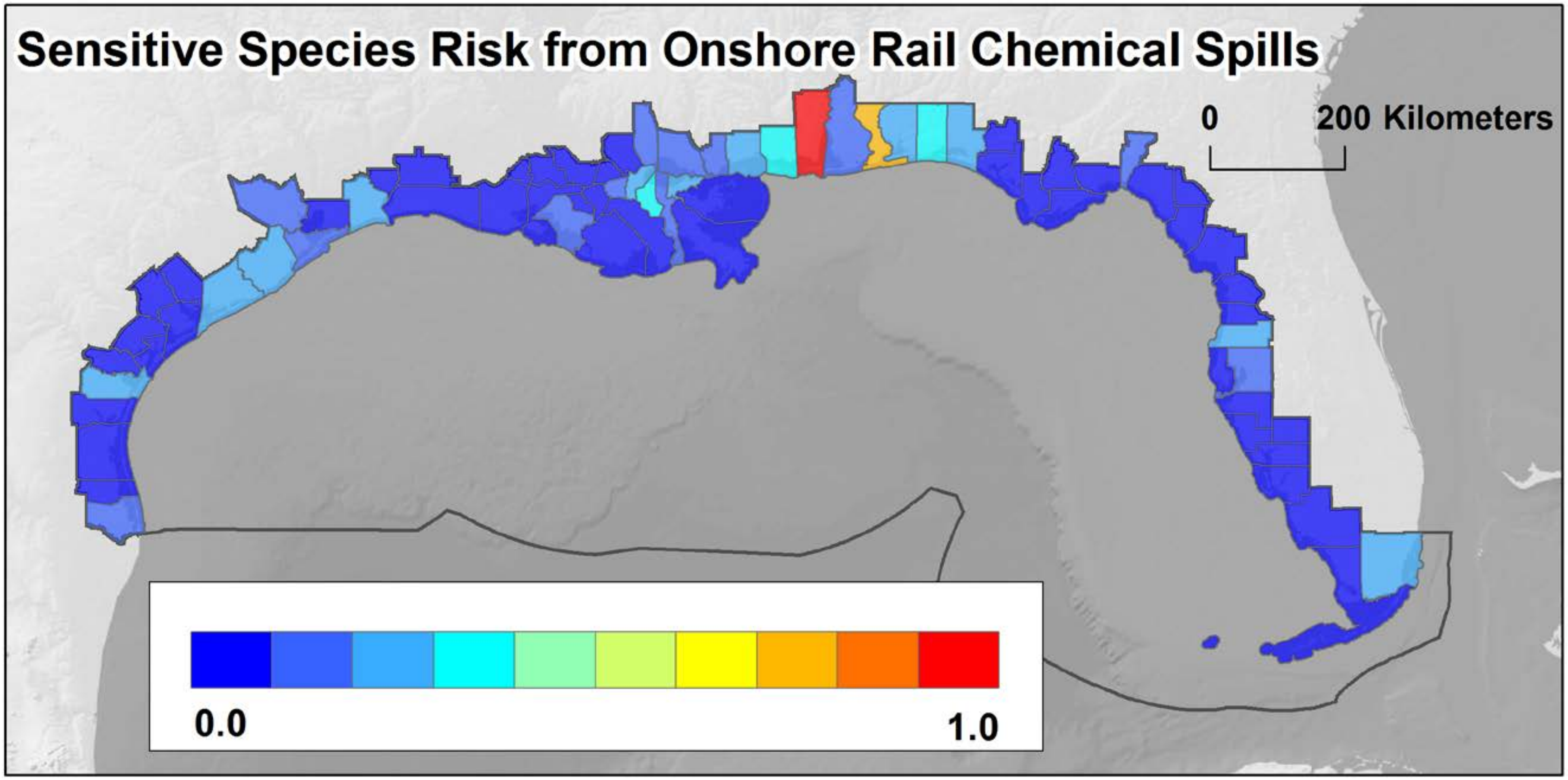

Sensitive Species Risk from Offshore/Inshore Barge Chemical Spills
0
200 Kilometers
0.0
1.0

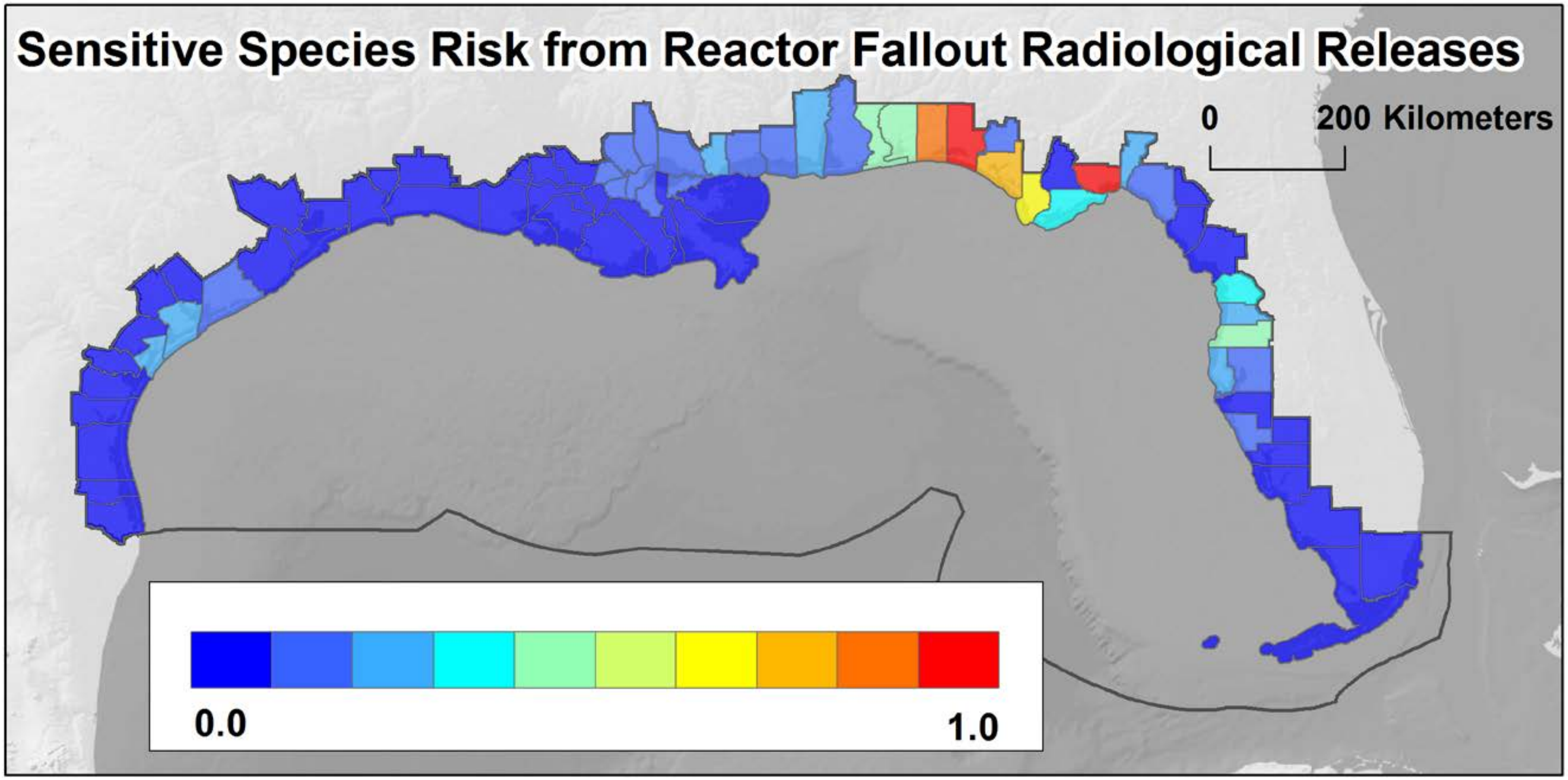

Sensitive Species Risk from Onshore Facility Chemical Spills
0
200 Kilometers
0.0
1.0

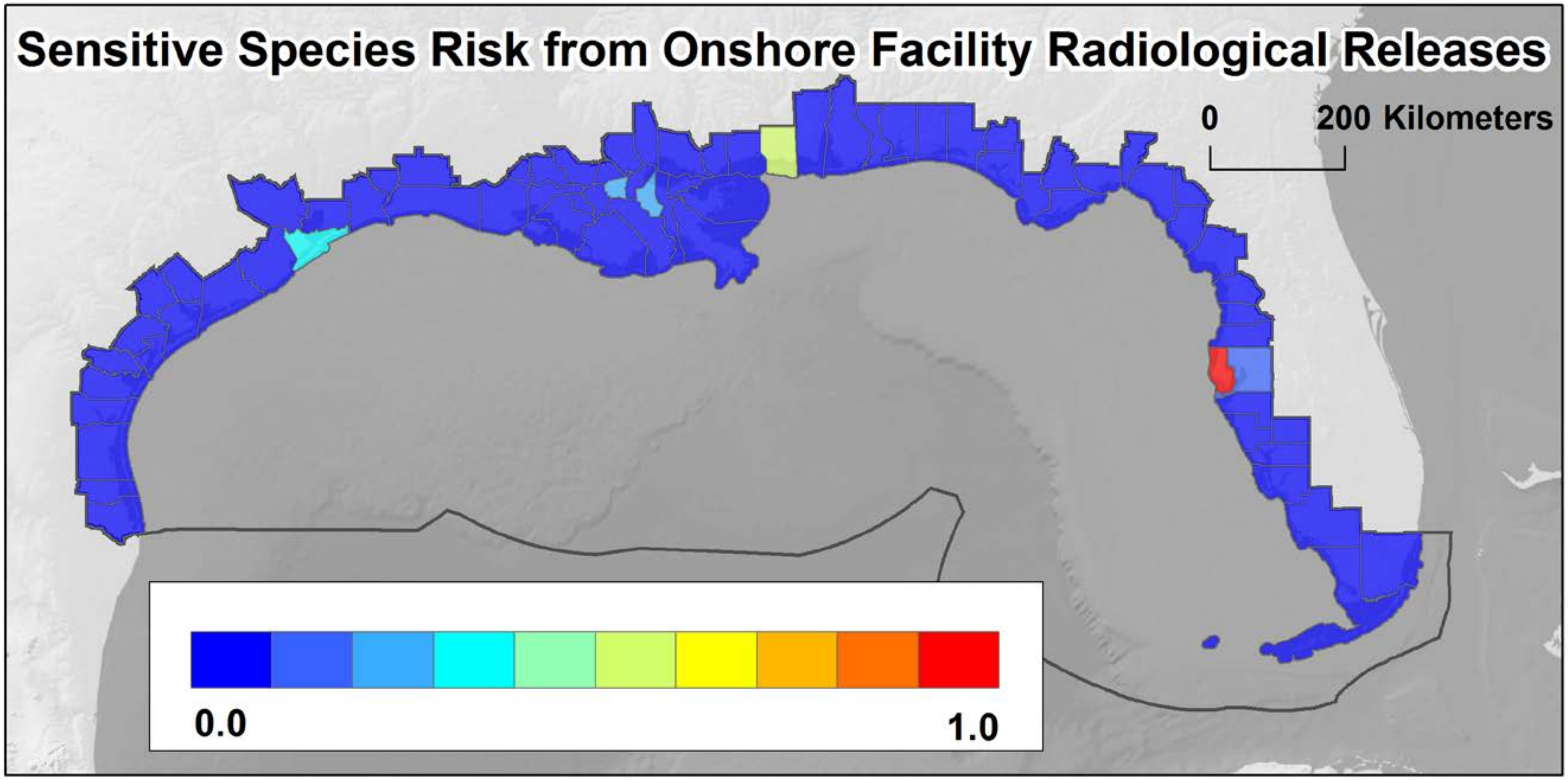

Sensitive Species Risk from Onshore Pipeline Chemical Spills
0
200 Kilometers
0.0
1.0



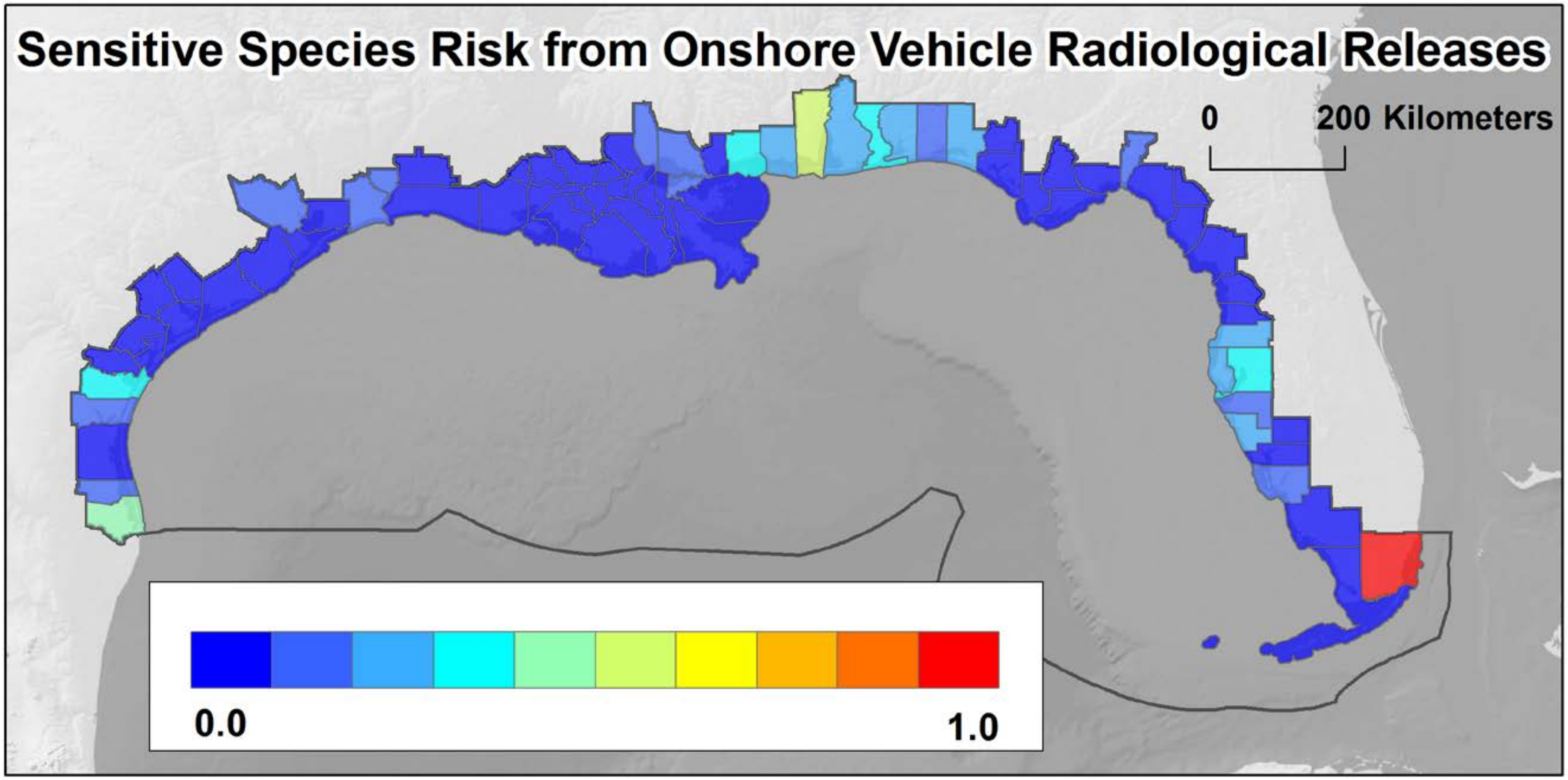
Sensitive Species Risk from Onshore Vehicle Chemical Spills
0
200 Kilometers
0.0
1.0

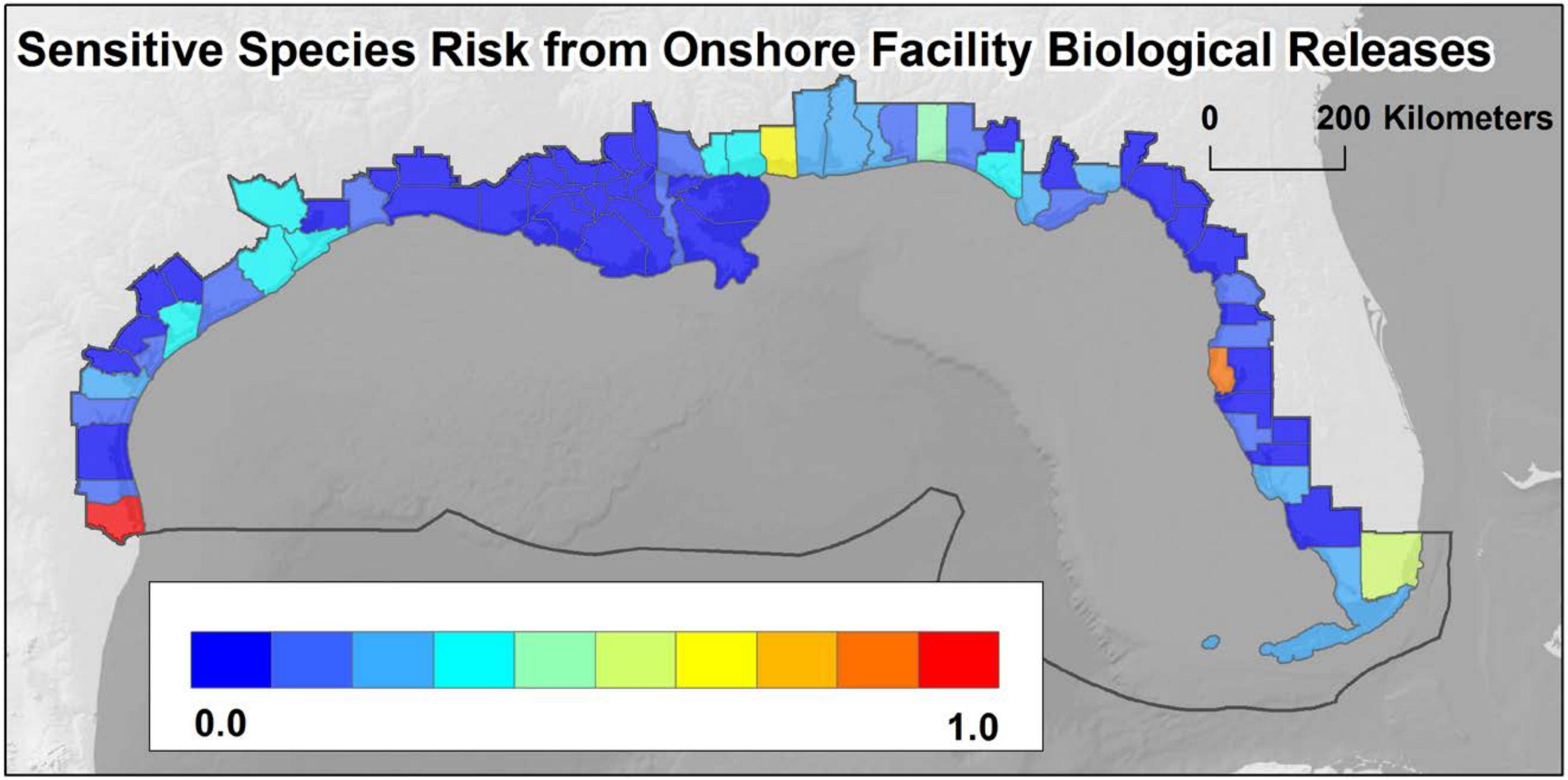

Sensitive Species Risk from Onshore Rail Chemical Spills
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Reactor Fallout Radiological Releases
0
200 Kilometers
0.0
1.0



Sensitive Species Risk from Onshore Facility Radiological Releases
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Onshore Vehicle Radiological Releases
0
200 Kilometers
0.0
1.0


Sensitive Species Risk from Onshore Facility Biological Releases
0
200 Kilometers
0.0
1.0