SOUTHEAST TEXAS HURRICANE EVACUATION STUDY HAZARD ANALYSIS – 2023

Final Report

NATIONAL HURRICANE PROGRAM

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EXECUTIVE SUMMARY – HAZARD ANALYSIS

The updated Hazard Analysis for the Texas coastal counties of Brazoria, Chambers, Galveston, Hardin, Harris, Jackson, Jasper, Jefferson, Liberty, Matagorda, Newton, and Orange includes the following enhancements and updates:

- A new methodology utilizing directional Maximum Envelope of Water (MEOW) output data was developed for this updated Hazard Analysis. Previous hazard mapping of Maximums of the Maximums (MOMs) was only according to storm intensity. The new analysis included effects from intensity and directional approach. Directional MEOW maps show the influence that approach direction has on storm surge. Equivalent inundation extent maps were developed from directional MEOWs of different intensities which produced similar maximum surge inundation extents. Only the maximum of "worst case" forward speed was utilized for this Hazard Analysis Update, and specifically for modeling equivalent inundation.-The forward speed that caused the maximum or "worst case" inundation per MEOW was utilized for this Hazard Analysis Update, and specifically for modeling equivalent inundation.
- National Hurricane Center (NHC) 2017 Texas SLOSH Super Basin (TX3) Model was used for the updated Hazard Analysis.
- Freshwater flood risk was also determined using the latest Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) mapping.
    - Mapping of modeled surge from directional MEOWs and MOMs also includes FEMA FIRM floodplain extents for freshwater flooding.
- Wind Extent Maps (WEMs) have been produced from directional Maximum Envelopes of Wind (MEOW)s that were developed for 5 forward speeds (8, 12, 16, 20, and 24 knots) using the 2021 National Oceanic and Atmospheric Administration (NOAA) Wind Speed Decay Modeling polygons based on the Saffir-Simpson Hurricane Wind Scale. They depict the estimated furthest inland wind extents for sustained wind speeds for representative tropical cyclones making landfall from the Gulf of America.
- A Geographic Information System (GIS) database containing all data from this analysis will be provided to the user at: https://texasatlas.arch.tamu.edu/

1 HAZARDS ANALYSIS

1.1 INTRODUCTION

1.1.1 OVERVIEW

The purpose of this updated Hazard Analysis is to determine storm surge, freshwater flooding, and wind threats that can be anticipated from tropical cyclones of various categories and tracks for the Texas counties of Brazoria, Chambers, Galveston, Hardin, Harris, Jackson, Jasper, Jefferson, Liberty, Matagorda, Newton, and Orange.

Three major hazards associated with tropical cyclones are the following:

1. **Storm Surge** - Still-water modeled storm surge heights from tropical cyclones of various categories, approach directions, and forward speeds are estimated and provide the basis of Evacuation Zones developed within the updated Vulnerability Analysis.
2. **Freshwater Flooding** - Freshwater flooding (including riverine with contributing creeks and streams) estimates from heavy rainfall runoff associated with tropical cyclones are considered in FEMA FIRMs products.
3. **Winds** - Wind speed decay modeling estimates the maximum sustained surface wind as a storm moves inland.

1.2 BACKGROUND

1.2.1 SAFFIR-SIMPSON HURRICANE WIND SCALE

The Saffir-Simpson Hurricane Wind Scale, developed by Herbert Saffir, a civil engineer, and Dr. Robert H. Simpson, a meteorologist, and former Director of the National Hurricane Center (NHC), is a 1 to 5 rating scale used by the National Weather Service (NWS) and NHC to quantify a hurricane's strength based on peak sustained wind speed (using the U.S. 1-minute average at the observation height of 10 meters or 33 feet over unobstructed exposure). Hurricanes with a Category 3 or higher are considered major hurricanes due to their potential for significant damage and loss of life.

Earlier versions of the scale, formerly the Saffir-Simpson Hurricane Scale, incorporated storm surge and central pressure as components of the categories. The central pressure was used as a proxy for the winds since accurate wind speed intensity measurements from aircraft reconnaissance were not routinely available until 1990. Actual storm surge values were sometimes substantially outside of ranges suggested in original scale since hurricane size, local bathymetry (or depth of near-shore waters), topography, and hurricane's forward speed and approach direction affect the surge produced. Therefore, to reduce public confusion about impacts associated with hurricane categories and to provide a more scientifically defensible scale, the flooding impact, storm surge ranges, and central pressure statements were removed from the scale.[1] An abbreviated version of the wind related damage potential of each hurricane category is described in Table 1-1. An extended table can be found at https://www.nhc.noaa.gov/pdf/sshws_table.pdf.

[1] Source: https://www.nhc.noaa.gov/pdf/sshws.pdf

Table 1-1: Saffir-Simpson Hurricane Damage Scale[2]

Category	Damage
1	Winds 74 to 95 miles per hour (64 to 82 knots). **Very dangerous winds will produce some damage**: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	Winds 96 to 110 miles per hour (83 to 95 knots). **Extremely dangerous winds will cause extensive damage**: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	Winds 111 to 129 miles per hour (96 to 112 knots). **Devastating damage will occur**. Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	Winds 130 to 156 miles per hour (113 to 136 knots). **Catastrophic damage will occur**. Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	Winds greater than 157 miles per hour (137 knots or higher). **Catastrophic damage will occur.** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

1.2.2 HURRICANE FORECASTING INACCURACIES

The worst-case approach is used in the hazards analysis because of inaccuracies in forecasting the precise tracks and other parameters of approaching hurricanes. The NHC conducts an annual analysis of tropical cyclone forecasts to determine the normal magnitude of error. According to the "NHC Forecast Verification Report 2022 Hurricane Season" (May 8, 2023) by John P. Cangialosi, the NHC issued 255 Atlantic basin tropical cyclone forecasts in 2022, which is below long-term averages making 2022 Atlantic hurricane season the least active since 2015. Mean track errors ranged from 21 nautical miles at 12 hours to 126 nautical miles at 120 hours. The mean official track forecast errors in 2022 were below the 5-year mean at all times, and up to 27% smaller at 120 hours. Over the past 30 years, there has been a reduction of the 24-72 hour track forecast error by 70-75% as shown in Figure 1-1. Over the past 15 to 20 years, track forecast

[2] Source: https://www.nhc.noaa.gov/aboutsshws.php

errors have been reduced by about 60% for the 96 hours and 120 hours forecast periods. On average, the NHC track errors decrease as the initial intensity of a cyclone increases.

In 2022, the mean forecast errors for intensity ranged from 5 knots at 12 hours to 21 knots at 120 hours. The errors were 11-24% lower than the previous 5-year means from 12 to 72 hours, setting records for accuracy, specifically for the 12 to 60 hour forecast periods. Errors were considerably higher than the 5-year means at 96 and 120 hours as shown in Figure 1-2. However, over the long-term, despite year-to-year variability, there has been a notable decrease in intensity error that began around 2010. Although forecasting techniques are improving, the risk from storm surge flooding cannot be determined alone from the forecasted intensity on the Saffir-Simpson Hurricane Wind Scale.

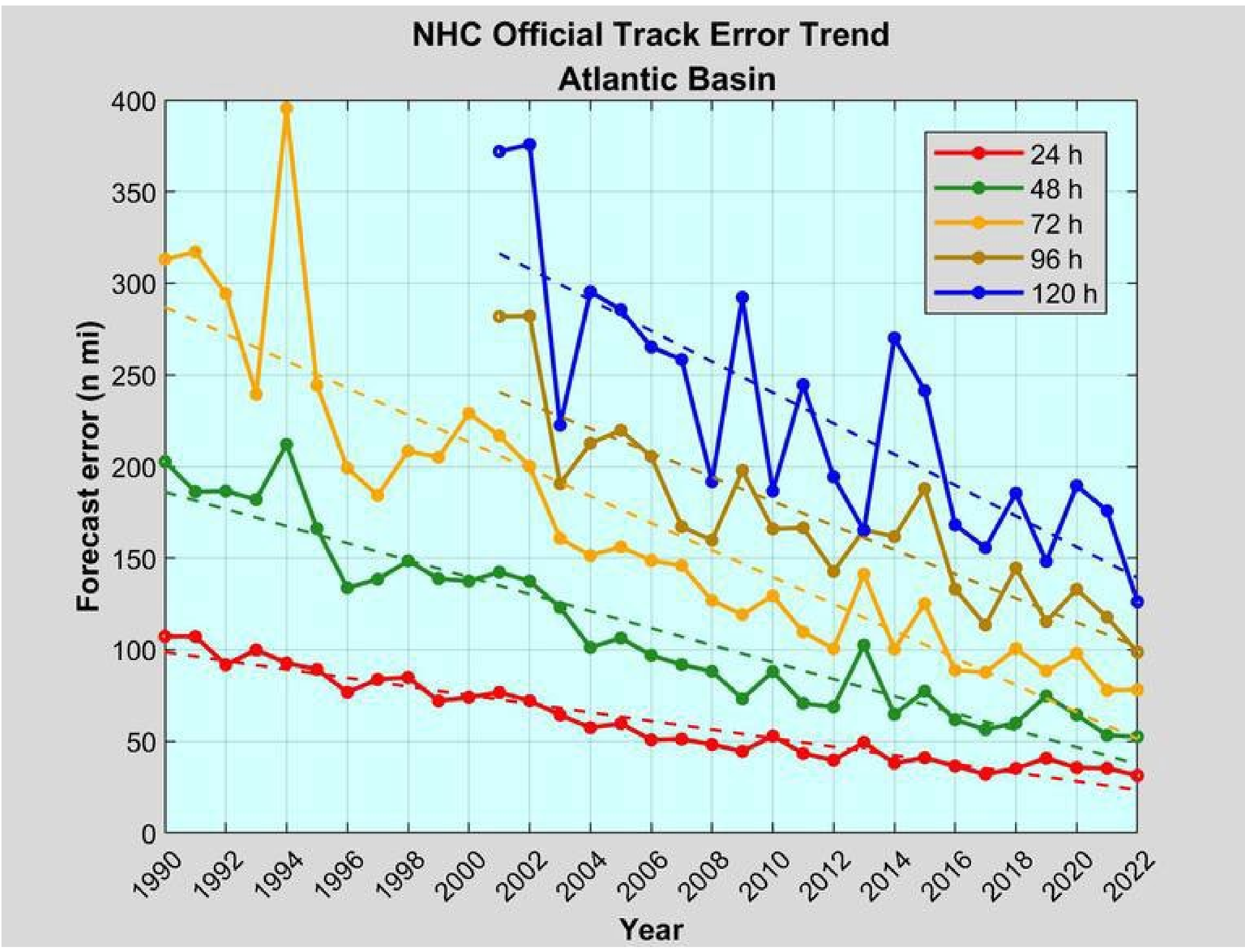


Figure 1-1 NHC Official Track Error Trend (1990 - 2022)[3]

[3]Source: https://www.nhc.noaa.gov/verification/pdfs/Verification_2022.pdf

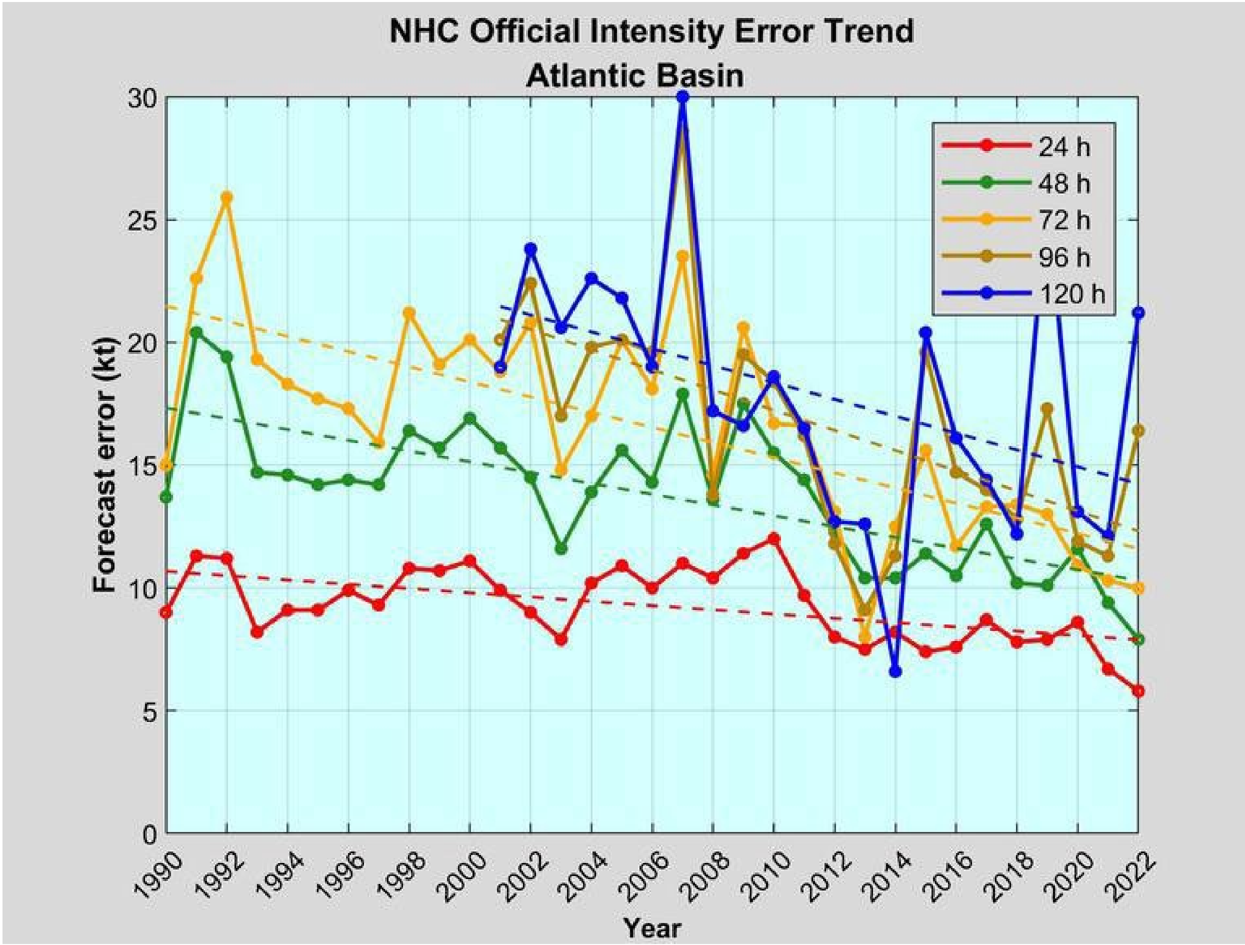


Figure 1-2 NHC Official Intensity Error Trend (1990 – 2022) [4]

1.3 STORM SURGE

1.3.1 INTRODUCTION

Storm surge is the abnormal rise in water level, over and above the predicted astronomical tides, caused by extreme wind and pressure forces. Storm surge along the coast is often the greatest threat to life and property from a hurricane. Various storm events can cause storm surge, but it is generally the result of a very large-scale meteorological disturbance with wind being the primary cause.

1.3.2 TOTAL FLOOD ELEVATION

Factors that contribute to the total flood elevation, or total water level, are storm tide and wave effects. The storm tide consists of the initial water level (e.g., normal astronomical tide) within the basin plus storm surge at the time the hurricane strikes. Since storm surge increases the water level above the normal astronomical tide, a low tide event is the best possible timing for landfall, while a high tide event is the worst. Figure 1-3 illustrates the relationship of the normal high tide, storm surge, storm tide, and wave setup. Normal astronomical tide and storm tide are both considered stillwater conditions.

[4]Source: https://www.nhc.noaa.gov/verification/pdfs/Verification_2022.pdf

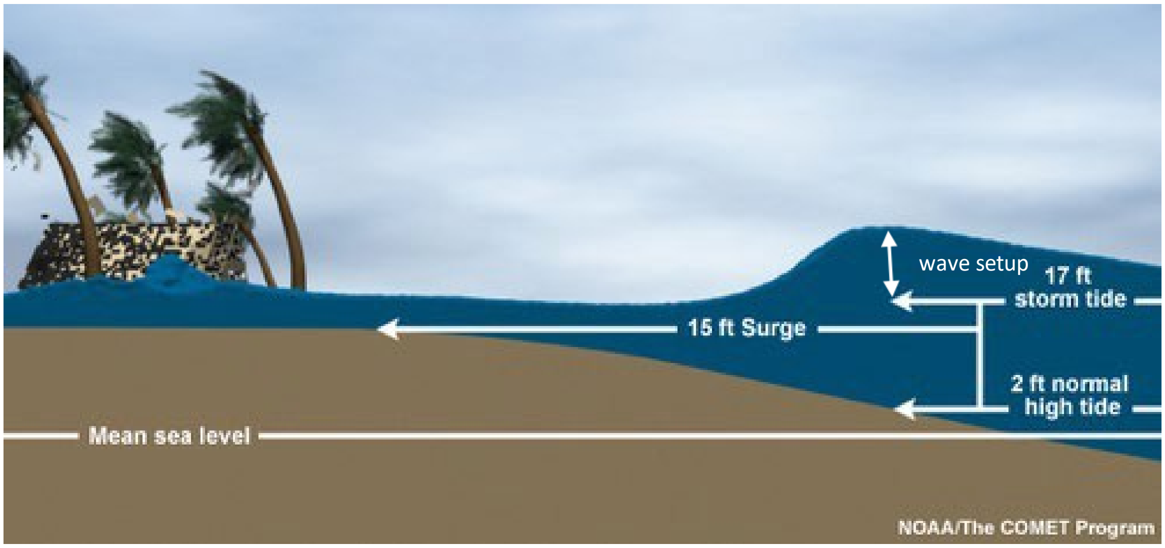


Figure 1-3 Relationship of Storm Surge to Mean Sea Level and Tides[5]

One factor that increases storm surge beyond storm tide is a localized phenomenon known as wave setup. Energy of the waves breaking near the shore forces water further landward. During severe storms, there is a significant increase in wave height and volume, and water cannot flow back to the sea as rapidly as it comes ashore. This increases the water level along the beachfront. Since waves break and dissipate their energy in shallow water, wave setup allows the waves to move further landward than under normal conditions. Also, a relatively steep offshore beach slope allows large ocean waves to get closer to the shore before breaking, resulting in greater wave setup than on a gradually sloping beach. Since large waves are generally not transmitted inland of the coastline, even if the beach has been overtopped, wave setup is primarily a concern near the beachfront. Progress has been made recently to capture wave set-up in the SLOSH model by coupling it with the Simulating Waves Nearshore (SWAN) model to include the wave set-up component.

It is assumed that for the open coast, maximum theoretical wave heights occur near the time of landfall. Immediately along the coastline or the shorelines of very large sounds and estuaries, wave crests can increase the expected still-water depth above the terrain by one-third, thus greatly increasing the hazard. Due to the presence of barriers such as structures, dunes, or vegetation, the waves break and dissipate a tremendous amount of energy within a few hundred yards of the coastline. Buildings within that zone that are not specifically designed to withstand the forces of wave action are often heavily damaged or destroyed. Also, currents created by tides combined with wave action severely erode beaches and coastal highways.

1.3.3 FACTORS AFFECTING STORM SURGE HEIGHT

The elevation reached by the storm surge depends upon the meteorological parameters of the hurricane and the physical characteristics along the coastline. The meteorological parameters affecting the height of the storm surge include the intensity of the hurricane (measured by the

[5] Source: https://www.nhc.noaa.gov/surge/

storm center sea level pressure), track (path) of the storm, forward speed, and radius of maximum winds. This radius, which is measured from the center of the hurricane eye to the location of the highest wind speeds within the storm, can vary from as little as 4 miles to greater than 50 miles. Due to the complementary effects of forward motion and the counterclockwise rotation of the wind field (in the northern hemisphere), highest surges from a hurricane usually occur on the right side of the storm's track in the region of the radius of maximum winds. As shown in Figure 1-4, the impact of surge from the storm's low pressure is minimal in comparison to the water being forced towards the shore by wind. Peak storm surge may vary drastically within a relatively short distance along the coastline, depending on the radius of maximum winds and the point of hurricane eye landfall. The geophysical characteristics that influence the surge heights include the basin bathymetry (e.g., water depths), roughness and slope of the continental shelf, configuration of the coastline (such as bays and estuaries), and natural or manmade barriers. A wide, gently sloping continental shelf or a large bay may produce particularly large storm surges, as compared to a continental shelf that drops off very quickly which may produce a smaller storm surge. Table 1-2 summarizes generalized storm surge impacts from meteorological and geophysical parameters mentioned above.

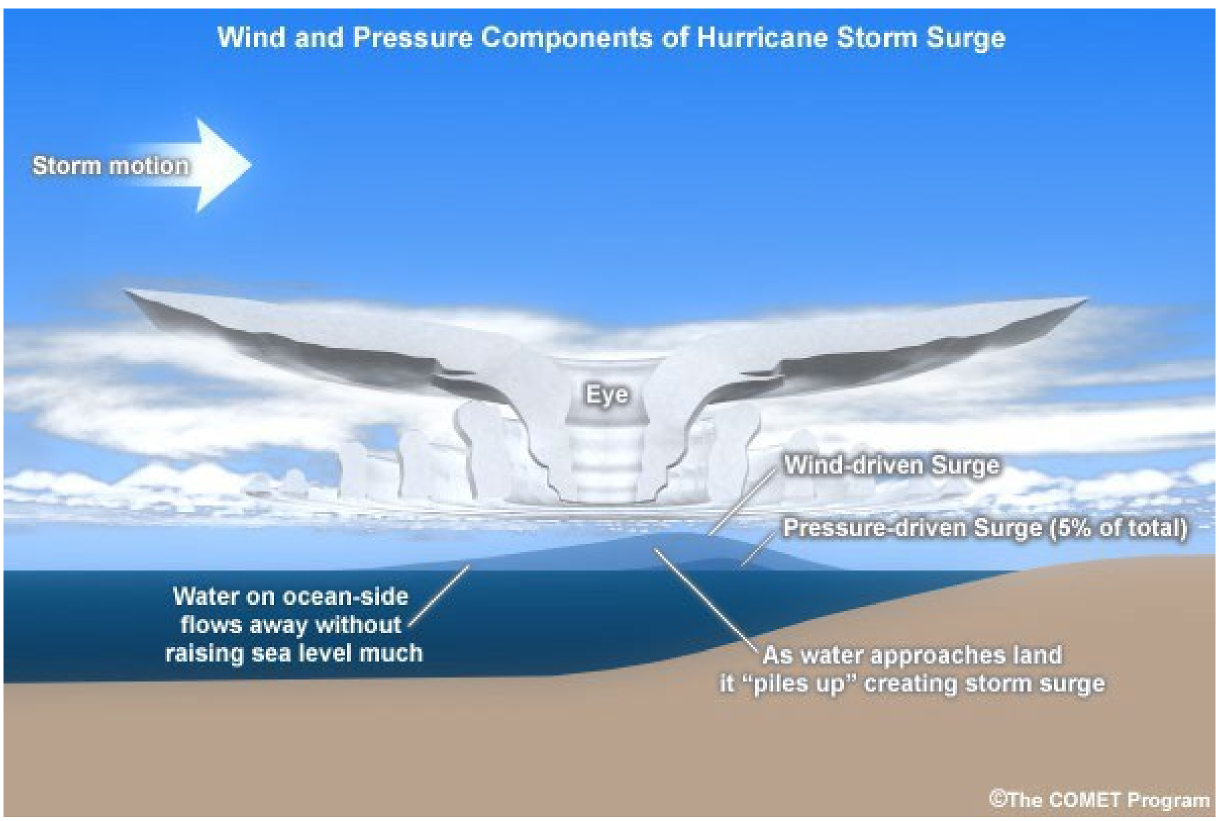


Figure 1-4 Wind and Pressure Components of Hurricane Storm Surge[6]

[6] Source: https://www.nhc.noaa.gov/surge/

Table 1-2 Generalized Storm Surge Impacts from Factors[7]

Impact Factor	Generalized Impacts
Hurricane Intensity	Higher wind speeds = increased storm surge
Central Pressure	Little impact
Forward Speed	• Slower storms = higher and broader storm surge inland including bays and estuaries • Faster storms = more storm surge along the open coast
Size	• Storm with large wind field = more storm surge • Storm with small wind field = less storm surge
Angle of approach	• Perpendicular to coastline = more storm surge • Parallel to coastline = less storm surge
Width and slope of continental shelf	• Wide shelf/gentle slope = more storm surge with relatively small waves • Narrow shelf/sharp slope = less storm surge with relatively big waves
Local features	• Concavity of coastlines, bays, rivers, headlands, islands, etc. = greater storm surge impact

The waters offshore of Texas can be characterized by gently sloping depths typically associated with the continental shelf. Depths gradually increase from the shore to approximately 15 fathoms (90 feet) in 90 miles.

1.4 STORM SURGE FORECASTING

1.4.1 SLOSH MODEL

The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) computerized numerical model is used by NOAA and NWS for coastal inundation risk assessment and the operational prediction of potential storm surge from hurricanes. The SLOSH model was first conceived for real-time forecasting of surges from approaching hurricanes. The SLOSH model is now also the basis of establishing the extents of worst-case storm surge hazards by modeling multiple storm scenarios of different intensity, approach directions, and forward speeds. The SLOSH model computes storm surge for open coast and overland locations, as well as routes storm surge into sounds, bays, estuaries, and coastal river basins, but it does not account for localized wave setup.

Geophysical characteristics of an area covered by a SLOSH model are constructed as input data within the model. These characteristics include the topography of inland areas; river basins and waterways; bathymetry of near-shore areas, sounds, bays, and large inland waterbodies; significant natural and manmade barriers such as barrier islands, dunes, roads, levees, etc.; and a segment of the continental shelf.

[7] Source: https://www.nhc.noaa.gov/surge/faq.php

The SLOSH model uses time-dependent meteorological data to determine the driving forces of a simulated storm. Input data includes the following:

1. Central pressure deficit at 6-hour intervals (approximated by subtracting the central pressure of the storm from 1013 mb).
2. Latitude and longitude of storm positions at 6-hour intervals.
3. Storm size measured by the radius of maximum winds. Wind speed is not an input parameter, since the model calculates a wind-field for the modeled storm based on the central pressure deficit using an internal symmetric wind model.
4. Height of the water surface before the storm directly affects the area of interest. This initial height is the observed water surface elevation occurring about 2 days before storm arrival.

Previous modeling for the Texas Hazard Analysis was conducted in 2004 for the Houston-Galveston study area and 2011 for the Sabine-Lake Study area using the Matagorda Bay (PS2), Galveston Bay (GL3), and Sabine Lake (BP3) SLOSH Basins (Figure 1-5). This updated Hazard Analysis utilizes data from the 2017 Texas SLOSH Super Basin (TX3) model which has a more detailed grid and greater inland extents than the previous basin versions. Figure 1-6 illustrates the area covered by the model grid (called a "basin") for the 2017 Texas SLOSH Super Basin (TX3) model.

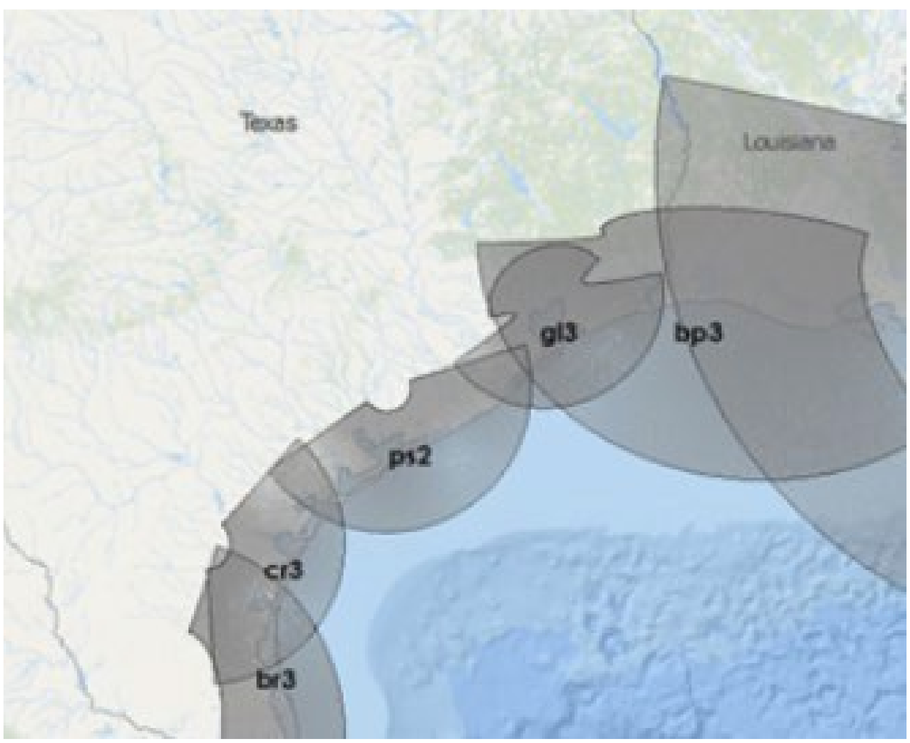


Figure 1-5 Historic Texas SLOSH Basins Matagorda Bay (PS2), Galveston Bay GL3, and Sabine Lake (BP3)

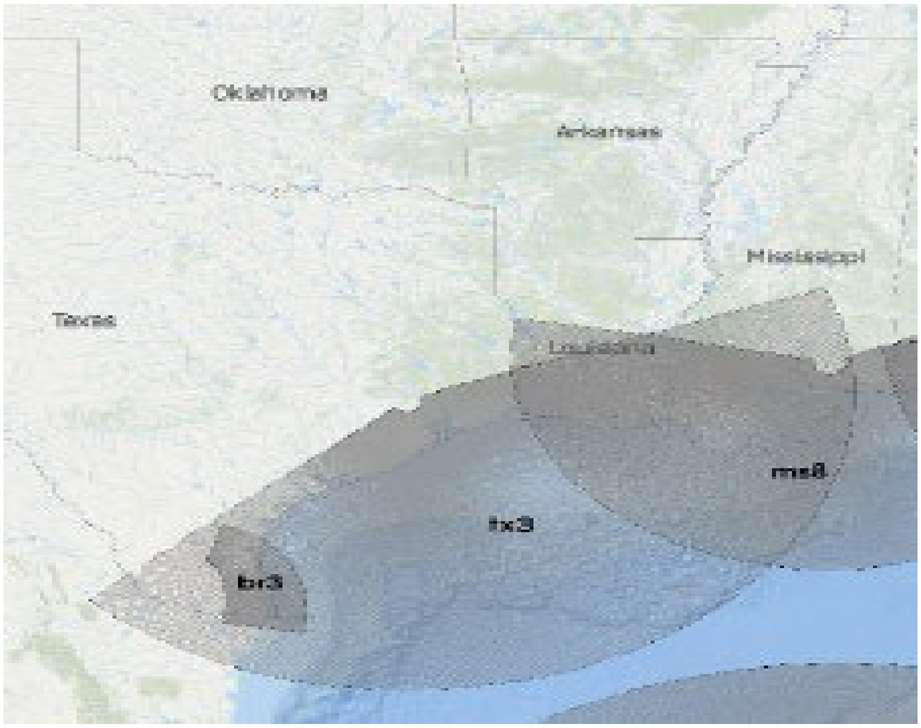


Figure 1-6 Texas SLOSH Super Basin (TX3)

The characteristics of the simulated hurricanes were determined from an analysis of historical hurricanes that have occurred within the study area. The parameters selected for the modeled storms were the intensities (Tropical Storm and Categories 1-5), forward speeds, approach directions, landfall location, initial water level, and radii of maximum winds that are considered to have the highest meteorological probability of occurrence within Texas SLOSH Basin. For this Hazard Analysis, only the high tide events were considered.

1.4.2 VERIFICATION OF SLOSH MODEL

After a SLOSH model has been constructed for a coastal basin, verification is conducted as real-time operational runs in which available meteorological data from historical storms are input into the model. The computed surge heights are compared with those measured from the historical storms and, if necessary, adjustments are made to the input or basin data. These adjustments are not made to force agreements between computed and measured surge heights from historical storms, but to represent the basin characteristics or historical storm parameters more accurately. In instances where the model has given realistic results in one area of a basin but not in another, closer examination has often revealed inaccuracies in the representation of barrier heights or missing values in bathymetric or topographic data.

1.4.3 MODEL OUTPUT

The SLOSH model output for a modeled storm consists of envelopes of high water above ground datum and contains the maximum surge height values calculated for each grid point in the model. Maximum surges along the coastline do not necessarily occur at the same time. The time of the maximum surge for one location may differ by several hours from the maximum surge that occurs at another location. Therefore, at each grid point, the water height value shown is the maximum that was computed at that point during the 72 hours of model time, irrespective of the time during the simulation that the maximum surge height occurred. An example of this computation is shown in Figure 1-7 below. Output of the Texas (TX3) model was produced for mean and high tide conditions using the North American Vertical Datum of 1988 (NAVD88). However, only high tide conditions were used for purposes of this Hazard Analysis update since high tide conditions represent the worst case.

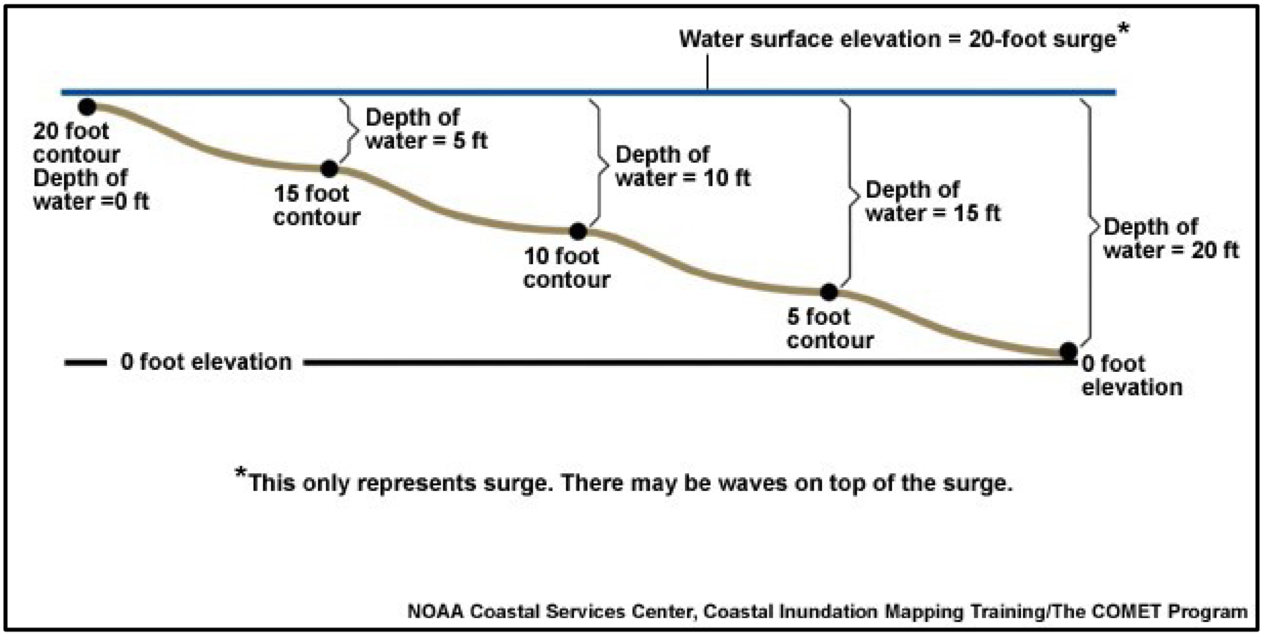


Figure 1-7 Storm Surge Inundation Shown as Height Above Ground Level[8]

1.4.3.1 DIRECTIONAL MAXIMUM ENVELOPES OF WATER

The highest surges reached at all locations within the affected area of the coastline during the passage of a hurricane are called the maximum or peak surges for those locations. The location of the peak surge depends on where the eye of a hurricane crosses the coastline, hurricane intensity, basin bathymetry, configuration of the coastline, approach direction, and radius of maximum winds. As discussed previously, the peak surge from a hurricane usually occurs to the right of the storm path and within a few miles of the radius of maximum winds.

The NHC's Storm Surge Unit developed MEOWs to determine the potential peak surge at every location within the SLOSH basin. For example, if there were two storms, identical in every respect and they followed parallel tracks separated by 50 miles, then very likely there would be locations having markedly different surge values resulting from the two storms. This dependency of surge height on storm track can be troublesome in evacuation planning. Accordingly, MEOWs were produced by running the SLOSH model to create a group of storms, all having the same characteristics, but with parallel tracks 5 to 10 miles apart. At each grid square, the maximum surge value that was calculated was saved. The result was a "maximum envelope of water." Thus, the MEOW is the "worst-case" surge that is likely to be produced at a modeled location from a storm with a particular combination of approach direction, forward speed, and intensity, regardless of where landfall may have occurred. Since the MEOW is the "worst case" at all grid square locations, no one storm can duplicate the flooding depicted by a MEOW.

[8] Source: https://www.nhc.noaa.gov/surge/faq.php

Table 1-3 summarizes the model runs related to MEOWs for the TX3 SLOSH basin. The 54 MEOWs were generated for various hurricane approach directions and various intensities for Tropical Storm (Category 0) and Categories 1 through 5 events which are initialized at a high tide.

Table 1-3 Texas SLOSH Super Basin Model Data for TX3 at High Tide Conditions

Direction	Intensities	MEOWs
N	TS, Cat. 1-5	6
NE	TS, Cat. 1-5	6
NNE	TS, Cat. 1-5	6
NNW	TS, Cat. 1-5	6
NW	TS, Cat. 1-5	6
PAR	TS, Cat. 1-5	6
W	TS, Cat. 1-5	6
WNW	TS, Cat. 1-5	6
WSW	TS, Cat. 1-5	6
	TOTALS	**54**

Note: 9 storm track directions x 6 intensities = 54 MEOWs

1.4.3.2 MAXIMUM OF THE MAXIMUMS

In addition to MEOWs the NHC produced MOMs data which are ensemble products of maximum storm surge heights representing the near worst-case scenario of flooding under worst-case storm conditions. The MOMs are created for each SLOSH basin by compositing all the MEOWs, separated by category, and selecting maximum storm surge values for each grid cell regardless of the forward approach speed, storm direction, or landfall location. It was from those MOMs that storm surge inundation maps were developed for high tide conditions in each of the counties within the Southeast Texas HES study area.

1.4.4 DIRECTIONAL MEOW ANALYSIS

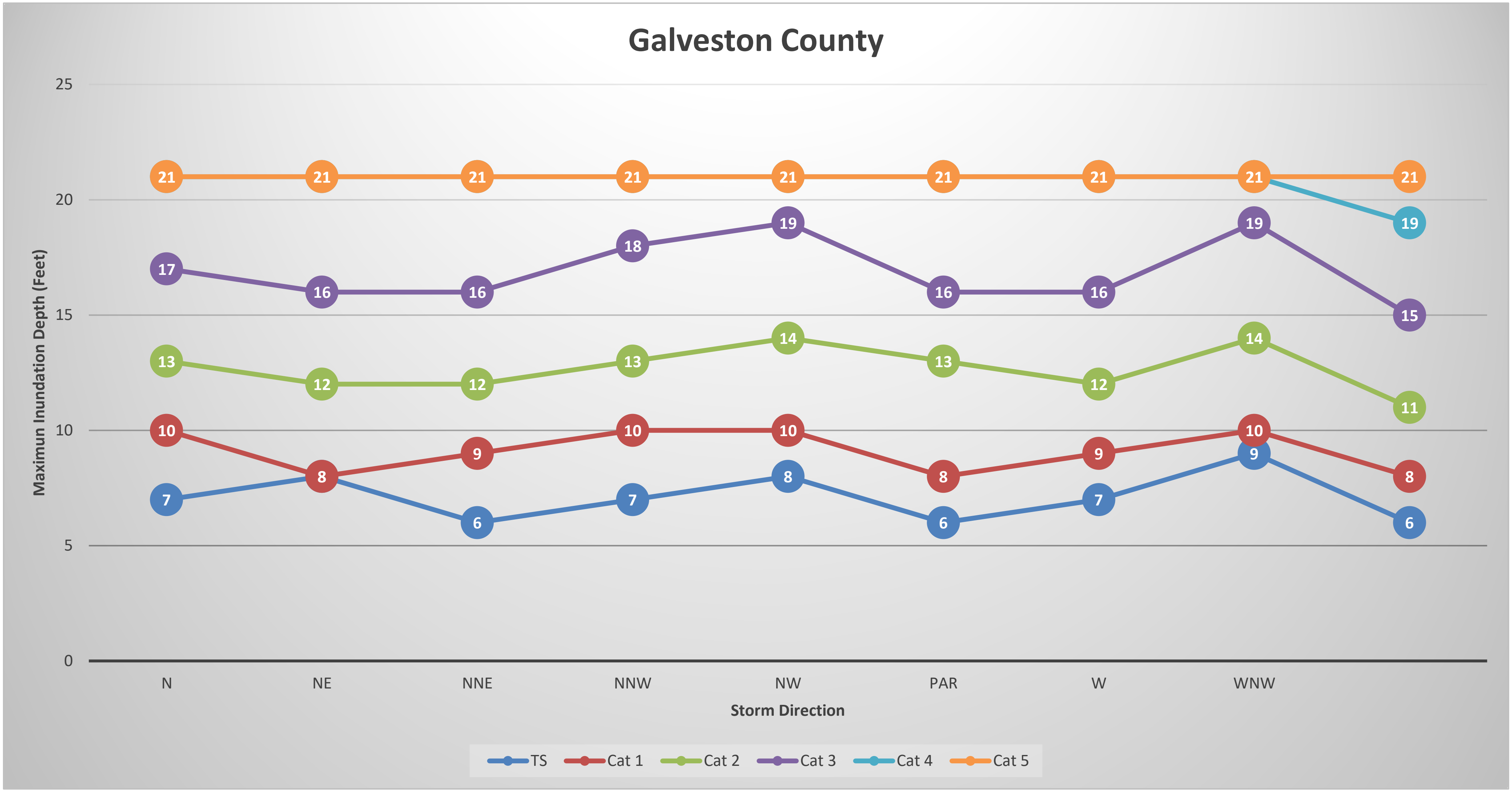
A new methodology for analyzing the MEOWs output data was developed to evaluate and determine areas of equivalent storm surge risk from various storm scenarios for each coastal county. The intent of this new methodology is to provide emergency planners with a more detailed look into the effects of storm intensity, direction, and forward speed to enhance emergency planning.

The MEOWs maximum depth data were first organized using an Excel pivot chart. Figure 1-8 graphically depicts the maximum modeled inundation depths for 54 directional MEOWs for Galveston County. The 54 MEOWs were generated by taking the 6 different intensity storms (e.g., Tropical Storm through Category 5 Hurricane) multiplied by the 9 different approach directions for the Southeast Texas area. The Max Inundation Depths of the Category 4 and Category 5 Storms are shown as they were modeled in SLOSH. Note that all the data has been included for these figures, including outliers of maximum depths that may have very small areas associated with them. Although the inundation depth appears to be the same for Category 4 and Category

5 in Figure 1-8, further analysis of the pivot table data for Galveston County (Table 1-4) indicates the flood elevation causing an increase in acreage extents is greater for a Category 5 and could potentially impact more population.

For somewhat protected areas, it was noted the storm intensity (i.e., storm category) and the approach direction typically have the most influence on surge height. The higher the intensity, generally the larger the storm size and the wider the wind field, which pushes more water further inland. However, when there is a wide-open fetch in the direction of the hurricane approach to land, the inundation depths produced are more sensitive to the forward speed. In addition, storms that are moving parallel to the coast, east to west, also exhibit a larger influence from forward speed than storms moving west to east, due to the additive relative velocity forces produced from forward speed and counterclockwise rotation of the winds in the upper right quadrant of the storm.

Maximum Inundation Depth graphs for each county are found in Appendix E. Pivot data tables for each county are found in Appendix F.



Note: There is overlap of data points for maximum inundation depths greater than 20 feet.

Figure 1-8 Galveston County, TX Maximum Inundation Depths for Directional MEOWs

Table 1-4 Galveston County, TX Grouping Based on Acreage of Inundation Extent

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	7	2.7	47923	50087.6235394288
N1	1	10	3.9	68154	72224.2729540011
N2	1	13	5.9	119762	92523.7910431879
N3	1	17	8.3	207596	127572.249030769
N4	1	21	10.9	280959	172387.727569985
N5	1	21	13.1	308263	200874.121521555
NE0	1	8	3.2	64694	66349.6539019029
NE1	1	8	3.2	64694	66349.6539019029
NE2	1	12	4.8	109460	88680.282658431
NE3	1	16	6.8	191415	118332.020849126
NE4	1	21	9.0	270899	162611.872786214
NE5	1	21	10.9	306099	197100.685739649
NNE0	1	6	2.4	45433	46990.2815495802
NNE1	1	9	3.5	65784	68697.1810223488
NNE2	1	12	5.3	113566	89775.4128254907
NNE3	1	16	7.5	197501	121099.209282426
NNE4	1	21	9.8	273587	164737.320571116
NNE5	1	21	11.9	307645	197589.429556945
NNW0	1	7	2.9	49582	53418.6585838425
NNW1	1	10	4.3	69660	75591.3593299543
NNW2	1	13	6.6	130054	97644.2820777664
NNW3	1	18	9.0	218621	135266.350808248
NNW4	1	21	11.9	292110	182900.306939317
NNW5	1	21	14.4	309219	204390.623718172
NW0	1	8	3.1	52236	56274.864812226
NW1	1	10	4.6	73483	77898.8593276112
NW2	1	14	7.2	136695	101738.223147418
NW3	1	19	9.7	227486	141736.832563755
NW4	1	21	12.7	300737	191545.757265134
NW5	1	21	15.6	309766	205902.175282125
PAR0	1	6	2.2	45628	45756.7948533158
PAR1	1	8	3.2	65303	65280.7482965319
PAR2	1	13	4.7	110917	88987.2570579714
PAR3	1	16	6.8	194500	119193.282735445
PAR4	1	21	8.9	274299	164933.234751939
PAR5	1	21	11.0	305759	198166.625308853
W0	1	7	2.5	45938	50342.863445656
W1	1	9	3.6	61509	68910.0130710663
W2	1	12	5.7	103968	87744.5268961107
W3	1	16	8.0	185284	120774.07520441
W4	1	21	10.4	268219	166861.505840849
W5	1	21	12.6	307634	200429.498012216
WNW0	1	9	4.7	98225	78090.3182306637
WNW1	1	10	4.3	73103	75564.6943040829
WNW2	1	14	7.1	135599	101065.997148111
WNW3	1	19	9.6	223701	140990.289259608
WNW4	1	21	12.7	302053	192831.949889084
WNW5	1	21	15.7	309766	205951.347850933
WSW0	1	6	2.0	39754	41322.2735746863
WSW1	1	8	2.9	53316	60655.0493293132
WSW2	1	11	4.5	85551	80472.8463658591
WSW3	1	15	6.8	155543	107888.802269242
WSW4	1	19	9.1	242988	152675.689429024
WSW5	1	21	11.4	299956	190417.374175696
MOM1	1	11	4.9	95702	77383.004402076
MOM2	1	15	7.5	148908	102406.958860377
MOM3	1	21	10.0	236174	146293.344652939
MOM4	1	21	13.4	302964	197502.694943297
MOM5	1	22	17.0	350682	230787.391569409

Considering all storm categories (e.g., Tropical Storm through Category 5 Hurricane) and storm direction, the maximum inundation depths were plotted for all 9 storm approach directions to determine the worst and best cases. Figure 1-9 and Figure 1-10 are the composited directional MEOW maps showing the worst case (e.g., highest maximum inundation) and best case (e.g., lowest maximum inundation) related to storm approach directions for the study area counties. The northwest approach direction (Figure 1-9) produced the most areas inundated with the highest surge heights due to water pushing across Southeast Texas and into its waterways. The West Southwest approach direction (Figure 1-9) produced the least areas inundated with the lowest surge heights due to the storm moving in an opposite direction to the coastline and not pushing as much water into Southeast Texas and into its waterways. Figures B-1 through B-7 in Appendix B depict the remainder of the composited directional MEOW maps related to storm approach directions for the maximum inundation depths associated with all storms and approach speeds for Southeast Texas.

1.4.5 EQUIVALENT EXTENTS OF STORM SURGE INUNDATION

The inundation extents for composited directional MEOWs for Southeast Texas were sorted into 6 groups (TS, Group I through V) according to maximum surge depths. This new approach enabled comparison of similar surge impacts from 6 different intensity storms (e.g., Categories 0 through 5) and 9 approach directions resulting in 54 scenarios. Figure 1-11 1-16 depict the equivalent inundation extents for each maximum surge depth group for directional MEOWs for the coastal counties. The associated tables in the figures show which storm intensities and directions produce equivalent maximum surge depths within groups. For instance, in -14, Southeast Texas Group III shows extents of surge inundation flooding over 20 feet (annotated as >20 feet) in depth for various Category 3 and 4 storms of varying approach directions that produce maximum depths of 18 to over 20 feet, whereas Figure 1-16 provides a good representation of a greater inundation area for Group V compared to Group IV in Figure 1-15. As indicated earlier, although inundation depth appears to be relatively similar when comparing category storms, it is also similar when comparing the different groupings. However, there are also differences in the inundation acreage numbers.

Additional inundation data analysis addressing impacts to critical facilities and identifying specific vulnerabilities across a given county's population and infrastructure will be performed during upcoming components of the Southeast Texas HES. Also, please note that Figures 1-9 to 1-16 illustrate levee locations **only** and **does not** represent overtopping at specific inundation depths.

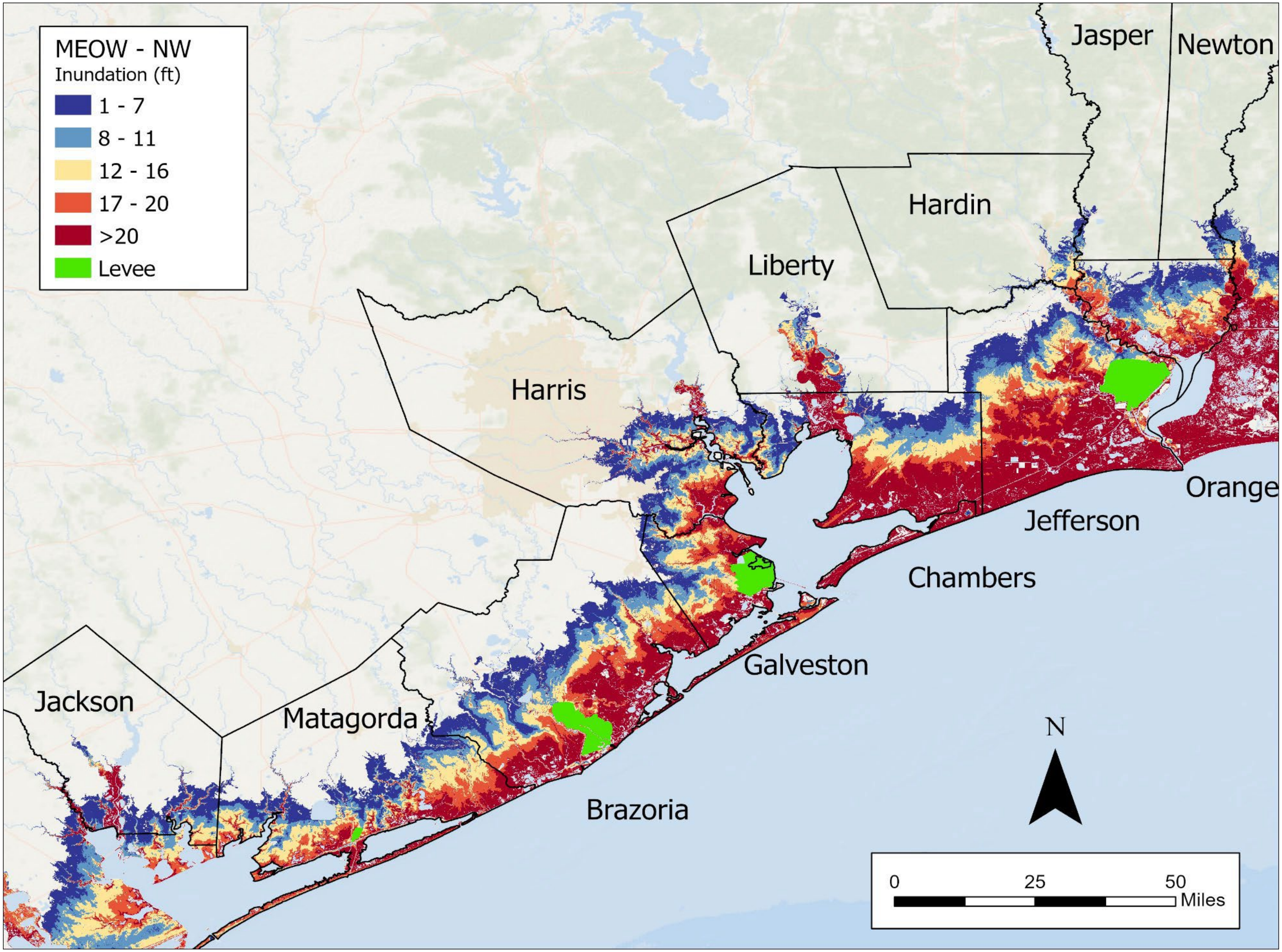


Figure 1-9 Northwest Directional MEOW Map (Worst Case Approach Direction – Highest Maximum Inundation)

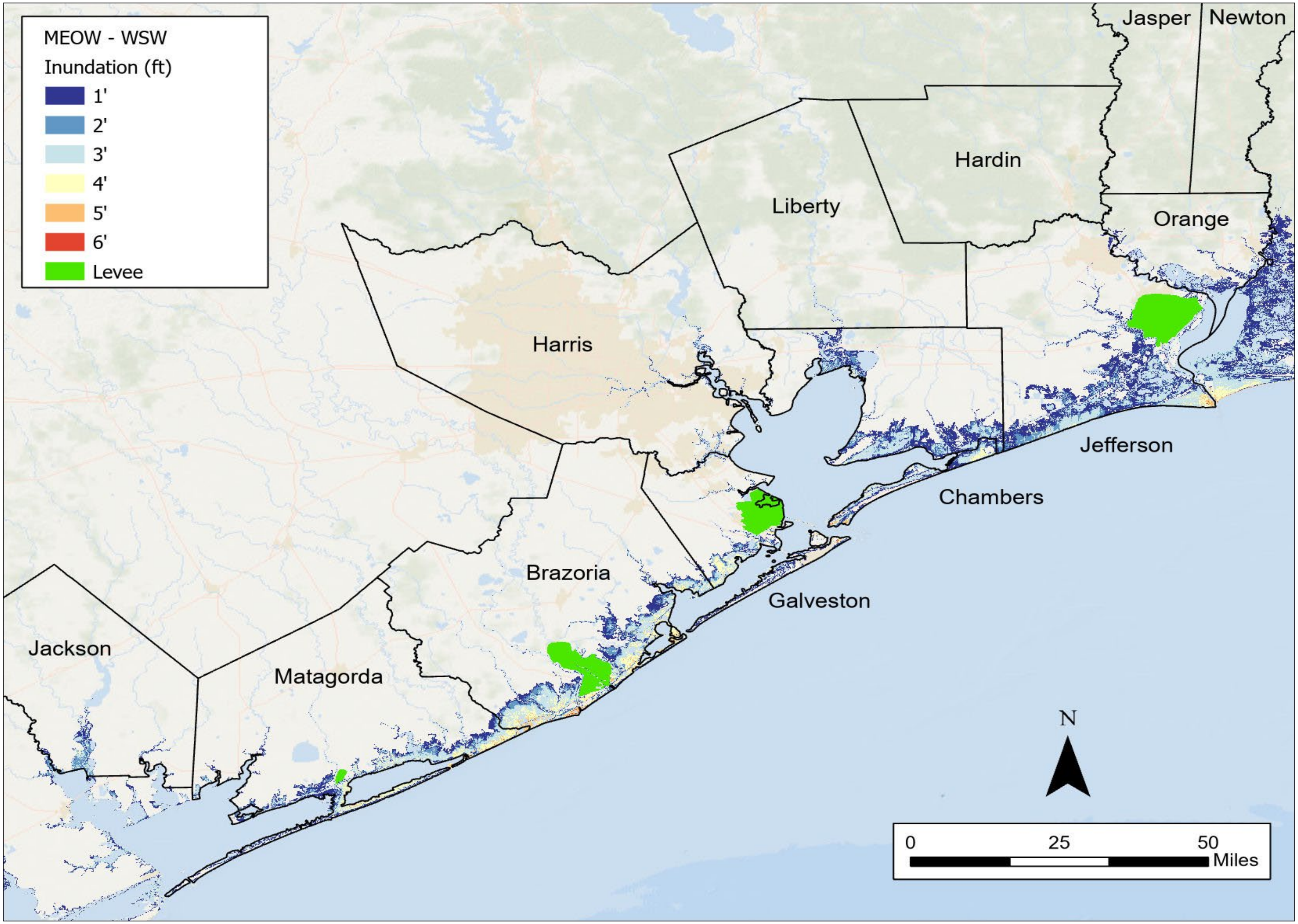
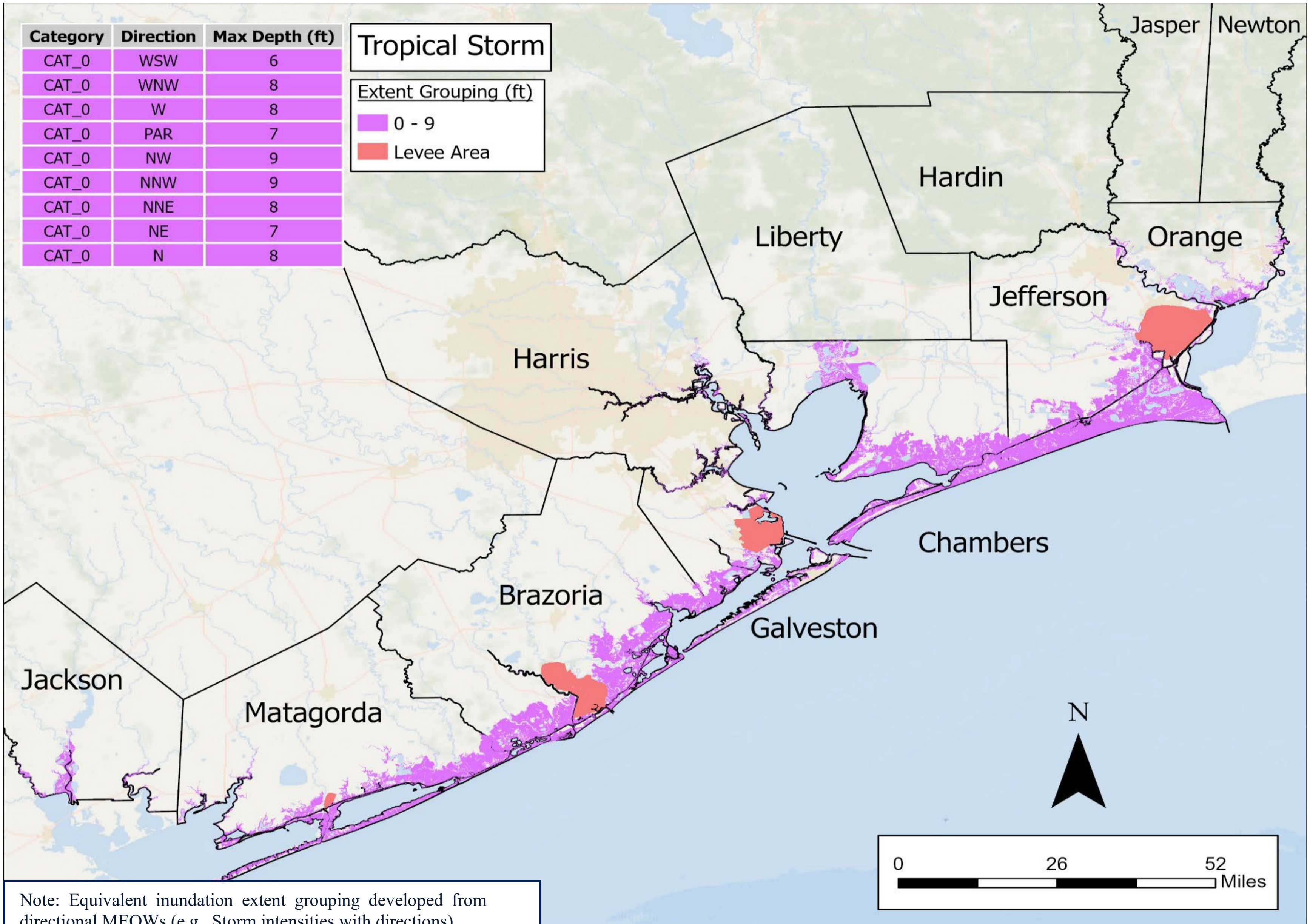


Figure 1-10 West Southwest Directional MEOW Map (Best Case Approach Direction – Lowest Maximum Inundation)



Note: Equivalent inundation extent grouping developed from directional MEOWs (e.g., Storm intensities with directions).

Figure 1-11 Equivalent Inundation Extent Map: Group TS

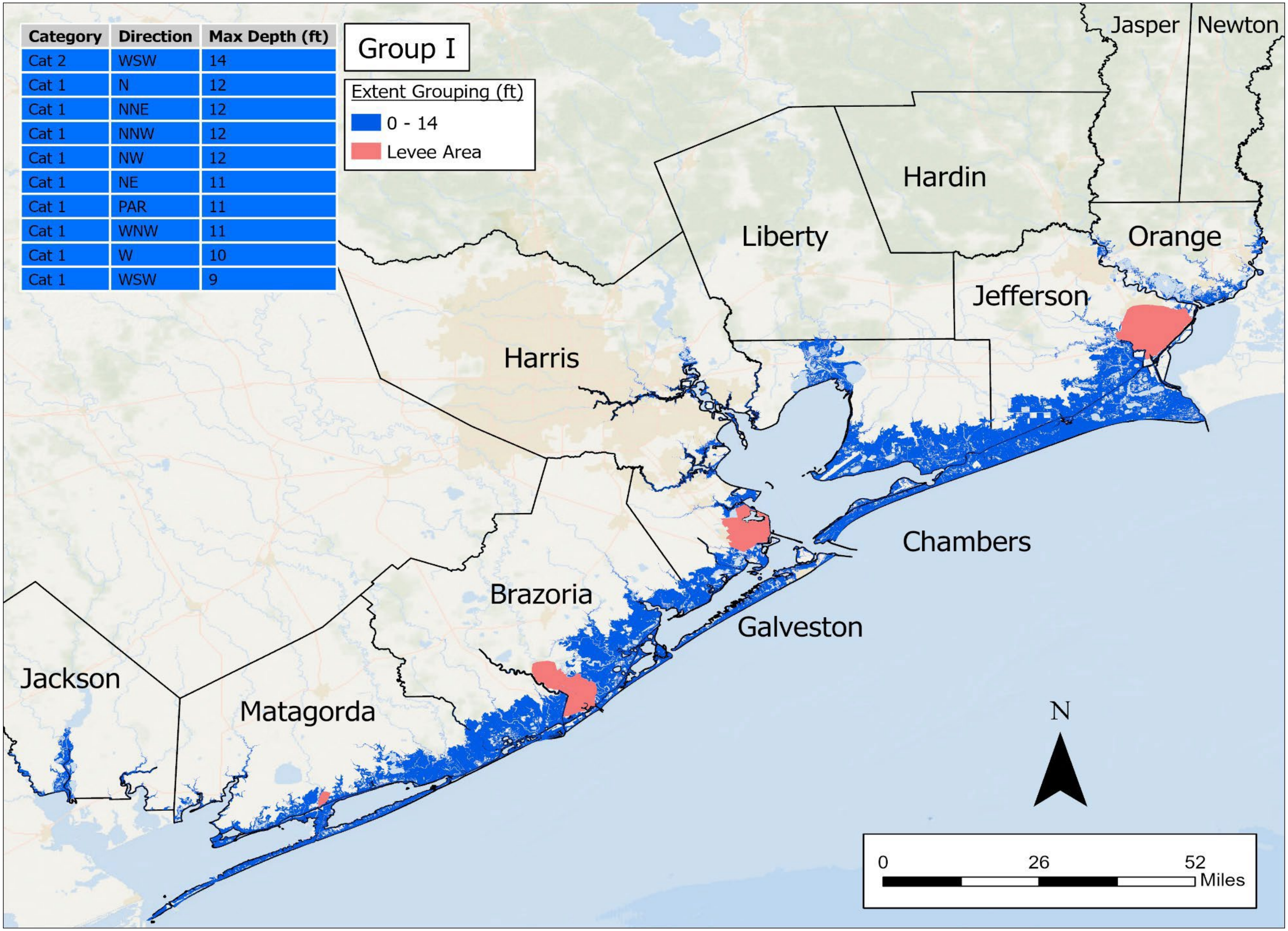


Figure 1-12 Equivalent Inundation Extent Map: Group II

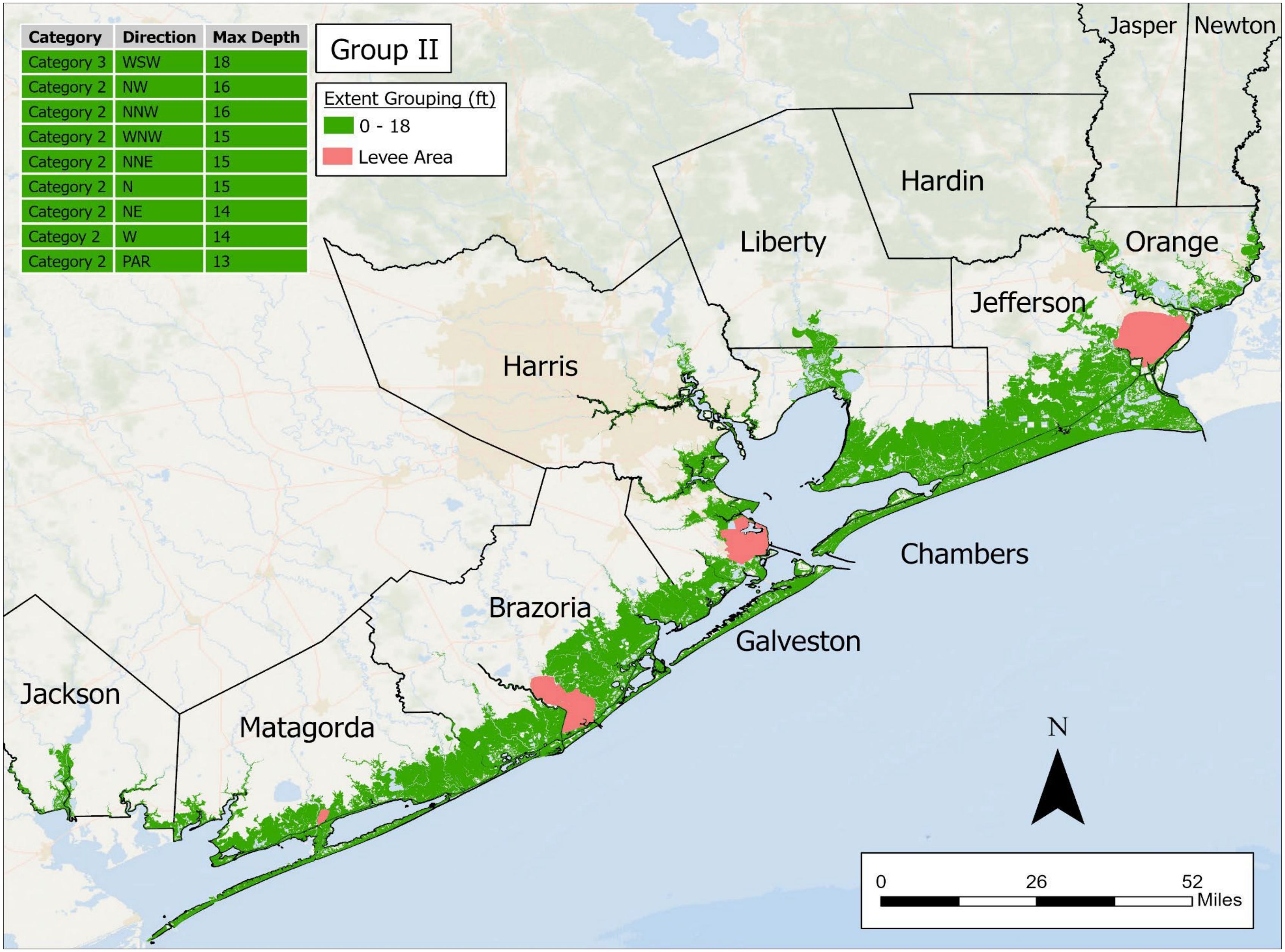


Figure 1-13 Equivalent Inundation Extent Map: Group II

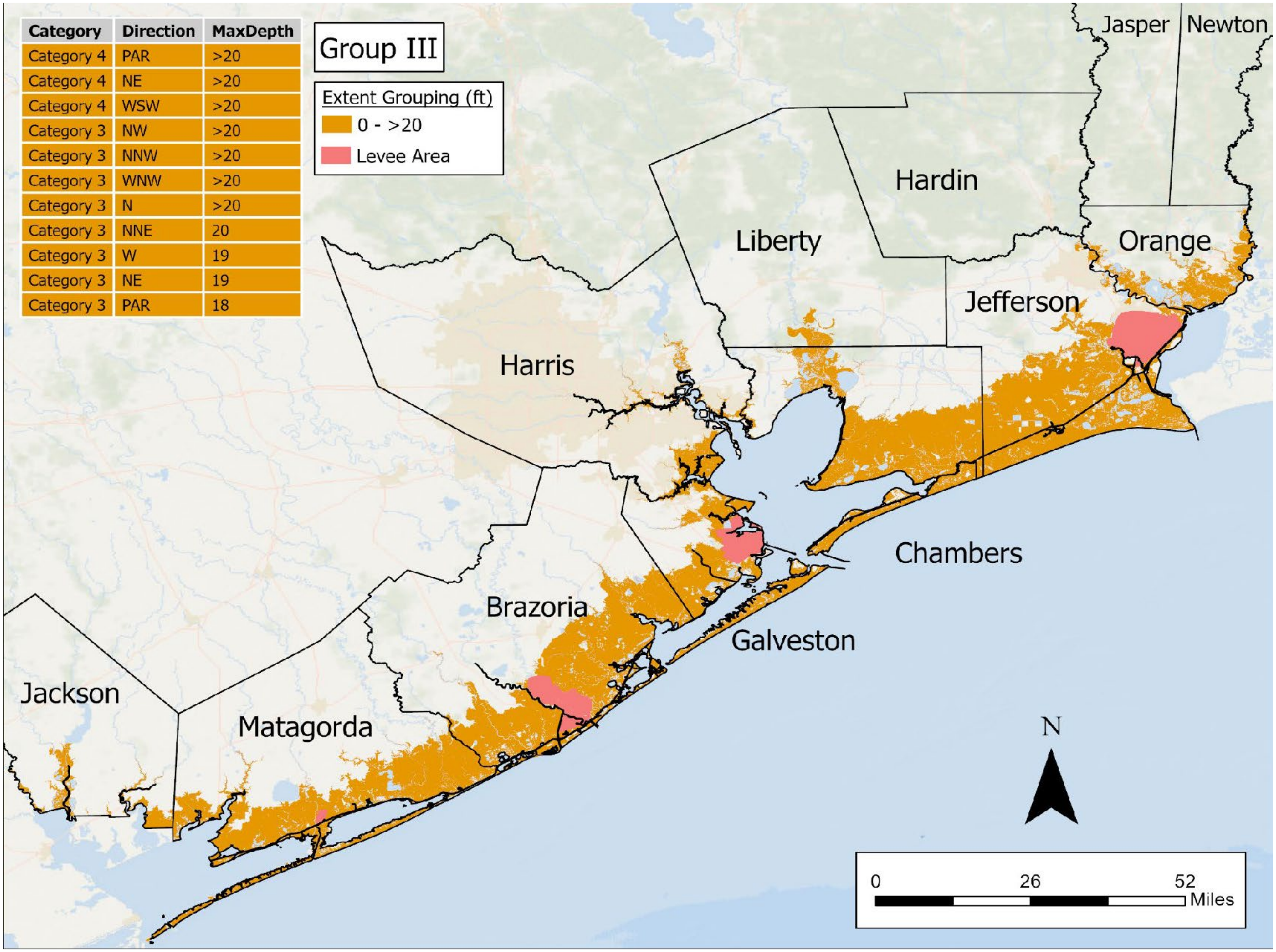


Figure 1-14 Equivalent Inundation Extent Map: Group III

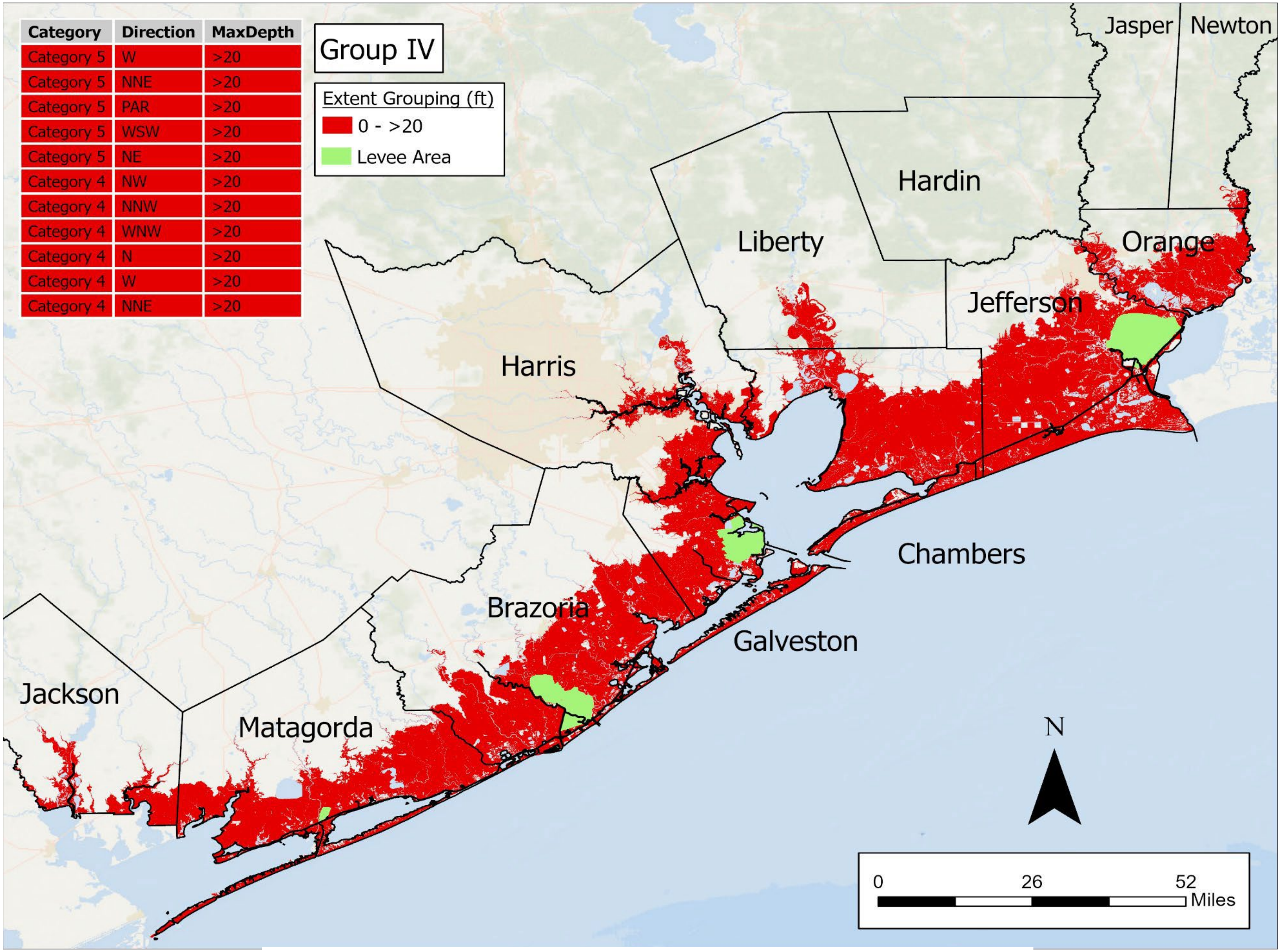


Figure 1-15 Equivalent Inundation Extent Map: Group IV

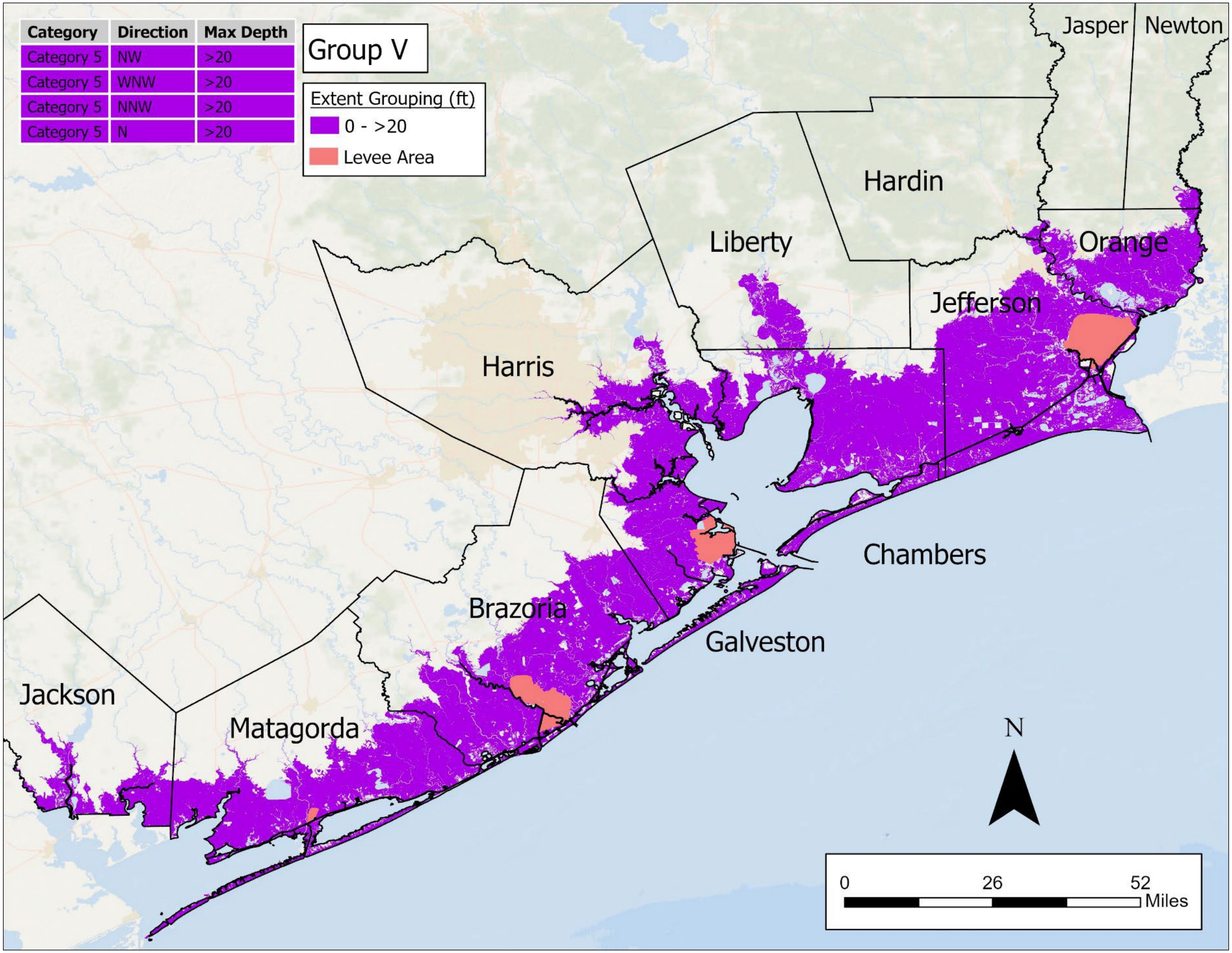


Figure 1-16 Equivalent Inundation Extent Map: Group V

The equivalent inundation extents for all groups are presented as a cumulative map in Figure 1-17, which show all the groups I through V in an overlapping fashion. For example, Group V is drawn underneath Groups I through IV so that the other groups can be seen. Modeled MEOWs inundation impacts extend far inland of the estuaries and tributaries of the Southeast Texas study area with more inundation anticipated along low-lying coastal areas due to topographical differences.

1.4.6 ADJUSTMENTS TO SLOSH MODEL VALUES / STATISICAL ANALYSIS

Hurricane evacuation decision-makers should keep in mind that the SLOSH model is a mathematical model and does not always produce perfect results, nor is it expected to. Based on the results of statistical analysis reviews and comparison of actual storm tides vs. SLOSH model results conducted by the NWS in past tropical cyclone storm events, an average variance of +/- 20 % has been observed. However, errors in wind input provided to SLOSH model may cause storm surge errors which are much larger than 20%. One limitation of the MEOWs that are simulated for theoretical storms is that they lack timing information of an actual storm which contains tidal water levels (highly dependent on time), abnormal water levels (e.g., sea level rise, disruptions of currents), and external wind fields. [9] However, the MEOWs used for hazard mapping are a conservative estimate to be used for planning purposes. Evacuation planners should remain cognizant of the potential for approximately 20 % over or underestimate of some predicted SLOSH surge values.

[9] Source: "Latest Developments in the NWS' Sea Lake and Overland Surges from Hurricanes Model," Arthur Taylor and Huiqing Liu, 1. NOAA/NWS/STI/Meteorological Development Laboratory, 2. Ace Info. Solutions, Inc., Presented at the 100th AMS Annual Meeting, Boston, MA, January 14, 2020.

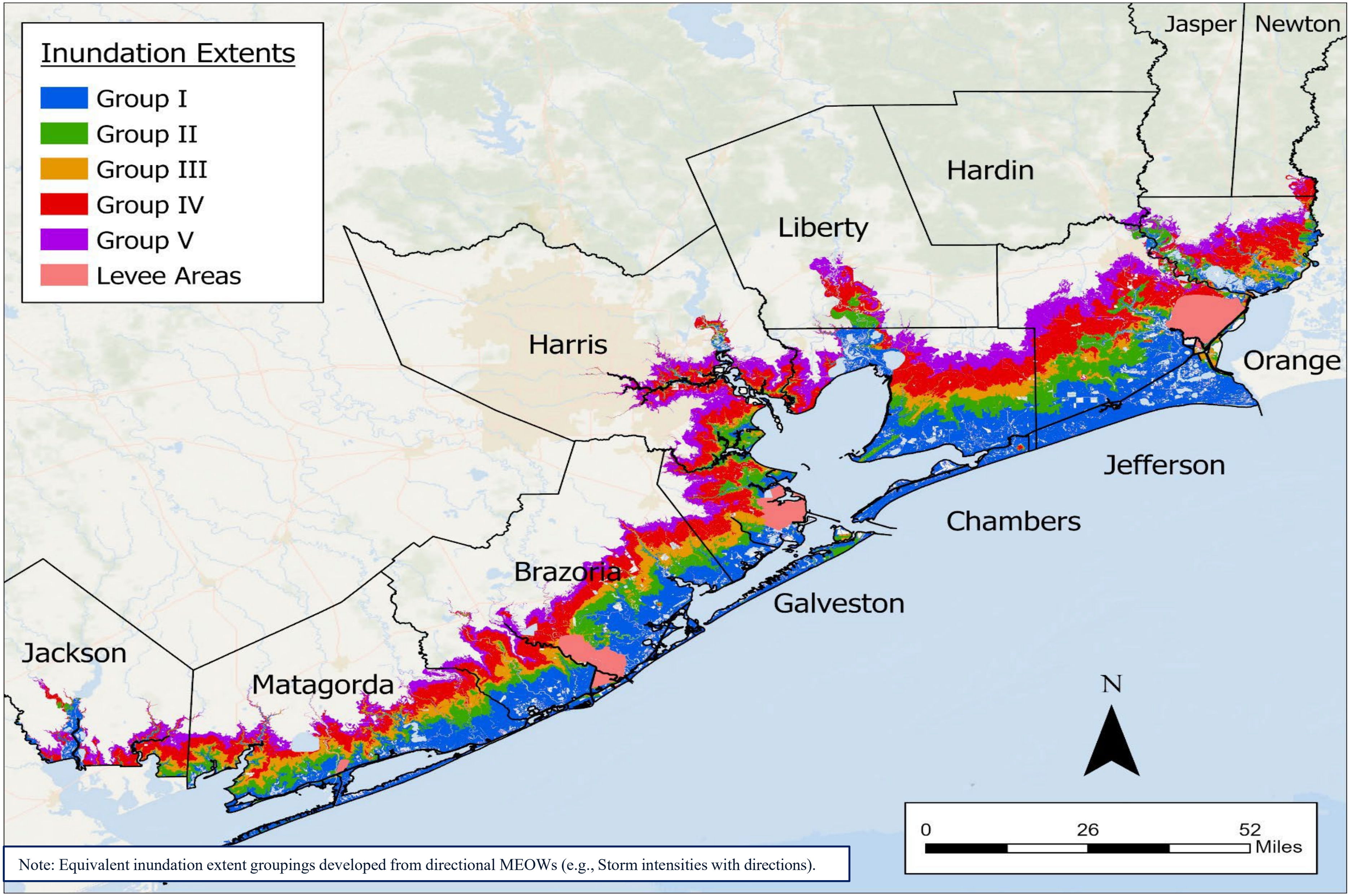


Figure 1-17 Southeast Texas Summary – Equivalent Inundation Extent Map: Groups I through V

1.4.7 POTENTIAL STORM SURGE FLOODING MAPS[10]

The NHC also uses the SLOSH models to depict the risk associated with coastal flooding from storm surge related to real tropical cyclones in real time. The Potential Storm Surge Flooding Map is based on probabilistic storm surge guidance developed by the NWS Meteorological Development Laboratory in cooperation with NHC, which is called Probabilistic Hurricane Storm Surge (P-Surge 2.8) [11] . The map shows a reasonable worst-case scenario of the flooding of normally dry land at particular locations due to storm surge. Storm surge values that have a 1-in-10 chance of being exceeded at each location are included in the Potential Storm Surge Flooding Map. Roadways are only included as a reference point on the map since flooding of roadways from fresh or salt water in a hurricane situation are not indicated.

On the Potential Storm Surge Flooding Map, it is possible to either choose potential storm surge flooding or the intertidal zone. Potential storm surge flooding is not depicted in the intertidal zone, that is the area that is above water at low tide and under water at high tide. The intertidal zone is displayed in a masked layer along with estuarine wetlands, or lands that are saturated with water either permanently or seasonally.

A storm surge watch / warning graphic is available with the Potential Storm Surge Flooding Map and highlights areas along the coast that have a significant risk of life-threatening storm inundation from a tropical storm or hurricane. Areas are displayed that would qualify for inclusion under a storm surge watch / warning by the NWS. More details can be found at https://www.nhc.noaa.gov/surge/warning/#:~:text=Storm%20Surge%20Warning%3A,%2C%20or%20post%2Dtropical%20cyclone.

The initial Potential Storm Surge Flooding Map is issued by the NHC with the first issuance of a hurricane watch or warning or in some cases a tropical storm watch or warning (anytime within 48 hours of the anticipated onset of tropical storm force winds). The issued map will change every six hours in association with every new NHC full advisory package. Due to the processing time required to produce the map, it is not available until approximately 60 to 90 minutes following the advisory release. When active, the mapping is available in HURREVAC and on the NHC website with an interactive viewer at: https://www.nhc.noaa.gov/surge/inundation/. An interactive example of the Potential Storm Surge Flooding Map is located at: https://www.nhc.noaa.gov/surge/inundation/interactive_example/

[10] Source: https://www.nhc.noaa.gov/surge/inundation/
[11] Source: https://slosh.nws.noaa.gov/psurge/

1.5 FRESHWATER FLOODING

1.5.1 BACKGROUND

In addition to the storm surge and high winds, tropical cyclones threaten the United States with torrential rains and flooding. Even after the wind and storm surge has diminished, the flooding potential of these storms remains for several days. Unfortunately, the SLOSH model, discussed in Section 1.4.1 of the Hazard Analysis, does not model rainfall, freshwater flooding, and normal river flow.

Approximately 25 % of deaths in U.S. from tropical cyclones from 1963 to 2012 occurred in inland counties, with more than half of deaths related to freshwater flooding.[12] From 1963 to 2012, 88% of fatalities from tropical cyclones were from either storm surge (49%), rainfall flooding (27%), high surf (6%), or occurred offshore within 50 nautical miles of the coast (6%).[13] Historically, over three-fourths (78%) of deaths among children in tropical cyclones were the result of drowning in freshwater floods.[14] In fact, more people are killed by floods than any other weather related cause. Most of these fatalities occur because people underestimate the power of moving water.

It is common to think the stronger and faster the storm the greater the potential for flooding. However, this is not always the case. A weak, slow moving tropical storms can cause more damage due to flooding than a more powerful fast moving tropical storm. This was evident with Hurricane Harvey in August 25-30, 2017 and Tropical Storm Imelda in September 16-19, 2019

Although Hurricane Harvey made landfall near Rockport, Texas as a Category 4 Hurricane on August 25, 2017, it weakened to a Tropical Storm within the following days as it stalled along the Southeast Texas coastline. As Harvey stalled over south and Southeast Texas for days, it produced catastrophic and deadly flash and river flooding. Southeast Texas bared the brunt of the heavy rainfall, with some areas receiving more than 40 inches of rain in less than 48 hours. Cedar Bayou in Houston received a storm total of 51.88 inches of rainfall which is a new North American record. Figure 1-18 shows a map of the radar derived rainfall estimates through September 1, 2017 associated with Hurricane Harvey.[15]

After making landfall near Freeport, Texas on September 17, 2019, Tropical Storm Imelda weakened to a Tropical Depression and stalled between Houston and Lufkin, Texas for 2 days. The surrounding area accumulated 30 to 44 inches of rainfall during the storm, with the greatest total of 44.29 inches recorded 2 miles south-southwest of Fannett, Texas. During the height of the flooding, numerous vehicles were either stuck or flooded on I-10 between Beaumont and Winnie for 2.5 days.[16]

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[12] Source: https://www.noaa.gov/stories/inland-flooding-hidden-danger-of-tropical-cyclones
[13] Source: https://weather.com/safety/hurricane/news/hurricanes-tropical-storms-us-deaths-surge-flooding
[14] Source: https://www.chicagotribune.com/sns-cane-inlandfloods-story.html
[15] Source: https://www.weather.gov/crp/hurricane_harvey
[16] Source: https://www.weather.gov/lch/2019Imelda.

Harvey Radar Derived Storm Total Rainfall

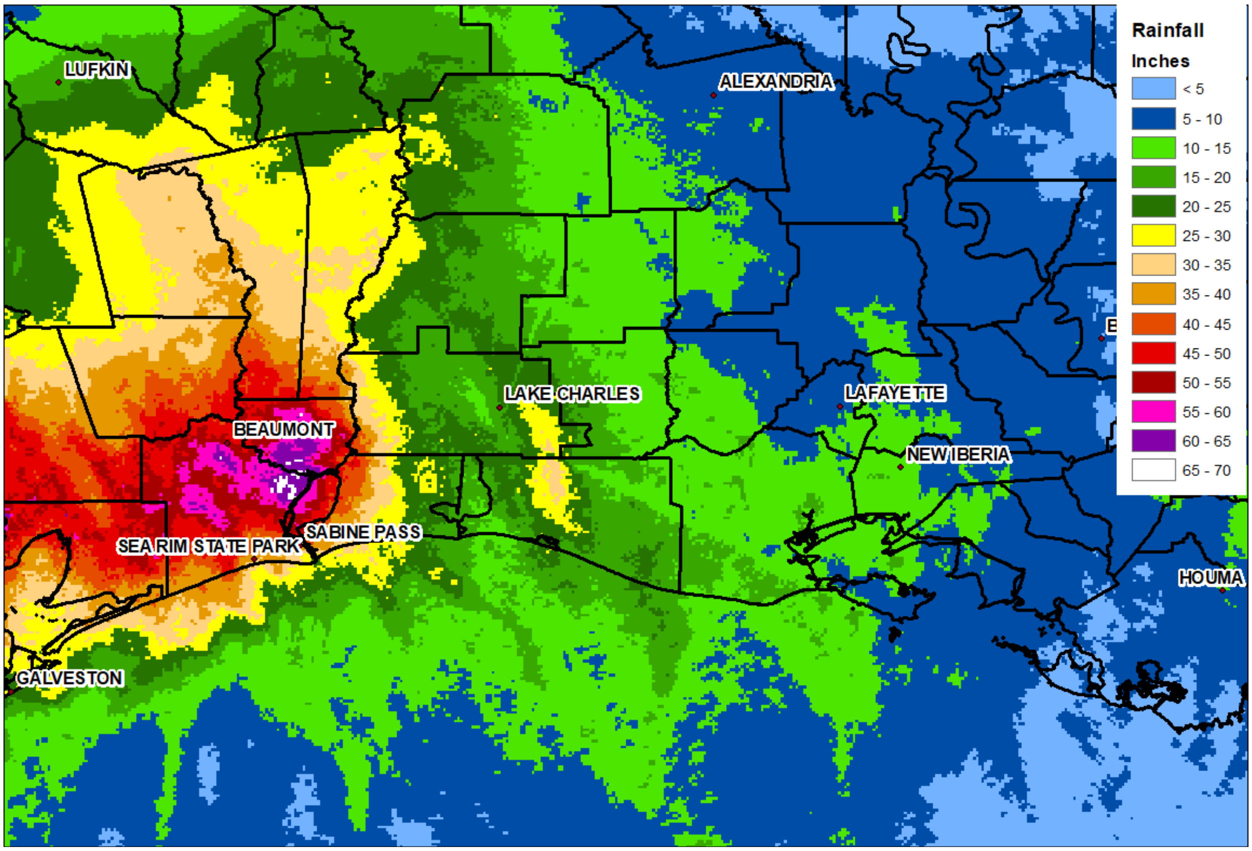

Figure 1-18 Raw NOAA Multi-radar multi-sensor quantitative precipitation estimation (inches) for Harvey in southeastern Texas from August 25-September 1, 2017[17]

1.5.2 FLASH FLOODING

Flash floods are rapid occurring events. This type of flood can begin within a few minutes or hours of excessive rainfall, but generally within 6 hours of the immediate cause. The rapidly rising water can potentially roll boulders, rip trees from the ground, and destroy buildings and bridges. Urban areas are especially prone to flash floods due to large amount of asphalt and concrete surfaces that are impervious, or do not easily allow water to penetrate into the soil.[18] Water that would have naturally infiltrated into the ground now runs into storm drains and sewers, which may be old and inadequate to handle floodwaters.

1.5.3 RIVER FLOODING

River floods occur when river levels rise and overflow their banks or edges of their main channel and inundate areas that are normally dry. They are longer term events and occur when the runoff from torrential rains, often brought on by decaying hurricanes or tropical storms, reach the rivers. A great deal of the excessive water in river floods may have begun as flash floods. River floods can occur in just a few hours and also last a week or longer. For designated river forecast points,

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[17] Source: https://www.weather.gov/lch/2017harvey
[18] Source: https://www.weather.gov/safety/flood-hazards

the NWS issues Flood Warnings where a flood stage has been established.[19] The NWS's Southeast River Forecast Center (RFC) provides hydrologic information to local NWS forecast offices which then issue the critical warning information to the emergency management community, public, and media.[20] The website for the Southeast River Forecast Center is located at: https://www.weather.gov/wgrfc//.

The National Weather Service Advanced Hydrologic Prediction Service (AFPS) is a web-based tool available for river stage forecasts out through several days. The NWS AFPS website associated with the NOAA Mobile, Alabama forecast office is located at: https://water.weather.gov/ahps2/index.php?wfo=mob .

Amounts and arrival times of rainfall associated with hurricanes are highly unpredictable. For most hurricanes, the heaviest rainfall begins near the time of arrival of sustained tropical storm winds; however, heavy rains in amounts exceeding 20 inches can precede an approaching hurricane by as much as 24 hours. Unrelated weather systems can also contribute significant rainfall amounts within a basin in advance of a hurricane.

No detailed modeling and analysis were conducted to quantify the effects of rainfall from hurricanes in this study. However, it should be assumed that locations and facilities which have historically flooded during periods of heavy rainfall are vulnerable to freshwater flooding from hurricane conditions. Additionally, other factors such as increased development and changes in land use, especially in urban areas, can also cause flooding in areas which have not historically been susceptible to excessive runoff or freshwater inundation.

1.5.4 FEMA FLOOD INSURANCE STUDY FLOOD INSURANCE RATE MAPS

Useful products of the FEMA Flood Insurance Study (FIS) are Flood Insurance Rate Maps (FIRMs) which are a mapping source that identify flood hazard areas. These products are produced to determine general overall risks to property and used by development officials and insurance professionals. These products are not intended to predict effects of different types of tropical cyclone events but are useful to hurricane evacuation studies in defining areas of inland flooding that may impact evacuation planning decisions and recovery staging.

FEMA FIS include separate analyses for coastal and riverine areas. In some areas, coastal analyses include complex localized model calculations for wave hindcasting, wave setup, storm surge, effects of dunes, overland and wave propagation, wave runup for wave setup, beach erosion, and wave heights. Riverine and stream analyses consider flooding from rainfall runoff. The statuses of the FIS studies for this project are provided in Table 1-5 below. Data is available in PDF and GIS formats on the following FEMA website: https://msc.fema.gov/portal/advanceSearch#searchresultsanchor.

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[19] Source: https://www.weather.gov/safety/flood-hazards

[20] Source: https://www.noaa.gov/stories/inland-flooding-hidden-danger-of-tropical-cyclones

Table 1-5 Status of FEMA Flood Insurance Study and FIRM Products

County	Effective Date	Preliminary/Pending
Brazoria, Texas	01/06/2017, 05/02/2019, 11/15/2019, 12/30/2020, 01/29/2021	
Chambers, Texas	06/15/1983, 12/02/1992, 05/18/1999, 05/04/2015, 01/06/2017, 01/19/2018, 11/15/2019	
Galveston, Texas	01/06/2017, 05/02/2019, 08/15/2019, 11/15/2019	
Hardin, Texas	10/06/2010	
Harris, Texas	08/18/2014, 01/06/2017, 01/19/2018 05/16/2019, 08/15/2019, 11/15/2019, 12/30/2020, 01/29/2021	
Jackson, Texas	9/17/2014	
Jasper, Texas	12/17/2010	
Jefferson, Texas	07/06/1982, 08/02/1982, 10/17/1983, 09/04/1987, 08/06/2002	08/30/2012 (1 FIRM Panel)
Liberty, Texas	01/19/2018	
Matagorda, Texas	01/15/2021	
Newton, Texas	11/16/2018	
Orange, Texas	12/16/2021	

FIRMs are produced from FIS and are the official map of a community on which FEMA has delineated both the Special Flood Hazard Areas (SFHAs) subject to inundation by the 1% annual chance flood and the risk premium flood zones applicable to the community. FIRMs are based on statistical occurrence rather than a hypothetical storm. On the FIRM, SFHAs are shown as shaded areas and are divided into different flood hazard zones depending upon the severity and type of flood hazard.

Flood hazard areas identified on FIRMs are based on two levels of probability of flooding events: flooding that has a 1% probability of being equaled or exceeded in any given year (e.g., 1% annual chance flood or 100-year flood) and flooding that has a 0.2% probability of being equaled or exceeded in any given year (e.g., 0.2% annual chance flood or 500-year flood). Digital FIRM data is shown for Southeast Texas in Figure 1-19. Note, the method for mapping floodways causes floodplains to be mapped over portions of freshwater and open water. There is also a lack of data within Jefferson County, which shows it as if it was without flooding, when it would experience similar flooding as its neighboring counties. A floodway is the channel of a stream plus any adjacent floodplain areas that must be kept free of encroachment so that the 1% annual chance flood can be carried without substantial increases in flood heights. The floodways are included in the 1% annual chance flood. Although the recurrence interval represents the long term, average period between floods of a specific magnitude, rare floods could occur at short intervals or even within the same year.

As shown in Figure 1-20, when the summary of equivalent surge inundation groups are plotted with the FEMA floodplain map, it is clear that the 1% annual chance flood coincides closely with the inundation extents for directional MEOWs. However, the floodways are not always included as experiencing surge.

The 1% and 0.2% annual change flood plains from the latest FEMA Floodplain maps for Southeast Texas are shown along with the Category 5 MOM inundation in Figure 1-21. The extent of MOMs and FEMA floodplains coincide closely.

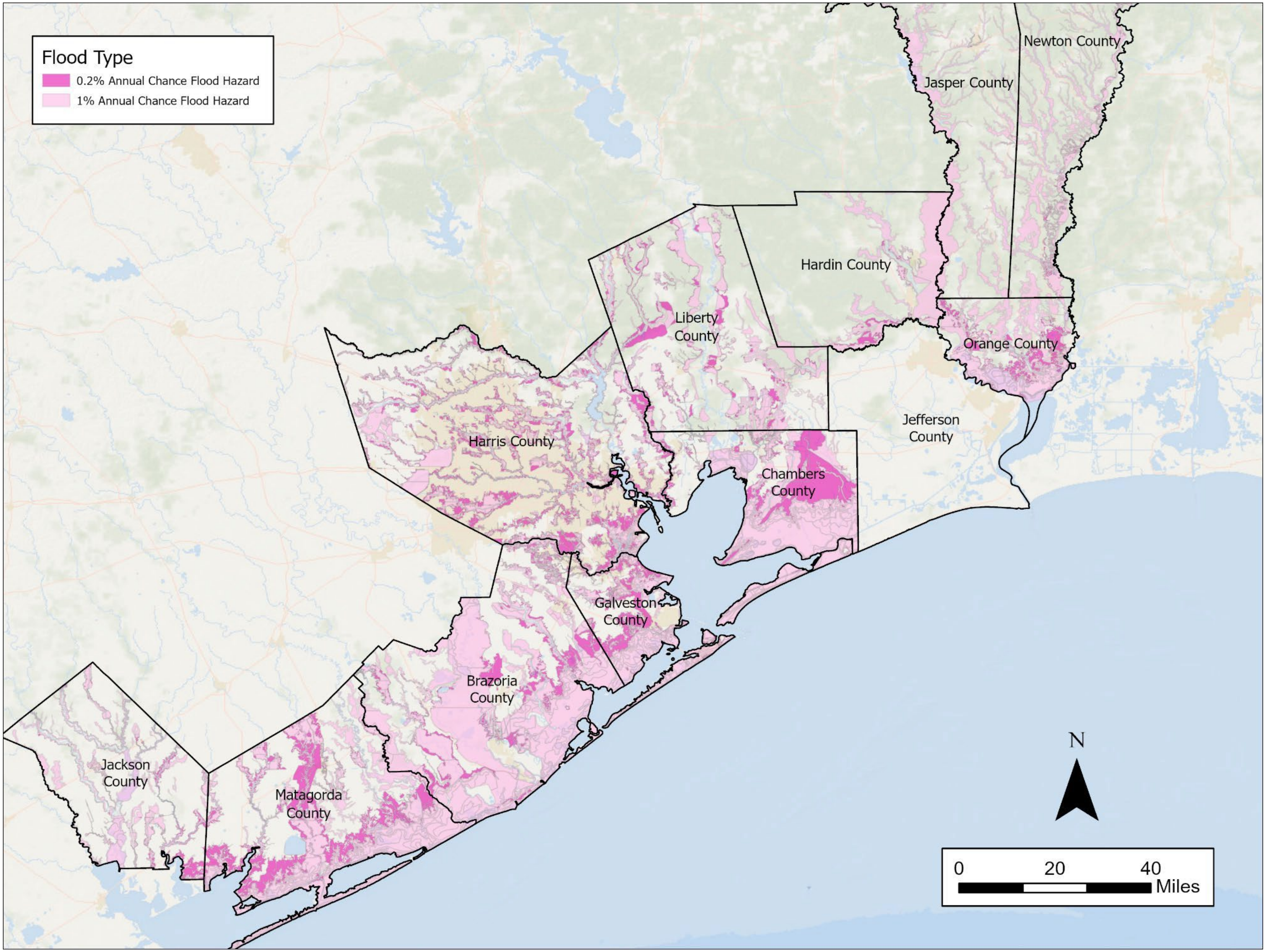
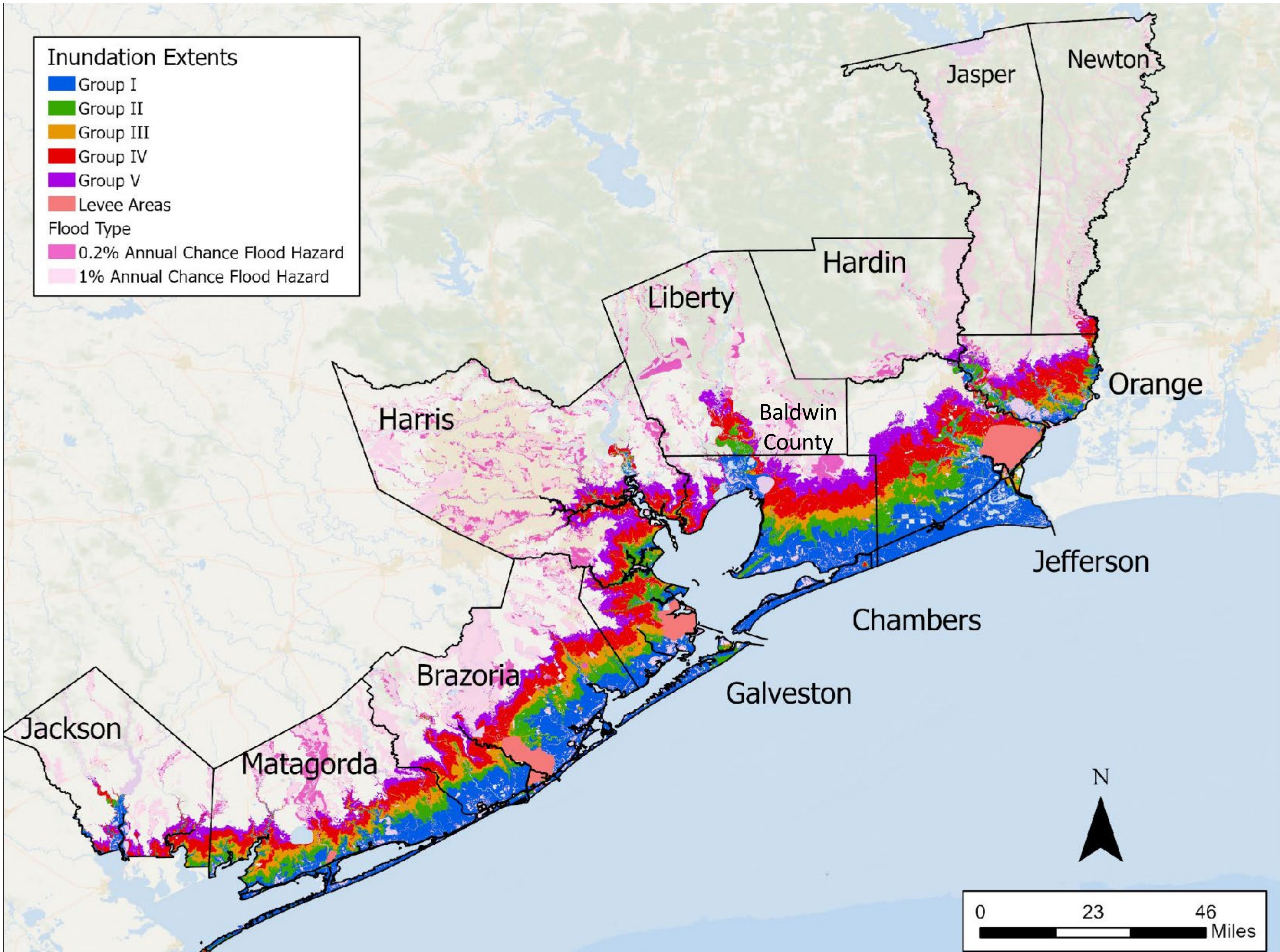


Figure 1-19 FEMA FIRM Floodplains for 1% and 0.2% Annual Probability Flooding



Note: Equivalent inundation extent groupings developed from directional MEOWs (e.g., storm intensities with directions).

Figure 1-20 Southeast Texas Summary – Equivalent Inundation Extent Map (Groups I through V) with FEMA FIRM Floodplain

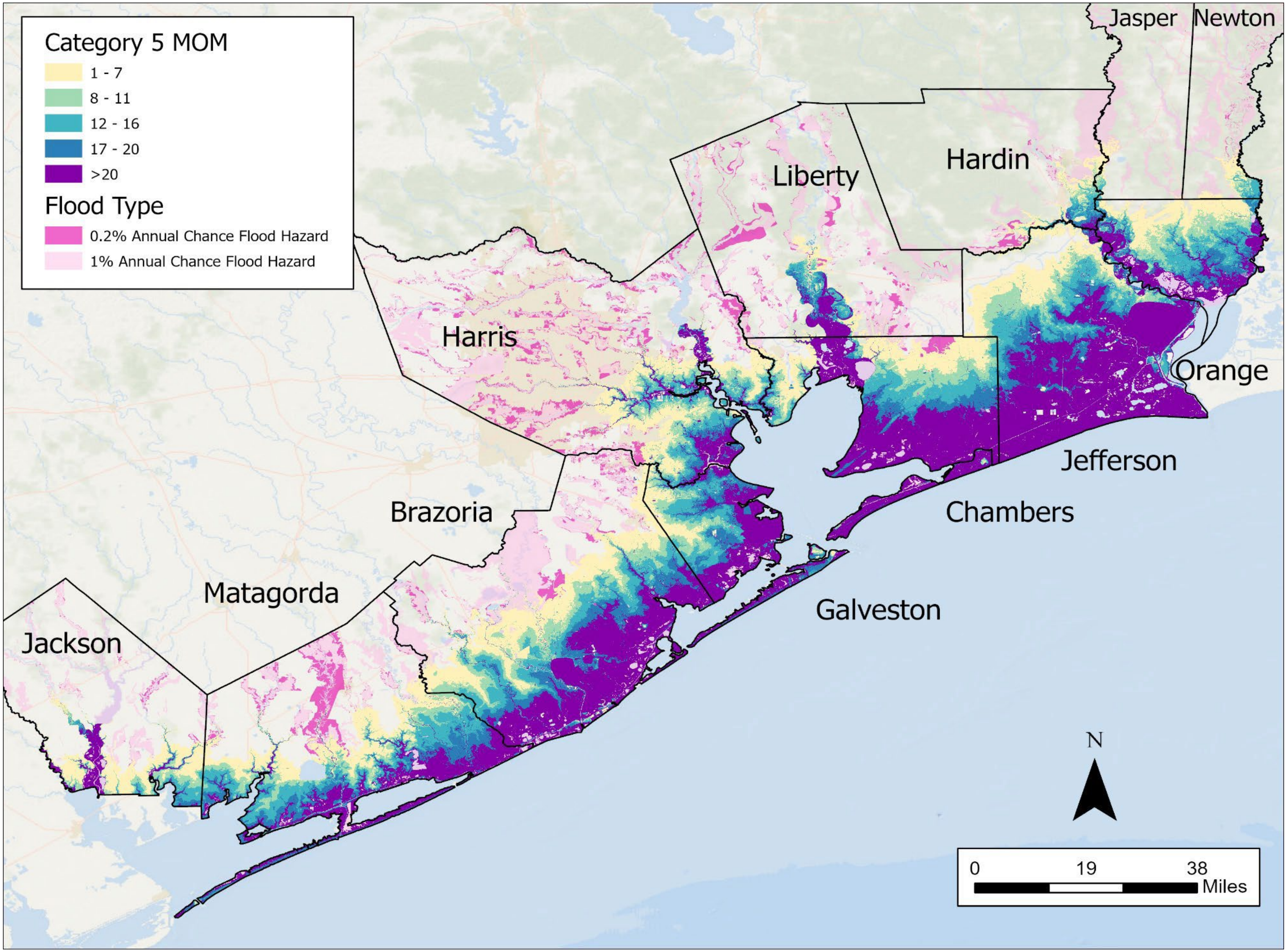


Figure 1-21 Category 5 MOM Map for all Southeast Texas Study Area Counties with Inundation Groupings with FEMA FIRM Floodplains

The rainfall depths for FEMA FIS modeling were based on 24-hour point precipitation frequency estimates from NOAA at https://hdsc.nws.noaa.gov/hdsc/pfds/. A summary of Partial Duration Series point precipitation frequency estimates for a 24-hour 1% annual chance storm and a 24-hour 0.2% annual chance storm at NOAA stations in Harris and Orange Counties is included in Table 1-6 below. These are provided for perspective as to the quantity of rainfall that is associated with the modeled 24-hour 1% annual chance and 24-hour 0.2% annual chance flood plains.

Table 1-6 PDS Based Precipitation Frequency Estimates with 90% Confidence Intervals[1]

NOAA Station Name	Location	24-hr. 1% Annual Chance Storm (inches)	24-hr. 0.2% Annual Chance Storm (inches)
Harris COUNTY			
Clear CK at Bay Area Blvd	League City, TX	17.9 (12.6-25.5)	26.9 (17.7-40.7)
Goose Creek	Baytown, TX	18.1 (12.7-25.7)	27.5 (18.1-41.8)
Houston WB City	Houston, TX	17.0 (12.0-23.9)	25.5 (16.8-38.2)
Cypress CK at Kuykendahl Rd	Houston, TX	16.7 (11.8-23.9)	24.9 (16.4-37.7)
Katy City	Katy, TX	16.0 (11.2-22.7)	23.4 (15.4-35.4)
Armand BYU at Genoared BLF RD	Pasadena, TX	17.9 (12.6-25.6)	26.9 (17.7-40.8)
Houston ALIEF	Houston, TX	16.5 (11.6-23.5)	24.3 (16.0-36.9)
Houston Hobby AP	Houston, TX	17.6 (12.4-25.0)	26.4 (17.4-40.1)
Orange COUNTY			
Orange	Orange, TX	17.1 (12.1-23.9)	25.1 (16.6-37.3)
Orange 9 N	Orange, TX	17.1 (12.0-24.1)	25.3 (16.7-37.8)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of (PDS). Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

The coastal analysis for FEMA FIS includes complex model calculations for wave hindcasting, wave setup, storm surge, effects of dunes, overland and wave propagation, wave runup for wave setup, beach erosion, and wave heights. On the FIRM maps, the 1% annual chance flood plain (e.g., 100-year flood plain) is split into flood hazard zones AE, VE, and VO with the following descriptions:

- Zones V are closest to the shoreline and subject to wave action, high velocity flow, and erosion during the 1% annual chance flood.
- Zones A are areas subject to flooding during the 1% annual chance flood, but where flood conditions are less severe than those in V zones.
- VE and AE zones have Base Flood Elevations (BFE), which are used for new construction, shown at selected intervals which is the expected elevation of flood water and wave effects during the 1% annual chance flood. Usually these are whole foot elevations derived from detailed hydraulic modeling.
- Zones AO are areas subject to shallow flooding or sheet flow during the 1% annual chance flood. They are likely on the landward slopes of coastal dunes.

Coastal hydrologic analyses modeled individual storms with different tracks and various combinations of storm parameters for synthetic hurricane simulations. Coastal high hazard zones are areas of coastline subject to significant wave attack. A 3 foot breaking wave is the criterion established by United States Army Corps of Engineers (USACE) for identifying the limit of coastal high hazard zones since it has been determined as the minimum size wave that can cause major damage to conventional brick veneer and wood frame structures. However, wave heights as little as 1.5 feet can cause damage and failure to construction in a Zone AE area. Therefore, for advisory purposes a limit of Moderate Wave Action (LiMWA) boundary, which represents the approximate landward limit of the 1.5 foot breaking wave, has been added in coastal areas subject to wave action. Where wave runup elevations dominate, the LiMWA is shown immediately landward of the VE/AE boundary. [21]

Figure 1-22 from the latest Southeast Texas Study Area county FIS reports shows what a typical transect (or cross-section for modeling) schematic and the relationship to energy dissipation or regeneration of waves as they move inland. Wave crest elevations are decreased by obstructions such as vegetation, buildings, and rising ground elevations, but wave crest elevations are increased by open, unobstructed areas with large wind fetches. The transects used for modeling were located to consider physical and cultural characteristics of the land so that they represent local conditions. In areas of dense development and complex topography, the transects were spaced closer together.

[21] Source: Flood Insurance Study Orange County, Texas, Federal Emergency Management Agency, Revised December 16, 2021 (Flood Insurance Study Number 48361CV001A).

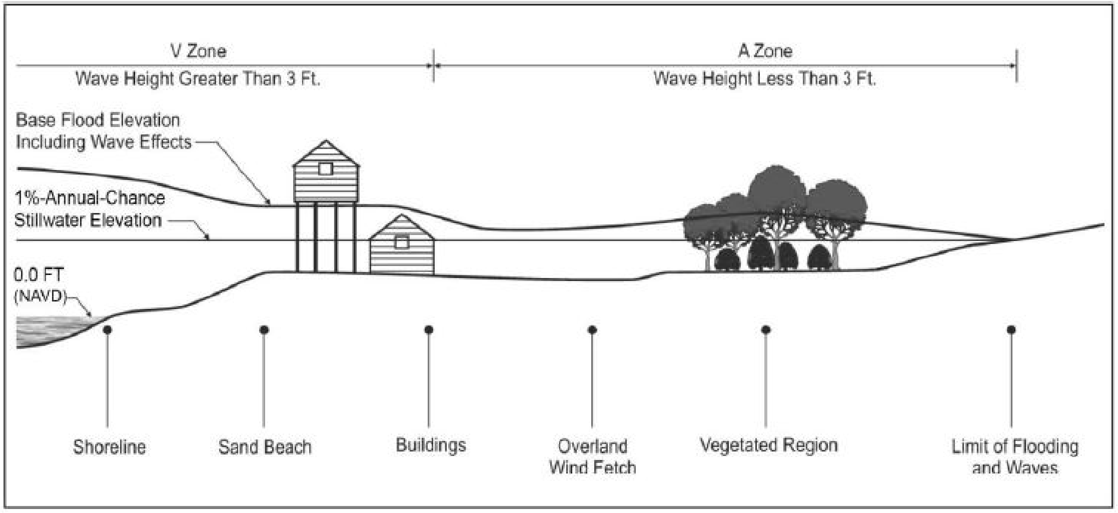


Figure 1-22 FEMA FIRM Example Transect Schematic for Coastal Hydraulic Modeling[22]

1.6 WINDS

Extreme winds can be a life-threatening feature of tropical cyclones. To some degree, all structures exposed to hurricane-force winds are vulnerable to wind-related hazards (see Table 1-17). This is especially true of intense storms, generally considered Category 3 and greater hurricanes. However, high-rise buildings merit special consideration. Wind pressures on upper portions of tall structures can be much greater than those at ground level. These pressures can cause significant problems during even a moderate hurricane. Within the transportation network, high-rise bridges are particularly vulnerable to the hazards of extreme winds and could experience wind-related structural problems. Several major high-rise bridges in the study area have been closed during past storms after gale-force winds caused high profile vehicles to overturn.

Destructive hurricane force winds and tornadoes can also affect many inland counties. NOAA's Hurricane Research Division has developed a model, the Wind Speed Decay Model, for predicting inland winds associated with landfalling hurricanes. The model accounts for wind speed decay as hurricanes move over land from water. The decay process is due to the interaction with land, where terrain roughness provides the friction needed to slow the wind, and the storm is cut off from the heat and moisture sources that sustain it. Wind gusts, rather than sustained speed, may actually increase because the greater turbulence over land mixes faster air to the surface in short bursts. Studies have shown that the sustained winds in a hurricane will decrease at a relatively constant rate, approximately half the wind speed in the first 24 hours. Therefore, the faster the forward speed of a landfalling hurricane, the further the inland penetration of hurricane force winds.

The model applies a decay equation to the hurricane wind field at landfall to estimate the maximum sustained surface wind as a storm moves inland. This model can be used for operational forecasting of the maximum winds of landfalling tropical cyclones. It can also be used

[22] Source: Flood Insurance Study Orange County, Texas, Federal Emergency Management Agency, Revised December 16, 2021 (Flood Insurance Study Number 48361CV001A).

to estimate the maximum inland penetration of hurricane force winds (or any wind threshold) for a given initial storm intensity and forward storm motion.

NOAA provided 2021 Wind Speed Decay Modeling results of MEOWs as geodatabase polygons based on the Saffir-Simpson Hurricane Wind Scale. They depict the estimated most inland wind extents for sustained wind speeds for representative tropical cyclones making landfall from the Gulf of America. Wind Extent Maps (WEMs) have been produced from directional MEOWs that were developed for 5 forward speeds (8, 12, 16, 20, and 24 knots) and sustained storm intensity wind speed of 60 knots (Tropical Storm), 75 knots (Category 1), 90 knots (Category 2), 105 knots (Category 3), 120 knots (Category 4), 135 knots (Category 4), and 140 knots (Category 5). Table 1-6 is provided as a reference of wind speeds in knots and mph for the different category storms.

Table 1-7 Wind Speeds for Category Storms in knots and mph

Category Storm	Wind Speed (knots)	Wind Speed (mph)
Tropical Storm	34 – 63	39 - 73
Category 1	64 - 82	74 – 95
Category 2	83 - 95	96 – 110
Category 3	96 - 112	111 – 129
Category 4	113 - 136	130 – 156
Category 5	137 +	157 +

Figure 1-233 depicts the extents of minimum tropical storm strength winds (34 knots) from the NOAA Wind Speed Decay Model for a Tropical Storm having 60 knots sustained winds with forward speeds ranging from 8 to 24 knots. It is evident that the forward speed of a tropical cyclone has great influence on how far inland the maximum sustained winds extend. Figure 1-24 depicts the modeled wind extents for a Tropical Storm having 60 knots sustained winds with the worst case forward speed of 24 knots. Note, tropical storm force winds extend inland and well beyond the study area counties for this modeled case.

Figure 1-25, Figure 1-26and Figure 1-27 depict the wind extents for a Category 4 storm having 135 knots sustained winds with forward speeds of 8, 16, and 24 knots respectively. The comparison of the three figures shows that increasing forward speed of a tropical cyclone causes higher wind speeds to extend further inland, thus increasing the area that is affected by higher sustained winds. Appendix D includes maps for storms with sustained winds of 74 knots (Category 1), 90 knots (Category 2), 105 knots (Category 3), 120 knots (Category 4), and 140 knots (Category 5) with forward speeds of 24 knots. All of the Wind Extent Maps are included in the GIS database included in the online ArcGIS Mapping Portal associated with this Hazard Analysis.

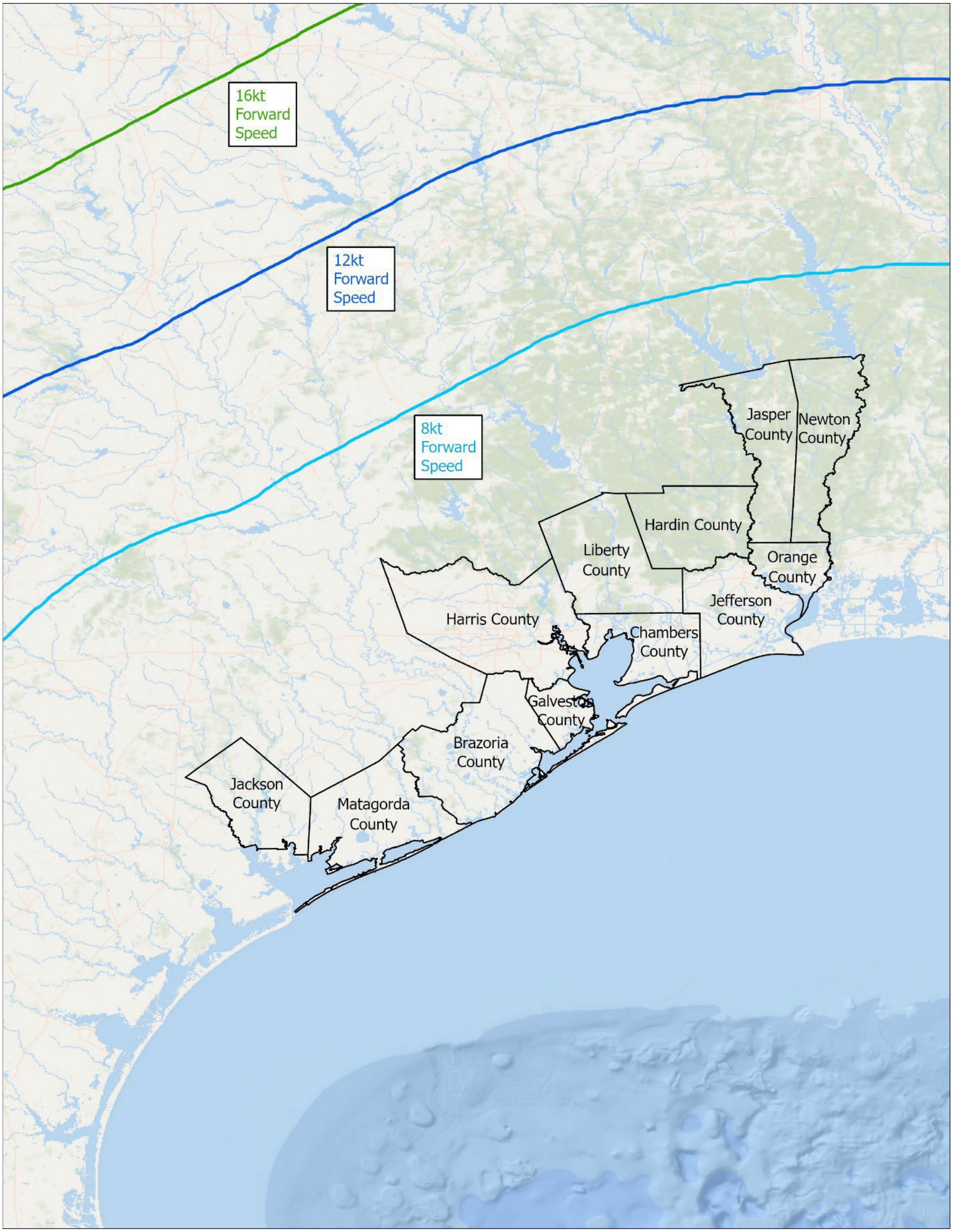


Figure 1-23 Wind Extent Map for Tropical Storm Strength Winds (34 kt) for Tropical Storm (60 kt) with 8 to 24 kt Forward Speed (Line Map)

Figure 1-24 Wind Extent Map for Tropical Storm (60 kt) with 24 kt Forward Speed (Shaded Map)

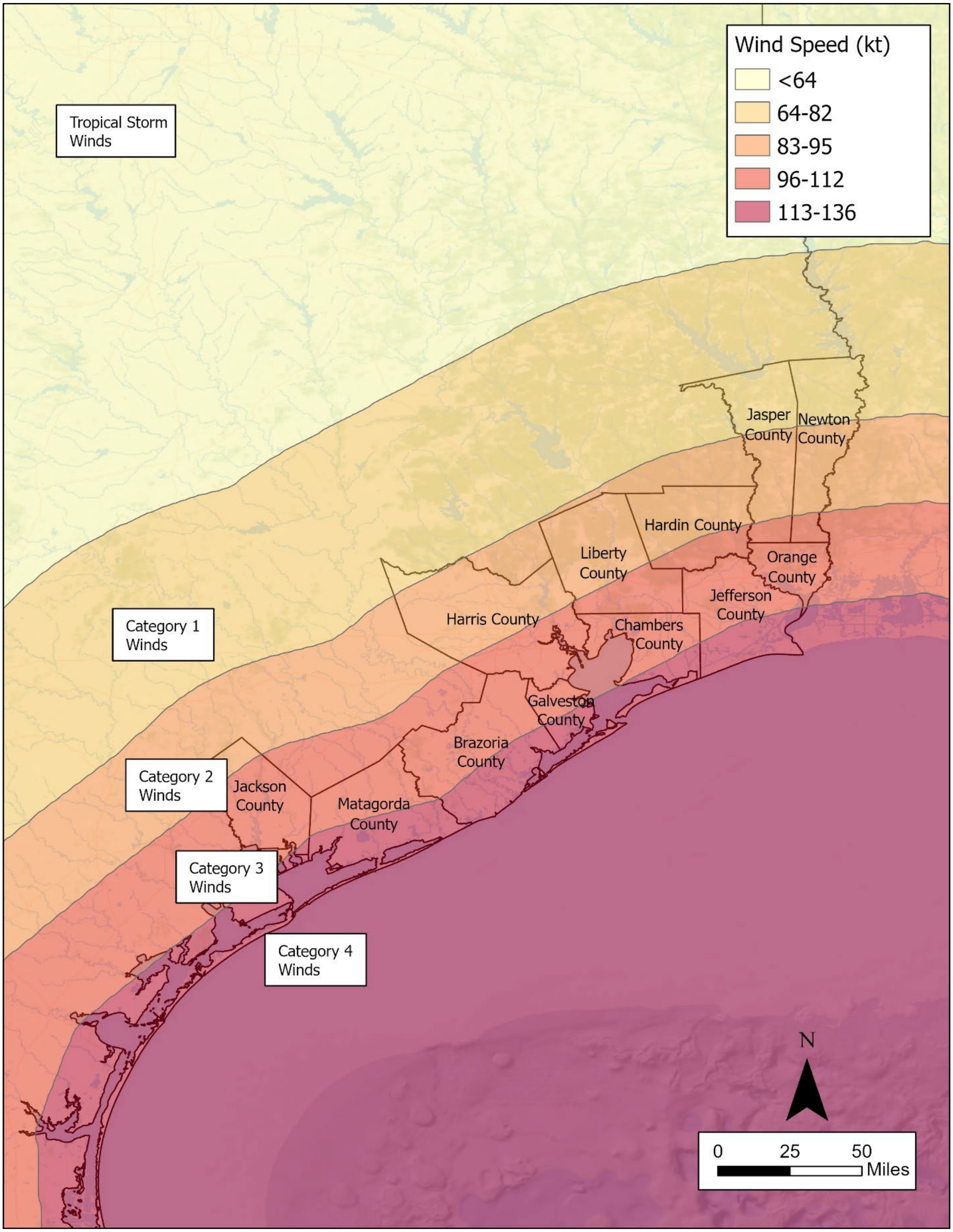


Figure 1-2510 Wind Extent Map for Category 4 Storm (135 kt) with 8 kt Forward Speed (Shaded Map)

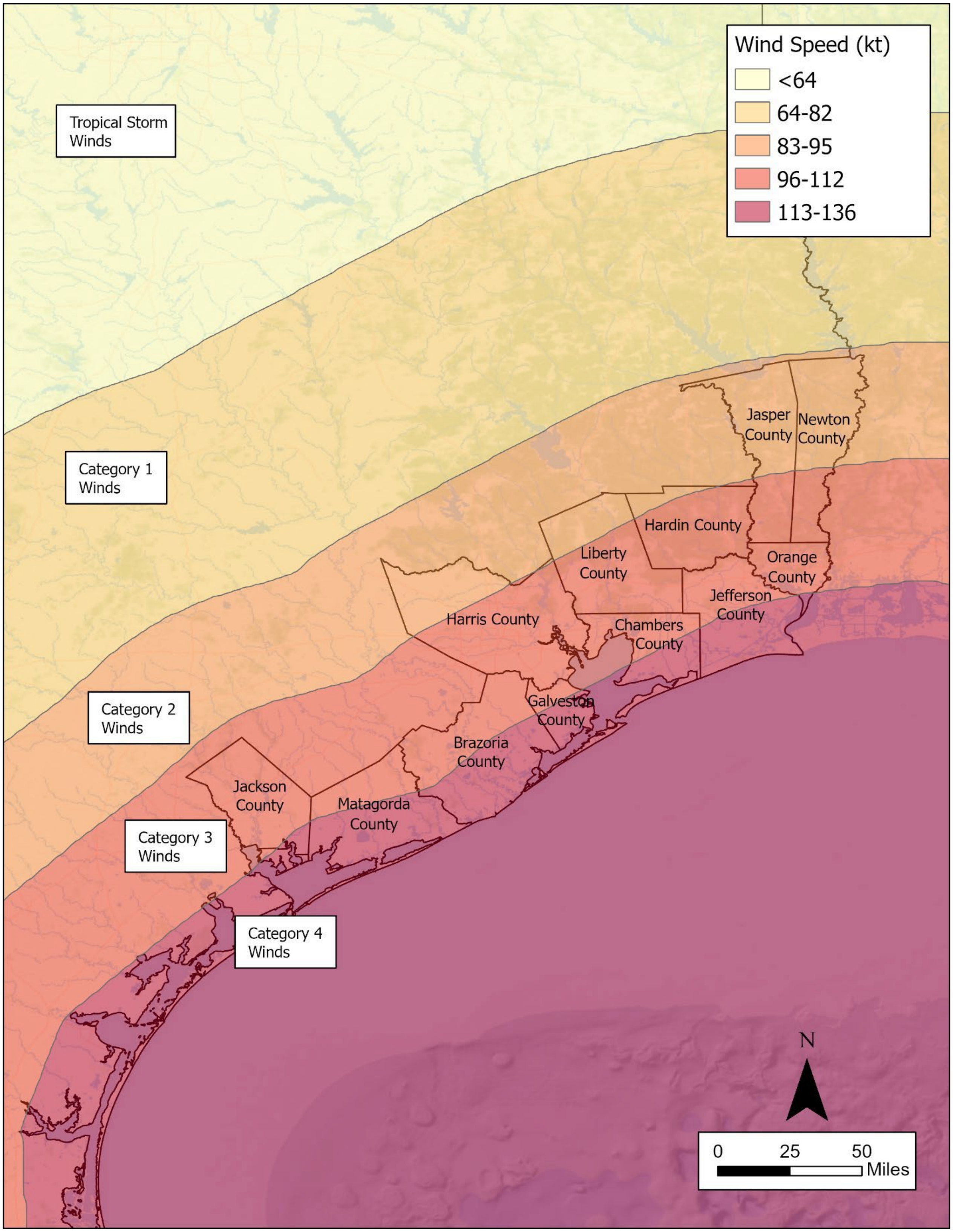


Figure 1-26 Wind Extent Map for Category 4 Storm (135 kt) with 16 kt Forward Speed (Shaded Map)

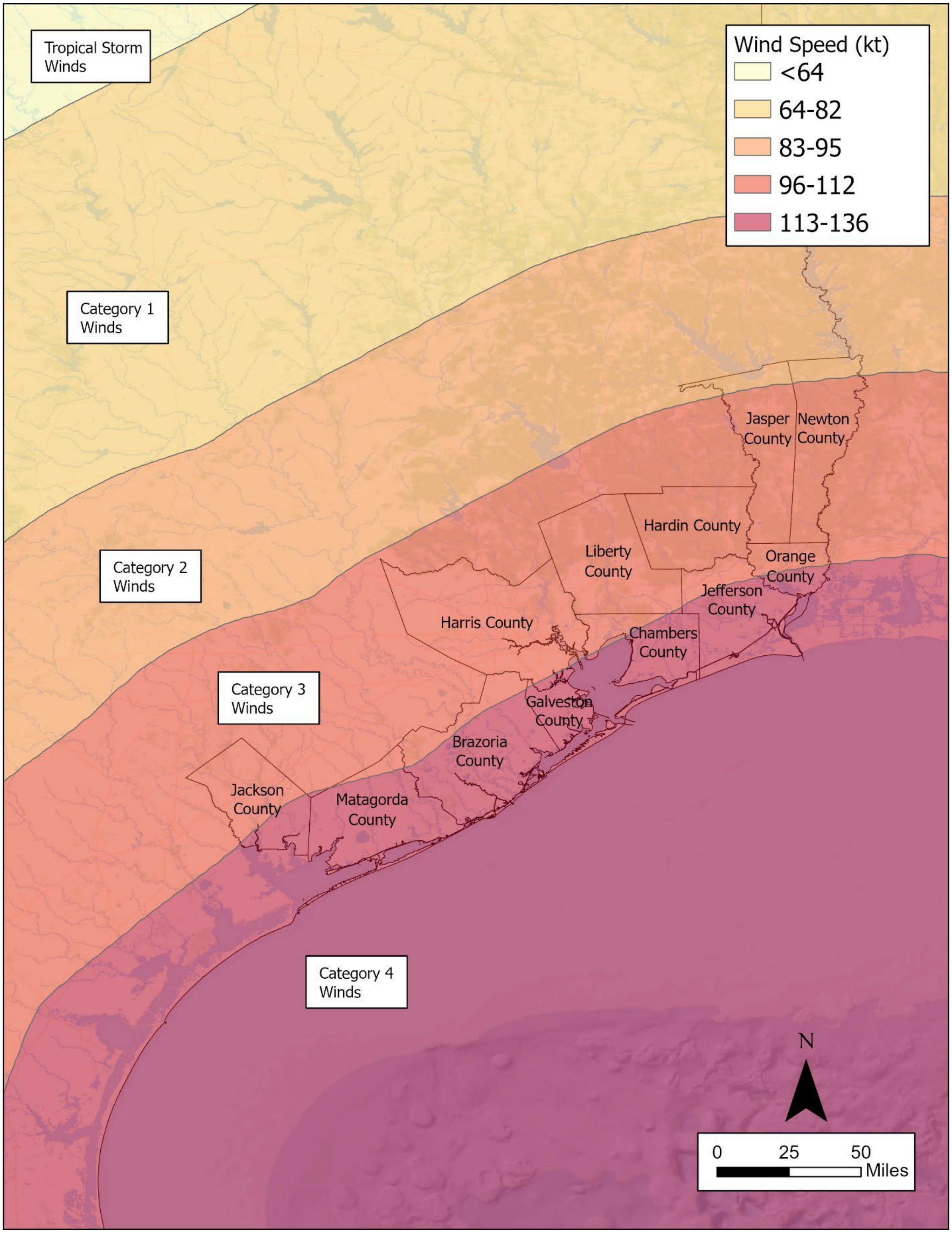


Figure 1-27 Wind Extent Map for Category 4 Storm (135 kt) with 24 kt Forward Speed (Shaded Map)

1.7 HURREVAC TOOL

HURREVAC (an abbreviation for HURRicane EVACuation) is a web browser-based decision support tool that assists local and state emergency managers in hurricane evacuation planning, training, and timely decision making. This real-time data analysis tool combines official NHC and NWS forecasts with Hurricane Evacuation Studies identifying vulnerable coastal populations and their evacuation clearance times under various storm scenarios. Information available within the program includes forecast track, timing, and wind speed; storm surge scenarios; evacuation timing; evacuation zones, and more. HURREVAC is developed and maintained by the National Hurricane Program, which is administered by FEMA, in partnership with the USACE, and the NOAA National Hurricane Center. HURREVAC is available free of charge to government emergency managers. Visit https://www.hurrevac.com/ for more information and link to registration page to apply for program access.

HURREVAC is also a useful tool for debriefing discussions and implementing recovery after real-time events such as Hurricane Nicholas in mid-September 2021, which made landfall as a Category 1 hurricane and then degraded to a tropical depression as it traveled along coastal Texas and into Louisiana, accompanied by extensive rain. Figure 1-28 below shows most likely arrival of tropical-storm-force winds and the track of the storm center.

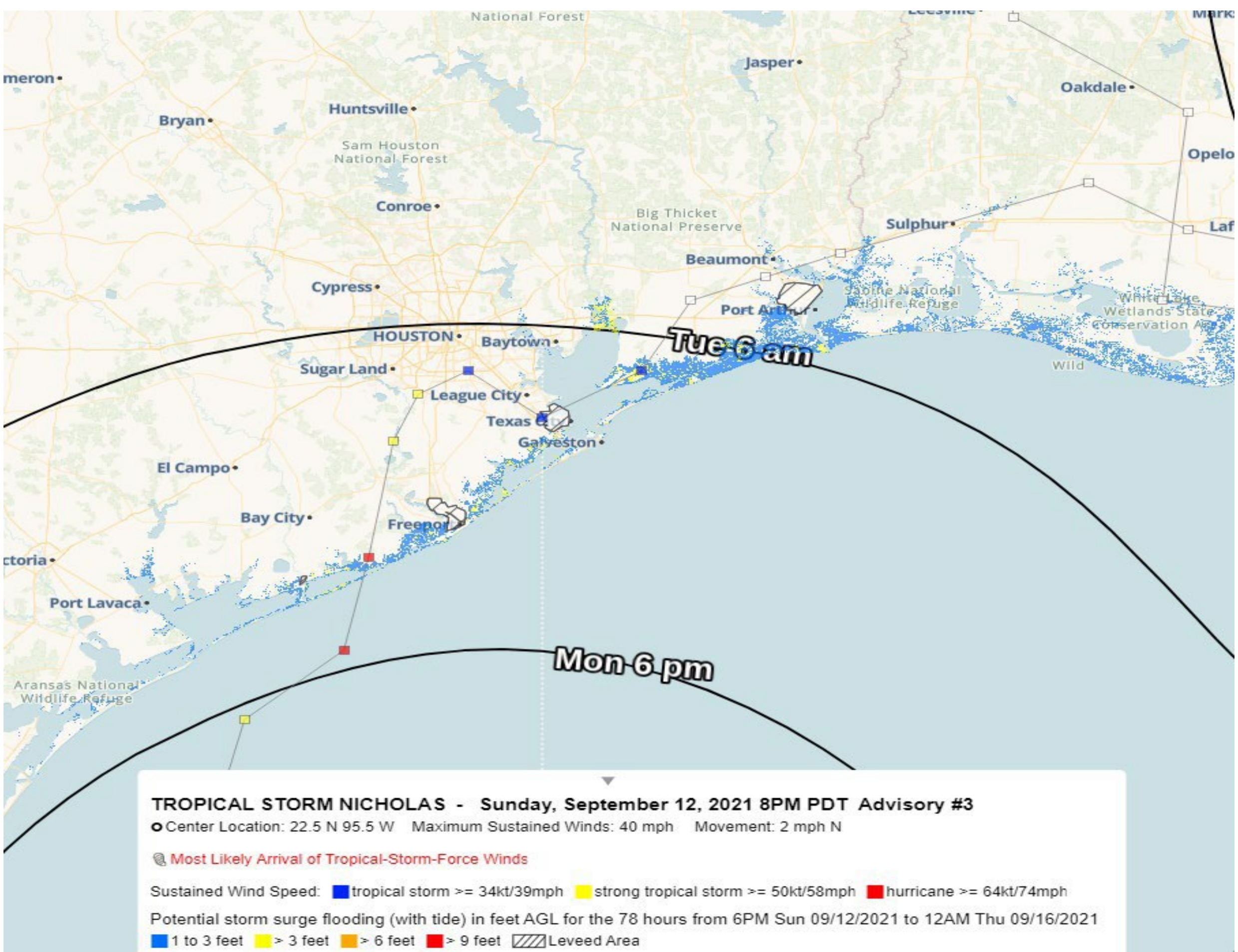


Figure 1-28 Arrival of tropical-force-winds vs. Track for Nicholas Sept. 2021, Source: HURREVAC 9/12/21

APPENDIX A: GLOSSARY

A

Advanced Hydrologic Prediction Service: service improves flood warnings and water resource forecasts to meet diverse and changing customer needs.

Astronomical Tide: Tidal levels which result from gravitational effects from the earth, sun, and moon, without any atmospheric influences.

B

Bathymetry: The measurement of the depth of large bodies of water, for example, lakes, oceans, and seas.

C

Critical Facilities: Facilities that may need assistance of special consideration and planning if they are to be evacuated.

E

Evacuation: People leaving their residence to go from a perceived dangerous place to a perceived safer place.

Evacuation Timing: Appropriate start and end times of an evacuation based on storm and traffic conditions.

Evacuation Zone: Designated by local officials and based on the surge inundation maps used in the transportation model. Surge inundation areas are divided up into zones for modeling purposes and evacuation notice dissemination.

F

Fathom: A unit of length equal to 1.83 m (6 ft), used mainly in nautical contexts for measuring the depth of water.

FEMA: Federal Emergency Management Agency

FIRM: Flood Insurance Rate Map

Flood Insurance Study: A compilation and presentation of flood risk data for specific watercourses, lakes, and coastal flood hazard areas within a community. When a flood study is completed for the NFIP, the information and maps are assembled into an FIS. The FIS report contains detailed flood elevation data in flood profiles and data tables.

G

GIS: Geographic Information Systems

H

HES: Hurricane Evacuation Study

HURREVAC: HURRicane EVACuation Tracking and Analysis Software

I

Inland Wind Model: Applies a simple two parameter decay equation to the hurricane wind field at landfall to estimate the maximum sustained surface wind as a storm moves inland. This model can be used for operational forecasting of the maximum winds of land falling tropical cyclones. It can also be used to estimate the maximum inland penetration of hurricane force winds (or any wind threshold) for a given initial storm intensity and forward storm motion.

M

MEOW: Maximum Envelope of Water; stores the maximum water surface elevation in each SLOSH grid cell for all the hurricane tracks in one direction for a particular forward speed, and storm intensity.

MOMs: Maximums of MEOWs; represents the maximum water surface elevation for each SLOSH grid cell regardless of approach direction, forward speed or track.

N

NAVD: North American Vertical Datum

NFIP: National Flood Insurance Program

NHC: National Hurricane Center

NOAA: National Oceanographic and Atmospheric Administration

NWS: National Weather Service

S

Saffir/Simpson Hurricane Scale: Scale developed to describe the potential storm surge generated by hurricanes: Category 1. Winds of 74 to 95 miles per hour Category 2. Winds of 96 to 110 miles per hour Category 3. Winds of 111 to 129 miles per hour Category 4. Winds of 130 to 156 miles per hour Category 5. Winds greater than 157 miles per hour.

Simulating Waves Nearshore (SWAN): numerical wave model to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions.

SLOSH Model: Acronym meaning Sea, Lake and Overland Surges (SLOSH) from **H**urricanes. SLOSH provides heights of storm surge for various combinations of hurricane strength, forward speed of storm, and direction of storm. SLOSH model is used for real-time forecasting of surges from approaching hurricanes within selected Gulf and Atlantic coastal basins.

Storm Category:
Category 0, Tropical Storm, winds 35-73 miles per hour
Category 1. Winds of 74 to 95 miles per hour
Category 2. Winds of 96 to 110 miles per hour
Category 3. Winds of 111 to 129 miles per hour
Category 4. Winds of 130 to 156 miles per hour
Category 5. Winds greater than 157 miles per hour.

Storm Surge: The abnormal rise in water level caused by wind and pressure forces of a hurricane, over and above the predicted astronomical tide. Storm surge produces most of the flood damage and drowning associated with tropical systems; highest surges from a hurricane usually occur on the northeast quadrant of the storm’s track.

Storm Tide: The water level rise during a storm due to the combination of storm surge and the astronomical tide.

T

Topography/ Topographic Features: Features on the surface of land, including natural features such as mountains and rivers and constructed features such as highways and railroads.

Tropical Cyclones: Defined by the National Weather Service as a non-frontal, low-pressure synoptic scale (large-scale) systems that develop over tropical or subtropical waters and have a definite organized circulation. Tropical depressions are < 33 knots (38 mph). Tropical storms are 34 to 63 knots (39-73 mph). Hurricanes are >64 knots. Geographical areas affected by tropical cyclones are referred to as tropical cyclone basins knots (74 mph). Atlantic tropical cyclone basin is one of six in the world and includes much of the North Atlantic Ocean, the Caribbean Sea, and the Gulf of America. Official Atlantic hurricane season begins on June 1 and extends through November 30 of each year.

U

USACE: United States Army Corps of Engineers

V

Vulnerability Analysis: Identifies those areas, populations, and facilities that are vulnerable to specific hazards under a variety of hurricane threats.

W

Wave Setup: An increase in the mean water level on a beach due to the effects of waves running up the beach and breaking. Under some conditions the set- up can be large enough to contribute to local flooding and over- topping of sea defenses.

WEM: Wind Extent Map

APPENDIX B: DIRECTIONAL MEOWS MAPS WITH MAXIMUM DEPTHS OF INNUNDATION BASED ON DIRECTION

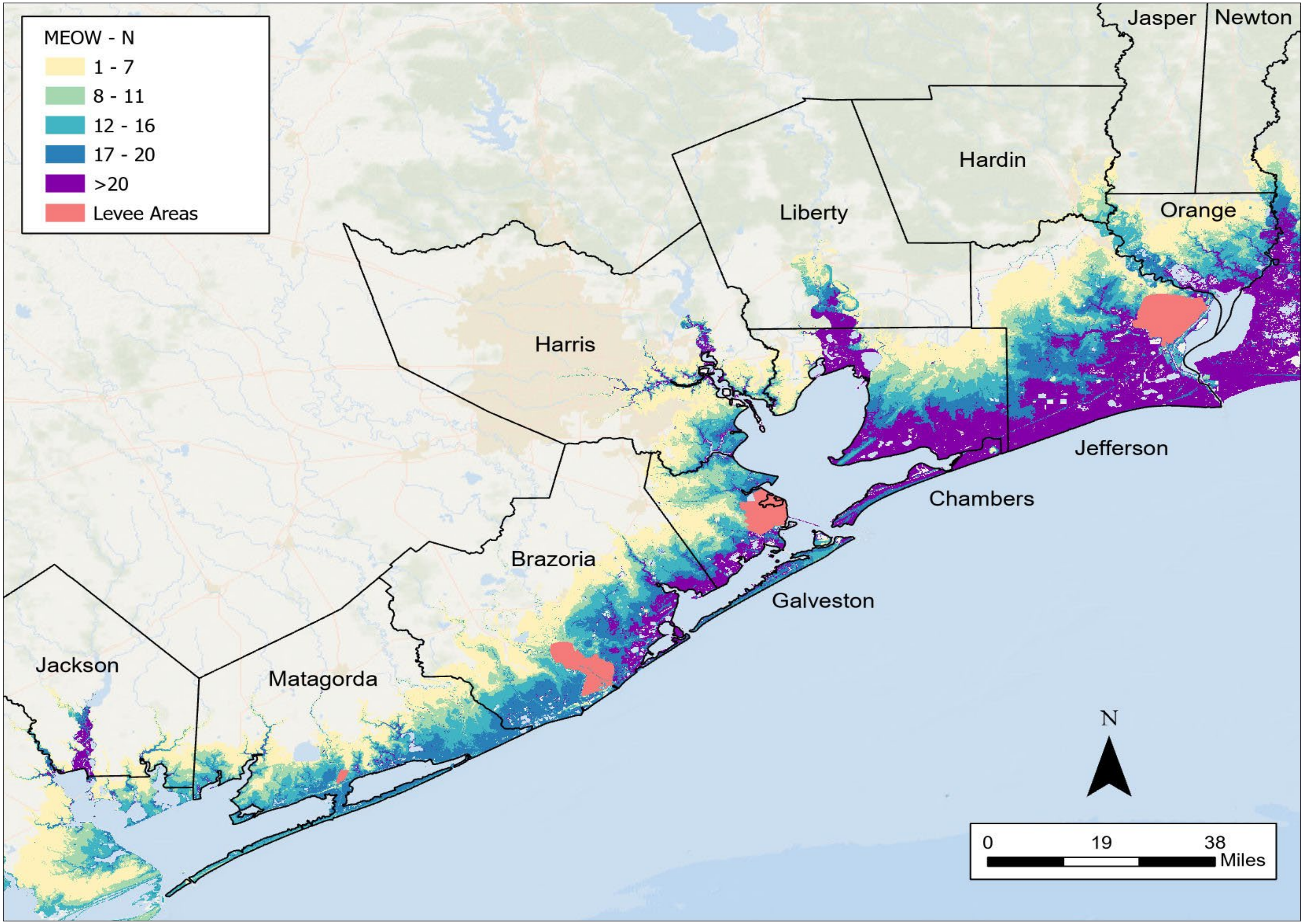


Figure B-1 North Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

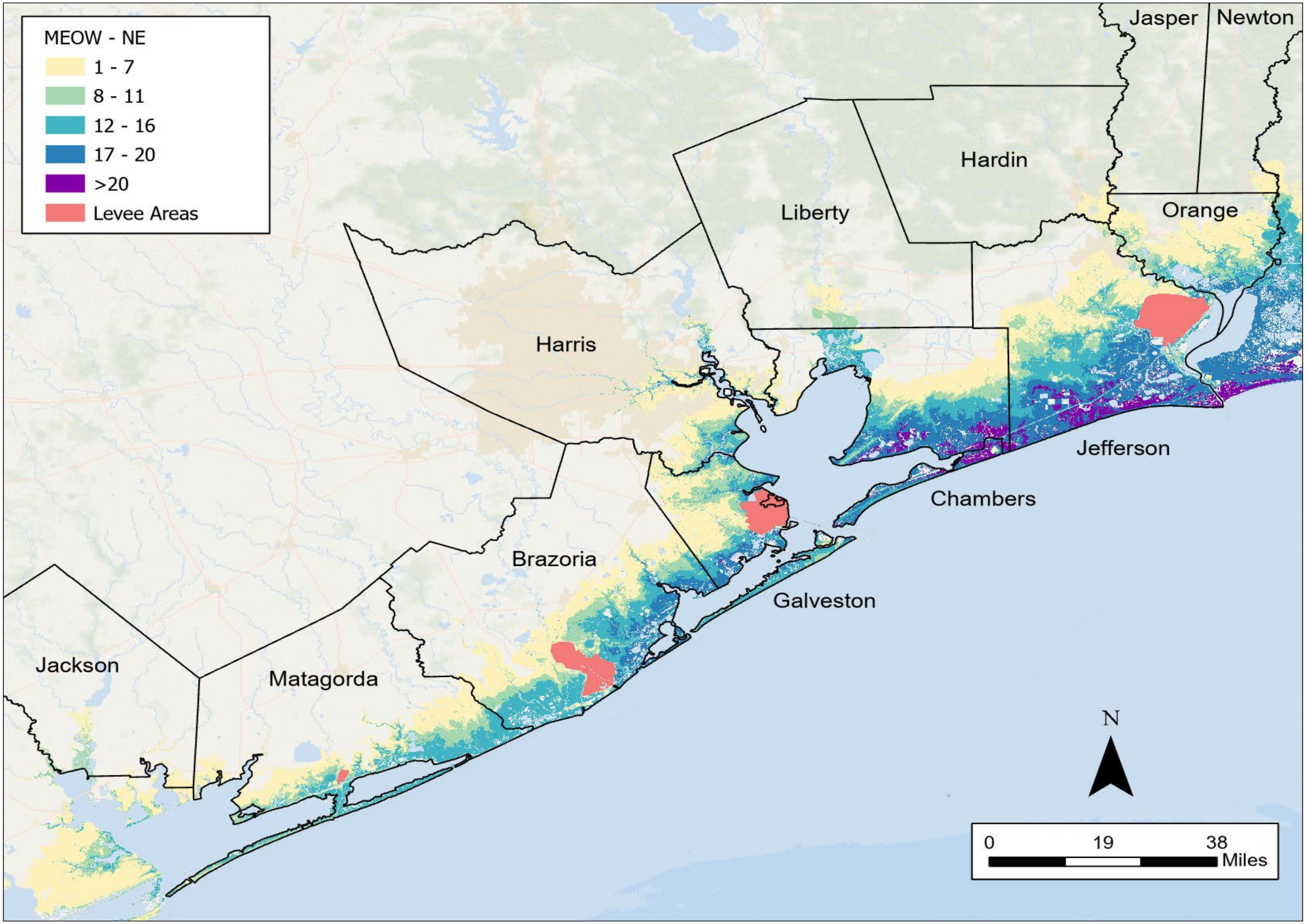


Figure B-2 Northeast Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

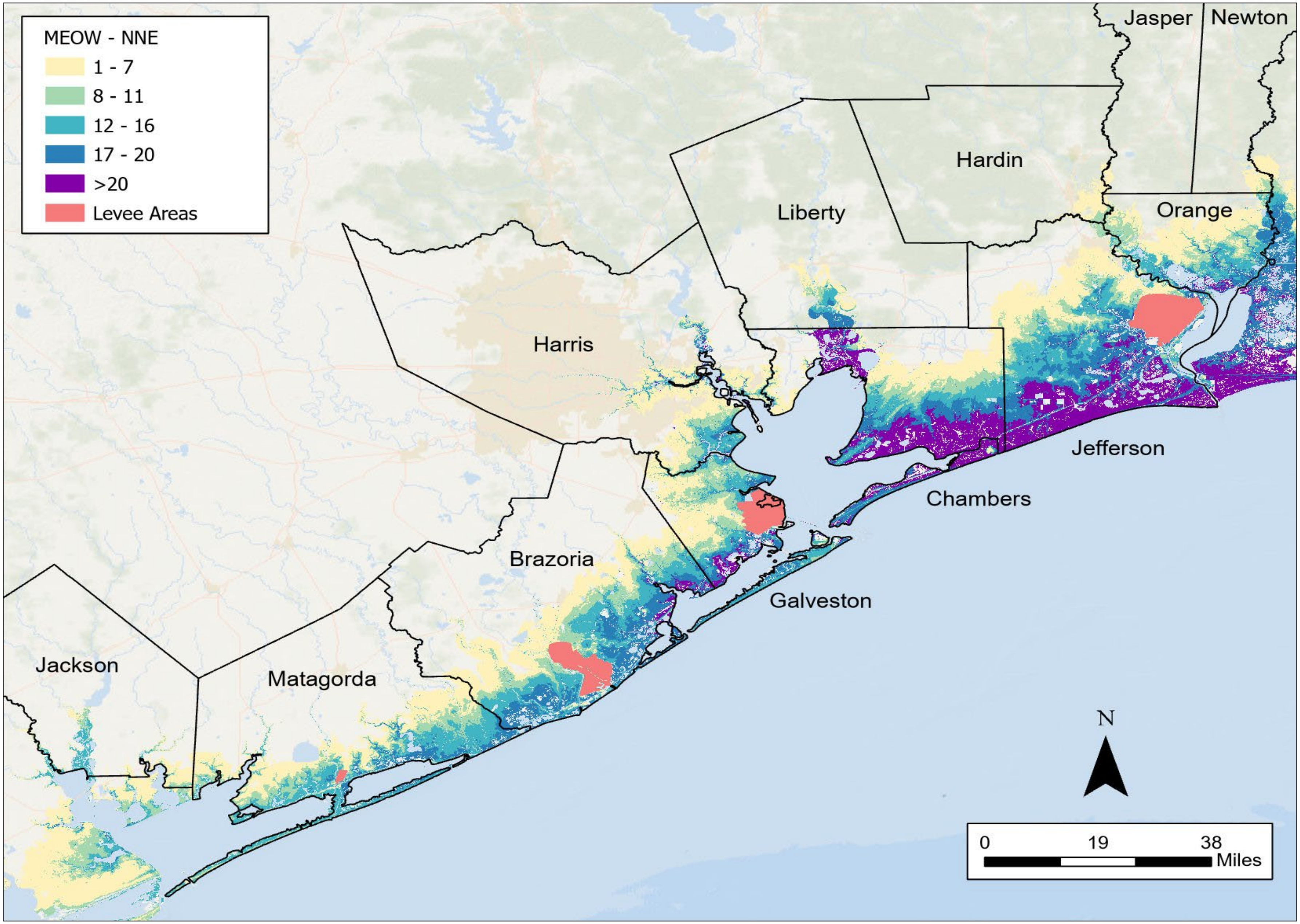


Figure B-3 North Northeast Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

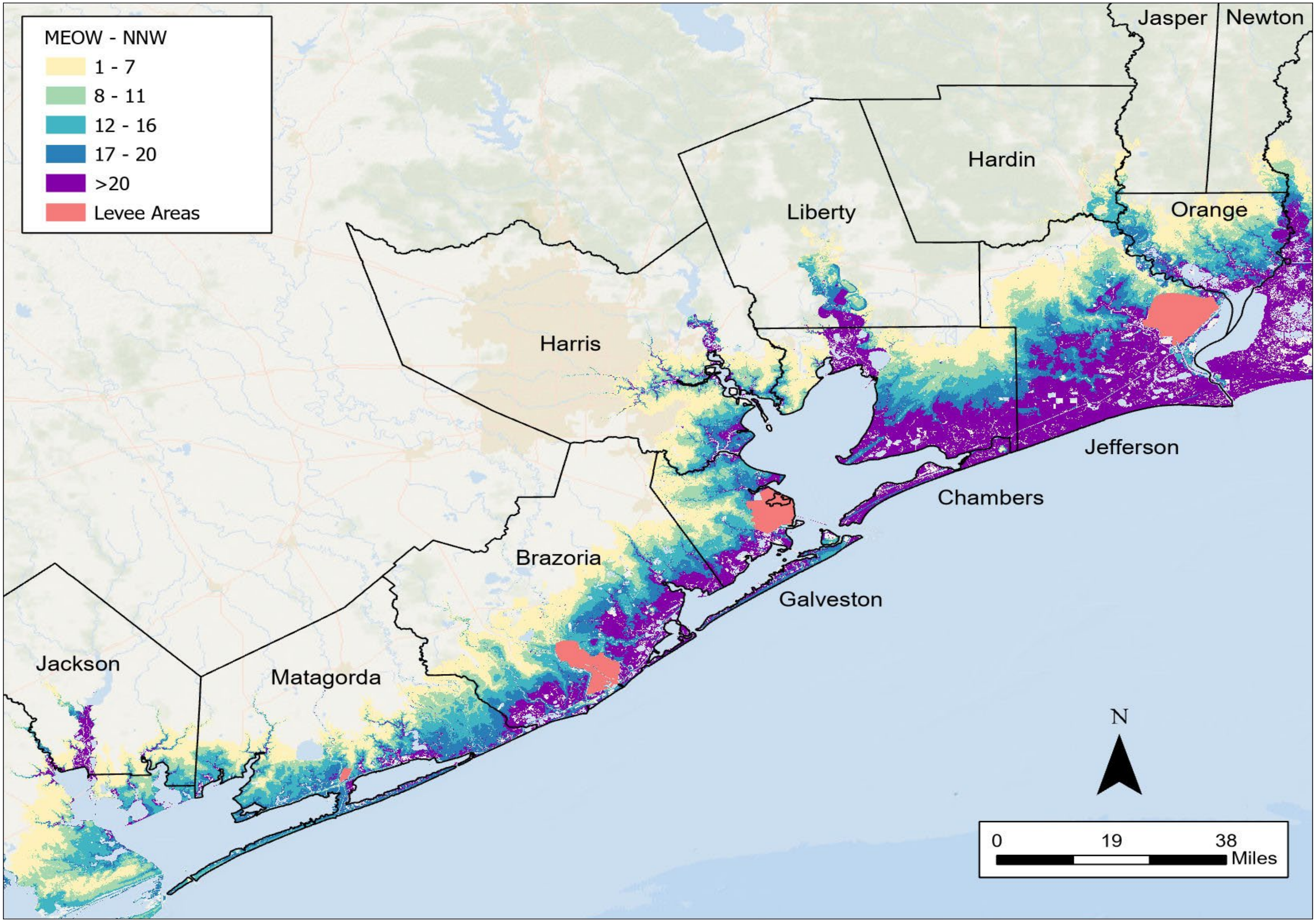


Figure B-4 North Northwest Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

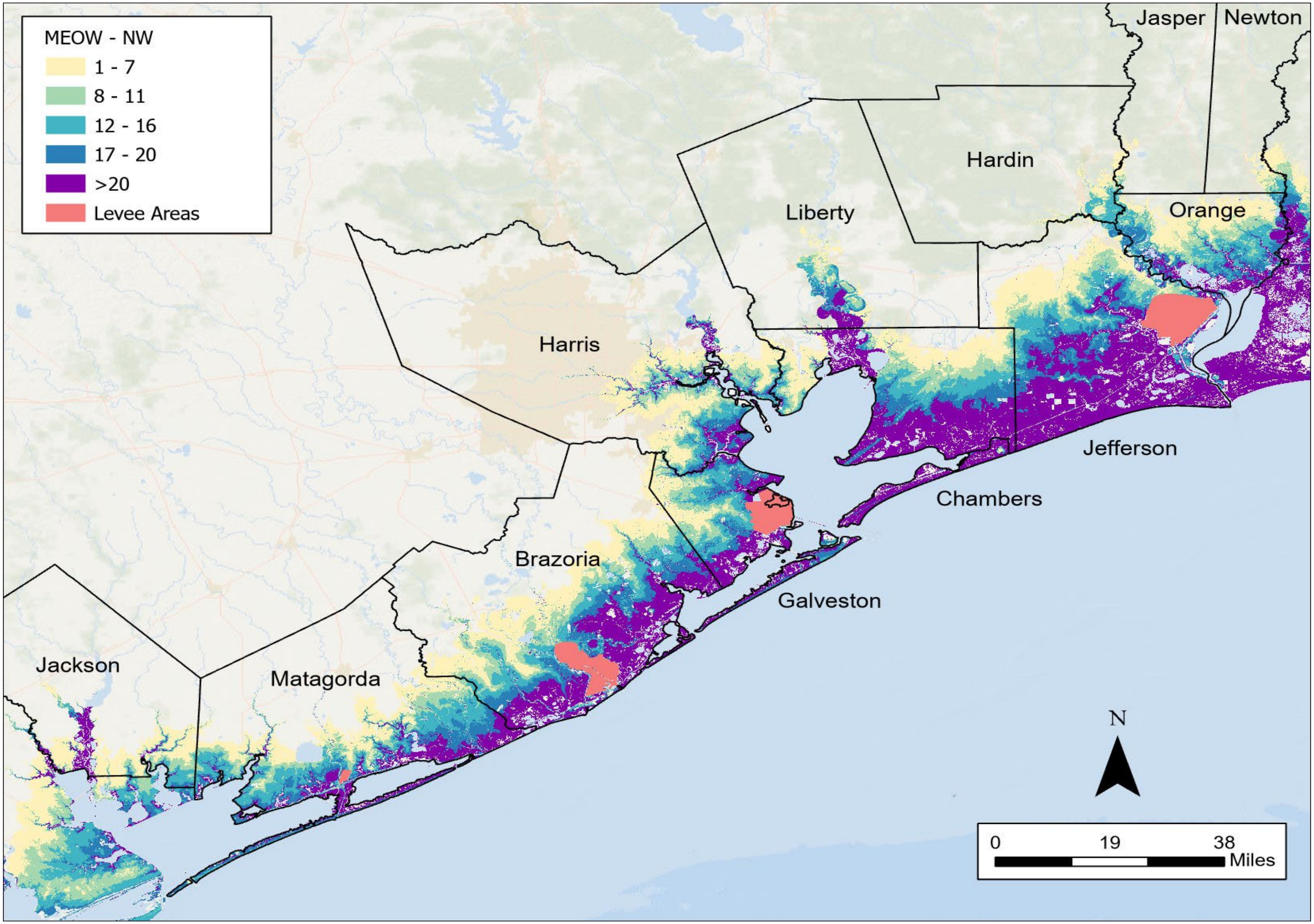


Figure B-5 Northwest Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

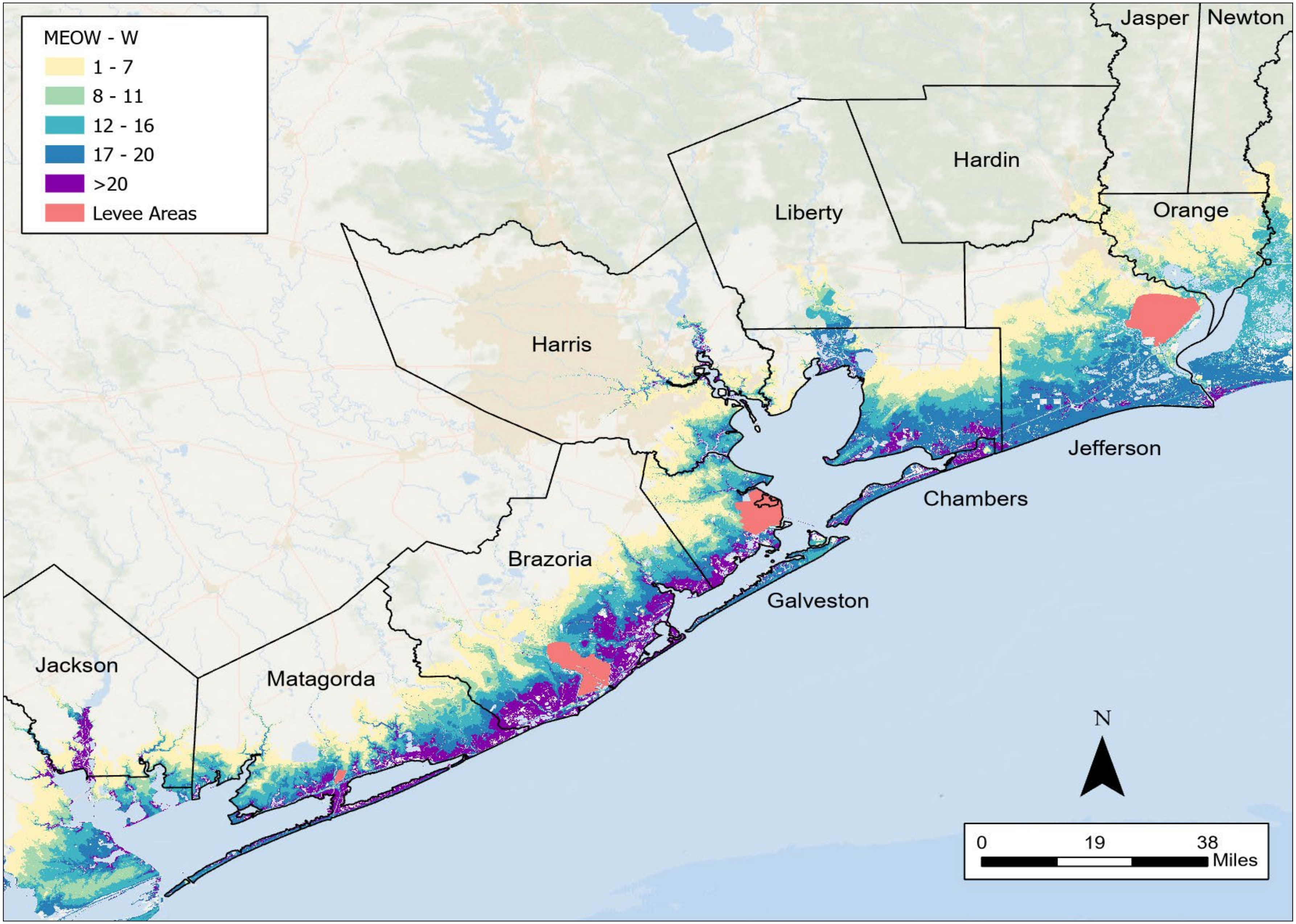


Figure B-6 West Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

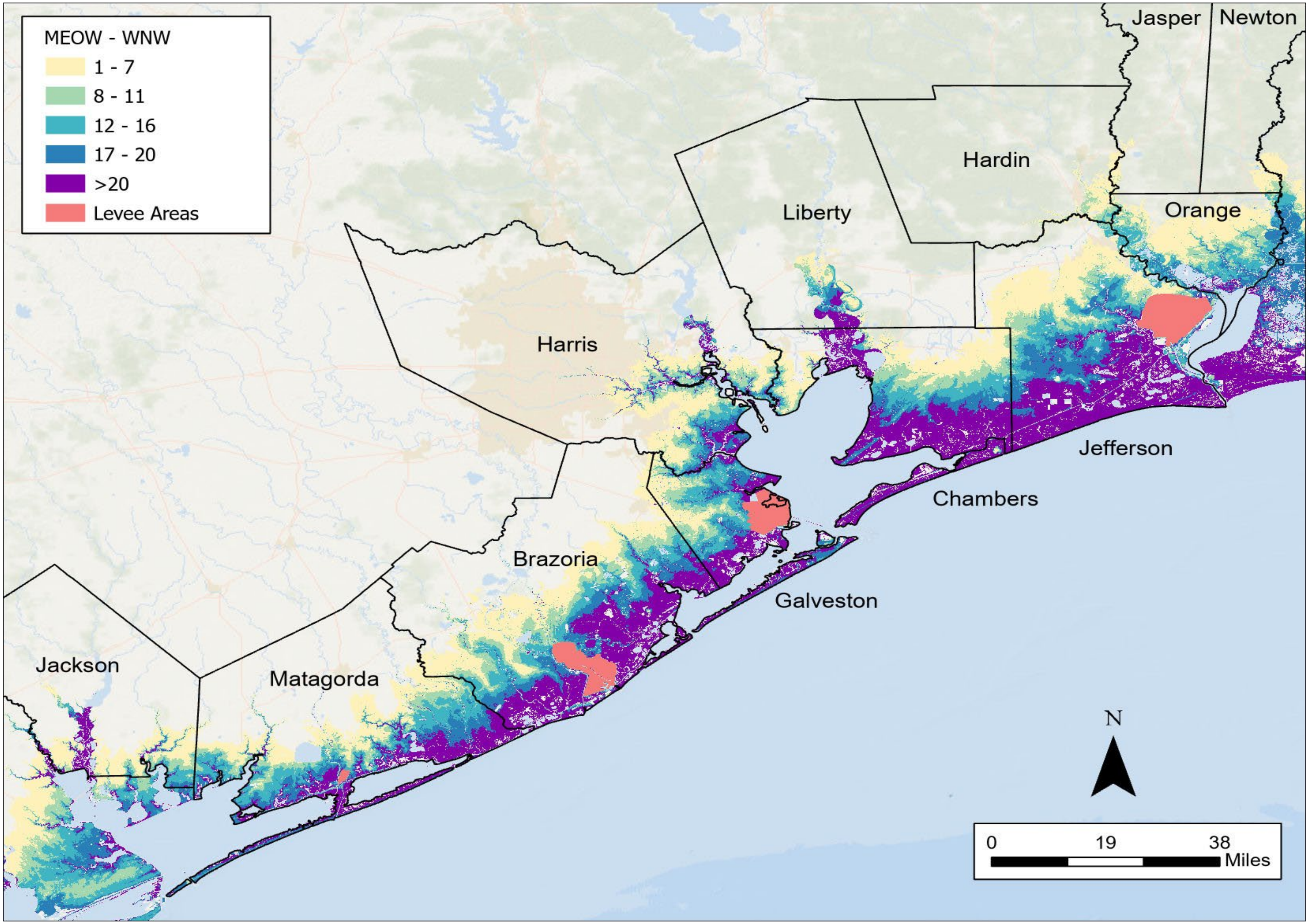


Figure B-7 West Northwest Directional MEOW Map (With Maximum Inundation for All Storm and Forward Speeds)

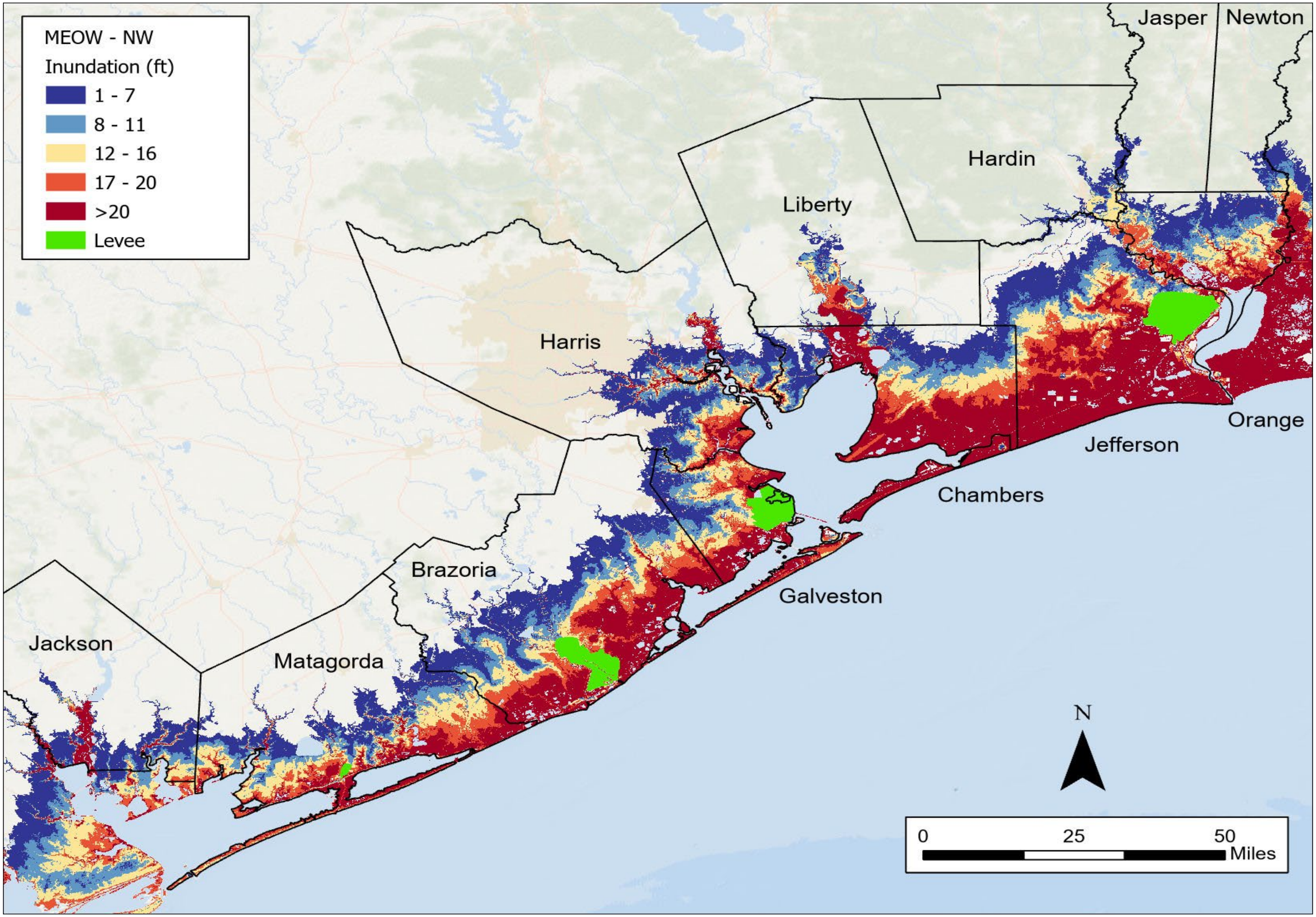


Figure B-8 Northwest Directional MEOW Map (Worst Case Approach Direction – Highest Maximum Inundation)

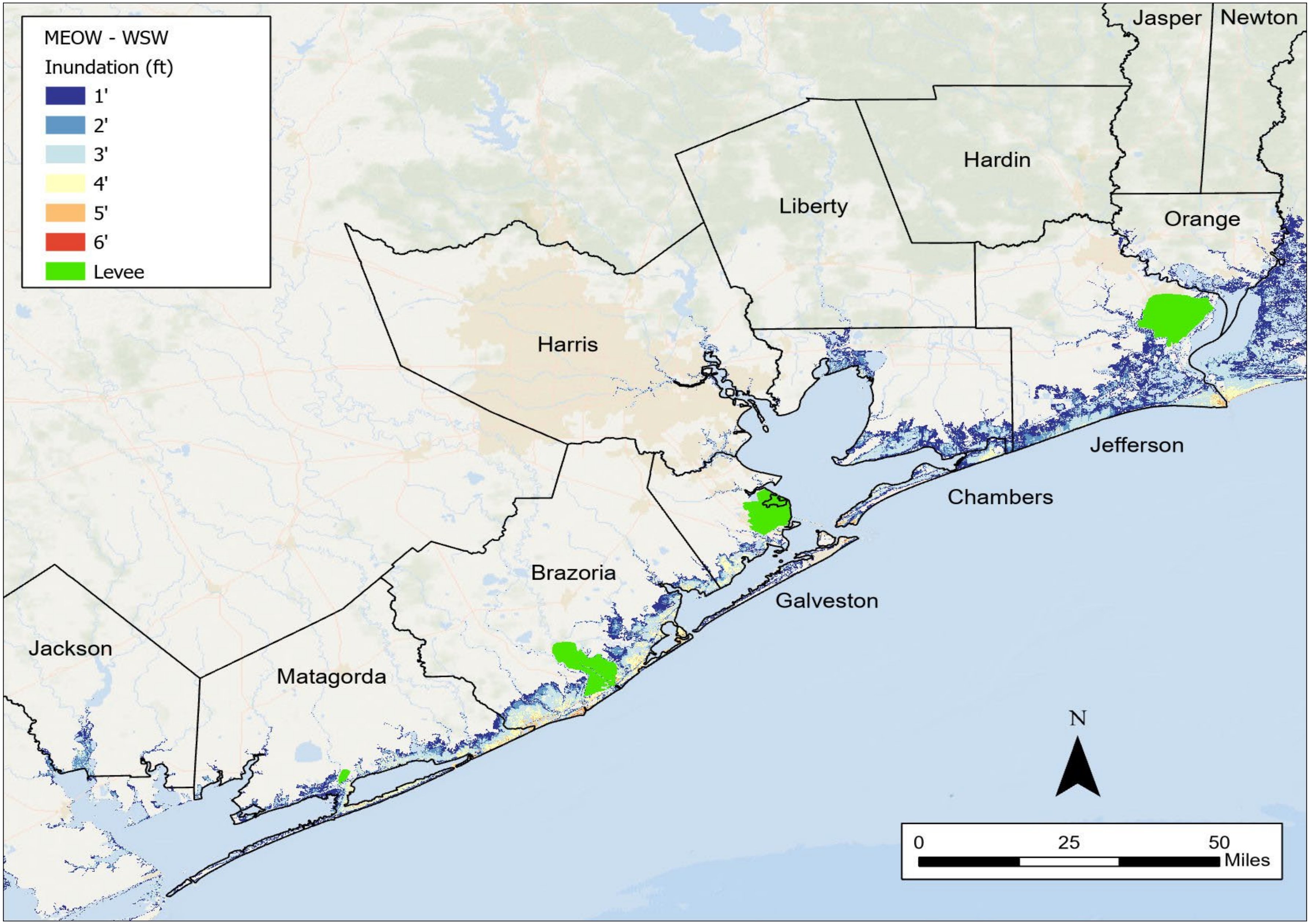


Figure B-119 West Southwest Directional MEOW Map (Best Case Approach Direction – Lowest Maximum Inundation)

APPENDIX C: CATEGORY STORM MOMS MAPS

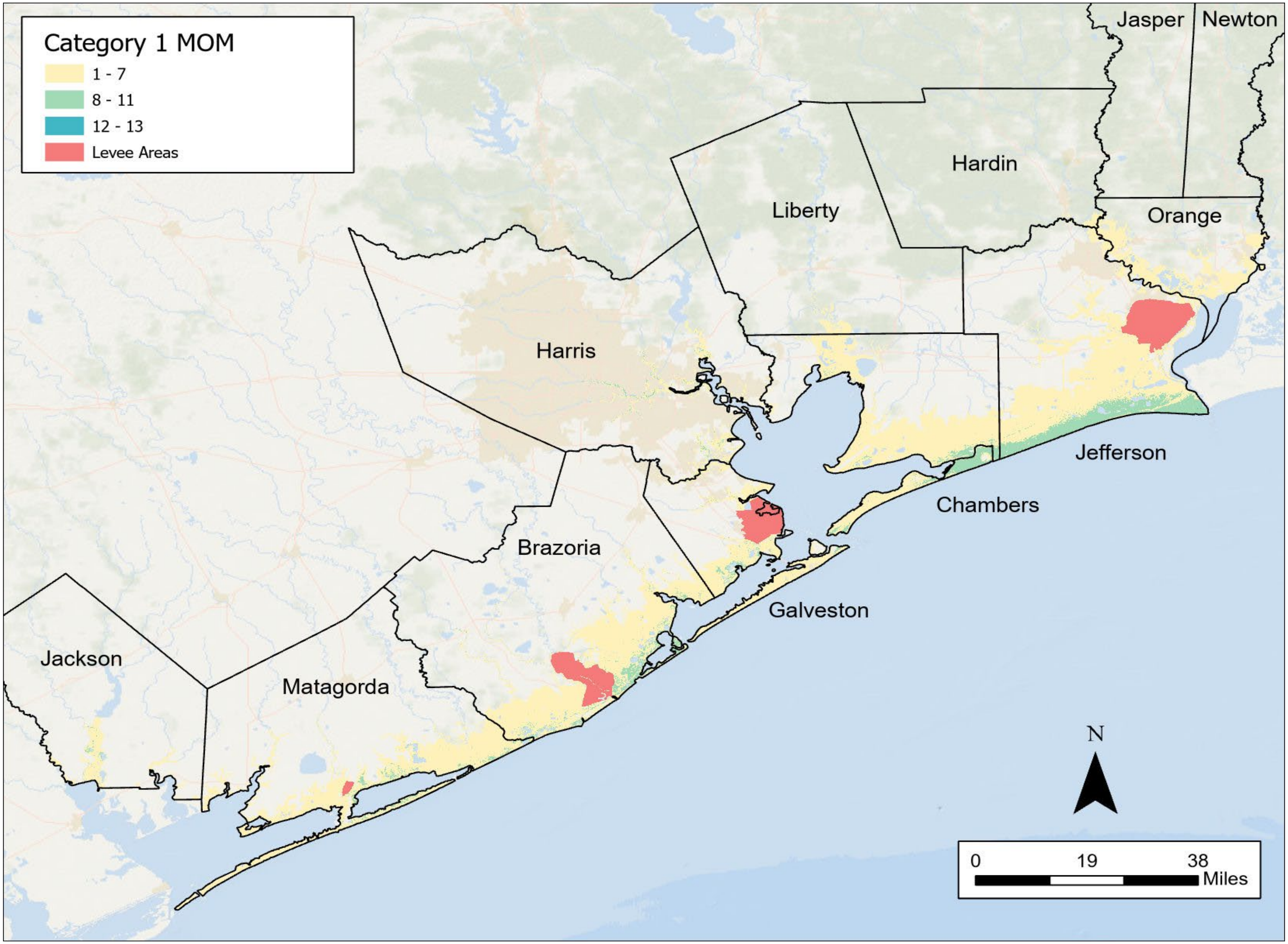


Figure C-1 Category 1 MOM map for all counties

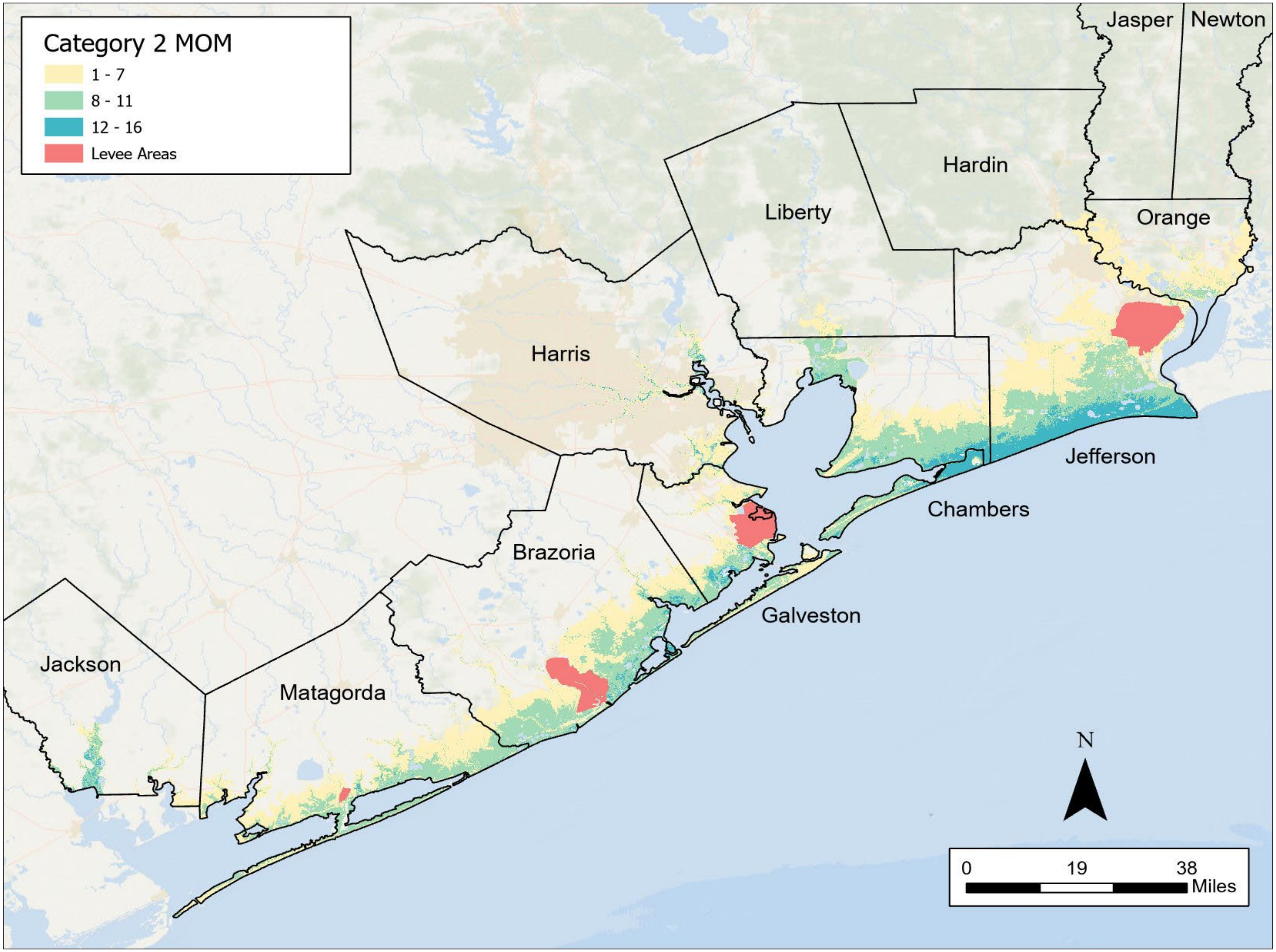


Figure C-1 Category 1 MOM map for all counties

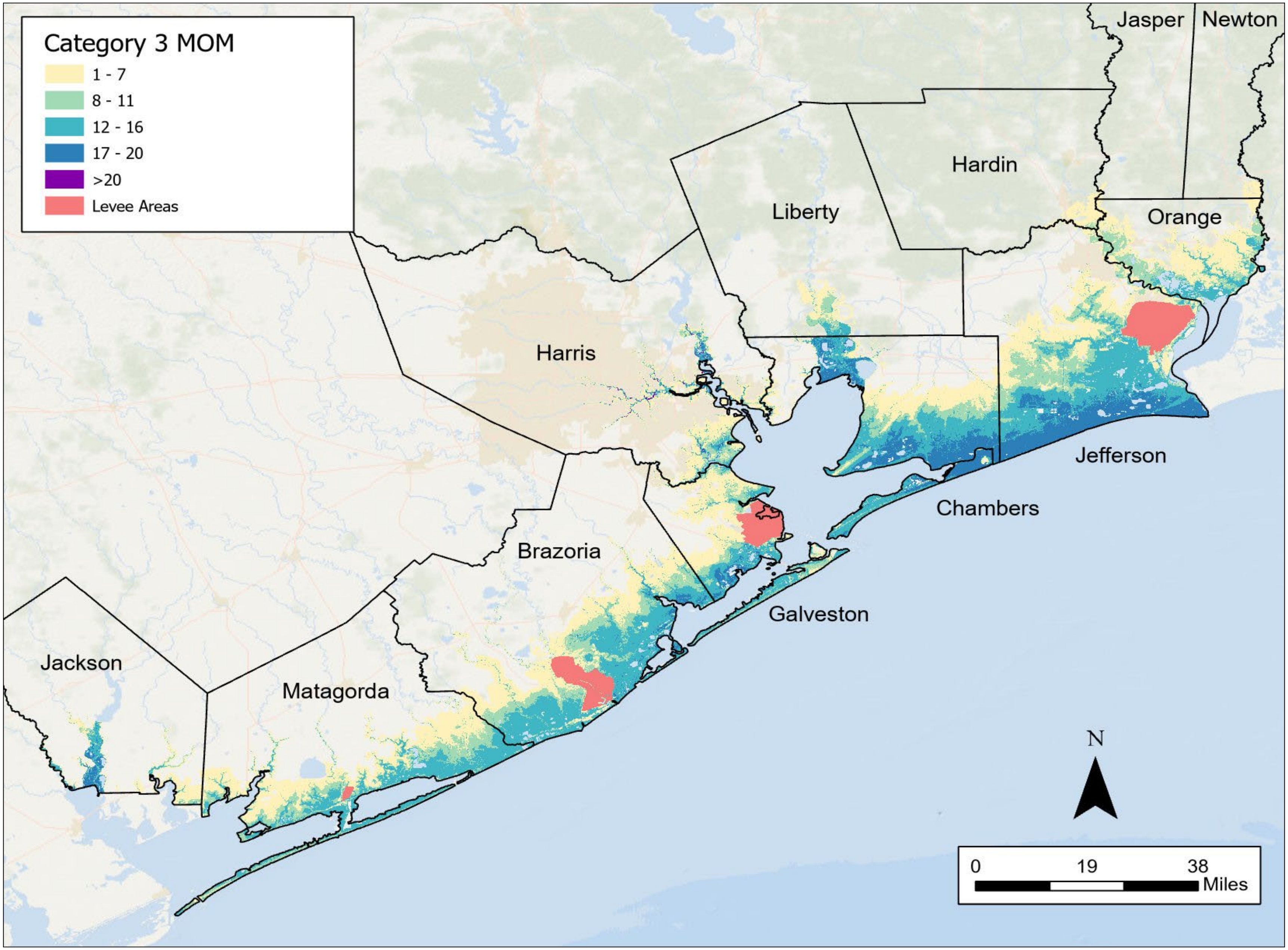


Figure C-3 Category 3 MOM map for all counties

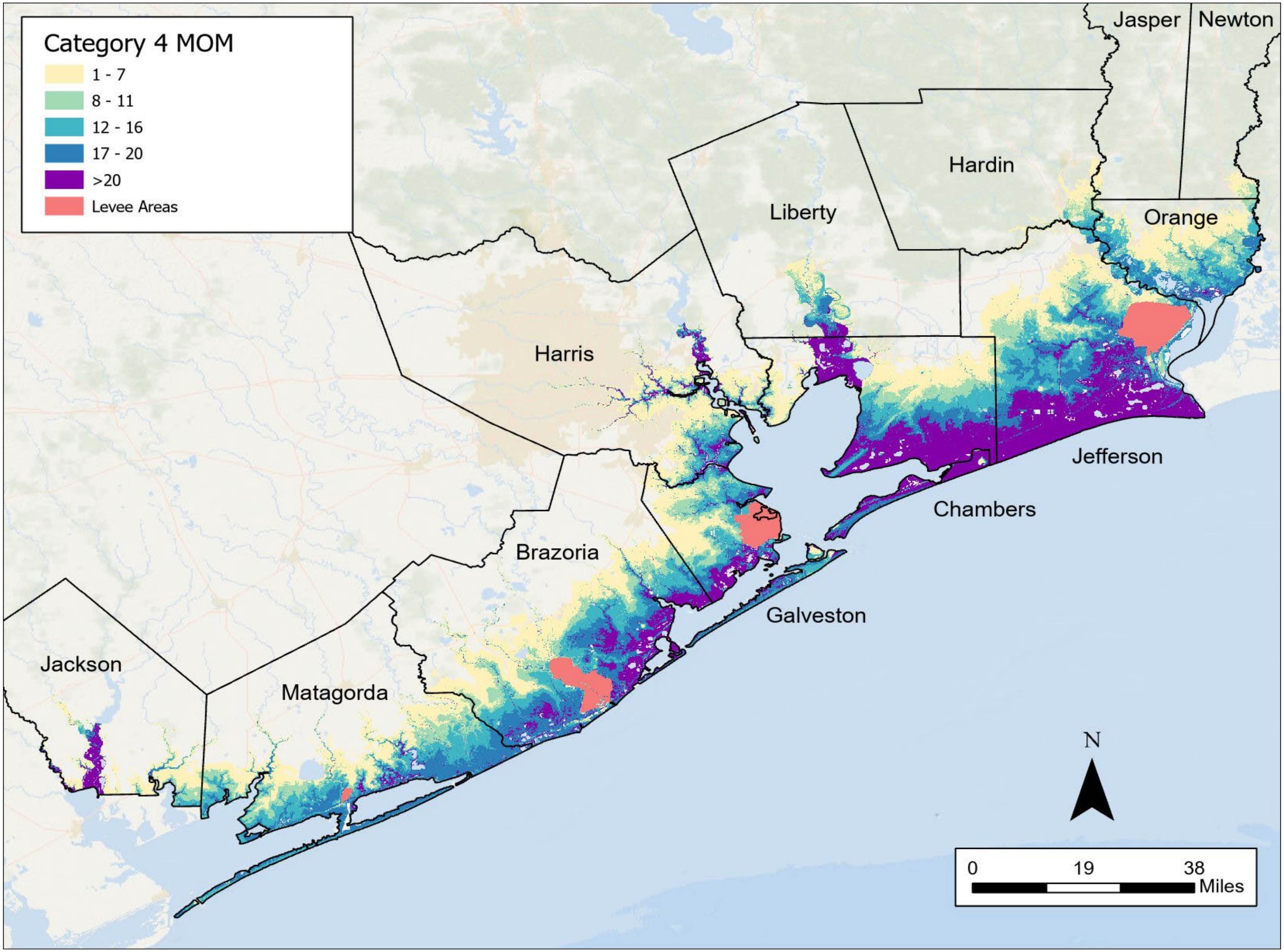


Figure C-4 Category 4 MOM map for all counties

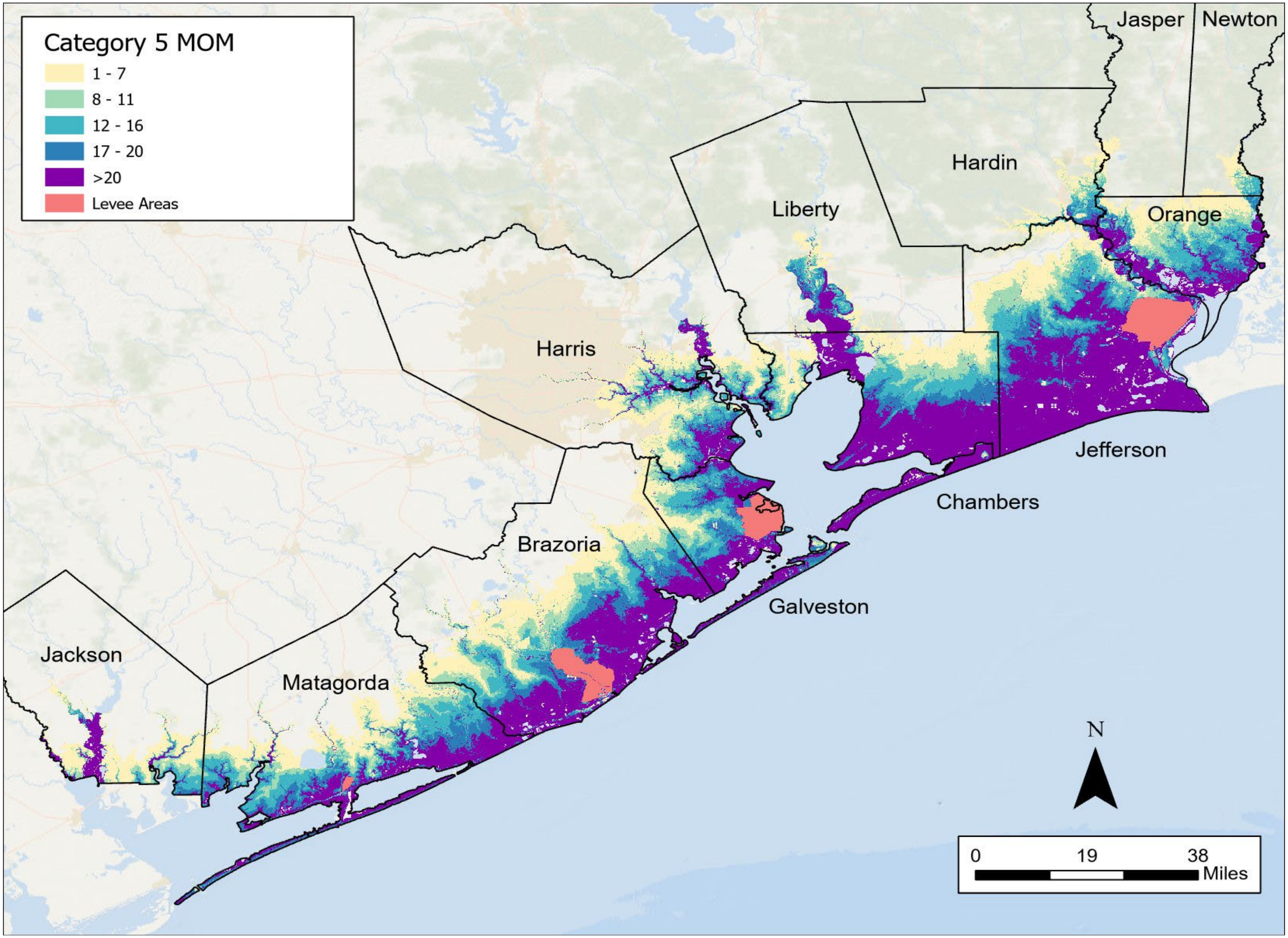


Figure C-5 Category 5 MOM map for all counties

APPENDIX D: WIND EXTENT MAPS (WEM) CATEGORIES 1, 2, 3, 4, AND 5 STORMS (WITH 24 KTS FORWARD SPEED)

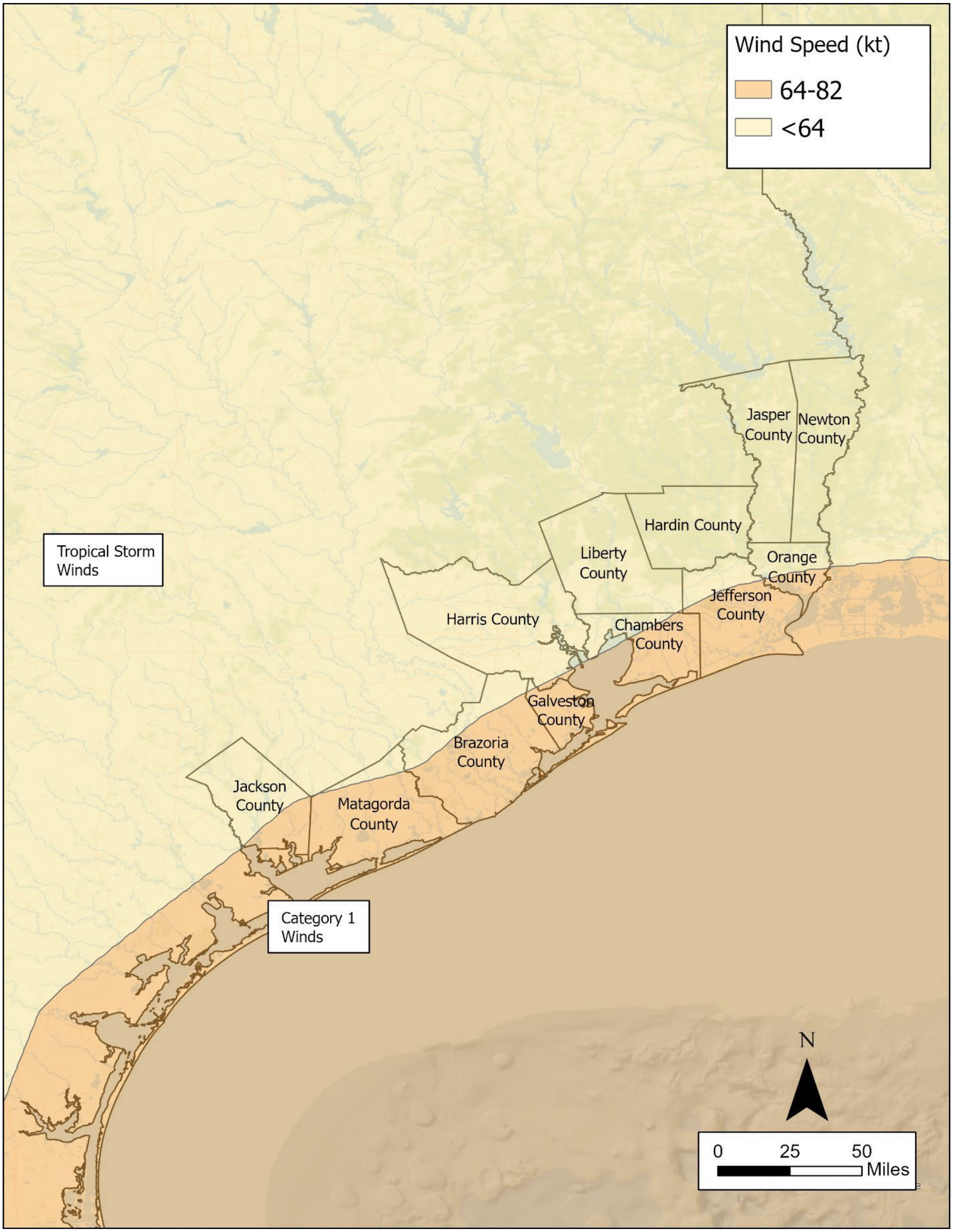


Figure D-1 Wind Extent Map for Category 1 Storm (75 kt) with 24 kt Forward Speed (Shaded Map)

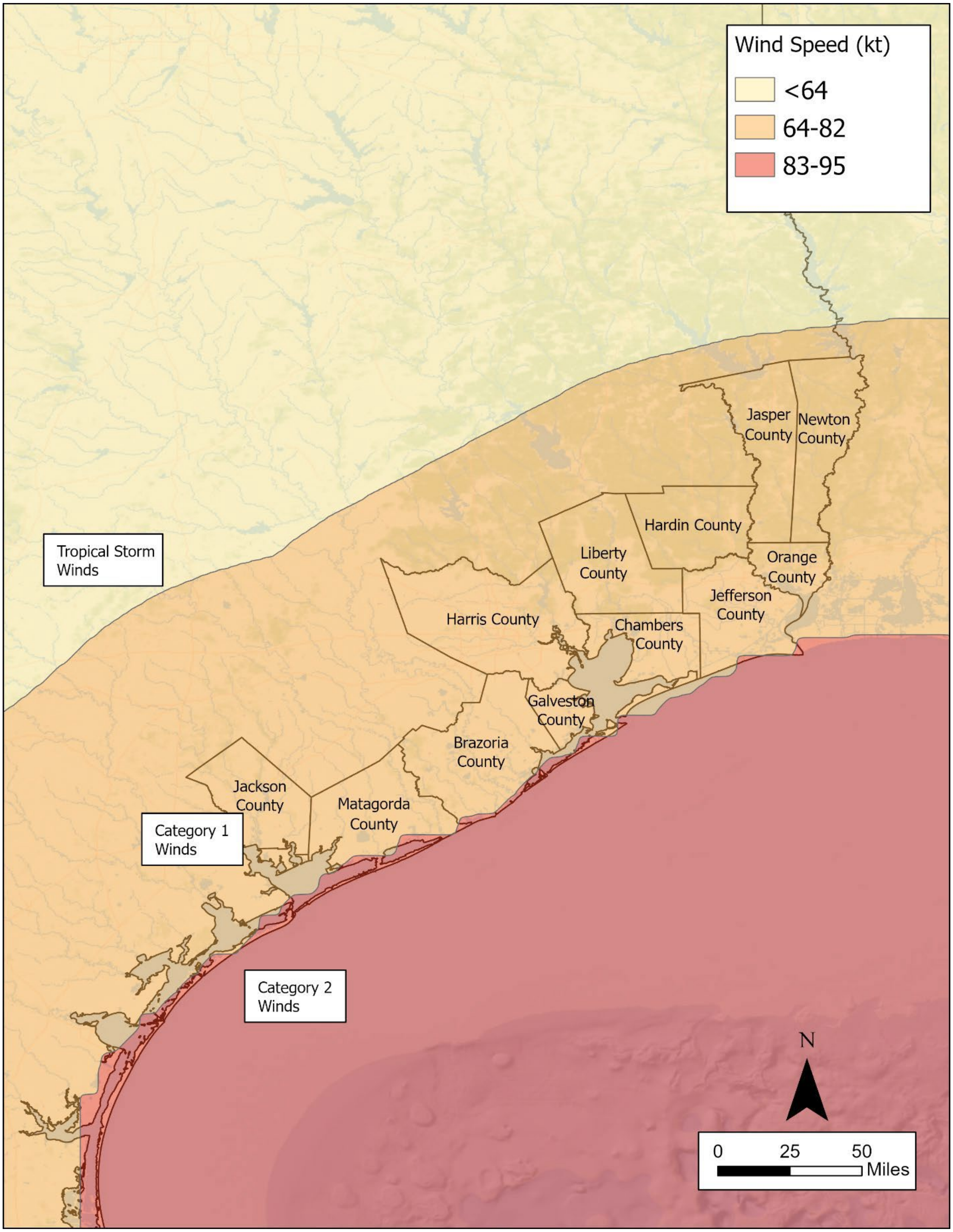


Figure D-2 Wind Extent Map for Category 2 Storm (90 kt) with 24 kt Forward Speed (Shaded Map)

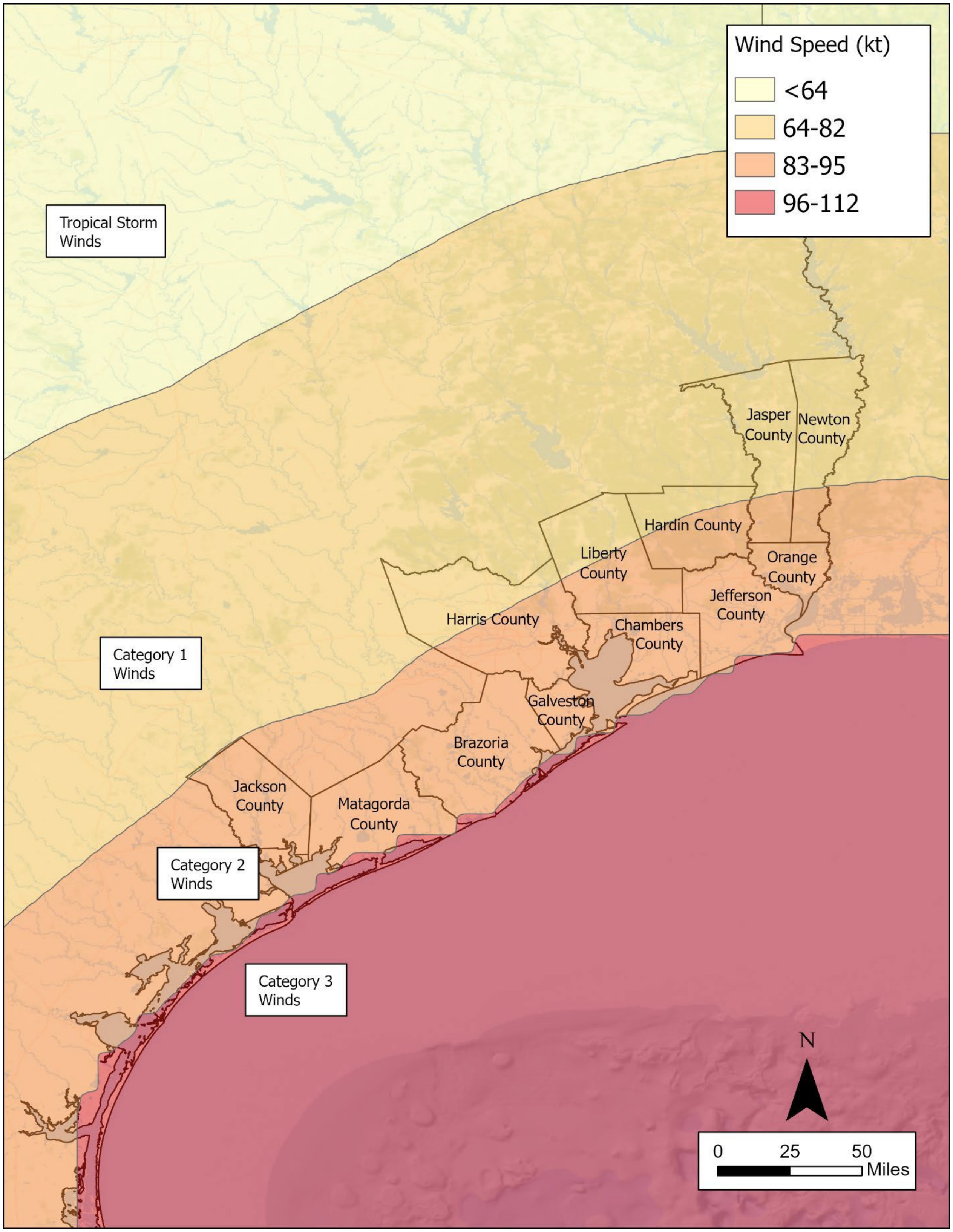


Figure D-3 Wind Extent Map for Category 3 Storm (105 kt) with 24 kt Forward Speed (Shaded Map)

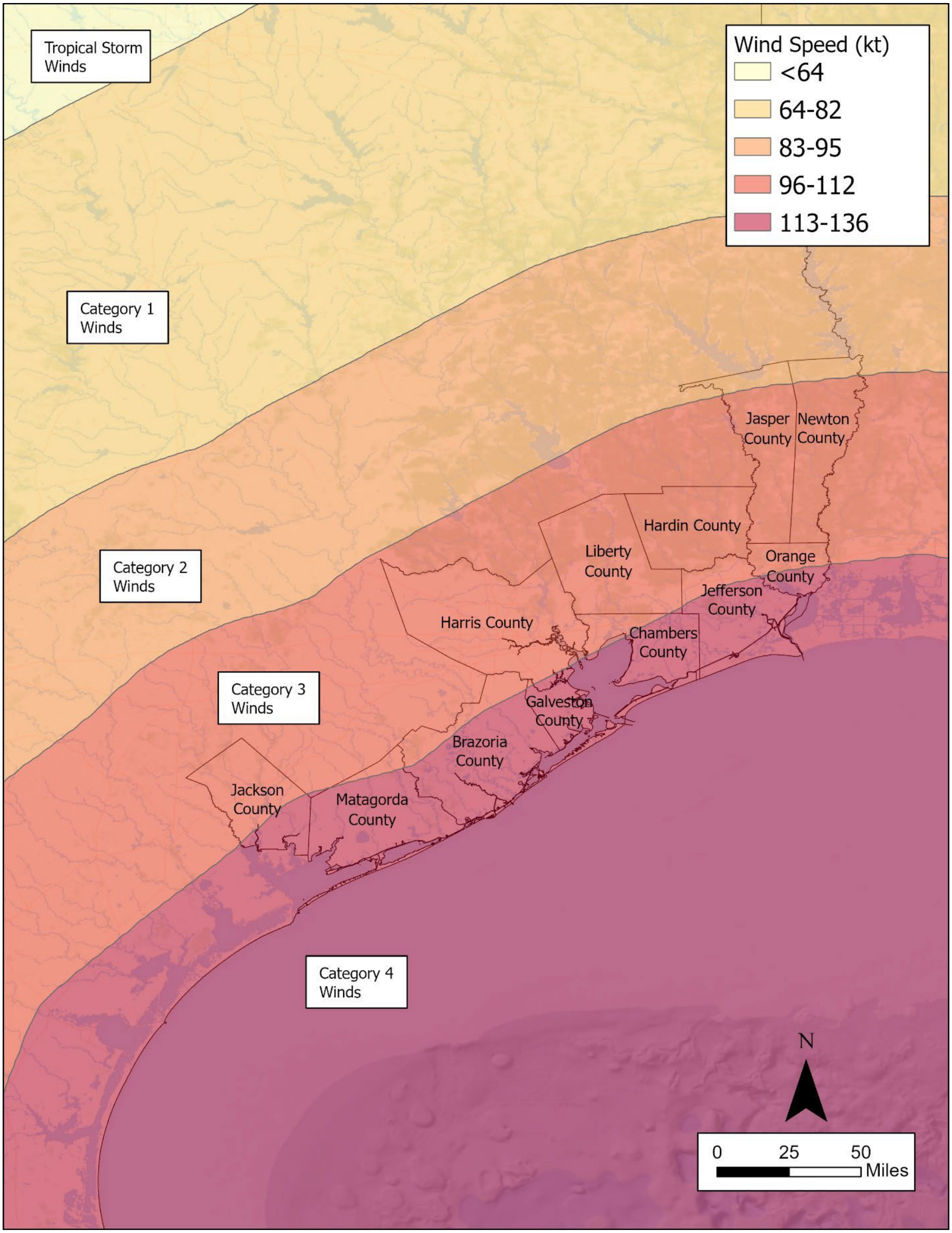


Figure D-4 Wind Extent Map for Category 4 Storm (120 kt) with 24 kt Forward Speed (Shaded Map)

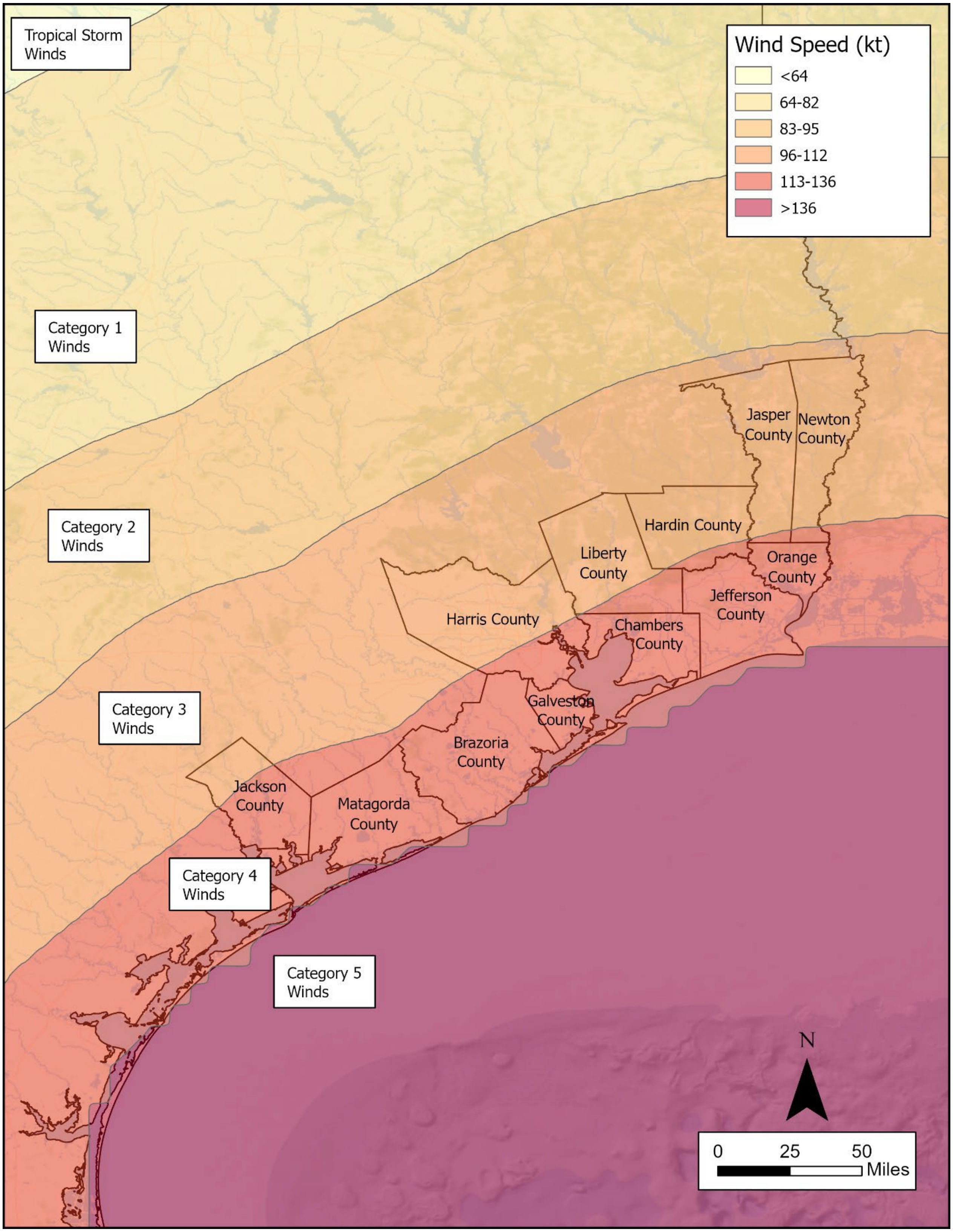


Figure D-5 Wind Extent Map for Category 5 Storm (140 kt) with 24 kt Forward Speed (Shaded Map)

APPENDIX E: MAXIMUM INUNDATION DEPTHS FOR DIRECTIONAL MEOW GRAPHS

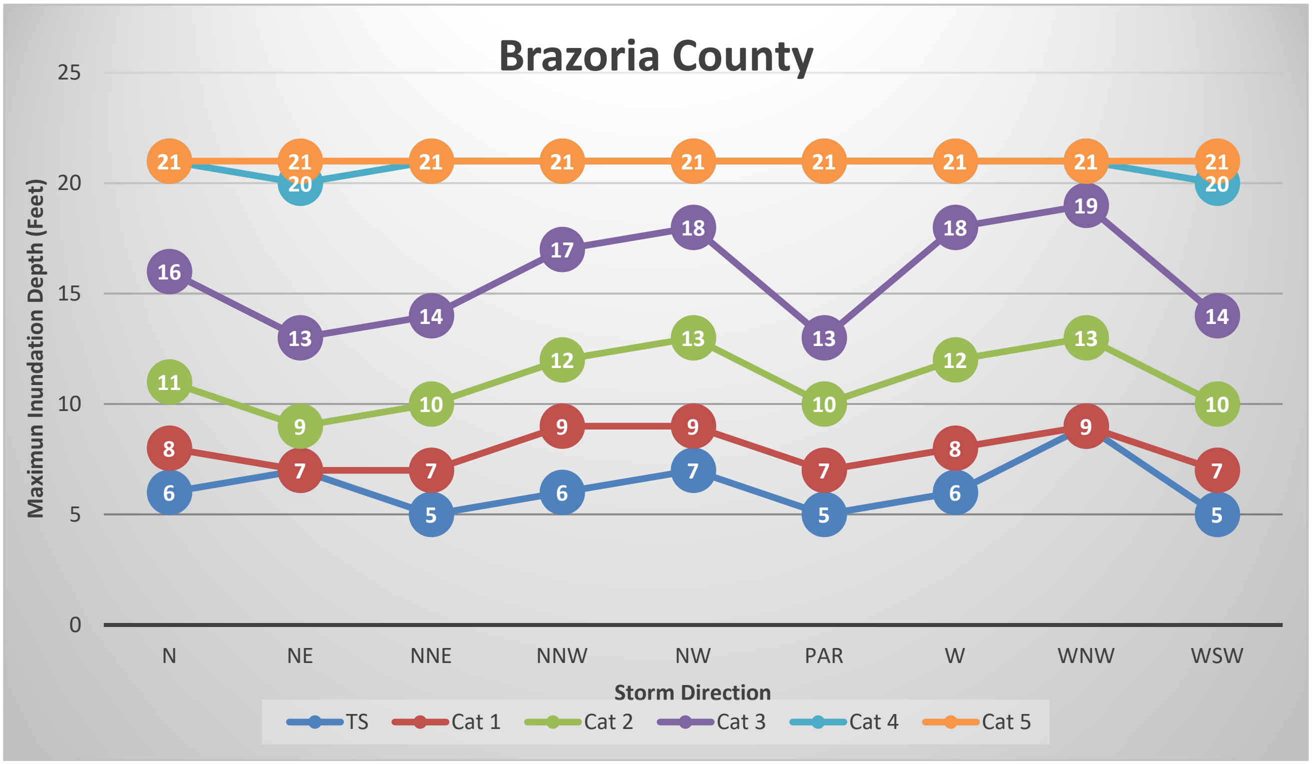


Figure E-1 Brazoria County, TX Maximum Inundation Depths for Directional MEOWs

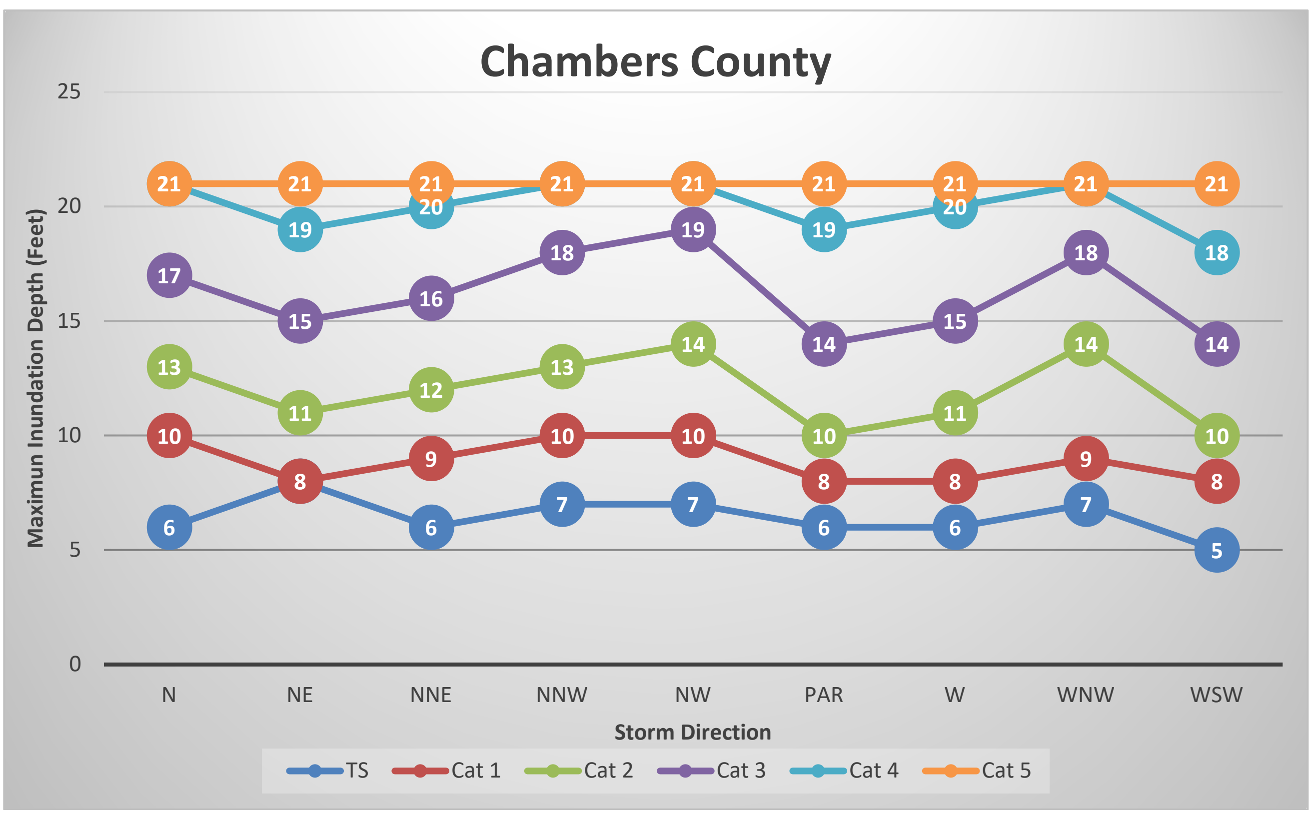


Figure E-2 Chambers County, TX Maximum Inundation Depths for Directional MEOWs

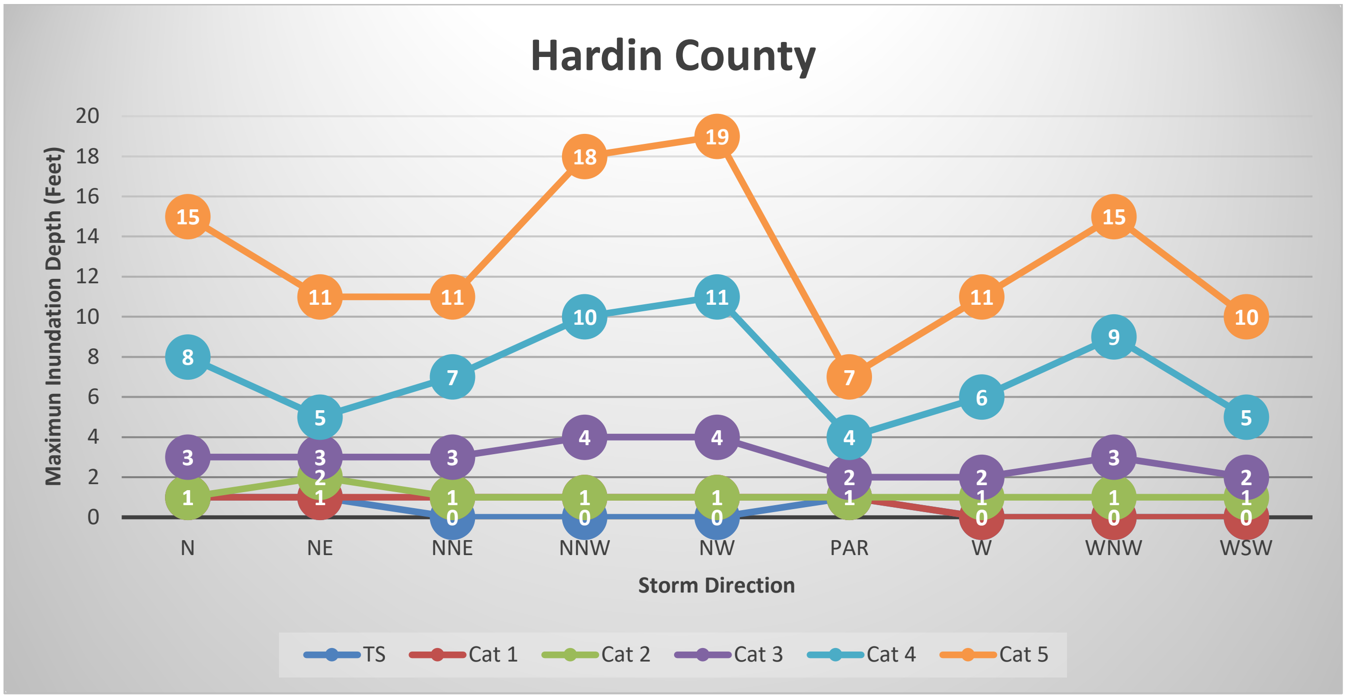


Figure E-3 Hardin County, TX Maximum Inundation Depths for Directional MEOWs

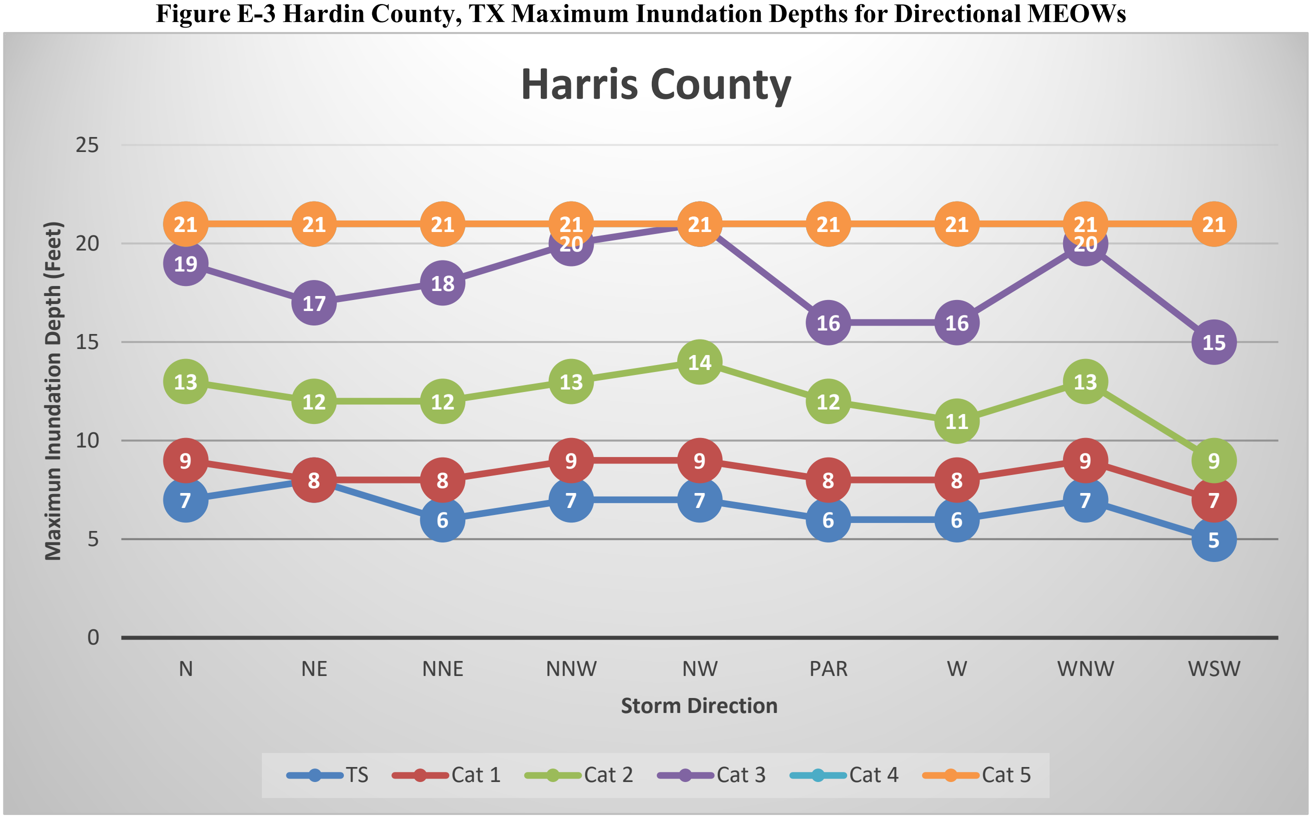


Figure E-4 Harris County, TX Maximum Inundation Depths for Directional MEOWs

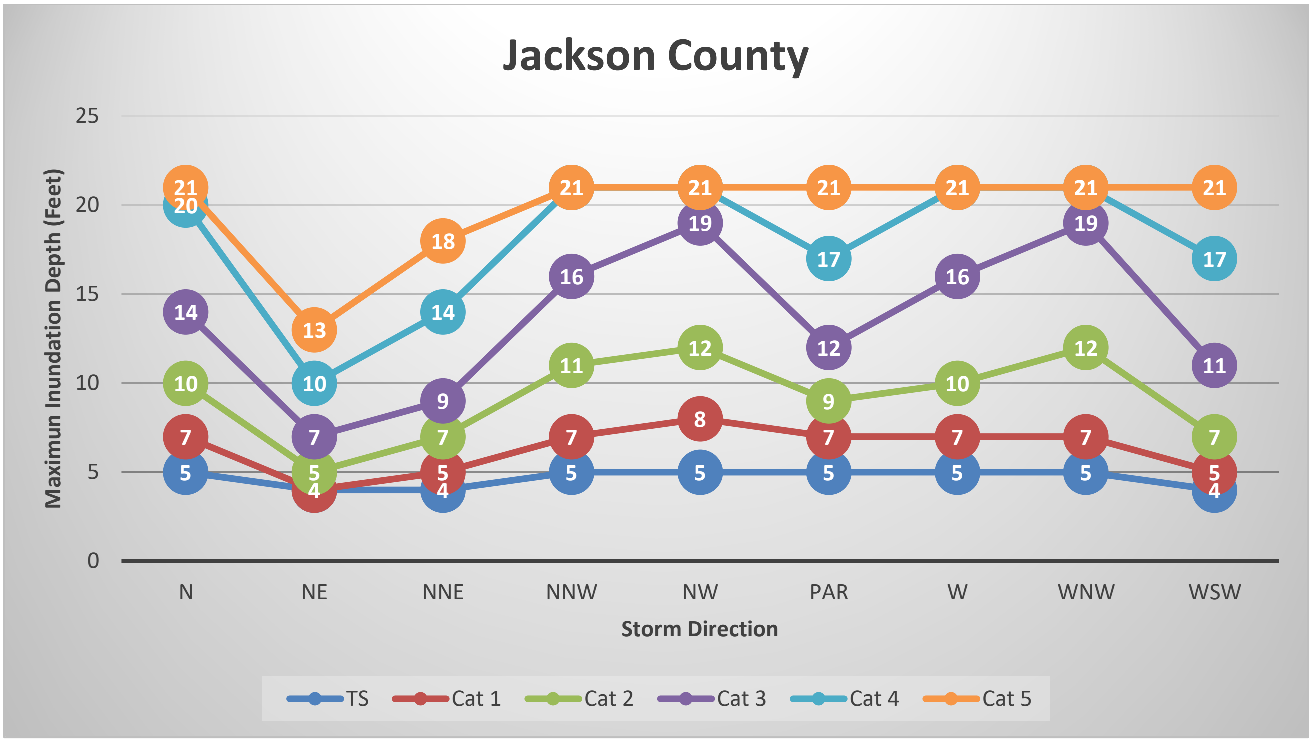


Figure E-5 Jackson County, TX Maximum Inundation Depths for Directional MEOWs

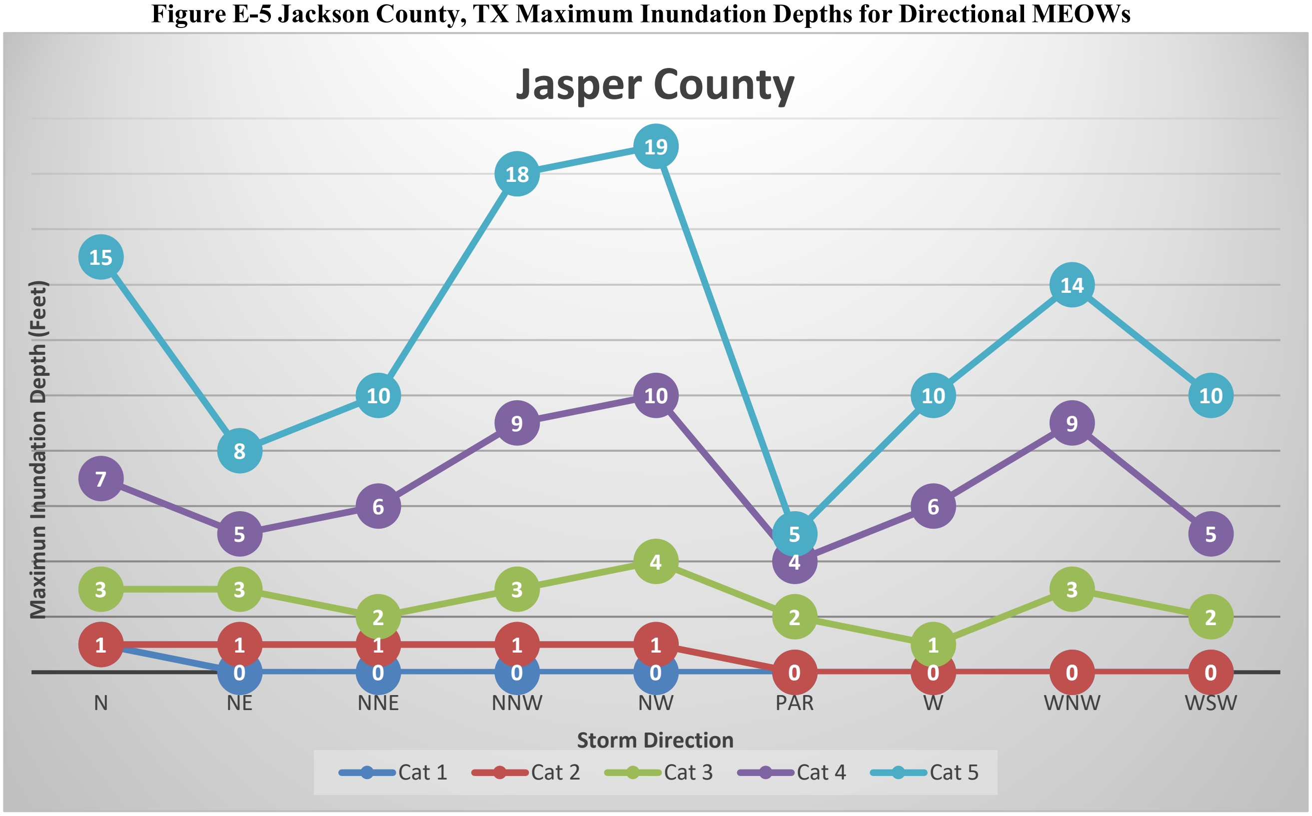


Figure E-6 Jasper County, TX Maximum Inundation Depths for Directional MEOWs

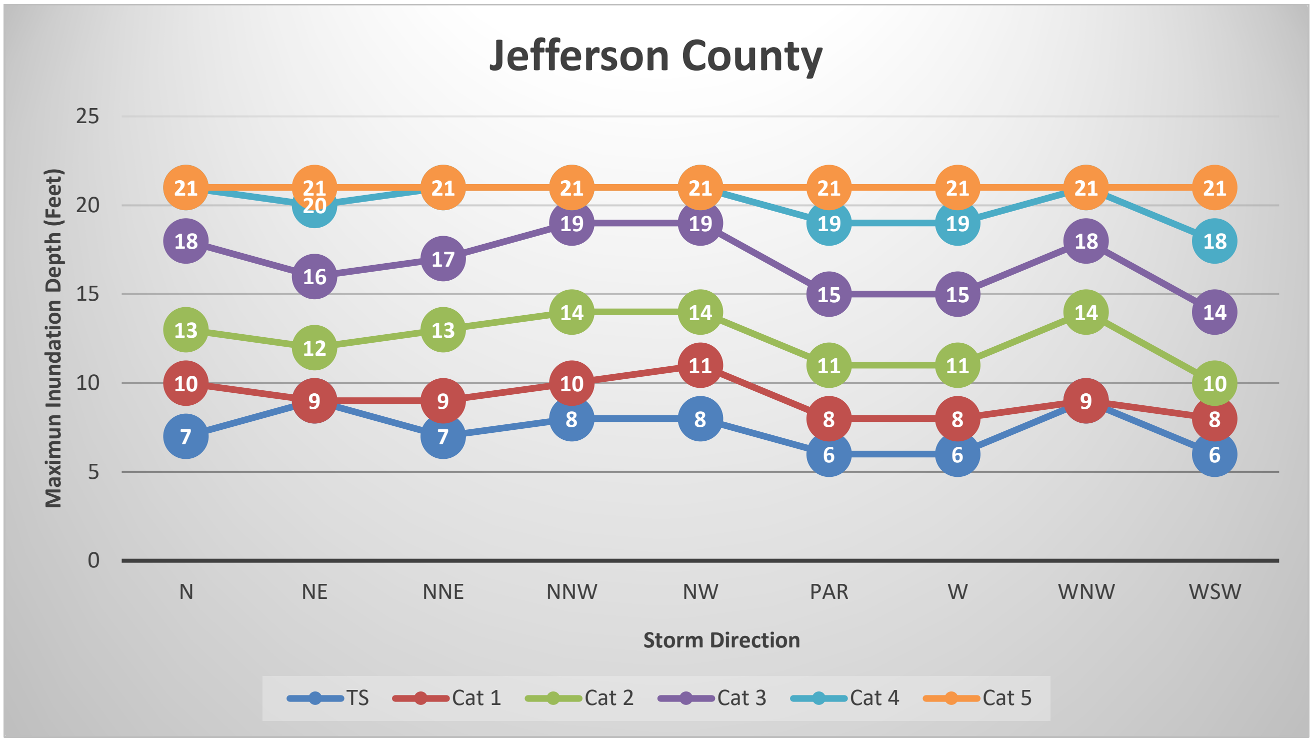


Figure E-7 Jefferson County, TX Maximum Inundation Depths for Directional MEOWs

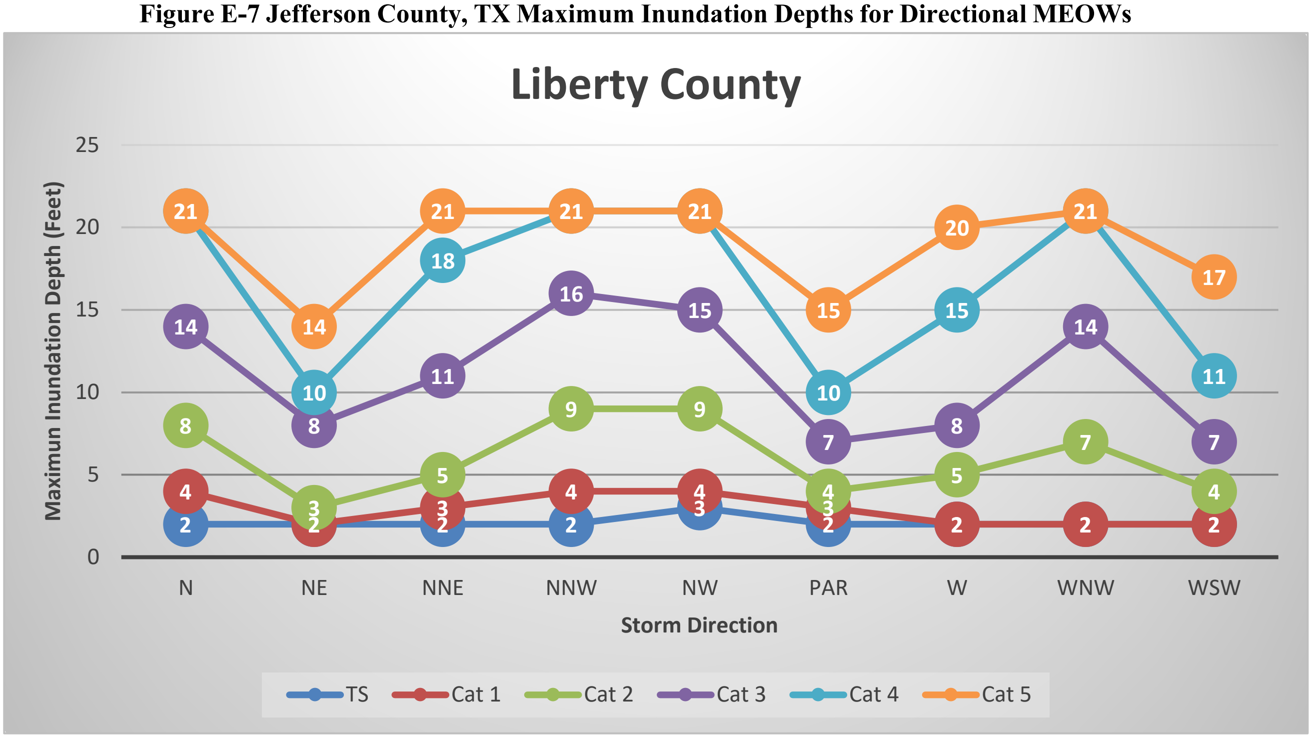


Figure E-8 Liberty County, TX Maximum Inundation Depths for Directional MEOWs

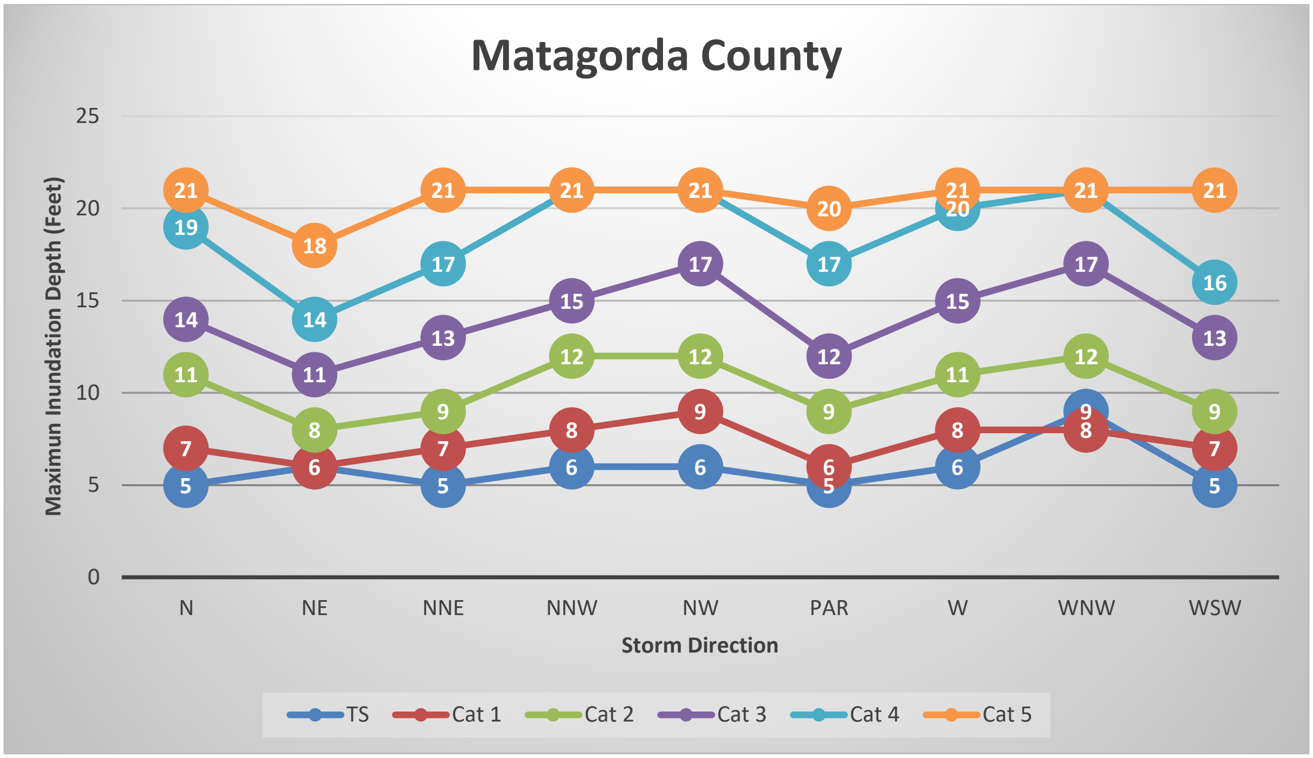


Figure E-9 Matagorda County, TX Maximum Inundation Depths for Directional MEOWs

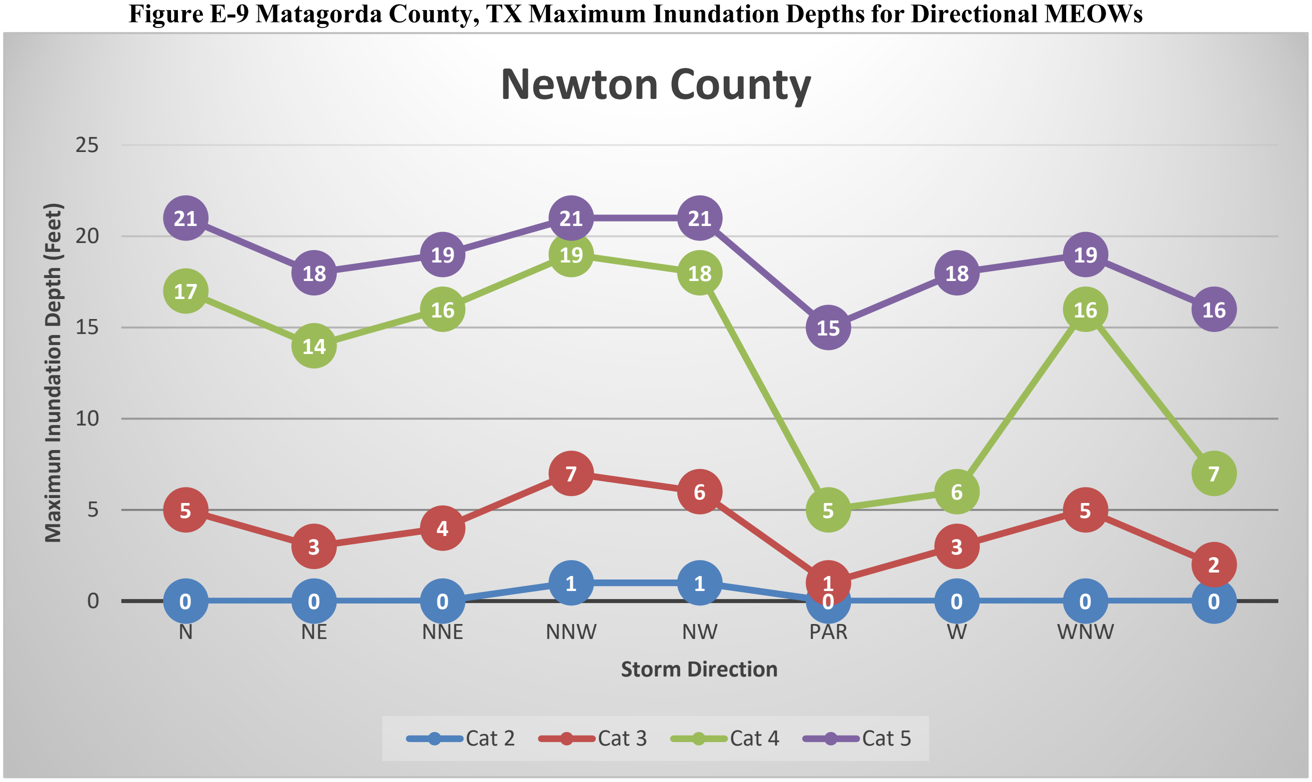


Figure E-10 Newton County, TX Maximum Inundation Depths for Directional MEOWs

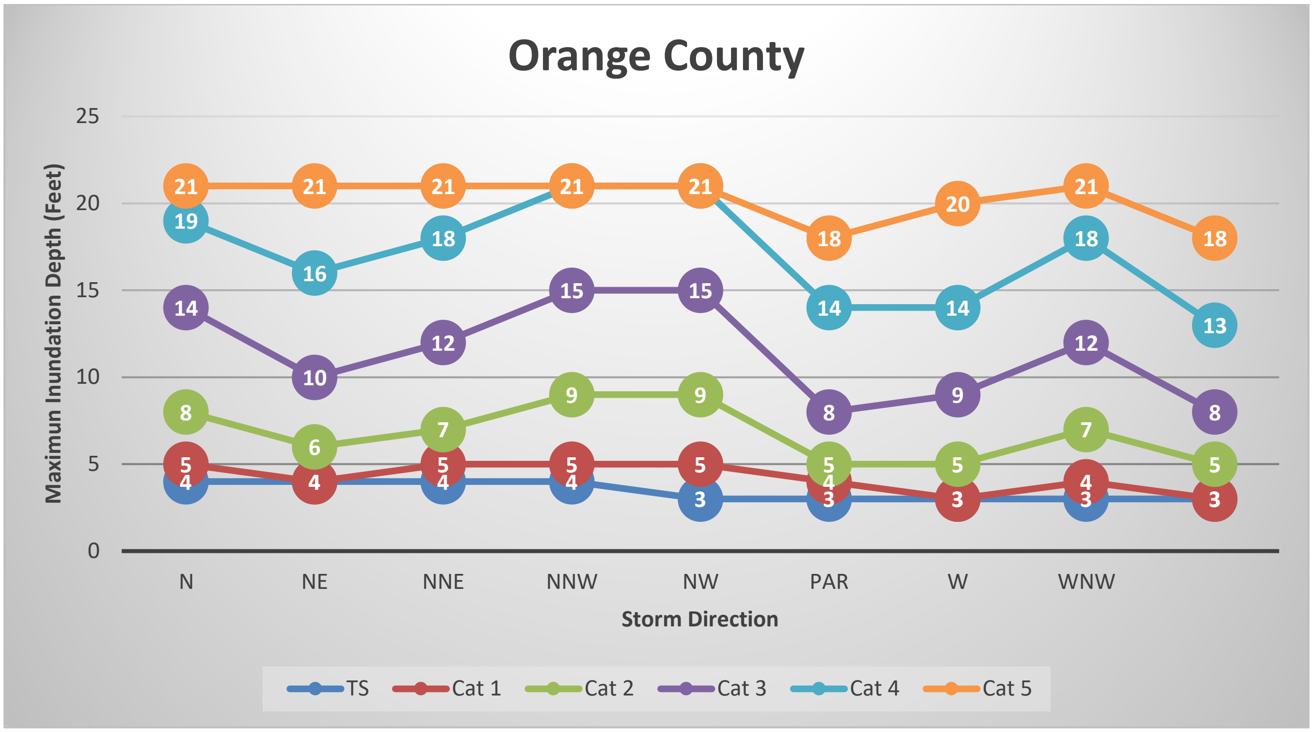


Figure E-11 Orange County, TX Maximum Inundation Depths for Directional MEOWs

APPENDIX F: COUNTY GROUPINGS BASED ON ACREAGE OF INUNDATION EXTENT

Brazoria

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundated
N0	1	6	2.5	7760	88937.399150
N1	1	8	3.7	9923	116174.472763001
N2	1	11	5.3	14484	161711.887856418
N3	1	16	7.6	27853	223179.526128231
N4	1	21	10.2	47958	298615.741149072
N5	1	21	12.0	77775	369912.637649062
NE0	1	7	2.9	8275	103632.654788686
NE1	1	7	2.9	8275	103632.654788686
NE2	1	9	4.2	12196	140990.98281352
NE3	1	13	6.0	21305	193963.241026638
NE4	1	20	8.3	37830	252954.687050649
NE5	1	21	9.9	51138	306850.73642187
NNE0	1	5	2.2	7707	84844.2032809139
NNE1	1	7	3.2	8506	108522.105425784
NNE2	1	10	4.7	13076	149893.909091477
NNE3	1	14	6.7	24498	208014.95726968
NNE4	1	21	9.2	42566	272373.434209928
NNE5	1	21	10.8	63839	338512.143853331
NNW0	1	6	2.8	7806	94727.2817426662
NNW1	1	9	4.2	10660	124324.076354207
NNW2	1	12	5.9	16364	176079.123867582
NNW3	1	17	8.4	30194	242359.111973727
NNW4	1	21	11.1	57858	334444.289770734
NNW5	1	21	12.7	91014	416102.060932962
NW0	1	7	3.0	8222	100448.78892361
NW1	1	9	4.5	11819	134124.153946102
NW2	1	13	6.4	18800	189010.459265276
NW3	1	18	9.1	35782	258518.071232629
NW4	1	21	11.8	72239	367110.396937121
NW5	1	21	13.0	106097	459148.377218977
PAR0	1	5	2.2	7718	83835.9994254865
PAR1	1	7	3.0	8510	106453.731337985
PAR2	1	10	4.4	13323	146496.54783444
PAR3	1	13	6.2	23832	202318.197666534
PAR4	1	21	8.6	41552	264986.835652714
PAR5	1	21	10.1	57491	326056.12482306
W0	1	6	2.8	7801	94808.4512521067
W1	1	8	3.9	11018	123231.826550581
W2	1	12	5.7	16649	171375.613170149
W3	1	18	8.0	29955	232120.268795181
W4	1	21	10.8	51822	316777.993785214
W5	1	21	12.5	82250	392883.216426289
WNW0	1	9	4.4	57415	130377.935709198
WNW1	1	9	4.2	11489	128345.933825508
WNW2	1	13	6.5	21114	194066.776549882
WNW3	1	19	9.2	40092	265280.767601735
WNW4	1	21	12.1	73253	372696.490850832
WNW5	1	21	13.2	107222	469260.024501695
WSW0	1	5	2.3	7506	83573.4601746397
WSW1	1	7	3.1	8163	104246.09651497
WSW2	1	10	4.5	13406	142153.90669129
WSW3	1	14	6.6	22113	196504.268831873
WSW4	1	20	9.1	40039	263244.198978904
WSW5	1	21	11.1	58776	328548.963182815
MOM1	1	11	4.9	95702	77383.004402076
MOM2	1	15	7.5	148908	102406.958860377
MOM3	1	21	10.0	236174	146293.344652939
MOM4	1	21	13.4	302964	197502.694943297
MOM5	1	22	17.0	350682	230787.391569409

Table F-1 Brazoria County, TX Grouping Based on Acreage of Inundation Extent

Chambers

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundated
N0	1	6	2.1	10196	77303.8603103381
N1	1	10	3.6	11543	101385.281730402
N2	1	13	6.3	12968	138241.368129387
N3	1	17	9.7	19899	185267.910701361
N4	1	21	12.5	31394	255898.37351495
N5	1	21	13.6	41741	311995.092908803
NE0	1	8	2.3	9637	81868.7180266672
NE1	1	8	2.3	9637	81868.7180266672
NE2	1	11	4.0	11758	114831.996288409
NE3	1	15	6.7	14591	150832.33074461
NE4	1	19	10.1	22273	191948.38370615
NE5	1	21	12.2	28544	230616.194716863
NNE0	1	6	1.9	10095	74166.3305220201
NNE1	1	9	2.9	10314	94718.6806393592
NNE2	1	12	5.3	12157	126654.448898042
NNE3	1	16	8.6	16766	165146.414912106
NNE4	1	20	11.8	25673	217819.477596807
NNE5	1	21	13.6	34352	263629.668429058
NNW0	1	7	2.2	9947	78074.6350094895
NNW1	1	10	4.0	11679	104901.807485347
NNW2	1	13	7.0	14348	143363.047192473
NNW3	1	18	10.5	21833	194078.764654774
NNW4	1	21	13.1	35485	271222.197848982
NNW5	1	21	14.0	44183	329885.483345764
NW0	1	7	2.2	9895	77102.0322862842
NW1	1	10	4.0	11772	104943.615376122
NW2	1	14	7.3	14348	143064.993160774
NW3	1	19	10.8	21863	191202.076349593
NW4	1	21	13.4	37239	267605.104865848
NW5	1	21	14.3	44124	323371.235648823
PAR0	1	6	1.7	9926	64605.8803510357
PAR1	1	8	2.3	10238	81518.5764130821
PAR2	1	10	4.0	11805	109528.008274685
PAR3	1	14	6.8	14002	144689.30247899
PAR4	1	19	10.4	19555	182611.406542978
PAR5	1	21	12.6	26850	218362.441716031
W0	1	6	1.7	9341	63640.0737727305
W1	1	8	2.4	9798	85950.5179230881
W2	1	11	4.6	11925	113820.455083606
W3	1	15	7.7	15277	148633.266563024
W4	1	20	11.2	22898	196208.848259572
W5	1	21	12.7	32175	247866.079875336
WNW0	1	7	2.1	9724	72415.8645045061
WNW1	1	9	3.2	10447	95623.6473235066
WNW2	1	14	6.6	12562	134839.653771073
WNW3	1	18	10.4	20402	175557.414343107
WNW4	1	21	13.3	32308	243760.191021217
WNW5	1	21	14.1	42690	301148.990119833
WSW0	1	5	1.5	9031	53757.1769004266
WSW1	1	8	1.9	9590	75562.2130562146
WSW2	1	10	3.4	11614	104937.052868252
WSW3	1	14	5.9	13117	139325.286215009
WSW4	1	18	9.5	18796	179190.340949679
WSW5	1	21	12.0	26792	220845.021706224
MOM1	1	11	4.5	13347	109054.291404141
MOM2	1	15	7.9	14721	146014.828723933
MOM3	1	20	11.6	22194	197591.698160289
MOM4	1	21	14.1	38507	276263.070698614
MOM5	1	21	15.0	44323	333205.109407626

Table F-2 Chambers County, TX Grouping Based on Acreage of Inundation Extent

Hardin

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	1	1.0	0	2.25142380624591
N1	1	1	1.0	0	21.0365807575879
N2	1	1	1.0	0	47.8981050064725
N3	1	3	1.4	1401	2178.16790756593
N4	1	8	3.5	3022	11917.6118839125
N5	1	15	6.2	4621	22643.9428796977
NE0	1	1	1.0	0	10.8098776499156
NE1	1	1	1.0	0	10.8098776499156
NE2	1	2	1.1	0	68.9692867010526
NE3	1	3	1.1	1401	2078.68677793255
NE4	1	5	2.8	2339	5045.86696274888
NE5	1	11	4.6	3904	13696.4899439277
NNE0				0	0.05
NNE1	1	1	1.0	0	16.3583105592827
NNE2	1	1	1.0	0	35.2507054199421
NNE3	1	3	1.1	1390	1913.72797401868
NNE4	1	7	2.4	2704	10329.216008173
NNE5	1	11	4.6	3937	18324.9461623747
NNW0				0	0.05
NNW1	1	1	1.0	0	18.9757595662818
NNW2	1	1	1.0	0	47.0783202007743
NNW3	1	4	1.8	1882	2758.71264004405
NNW4	1	10	4.6	3904	13809.8819447611
NNW5	1	18	7.9	5821	28659.6794412724
NW0				0	0.05
NW1	1	1	1.0	0	7.2641019380389
NW2	1	1	1.0	0	28.7320299526866
NW3	1	4	1.9	2048	2948.39587001535
NW4	1	11	4.4	3904	16173.8405209213
NW5	1	19	7.8	6168	29848.7926551286
PAR0	1	1	1.0	0	0.376609765757192
PAR1	1	1	1.0	0	0.572893242616083
PAR2	1	1	1.0	0	16.5619100801603
PAR3	1	2	1.4	0	120.255467406584
PAR4	1	4	2.1	2048	3182.44648344723
PAR5	1	7	2.4	2716	10348.8557014121
W2	1	1	1.0	0	16.3583105592827
W3	1	2	1.3	0	94.3881081258388
W4	1	6	3.0	2066	4049.82634495926
W5	1	11	5.0	3904	13557.2079898751
WNW2	1	1	1.0	0	22.1486303427977
WNW3	1	3	1.1	1000	1802.5037600931
WNW4	1	9	4.1	3697	12596.7906993668
WNW5	1	15	6.0	5543	27211.7171580763
WSW2	1	1	1.0	0	16.3583105592827
WSW3	1	2	1.5	0	132.262655871823
WSW4	1	5	2.9	2066	3907.96373738615
WSW5	1	10	4.2	3022	11873.1936316638
MOM1	1	4	1.8	1827	1327.33331212663
MOM2	1	6	2.5	1982	2616.40480292271
MOM3	1	10	3.8	2340	8927.73192183105
MOM4	1	18	7.9	4913	20287.7815247256
MOM5	1	21	9.9	8363	35486.923178886

Table F-3 Hardin County, TX Grouping Based on Acreage of Inundation Extent

Harris

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	7	2.6	49443	5650.36120467904
N1	1	9	3.2	71070	10235.9044295844
N2	1	13	3.9	105040	22766.6985071289
N3	1	19	5.5	167519	48794.4072872993
N4	1	21	7.4	358281	97216.2944407448
N5	1	21	8.6	611120	154213.146685222
NE0	1	8	2.7	67150	8527.27643088503
NE1	1	8	2.7	67150	8527.27643088503
NE2	1	12	3.2	93018	18520.6758015681
NE3	1	17	4.3	140202	39523.054098653
NE4	1	21	6.1	253770	70456.7873124
NE5	1	21	6.8	443575	114194.61134424
NNE0	1	6	2.4	48380	5260.16231735079
NNE1	1	8	2.9	69378	9450.68913688492
NNE2	1	12	3.5	97637	20651.9533907054
NNE3	1	18	4.8	155125	44189.7877221604
NNE4	1	21	6.6	302992	83172.403553729
NNE5	1	21	7.6	523347	132979.124492569
NNW0	1	7	2.8	57559	6018.42041332494
NNW1	1	9	3.4	73745	11463.4830584007
NNW2	1	13	4.3	110553	25972.1897424909
NNW3	1	20	6.2	193878	58221.5259157327
NNW4	1	21	7.8	487755	127651.766396353
NNW5	1	21	9.4	793332	192394.16933597
NW0	1	7	2.8	59837	6200.85252986102
NW1	1	9	3.4	77351	12337.635990596
NW2	1	14	4.5	118203	29124.0491643437
NW3	1	21	6.6	228760	65856.7998828843
NW4	1	21	8.3	580292	147984.852928749
NW5	1	21	10.1	930973	217371.367428975
PAR0	1	6	2.3	48295	5056.21884007737
PAR1	1	8	2.9	67129	8526.62384945226
PAR2	1	12	3.4	92891	18469.4905373766
PAR3	1	16	4.5	137369	38921.5376895392
PAR4	1	21	6.4	247093	68854.5985932231
PAR5	1	21	7.2	424860	110589.608552744
W0	1	6	2.1	45650	4537.85692524585
W1	1	8	2.6	64529	7102.24639169754
W2	1	11	3.3	87428	15819.7321536286
W3	1	16	4.4	136212	38173.8494414273
W4	1	21	6.7	270301	74052.1319353434
W5	1	21	8.0	478636	123070.138920219
WNW0	1	7	2.6	58932	5927.7295312922
WNW1	1	9	3.0	68241	9269.64118919729
WNW2	1	13	4.2	111639	26333.4388380676
WNW3	1	20	6.4	195111	57020.6184233753
WNW4	1	21	8.1	507625	129342.511098675
WNW5	1	21	9.7	861033	199346.976032548
WSW0	1	5	1.7	43047	3540.17468226684
WSW1	1	7	2.2	57134	5449.04746666859
WSW2	1	9	2.7	75279	11813.4062492846
WSW3	1	15	3.7	118188	30492.1429941947
WSW4	1	21	5.6	215832	61783.8207617898
WSW5	1	21	7.5	380919	102414.721654566
MOM1	1	10	4.1	94146	11045.7144323744
MOM2	1	15	5.2	129701	26931.1731115776
MOM3	1	21	7.6	245839	63064.5362549047
MOM4	1	21	9.5	592184	144658.685885158
MOM5	1	21	11.3	945971	216092.057447713

Table F-4 Harris County, TX Grouping Based on Acreage of Inundation Extent

Jackson

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	5	2.3	585	10379.7503005955
N1	1	7	3.2	600	12802.7016375784
N2	1	10	4.6	743	16934.8696954048
N3	1	14	6.7	1264	26290.2072316601
N4	1	20	8.5	1743	42403.1820833876
N5	1	21	9.2	1997	60925.3769573711
NE0	1	4	1.7	552	8252.29498020499
NE1	1	4	1.7	552	8252.29498020499
NE2	1	5	2.3	585	10192.088938808
NE3	1	7	3.3	674	14579.4093203332
NE4	1	10	4.7	985	20273.787977825
NE5	1	13	5.7	1191	24806.1452018778
NNE0	1	4	1.7	571	8268.835628361
NNE1	1	5	2.1	585	9792.64594713414
NNE2	1	7	2.9	655	12953.872934684
NNE3	1	9	4.4	883	19483.4071315486
NNE4	1	14	6.2	1303	27596.1919293616
NNE5	1	18	7.4	1472	35804.822921
NNW0	1	5	2.4	589	10790.2741811264
NNW1	1	7	3.5	642	13612.4501152702
NNW2	1	11	5.3	951	19186.8884990467
NNW3	1	16	7.7	1535	30451.4623536765
NNW4	1	21	9.3	1959	50448.7942064066
NNW5	1	21	8.8	2070	83135.2680077421
NW0	1	5	2.4	589	10816.6765729319
NW1	1	8	3.6	655	14422.4150653981
NW2	1	12	5.9	1103	21449.3822174699
NW3	1	19	8.0	1705	33725.5270855731
NW4	1	21	9.1	1985	59992.8772710686
NW5	1	21	8.9	2296	98387.1455803072
PAR0	1	5	2.2	574	9512.26372159025
PAR1	1	7	3.0	600	11588.8800396706
PAR2	1	9	4.1	685	14697.9626714281
PAR3	1	12	5.7	1176	22884.406879088
PAR4	1	17	7.5	1630	35920.1222544968
PAR5	1	21	8.6	1761	48886.1723282196
W0	1	5	2.0	585	10225.320681676
W1	1	7	3.2	642	13833.7242088443
W2	1	10	5.3	1011	19396.713793222
W3	1	16	7.3	1352	28725.8556965561
W4	1	21	8.9	1763	48523.4674276557
W5	1	21	8.7	2059	80205.1810787143
WNW0	1	5	2.3	589	10821.860129011
WNW1	1	7	3.1	606	13157.3467028271
WNW2	1	12	6.0	1108	21644.7874103586
WNW3	1	19	8.0	1705	33449.4839282536
WNW4	1	21	9.0	1981	59972.2730074744
WNW5	1	21	9.0	2200	97889.8759532688
WSW0	1	4	1.5	552	7882.01581486213
WSW1	1	5	2.1	585	10636.7609575615
WSW2	1	7	3.5	659	14605.399158315
WSW3	1	11	5.7	1029	20199.2936561237
WSW4	1	17	7.6	1415	29825.3039787219
WSW5	1	21	8.9	1739	41635.5618048348
MOM1	1	9	4.7	649	13712.6863380673
MOM2	1	15	7.4	1092	20727.1249652258
MOM3	1	20	9.0	1603	33506.10705304
MOM4	1	21	9.7	1950	60884.311112155
MOM5	1	21	9.9	2322	99131.7129787944

Table F-5 Jackson County, TX Grouping Based on Acreage of Inundation Extent

Jasper

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N1	1	1	1.0	0	0.39938013658961
N2	1	1	1.0	93	4.61613680117344
N3	1	3	1.6	145	28.7162387083756
N4	1	7	2.8	578	985.489519043178
N5	1	15	5.0	786	3350.13317119916
NE2	1	1	1.0	145	5.83671112205823
NE3	1	3	1.8	145	26.2227396793622
NE4	1	5	2.3	145	151.833973435862
NE5	1	8	3.6	578	1333.29115134032
NNE2	1	1	1.0	0	1.00970252504385
NNE3	1	2	1.6	145	24.8128188290388
NNE4	1	6	1.7	145	613.106756533314
NNE5	1	10	3.3	641	2664.40043366671
NNW2	1	1	1.0	0	1.82342062364648
NNW3	1	3	1.9	145	40.489095870635
NNW4	1	9	3.3	578	1407.80289268074
NNW5	1	18	5.7	1148	5268.18747610114
NW2	1	1	1.0	0	0.39938013658961
NW3	1	4	2.0	145	45.149900869393
NW4	1	10	3.0	641	1982.55792125433
NW5	1	19	5.8	1048	5166.98413733817
PAR3	1	2	1.1	145	12.4791290817957
PAR4	1	4	1.8	145	61.6460432918615
PAR5	1	5	1.5	145	583.925909099389
W3	1	1	1.0	145	9.24377341313341
W4	1	6	2.4	145	93.2154107632231
W5	1	10	3.8	578	1309.19313694533
WNW3	1	3	1.7	145	22.0852922492611
WNW4	1	9	3.3	578	1020.2439503345
WNW5	1	14	4.4	1048	4648.14476420032
WSW3	1	2	1.2	145	14.1064440727426
WSW4	1	5	2.2	145	83.4528704462726
WSW5	1	10	2.9	204	924.238245098261
MOM2	1	1	1.0	93	5.48582811688238
MOM3	1	4	1.3	145	243.699447835625
MOM4	1	12	4.6	641	2603.32185906154
MOM5	1	19	7.1	1193	5026.3065479345

Table F-6 Jasper County, TX Grouping Based on Acreage of Inundation Extent

Jefferson

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	7	2.2	5074	110375.836048843
N1	1	10	4.0	5452	146812.329890198
N2	1	13	6.4	7287	204006.910187592
N3	1	18	9.2	18675	286572.146117313
N4	1	21	12.7	82795	375329.394139443
N5	1	21	15.1	138780	435289.174602746
NE0	1	9	2.8	5444	137110.041154451
NE1	1	9	2.8	5444	137110.041154451
NE2	1	12	4.8	7001	186726.710186166
NE3	1	16	7.3	12554	248102.747531712
NE4	1	20	10.3	33717	323335.237959256
NE5	1	21	12.8	83882	378558.739350301
NNE0	1	7	1.9	5074	104856.793442649
NNE1	1	9	3.4	5444	139754.636383901
NNE2	1	13	5.6	7146	190225.309526345
NNE3	1	17	8.3	16107	266046.570064075
NNE4	1	21	11.6	53363	346009.893534892
NNE5	1	21	14.0	112684	403550.189196064
NNW0	1	8	2.5	5285	114321.235257233
NNW1	1	10	4.4	5554	154603.338386447
NNW2	1	14	6.7	8391	219145.5898912
NNW3	1	19	10.0	20575	298119.413214812
NNW4	1	21	13.6	97722	391896.019053107
NNW5	1	21	15.8	144427	449626.120227082
NW0	1	8	2.6	5074	115365.333799301
NW1	1	11	4.5	5542	154030.565132173
NW2	1	14	7.0	8281	211674.509080862
NW3	1	19	10.2	19016	290431.239157007
NW4	1	21	13.9	92924	383708.739415118
NW5	1	21	16.0	141747	440053.811291473
PAR0	1	6	1.6	4684	98339.8620133867
PAR1	1	8	2.6	5409	132109.669483063
PAR2	1	11	4.6	6551	173272.911219126
PAR3	1	15	6.9	9099	232269.43915868
PAR4	1	19	10.0	21172	296224.822393729
PAR5	1	21	12.3	52950	347845.42253229
W0	1	6	1.9	4509	99260.7128163231
W1	1	8	2.8	5122	128782.007643969
W2	1	11	4.9	6053	171563.777648157
W3	1	15	7.2	11942	236526.350635815
W4	1	19	10.3	26400	309798.679055066
W5	1	21	12.4	82487	376050.397242875
WNW0	1	9	4.2	99197	152875.307255086
WNW1	1	9	3.8	4890	139801.994231261
WNW2	1	14	6.4	7302	199530.533568633
WNW3	1	18	9.2	16629	274986.179637342
WNW4	1	21	12.6	75314	368489.729675587
WNW5	1	21	14.7	137044	435892.948130239
WSW0	1	6	1.6	4495	88637.5598467448
WSW1	1	8	2.3	5027	118169.827903283
WSW2	1	10	4.0	5921	165516.043155857
WSW3	1	14	6.1	11767	227213.065913131
WSW4	1	18	8.8	21010	294952.110763643
WSW5	1	21	11.7	62736	358156.358755596
MOM1	1	12	5.1	9995	179384.437239011
MOM2	1	16	7.8	11864	244785.906842299
MOM3	1	21	11.4	27461	317272.554699549
MOM4	1	21	15.0	111344	406483.706300357
MOM5	1	22	17.1	243345	506036.867529564

Table F-7 Jefferson County, TX Grouping Based on Acreage of Inundation Extent

Liberty

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	2	1.1	1667	137.99047379497
N1	1	4	1.6	1678	360.505366508102
N2	1	8	2.7	2891	7496.32349660831
N3	1	14	6.2	4050	18186.3770144844
N4	1	21	9.1	5270	34345.6681250778
N5	1	21	11.9	7904	44961.4403830101
NE0	1	2	1.1	1667	82.4193443026892
NE1	1	2	1.1	1667	82.4193443026892
NE2	1	3	1.4	1667	274.009904869637
NE3	1	8	2.5	2891	6586.26130324988
NE4	1	10	4.6	3225	13710.3421147012
NE5	1	14	6.2	4457	21643.4445798162
NNE0	1	2	1.1	1667	136.164588866741
NNE1	1	3	1.3	1667	253.23864734056
NNE2	1	5	1.4	2489	6103.02565274364
NNE3	1	11	4.4	2994	12280.4959302817
NNE4	1	18	7.7	4561	23194.1949156778
NNE5	1	21	9.5	5457	33489.8870244891
NNW0	1	2	1.1	1667	123.339553176462
NNW1	1	4	1.5	2319	696.007502265219
NNW2	1	9	3.5	2942	9603.40806017659
NNW3	1	16	6.9	4333	21810.4772192349
NNW4	1	21	10.4	5836	39272.8042334074
NNW5	1	21	12.1	12169	54719.6121280388
NW0	1	3	1.2	1667	104.39182329211
NW1	1	4	1.6	1678	435.743020685662
NW2	1	9	3.3	2942	9430.17593094386
NW3	1	15	6.8	4333	20892.9978893104
NW4	1	21	10.3	5851	38717.0757575221
NW5	1	21	12.6	11399	52347.9651661049
PAR0	1	2	1.1	1667	91.6289585026641
PAR1	1	3	1.2	1667	140.583891031705
PAR2	1	4	1.5	1667	340.431911893866
PAR3	1	7	1.8	2942	8171.19614148013
PAR4	1	10	4.2	3225	13229.9443714773
PAR5	1	15	6.4	4388	20906.9687072218
W0	1	2	1.1	1667	46.3485733988833
W1	1	2	1.0	1667	125.611510656512
W2	1	5	1.2	2329	2727.44834097038
W3	1	8	3.1	2942	10710.0631612508
W4	1	15	6.4	4212	20110.9974325843
W5	1	20	9.1	5024	28076.9145728506
WNW0	1	2	1.1	1667	66.9166990404342
WNW1	1	2	1.1	1667	79.9872949484415
WNW2	1	7	2.4	2942	8427.5988127671
WNW3	1	14	5.9	3778	16324.7484124458
WNW4	1	21	9.2	5257	31876.1973294501
WNW5	1	21	12.2	7720	43453.9859380099
WSW0	1	2	1.1	1667	39.1972976281223
WSW1	1	2	1.1	1667	60.7763098274585
WSW2	1	4	1.6	1667	349.956181123127
WSW3	1	7	2.7	2942	9397.08726278582
WSW4	1	11	4.3	4021	17148.6235179212
WSW5	1	17	7.2	4522	24073.2812215367
MOM1	1	6	2.0	2402	3212.27286550492
MOM2	1	10	4.2	2964	8382.78814684122
MOM3	1	18	7.9	4394	20638.2379048587
MOM4	1	21	11.7	8961	40104.1818578301
MOM5	1	21	14.4	14536	52993.5384928906

Table F-8 Liberty County, TX Grouping Based on Acreage of Inundation Extent

Matagorda

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	5	2.2	2863	65437.1837818342
N1	1	7	3.4	3400	92526.1672306525
N2	1	11	4.8	4345	132769.692565679
N3	1	14	6.7	7712	191724.230143653
N4	1	19	9.0	9121	257581.561714446
N5	1	21	11.1	9460	301784.257781752
NE0	1	6	2.5	2638	72437.8424861387
NE1	1	6	2.5	2638	72437.8424861387
NE2	1	8	3.6	2996	98617.0169301529
NE3	1	11	5.0	3458	134273.329336729
NE4	1	14	6.7	4377	180414.280525851
NE5	1	18	8.1	5350	213343.689248354
NNE0	1	5	1.9	2818	59168.1439601588
NNE1	1	7	3.0	3081	85155.8961293793
NNE2	1	9	4.3	3690	117461.479460366
NNE3	1	13	6.0	4860	165639.174633487
NNE4	1	17	8.0	7559	223782.596300205
NNE5	1	21	9.7	8885	263283.043313401
NNW0	1	6	2.4	2900	70108.7825702622
NNW1	1	8	3.7	3496	100444.552295638
NNW2	1	12	5.3	4748	144710.732432883
NNW3	1	15	7.4	8199	208497.112039636
NNW4	1	21	10.1	9214	274853.901040422
NNW5	1	21	12.2	9692	321706.959435114
NW0	1	6	2.7	2940	74420.1302335438
NW1	1	9	4.0	3503	106302.765099307
NW2	1	12	5.7	4911	156464.264279852
NW3	1	17	8.0	8534	221936.921840514
NW4	1	21	11.0	9313	287699.136429364
NW5	1	21	13.0	9906	340223.336862129
PAR0	1	5	2.0	2788	58382.7077367866
PAR1	1	6	2.9	3340	84613.3659478771
PAR2	1	9	4.2	3954	118400.502017739
PAR3	1	12	5.7	6319	172443.528862748
PAR4	1	17	7.8	8998	235043.783231251
PAR5	1	20	9.5	9256	277671.90301766
W0	1	6	2.7	2860	72354.6177735482
W1	1	8	3.8	3389	102092.322990659
W2	1	11	5.4	4437	148165.796016404
W3	1	15	7.5	7443	205678.730270839
W4	1	20	10.3	9125	267671.765603926
W5	1	21	12.6	9661	311059.726702288
WNW0	1	9	3.0	3202	77563.7857303772
WNW1	1	8	3.7	3372	104103.180959426
WNW2	1	12	5.9	4864	159806.482123435
WNW3	1	17	8.1	8405	225569.724880628
WNW4	1	21	11.3	9378	292278.557068674
WNW5	1	21	13.2	10231	346039.816934511
WSW0	1	5	2.1	2626	60779.3657327361
WSW1	1	7	3.1	2876	83248.7324349553
WSW2	1	9	4.3	3547	116412.267448281
WSW3	1	13	6.2	4546	161048.438910143
WSW4	1	16	8.2	7909	218911.51142016
WSW5	1	21	10.1	8883	263915.409407167
MOM1	1	9	4.2	3521	106706.566901521
MOM2	1	13	6.1	4944	159510.929693854
MOM3	1	18	8.5	8366	225495.427048518
MOM4	1	21	11.8	9623	294444.752540128
MOM5	1	22	13.8	10468	351132.64972587

Table F-9 Matagorda County, TX Grouping Based on Acreage of Inundation Extent

Newton

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N3	1	5	1.6	260	841.302874034239
N4	1	17	4.2	925	6175.02333172717
N5	1	21	6.7	1362	10456.9398377868
NE3	1	3	1.4	26	7.33304997507734
NE4	1	14	2.9	523	3237.68719404932
NE5	1	18	4.2	925	7534.24290293626
NNE3	1	4	1.2	233	314.885918919338
NNE4	1	16	2.8	832	5015.62114198185
NNE5	1	19	4.7	1202	9167.37316330146
NNW2	1	1	1.0	26	0.203433470263067
NNW3	1	7	1.9	260	1048.82039374551
NNW4	1	19	4.9	925	6973.1376745646
NNW5	1	21	6.6	1816	14178.0975463044
NW2	1	1	1.0	26	0.203433470263067
NW3	1	6	1.9	260	1002.57889161657
NW4	1	18	4.4	925	6639.47433029989
NW5	1	21	6.8	1621	11854.2610965164
PAR3	1	1	1.0	26	1.01717129636297
PAR4	1	5	1.7	233	556.850487902485
PAR5	1	15	2.9	540	3664.04973979111
W3	1	3	1.5	26	5.37080641657497
W4	1	6	2.4	346	2249.11027014313
W5	1	18	3.6	912	6077.99352733956
WNW3	1	5	1.5	233	413.042747464126
WNW4	1	16	3.2	802	5204.3321503394
WNW5	1	19	4.8	1236	9630.06214431042
WSW3	1	2	1.1	26	3.03445091782517
WSW4	1	7	2.0	260	1267.97094687275
WSW5	1	16	4.0	733	4535.13399256747
MOM3	1	6	2.3	777	3223.43265530693
MOM4	1	12	5.7	1166	8183.70988481128
MOM5	1	18	8.1	2000	15761.4612410483

Table F-10 Newton County, TX Grouping Based on Acreage of Inundation Extent

Orange

Storm/Direction	Min Depth (ft)	Max Depth (ft)	Avg Depth (ft)	Population Impacts	Acres Inundation
N0	1	4	1.4	8359	12928.2181867243
N1	1	5	1.8	10500	18359.0771954355
N2	1	8	2.8	16986	35466.1708250111
N3	1	14	4.8	40841	71710.2395684155
N4	1	19	7.8	60741	126430.900684635
N5	1	21	10.7	79951	169301.358831096
NE0	1	4	1.4	9017	16180.6667835523
NE1	1	4	1.4	9017	16180.6667835523
NE2	1	6	2.1	13745	32119.2607684604
NE3	1	10	3.3	32662	58569.0866187809
NE4	1	16	5.5	54362	100137.205011907
NE5	1	21	7.4	67054	141734.059555135
NNE0	1	4	1.4	8359	13181.6340448044
NNE1	1	5	1.7	10080	18103.7467590555
NNE2	1	7	2.5	14802	33062.688464443
NNE3	1	12	4.0	35861	64991.0405234088
NNE4	1	18	6.6	57268	110898.903197784
NNE5	1	21	9.0	72543	153324.124428337
NNW0	1	4	1.4	8348	12127.5731656065
NNW1	1	5	1.9	10500	18368.9866227664
NNW2	1	9	3.1	19964	37529.3884936896
NNW3	1	15	5.3	46367	76673.7677706294
NNW4	1	21	8.6	65693	139454.070895913
NNW5	1	21	11.6	83376	186181.670875347
NW0	1	3	1.4	8207	10448.5355452068
NW1	1	5	1.8	9996	17579.6159761237
NW2	1	9	3.0	19996	37105.9184427794
NW3	1	15	5.1	45755	76082.3422602696
NW4	1	21	8.5	66404	138407.287033751
NW5	1	21	11.7	82648	180523.438035169
PAR0	1	3	1.3	7840	10252.940195051
PAR1	1	4	1.4	8331	12784.7963367038
PAR2	1	5	1.7	10597	22690.3649742214
PAR3	1	8	2.8	21902	42544.9703622187
PAR4	1	14	4.6	49553	79452.1665350696
PAR5	1	18	6.5	55733	109665.663820507
W0	1	3	1.2	7677	7400.48430292977
W1	1	3	1.2	7807	9668.90928242266
W2	1	5	1.6	10865	20157.9196174141
W3	1	9	3.0	25222	45547.3559495879
W4	1	14	4.8	52631	88892.8444882627
W5	1	20	6.6	63594	132311.526387116
WNW0	1	3	1.3	7683	8864.89151393214
WNW1	1	4	1.5	8180	10823.3140026789
WNW2	1	7	2.5	14698	31491.265229692
WNW3	1	12	4.1	38200	66912.6751778545
WNW4	1	18	6.6	59776	122024.599668031
WNW5	1	21	9.3	80142	166009.975181497
WSW0	1	3	1.2	7677	6708.86810820908
WSW1	1	3	1.2	7677	8358.11700843855
WSW2	1	5	1.5	10579	21157.1620868062
WSW3	1	8	2.6	22006	42432.720729127
WSW4	1	13	4.1	48460	79749.0637127531
WSW5	1	18	6.6	58384	116835.695208194
MOM1	1	6	2.5	14943	33289.6468001698
MOM2	1	9	4.2	33892	53209.6455693881
MOM3	1	15	6.8	58162	97351.2200612534
MOM4	1	21	10.2	75975	152017.722666392
MOM5	1	21	13.3	84193	192510.117347294

Table F-11 Orange County, TX Grouping Based on Acreage of Inundation Extent